Janos J. Bogardi
Joyeeta Gupta
K. D. Wasantha Nandalal
Léna Salamé
Ronald R. P. van Nooijen
Navneet Kumar
Tawatchai Tingsanchali
Anik Bhaduri
Alla G. Kolechkina
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Handbook of Water Resources Management: Discourses, Concepts and Examples

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Editors
Janos J. Bogardi
Center for Development Research
University of Bonn
Bonn, Germany

Institute of Advanced Studies Köszeg
Köszeg, Hungary

Léna Salamé
Lawyer, Conflict Resolution Specialist
Paris, France

Navneet Kumar
Center for Development Research (ZEF)
University of Bonn
Bonn, Germany

Anik Bhaduri
Sustainable Water Future Programme
Griffith University
Brisbane, Australia

Joyeeta Gupta
University of Amsterdam and IHE-Delft Institute
for Water Education
Delft, The Netherlands

K. D. Wasantha Nandalal
Department of Civil Engineering
University of Peradeniya
Peradeniya, Sri Lanka

Ronald R. P. van Nooijen
Department of Water Management
Delft University of Technology
Delft, The Netherlands

Tawatchai Tingsanchali
Water Engineering and Management
Asian Institute of Technology
Pathum thani, Thailand

Alla G. Kolechkina
Delft Center for Systems and Control
Delft University of Technology
Delft, The Netherlands

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Foreword

Water crises have begun. The drama of too little water, too much water and polluted water is unfolding before our eyes—with all their consequences for societies, economies and the environment. We all know that there is no such phenomenon as an isolated crisis. In a world in which natural systems are strongly interactive, in which our economies are organized around global supply chains and in which the seismic effects of crises on societies rarely stop at national borders, we would be deluding ourselves if we failed to recognize the systemic challenge we face.

The first months of 2020 have shocked the world. The pandemic caused by the coronavirus has compelled our societies to mount defensive action of a kind not seen since the wartime conditions experienced by our older generation. This immense ordeal will probably exacerbate other existing global crises.

While we are fighting the gravest pandemic of the past one hundred years, we should not forget that by failing to make sufficient investment in water infrastructure we are kicking the can down the road. The approaching water crises in many parts of the world pose at least as great a threat as the spread of the coronavirus.

Water specialists have long been involved in the search for solutions to this systemic challenge, which requires insights gained from every scientific field. Therefore, integrating knowledge from all relevant scientific areas has been a priority goal for such prestigious bodies and fora as the High Level Panel on Water—which was jointly convened by the UN Secretary General and the President of the World Bank Group—and the Budapest Water Summits. This handbook adopts the same approach. For as long as we are still seeking solutions, we need to repeatedly ask these fundamental questions:

- What is the real value of water? What are we doing to ensure that this value is recognized by our societies?
- How can we spread the message that neither economic growth nor social stability and peace can be ensured without water in adequate quantities and of adequate quality?
- How can we change bad practice in how water is used by households, agriculture and industry?
- Have we pooled best practice and made it generally accessible?
- What tasks should be performed by those involved in water science and the water industry? And what is the responsibility of policymakers?
- What institutional systems do we need at national and international levels?

Water crises have expanded beyond local or regional territories. The time has come for us to frame the challenge we face in a global context. This handbook analysing the key questions in water resource management is an excellent basis for preparations for the 2023 UN Water Conference.

I hope that this publication will be able to offer answers to students and specialists familiar with water issues, as well as to readers without experience in hydrology, but with an interest in sustainability.

Budapest, Hungary

János Áder
President of Hungary

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The editors wish to express their thanks and appreciation for the manifold support and encouragement they have received during the conceptual, drafting and editorial phases of the Handbook of Water Resources Management: Discourses, Concepts and Examples.

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Collaboration and exchange with representatives and members of scientific professional associations such as the International Association of Hydrogeologists (IAH), the International Association of Hydrological Sciences (IAHS), the International Association of Hydro-Environmental Engineering and Research (IAHR), the International Commission of Large Dams (ICOLD) and the International Water Association (IWA) were very helpful and rewarding.

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It is unusual to acknowledge authors and co-authors whose names are listed elsewhere in this volume. However, we would like to highlight the contributions of many young colleagues from research institutions and from universities from all over the world. Irrespective of the less than conducive academic reward systems which unjustly neglect to recognize the scholastic and professional value of contributions to books or other non-peer-reviewed journal article type of publications, several young colleagues volunteered to contribute to this Handbook. Their dedication to cultivate this well-established and effective, though maybe less glamourous way of knowledge dissemination is highly applauded. Collaborating with them was not only a pleasant experience but also a source of inspiration.

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The Editors

Janos J. Bogardi
Tawatchai Tingsanchali
K. D. Wasantha Nandalal
Joyeeta Gupta
Léna Salamé
Ronald R. P. van Nooijen
Alla G. Kolechkina
Navneet Kumar
Anik Bhaduri

Contents

About the Editors

Janos J. Bogardi is Senior Fellow of the Center for Development Research of the University Bonn, where he is also Professor for water resources management. He is Senior Scientific Advisor of the Institute of Advanced Studies Köszeg (iASK) in Hungary and Fellow of the Stellenbosch Institute of Advanced Study (STIAS), South Africa. Since 2014 Distinguished Adjunct Professor of the Asian Institute of Technology (AIT, Bangkok). He was Executive Officer of the GWSP (2009–2012). He served till his retirement from the UN as Director of the United Nations University (UNU) Institute for Environment and Human Security 2003–2009 and as Vice Rector a. i. in Europe 2007–2009. He was Chief of Section in the Division of Water Science in UNESCO, Paris (1995–2003) and Chair Professor of hydrology, hydraulics and quantitative water resources management at the Wageningen Agricultural University in the Netherlands 1989–1995. He was Associate Professor at AIT between 1985 and 1988. Between 1969 and 1985 he had research and consulting appointments in Europe and in Africa. He graduated in civil engineering at the University of Technology Budapest in 1969. He holds a doctorate in water resources engineering (Dr.-Ing.) from Karlsruhe University 1979 and three Dr. honoris causa distinctions from universities in Poland, Hungary and Russia.

Affiliation: University of Bonn and Institute of Advanced Studies Köszeg (iASK), e-mail: jbogardi@uni-bonn.de

Tawatchai Tingsanchali is Emeritus Professor of the Asian Institute of Technology (AIT), Thailand. He received his doctoral degree in Water Resources Engineering from AIT in 1975. He received many awards such as Alexander von Humboldt Research Fellowship in 1983–84, Outstanding Hydrologist of Indian Institute of Hydrologists in 1995, Outstanding Researcher of National Research Council of Thailand in 2001 and Honorary Distinguished Engineer of ASEAN Federation of Engineering Organization in 2004. He has 40-year experience in teaching, research and water resources engineering consultancy projects. He published 74 papers in international journals, 200 papers in conference proceedings and 41 research project reports.

Affiliation: Asian Institute of Technology, e-mail: tawatchai2593@gmail.com

K. D. Wasantha Nandalal is a Senior Professor at the Department of Civil Engineering, University of Peradeniya, Sri Lanka. He received his Ph.D. in 1995 in the field of Water Resources Management from Wageningen Agricultural University in The Netherlands. His research interests are in the areas of application of soft computing techniques in water resources management, system dynamics modelling and flood modelling.

Affiliation: Department of Civil Engineering, University of Peradeniya, e-mail: kdwn@pdn.ac.lk

Joyeeta Gupta is Professor of Environment and Development in the Global South at the University of Amsterdam and IHE Institute for Water Education. She has been a lead author with the Intergovernmental Panel on Climate Change and the Millennium Ecosystem Assessment and has just completed her role as Co-Chair (2017–2019) of UNEP's Global

Environment Outlook-6 published by Cambridge University Press. She is presently the Co-Chair of the Earth Commission (2019–2021).

Affiliation: University of Amsterdam and IHE-Delft Institute for Water Education, e-mail: J.Gupta@uva.nl

Léna Salamé graduated from the Sorbonne University in Paris as a lawyer in international public law. She specialized in conflict management and mediation, at a Harvard-MIT-Tufts joint programme and MWI, Boston, respectively. She served in the United Nations' system for 17 years as the strategic and operational coordinator of its programme on water conflict and cooperation.

Léna conceived around a 100 training courses and capacity building activities on international law, conflict management, confidence building and cooperation processes. She trained over 1500 persons on related topics. She also lectured in over 200 international events around the world. Her audiences encompass young, mid and high-level professionals, executive officers, as well as media professionals, decision-makers and the civil society from all continents (i.e. South East Asia, Arab States, Africa, Europe, Latin America, Central Asia). She published a number of scientific articles and scientifically edited over 5000 pages of research related to topics of her competence. Because of this, she is credited for having played a central role in the development and promotion of the modern concept of hydro-diplomacy.

Affiliation: Lawyer, specialist in conflict management, e-mail: lenasalame@gmail.com

Ronald R. P. van Nooijen has M.Sc. degrees in mathematics and theoretical physics from Leiden University and a doctorate in Mathematics and Information Science from the University of Amsterdam. After working as a Post-doctoral Researcher in the field of massively parallel computing applied to fluid dynamics, he switched to research into water management at the Faculty of Civil Engineering and Geosciences of Delft University of Technology. After serving as Chair for the IFAC technical committee on modelling and control of environmental systems from 2014 to 2020 he was appointed as member of the technical board of IFAC for the period 2020–2023. He is particularly interested in the theoretical aspects of the application of automatic control and statistics to water resource systems. He serves as an Associate Editor of the Hydrological Sciences Journal since 2016 and is a member of the Advisory Board for the Springer Water Program.

Affiliation: Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, e-mail: r.r.p.vannooyen@tudelft.nl

Alla G. Kolechkina started out studying electrical engineering with specialization control systems, then obtained a Ph.D. on a topic in automatic control of nonlinear systems with delay. As associate professor she taught control theory to engineering students for 15 years. After a short stint in the private sector, she started participating in research into applications of automatic control in the field of water resources at Delft University of Technology. She was convener of sessions on automatic control in water management at EGU and various IAHS conferences. In 2019, she was Chair of the National Organizing Committee of the IFAC workshop on control methods for water resource systems (CMWRS2019) in Delft. She is primarily interested in real-life controlled nonlinear systems, in particular, for complex water systems and water/energy systems. She is also active in the field of statistics for water systems.

Affiliation: Delft Center for Systems and Control, Delft University of Technology, e-mail: A.G.Kolechkina@tudelft.nl

Navneet Kumar (Dr.-Ing.) works as a Senior Researcher at ZEF, University of Bonn in Germany and currently acts as disciplinary course coordinator for the doctoral program at ZEF. He earned his Ph.D. in Engineering from University of Bonn. His main research themes are water and natural resources management and geoinformatics. Particular topics include hydrological modelling, flood management, climate change, risk and impact assessment, irrigation, remote sensing and GIS applications in water management and agriculture, etc. He has contributed to several research projects in Africa and Asia (Algeria, Ethiopia, India, Mali, Niger and Uzbekistan). In addition, he has been involved in a capacity and network building project with PAUWES: Pan African University—Institute of Water and Energy Sciences in Algeria and recently involved in global classroom program with partner institutions from USA and Brazil. He has contributed to the development of e-Learning courses on spatial planning in water management in urban settings and conducted several lectures, summer schools and workshops in Africa, Asia and Germany. He has presented his work at several international conferences and published his researches in peer-reviewed journals. He is a reviewer for several peer-reviewed journals and research grant proposals.

Affiliation: Center for Development Research (ZEF), University of Bonn, e-mail: nkumar@uni-bonn.de

Anik Bhaduri is an accomplished leader in the field of water economics, global water policy and water governance with over 20 years of experience. He is the Director of the Sustainable Water Future Programme (Water Future) of Future Earth. Water Future is a global platform facilitating international scientific collaboration to drive solutions to the world's water problems.

Anik is also an Associate Professor within the Australian Rivers Institute, Griffith University. Previously, he served as Executive Officer of the Global Water System Project (GWSP). With a background in environment and natural resource economics, he has specialized in water resource management. He has worked on several topics and projects, ranging from transboundary water sharing to adaptive water management under climate change. He also serves as a Senior Fellow at the Centre of Development Research, University of Bonn, Germany.

Affiliation: Sustainable Water Future Programme, Griffith University, e-mails: a.bhaduri@water-future.org; a.bhaduri@griffith.edu.au

Contributors

Adamson, David
Co-author Sect. 10.2
Affiliation: The University of Adelaide, Australia
Email: david.adamson@adelaide.edu.au

Akhtar, Fazlullah
Co-author Sect. 19.2
Affiliation: Center for Development Research (ZEF), University of Bonn, Germany
Email: fakhtar@uni-bonn.de

Albrecht, Tamee R.
Co-author Chap. 8
Affiliation: School of Geography, Development and Environment, Udall Center for Studies in Public Policy, University of Arizona, Tucson, USA
Email: talbrecht@email.arizona.edu

Altamirano, Mónica A.
Co-author Sect. 10.4
Affiliation: Deltares, Delft, The Netherlands
Email: Monica.Altamirano@deltares.nl

Andreu, Ana
Co-author Chap. 13
Affiliation: IFAPA Research Center, Sevilla, Spain
Email: anandreum@posteo.net

Argent, Robert
Co-author Chap. 13
Affiliation: Water Program of the Bureau of Meteorology, Melbourne, Australia
Email: Robert.Argent@bom.gov.au

Asbjornsen, Heidi
Co-author Sect. 10.4
Affiliation: University of New Hampshire, Durham, USA
Email: Heidi.Asbjornsen@unh.edu

Avellán, Tamara
Co-author Chap. 13 and Lead Author Sect. 19.6
Affiliation: Self-employed Expert in participatory water resource management, Dresden, Germany
Email: tamara.avellan@posteo.de

Awan, Usman Khalid
Co-author Sect. 19.2
Affiliation: International Water Management Institute (IWMI), Lahore, Pakistan
Email: u.k.awan@cgiar.org

Balachandran, Sanjana
Co-author Sect. 19.6
Affiliation: TU Dresden (Student), Germany

Bárdossy, András
Lead Author Chap. 14
Affiliation: Department of Hydrology and Geohydrology, University of Stuttgart, Germany
Email: Andras.Bardossy@iws.uni-stuttgart.de

Bekchanov, Maksud
Lead Author Sect. 19.4, ***Co-author Sects.*** 10.5, 19.1 ***and*** 19.2
Affiliation: Research Unit Sustainability and Global Change, Center for Earth System Research and Sustainability (CEN), University of Hamburg, Germany
Email: maksud.bekchanov@uni-hamburg.de

Bhaduri, Anik
Editor Chap. 10, ***Lead Author Sects.*** 10.1 ***and*** 10.5, ***Co-author Chap.*** 1, ***Sects.*** 10.3, 19.1 ***and*** 19.4
Affiliation: Sustainable Water Future Programme, Griffith University, Brisbane, Australia
Email: a.bhaduri@water-future.org; a.bhaduri@griffith.edu.au

Bharati, Luna
Lead Author Sect. 3.2, Co-author Sect. 3.4
Affiliation: International Water Management Institute (IWMI), Bonn, Germany
Email: l.bharati@cgiar.org

Birkett, Charon M.
Co-author Chap. 13
Affiliation: Geodesy and Geophysics Branch, NASA Goddard Space Flight Center, Greenbelt ML, USA
Email: charon.m.birkett@nasa.gov

Bogardi, Janos J.
Corresponding Editor, Editor Chaps. 1, 16, 19, 21, Co-Editor Chaps. 2, 3, 13, 22, 25, Co-author Chaps. 1, 2, 12, Lead Author Sect. 3.4, Co-author Sects. 11.2, 19.1, 22.1
Affiliation: Center for Development Research (ZEF), University of Bonn, Germany and Institute of Advanced Studies Köszeg (iASK), Köszeg, Hungary
Email: jbogardi@uni-bonn.de

Borchardt, Dietrich
Co-author Chap. 12
Affiliation: Department Aquatic Ecosystems Analysis (ASAM) Helmholtz Centre for Environmental Research-UFZ, Magdeburg, Germany
Email: dietrich.borchardt@ufz.de

Brüggemann, Kurt
Co-author Sect. 19.6
Affiliation: TU Dresden, Germany
Email: kurt.brueggemann@posteo.de

Bui, Anh
Co-author Sect. 19.6
Affiliation: Department of Civil Engineering, Construction Management and Environmental Engineering, Northern Arizona University, Flagstaff, AZ, USA
Email: anhphibui023@gmail.com

Calatrava, Javier
Co-author Sect. 10.2
Affiliation: Universidad Politécnica de Cartagena, Spain
Email: j.calatrava@upct.es

Calli, Burcu
Co-author Sect. 11.3
Affiliation: Turkish Water Institute (SUEN), Istanbul, Turkey
Email: burcu.calli@SUEN.GOV.TR

Carmi, Natasha
Co-author Sect. 7.11
Affiliation: Geneva Water Hub, Geneva, Switzerland
Email: ncarmi@genevawaterhub.org

Caucci, Serena
Co-author Chap. 13
Affiliation: United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany
Email: caucci@unu.edu

Cohen, Sagy
Co-author Chap. 13
Affiliation: University of Alabama, Tuscaloosa, AL, USA
Email: sagy.cohen@ua.edu

Darwish, Mohammed
Co-author Chap. 17
Affiliation: Environment and Energy Research Institute Hamad Bin Khalifa University, Ar-Rayyan, Qatar

de Silva, Lynette
Lead Author Sect. 7.10
Affiliation: Program in Water Conflict Management and Transformation, Oregon State University, Corvallis, OR, USA
Email: desilval@geo.oregonstate.edu

Dellapenna, Joseph
Co-author Chap. 6
Affiliation: Peking University School of Transnational Law, Shenzhen, China

Delli Priscoli, Jerome
Author Sect. 7.3
Affiliation: GWP TEC; IWR USACE (ret.), Arlington, VA, USA

Dhaubanjar, Sanita
Co-author Sects. 3.2, 3.4
Affiliation: Utrecht University, the Netherlands and ICIMOD, Patan, Nepal

Diez Santos, Cristina
Co-author Chap. 24
Affiliation: International Hydropower Association (IHA), London, UK
Email: Cristina.diez-santos@hydropower.org

Dimitriadis, Panayiotis
Co-author Chap. 20
Affiliation: School of Civil Engineering National Technical University of Athens, Greece
Email: pandim@itia.ntua.gr

Dombrowsky, Ines
Co-author Chap. 9
Affiliation: Programme "Environmental Governance and Transformation to Sustainability", German Development Institute (DIE), Bonn, Germany
Email: ines.dombrowsky@die-gdi.de

Dube, Timothy
Co-author Chap. 13
Affiliation: Department of Earth Sciences, University of Western Cape, Bellville, Cape Town, South Africa
Email: tidube@uwc.ac.za

El Hachem, Abbas
Co-Author Chap. 14
Affiliation: Department of Hydrology and Geohydrology, University of Stuttgart, Germany
Email: abbas.el-hachem@iws.uni-stuttgart.de

Efstratiadis, Andreas
Co-author Chap. 20
Affiliation: School of Civil Engineering National Technical University of Athens, Greece
Email: andreas@ntua.gr

Ertsen, Maurits W.
Lead Author Chap. 4
Affiliation: Water Resources Management Group Delft University of Technology, Delft, The Netherlands
Email: M.W.Ertsen@tudelft.nl

Escriva-Bou, Alvar
Author Sect. 10.2
Affiliation: PPIC Water Policy Centre, San Francisco & Sacramento, CA, USA
Email: escriva@ppic.org

Fekete, Alexander
Co-author Sect. 22.1
Affiliation: TH Köln - University of Applied Sciences Institute of Rescue Engineering and Civil Protection, Cologne Germany
Email: alexander.fekete@th-koeln.de

Fekete, Balázs M.
Lead Author Chap. 13, Co-author Chap. 2
Affiliation: Grove School of Engineering, The City College of New York; Environmental Sciences Initiative, Advanced Science Research Center at the Graduate Center, City University of New York, New York NY, USA
Email: bfekete@gc.cuny.edu

Foster, Stephen
Author Sect. 3.3
Affiliation: University College London, UK
International Water Association - Groundwater Management Group, Den Haag, The Netherlands.
International Association of Hydrogeologists, Reading, UK
Email: DrStephenFoster@aol.com

Gain, Animesh K.
Co-author Chap. 15
Affiliation: Department of Urban Studies and Planning, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA
Email: again@mit.edu

Gerlak, Andrea K.
Co-author Chap. 8
Affiliation: School of Geography and Development, Udall Center for Studies in Public Policy, Tucson, AZ, USA
Email: agerlak@email.arizona.edu

Groenfeldt, David
Author Chap. 5
Affiliation: Water Culture Institute, University of New Mexico, Santa Fe, and Department of Anthropology, University of New Mexico, Albuquerque, NM, USA
Email: dgroenfeldt@waterculture.org

Gupta, Joyeeta
Editor Chaps. 5, 6, 9, Co-author Chaps. 1, 6
Affiliation: University of Amsterdam and IHE-Delft Institute for Water Education, Delft, The Netherlands
Email: J.Gupta@uva.nl

Hülsmann, Stephan
Lead Author Chap. 24
Affiliation: United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany and Global Change Research Institute CAS (CzechGlobe), Brno, Czech Republic

Hussein, Hussam
Author Sect. 7.8
Affiliation: Department of Politics and International Relations (DPIR), University of Oxford, UK

Iftekhar, Sayed
Lead Author Sect. 10.6
Affiliation: Griffith University, Brisbane, Australia
Email: m.iftekhar@griffith.edu.au

Iliopoulou, Theano
Co-author Chap. 20
Affiliation: School of Civil Engineering National Technical University of Athens, Greece

Ioannidis, Romanos
Co-author Chap. 20
Affiliation: School of Civil Engineering National Technical University of Athens, Greece

Jones, Kelly
Co-author Sect. 10.4
Affiliation: Colorado State University, Fort Collins, CO, USA
Email: kelly.jones@colostate.edu

Karthe, Daniel
Lead Author Chap. 12
Affiliation: Engineering Faculty, German-Mongolian Institute for Resources and Technology, Nalaikh, Mongolia, and Resource Nexus for Regions in Transformation Programme, United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany
Email: karthe@unu.edu

Kaushik, Aditya K.
Lead Author Sect. 10.3
Affiliation: Water Solution Lab at Divecha Centre for Climate Change; Bengaluru, India

Kerc, Aslihan
Co-author Sect. 11.3
Affiliation: Marmara University, Environmental Engineering Department, Istanbul, Turkey
Email: aslihan.kerc@SUEN.GOV.TR

Kirschke, Sabrina
Co-author Chaps. 13 and 25
Affiliation: United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany
Email: kirschke@unu.edu

Koike, Toshio
Author Sect. 7.4
Affiliation: International Centre for Water Hazard and Risk Management, Tsukuba, Japan
Email: koike@icharm.org

Kolechkina, Alla G.
Editor Chap. 20, ***Co-editor Chap.*** 14, ***Co-author Chap.*** 1
Affiliation: Delft Center for Systems and Control, Delft University of Technology, Delft, The Netherlands
Email: A.G.Kolechkina@tudelft.nl

Koutsoyiannis, Demetris
Co-author Chap. 20
Affiliation: School of Civil Engineering National Technical University of Athens, Greece
Email: dk@itia.ntua.gr

Kron, Wolfgang
Author Sects. 22.2, 22.4; 22.5, 22.6, 22.8, 22.9
Affiliation: Geo Risk Research, Munich Re (ret.), Munich, Germany

Kuipally, Neenu
Co-author Chap. 23
Affiliation: Environmental and Water Resources Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India

Kumar, Navneet
Co-editor Chaps. 2, 3, 22, ***Co-author Chap.*** 1, ***Sect.*** 19.2
Affiliation: Center for Development Research (ZEF), University of Bonn, Germany
Email: nkumar@uni-bonn.de

Kunz, Nadja C.
Co-author Chap. 21
Affiliation: School of Public Policy and Global Affairs and the Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, BC, Canada
Email: nadja.kunz@ubc.ca

La Barca Pedrosa, Lúcia
Co-author Sect. 19.6
Affiliation: TU Dresden (Student), Dresden, Germany

Lamers, John P. A.
Co-author Sects. 19.1, 19.2 and 19.4
Affiliation: Center for Development Research (ZEF), University of Bonn, Germany
Email: jlamers@uni-bonn.de

Looser, Ulrich
Co-author Chap. 13
Affiliation: Global Runoff Data Centre (GRDC), Federal Institute of Hydrology (BfG), Coblence, Germany
Email: looser@bafg.de

Lopez-Gunn, Elena
Co-author Sect. 10.4
Affiliation: ICATALIST, Madrid, Spain
Email: elopezgunn@icatalist.eu

Loucks, Daniel P.
Author Sect. 22.4
Affiliation: School of Civil and Environmental Engineering Cornell University, Ithaca, NY, USA
Email: loucks@cornell.edu

Mamassis, Nikos
Lead Author Chap. 20
Affiliation: School of Civil Engineering National Technical University of Athens, Greece
Email: nikos@itia.ntua.gr

Mariano, Renato
Co-author Sect. 19.6
Affiliation: TU Dresden (Student), Dresden, Germany
Email: Renato.mariano@outlook.com

McIntyre, Owen
Author Sect. 7.7
Affiliation: University College Cork, Ireland
Email: o.mcintyre@ucc.ie

McKinney, Daene C.
Author Sect. 7.2
Affiliation: Department of Civil, Architectural and Environmental Engineering, University of Texas, Austin, TX, USA
Email: daene@aol.com

Mirumachi, Naho
Co-author Chap. 9
Affiliation: Department of Geography, King's College London, UK
Email: naho.mirumachi@kcl.ac.uk

Mohan, Sankaralingam
Lead Author Chap. 23
Affiliation: Environmental and Water Resources Engineering, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India
Email: smohan@iitm.ac.in

Mohtar, Rabi H.
Co-author Chap. 17
Affiliation: Faculty of Agricultural and Food Sciences (FAFS) at the American University of Beirut, Lebanon, TEES Research Professor at Texas A&M University, College Station, TX, USA
Email: mohtar@aub.edu.lb; mohtar@tamu.edu

Moran, Chris J.
Co-author Chap. 21
Affiliation: Research Office at Curtin University, Perth, Australia
Email: Chris.Moran@curtin.edu.au

Morgan, Ruth A.
Co-author Chap. 4
Affiliation: School of History, Australian National University, Canberra, Australia
Email: ruth.morgan@anu.edu.au; ruth.morgan@monash.edu

Moss, Jack
Author Sect. 7.5
Affiliation: Former Executive Director of AquaFed, Paris, France
Email: info@aquafed.org

Motlagh, Mahsa
Author Sect. 7.9, ***Co-author Sect.*** 10.5
Affiliation: Bonn Alliance for Sustainability Research/Innovation Campus, Bonn, Germany

Münger, François
Co-author Sect. 7.11
Affiliation: Geneva Water Hub, Geneva, Switzerland
Email: fmuenger@genevawaterhub.org

Nachtnebel, Hans Peter
Co-author Chap. 18
Affiliation: Department of Water-Atmosphere-Environment, University of Natural Resources and Life Sciences, Vienna, Austria
Email: hans_peter.nachtnebel@boku.ac.at

Nandalal, K. D. Wasantha
Editor Chaps. 15, 18, 23, 24, ***Co-editor Chap.*** 25, ***Co-author Chaps.*** 1, 18
Affiliation: Department of Civil Engineering, University of Peradeniya, Sri Lanka
Email: kdwn@pdn.ac.lk

Nevado Amell, Mauricio
Co-author Sect. 19.6
Affiliation: TU Dresden, Germany

Newig, Jens
Co-author Chap. 25
Affiliation: Leuphana University Lüneburg, Germany
Email: newig@uni.leuphana.de

Van Nooijen, Ronald R. P.
Editor Chaps. 4, 14, ***Co-editor Chaps.*** 13, 20, ***Co-author Chap.*** 1
Affiliation: Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands
Email: r.r.p.vannooyen@tudelft.nl

Pahl-Wostl, Claudia
Lead Author Chap. 9
Affiliation: Institute for Environmental Systems Research, Osnabrück University, Germany
Email: cpahlwos@uni-osnabrueck.de

Palomo-Hierro, Sara
Co-author Sect. 10.2
Affiliation: Department of Applied Economics, University of Malaga, Spain
Email: sara.palomo@uma.es; sara.palomo@uco.es

Paul, Lothar
Co-author Chap. 24
Affiliation: Neunzehnhain Ecological Station, TU Dresden, Pockau-Lengefeld, Germany
Email: lopapo@t-online.de

Pérez-Blanco, Carlo Dionisio
Lead author Sect. 10.4, ***Co-author Sect.*** 10.1
Affiliation: University of Salamanca, Spain
Email: dionisio.perez@usal.es

Polyakov, Maksym
Co-author Sect. 10.6
Affiliation: Manaaki Whenua-Landcare Research, Auckland, New Zealand
Email: polyakovm@landcareresearch.co.nz

Renaud, Fabrice G.
Co-author Chap. 15, ***Author Sect.*** 22.7
Affiliation: University of Glasgow, School of Interdisciplinary Studies, Dumfries, UK
Email: Fabrice.Renaud@glasgow.ac.uk

Rey, Dolores
Lead Author Sect. 10.2, Co-author Sect. 10.1
Affiliation: Cranfield University, Cranfield, UK
Email: d.reyvicario@cranfield.ac.uk

Rinke, Karsten
Co-author Chap. 24
Affiliation: Helmholtz Centre for Environmental Research (UFZ), Department of Lake Research, Magdeburg, Germany
Email: karsten.rinke@ufz.de

Salamé, Léna
Editor Chaps. 7, 8, 11, 12, 17, ***Author Sects.*** 7.1, 11.1, ***Co-author Chap.*** 1
Affiliation: Lawyer, specialist in conflict management, Paris, France

Schwärzel, Kai
Co-author Sects. 19.3 and 19.5
Affiliation: Thünen Institute of Forest Ecology, Eberswalde, Germany
Email: kai.schwaerzel@thuenen.de

Sebesvári, Zita
Co-author Chap. 15, Sect. 11.2
Affiliation: Environmental Vulnerability and Ecosystem Services (EVES) Section at United Nations University, Institute for Environment and Human Security, Bonn, Germany
Email: sebesvari@ehs.unu.edu

Staddon, Chad
Co-author Chap. 8
Affiliation: Department of Geography & Environmental Management, University of the West of England, Bristol, UK
Email: Chad.Staddon@uwe.ac.uk

Tesch, Luana
Co-author Sect. 19.6
Affiliation: TU Dresden (student), Dresden, Germany

Tignino, Mara
Author Sect. 7.6
Affiliation: Faculty of Law and Institute for Environmental Sciences/Geneva Water Hub, University of Geneva, Switzerland
Email: Mara.Tignino@unige.ch

Tingsanchali, Tawatchai
Co-editor Chaps. 2, 3, 14, 18, 22, 23, 24, Author Sect. 22.3, Co-author Chap. 1
Affiliation: Asian Institute of Technology, Pathumthani, Thailand

Tischbein, Bernhard
Lead Author Sect. 19.2
Affiliation: Center for Development Research (ZEF), University of Bonn, Germany
Email: tischbein@uni-bonn.de

Tockner, Klement
Author Chap. 16, ***Co-Author Sect.*** 11.2
Affiliation: Senckenberg Gesellschaft für Naturforschung and Goethe University Frankfurt am Main, Germany
Email: klement.tockner@senckenberg.de

Turan, Fatma
Co-author Sect. 11.3
Affiliation: Turkish Water Institute (SUEN), Istanbul, Turkey
Email: fatma.turan@SUEN.GOV.TR

Türk, Danilo
Co-author Sect. 7.11
Affiliation: Former President of Slovenia and Chairman of the Global High-level Panel on Water and Peace. Currently, Lead Political Advisor to the Geneva Water Hub, Geneva, Switzerland
Email: danilo.turk@up-rs.si

Ünver, Olcay
Author Sect. 11.4
Affiliation: Polytechnic School, Environmental and Resource Management Program, Arizona State University, Mesa, AZ, USA

Varady, Robert G.
Lead author Chap. 8
Affiliation: Udall Center for Studies in Public Policy, University of Arizona, Tucson, AZ, USA
Email: rvarady@email.arizona.edu

Walz, Yvonne
Author Sect. 11.5
Affiliation: United Nations University Institute for Environment and Human Security (UNU-EHS) Bonn, Germany
Email: walz@ehs.unu.edu

Wang, Yanhui
Co-author Sect. 19.5
Affiliation: Research Institute of Forest Ecology, Environment and Protection, Chinese Academy of Forestry, Beijing, China
Email: wangyh@caf.ac.cn

Wolf, Aaron
Co-author Sect. 7.10
Affiliation: College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA
Email: wolfa@geo.oregonstate.edu

Yazici, Burcu
Co-author Sect. 11.3
Affiliation: Turkish Water Institute (SUEN), Istanbul, Turkey
Email: burcu.yazici@SUEN.GOV.TR

Yu, Pengtao
Co-author Sect. 19.5
Affiliation: Research Institute of Forest Ecology, Environment and Protection, Chinese Academy of Forestry, Beijing, China
Email: yupt@caf.ac.cn

Zhang, Lulu
Co-author Sects. 19.3 and 19.5
Affiliation: United Nations University, Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany
Email: lzhang@unu.edu

Zuniga-Teran, Adriana A.
Co-author Chap. 8
Affiliation: School of Landscape Architecture and Planning, Udall Center for Studies in Public Policy, University of Arizona, Tucson, AZ, USA
Email: aazuniga@email.arizona.edu

Part I

Water on Earth: Occurrence, History, Management and Challenges

1 Introduction and Guide to the Handbook of Water Resources Management: Discourses, Concepts and Examples

Janos J. Bogardi, Tawatchai Tingsanchali, Anik Bhaduri, K. D. Wasantha Nandalal, Ronald R. P. van Nooijen, Joyeeta Gupta, Alla G. Kolechkina, Léna Salamé, and Navneet Kumar

Abstract

This chapter provides the background and rationale of this handbook. It touches upon the main challenges of contemporary water resources management. It guides the reader through the four distinct parts and 25 chapters of the handbook. The structure of this handbook facilitates different disciplinary and thematic perspectives whereby conceptually the review of ongoing discourses, introduction and analysis of concepts and contexts as well as examples to highlight successes and lessons to be learned provide the framework.

Keywords

Water resources governance and management • Water cycle • Guide • Structure of the handbook

Abbreviations

IWRM	Integrated Water Resources Management
NGO	Non-Governmental Organization
SDGs	Sustainable Development Goals
UN	United Nations
UNGA	United Nations General Assembly
WRM	Water Resources Management

1.1 Background and Rationale of the Handbook

Thanks to the general increase of environmental awareness and some efficient lobbying by different actors (scientists, politicians, NGOs, business, faith-based organizations) water is no longer taken for granted and is now one of the main topics on the global agenda. Many events like the triennial World Water Forum and the Budapest Water Summit, the annual World Water Week in Stockholm and similar water weeks in Amsterdam and Singapore, and the annual World Economic Forum in Davos, several high ranking global advisory committees addressing different contexts of water, as well as the sequence of various water decades underline this trend. Clearly, water is neither a simple economic good, nor a global common free for all. It is not an easy task to find consensus attributes and a common classification of water. We need to survive in a breathable atmosphere at the right

J. J. Bogardi (✉)
Center of Development Research (ZEF), University of Bonn and Institute of Advanced Studies Kőszeg (iASK), Kőszeg, Hungary
e-mail: jbogardi@uni-bonn.de

T. Tingsanchali
Asian Institute of Technology, Pathumthani, Thailand
e-mail: tawatchai2593@gmail.com

A. Bhaduri
Sustainable Water Future Programme, Griffith University, Brisbane, Australia
e-mail: a.bhaduri@griffith.edu.au

K. D. W. Nandalal
Department of Civil Engineering, University of Peradeniya, Kandy, Sri Lanka
e-mail: kdwn@pdn.ac.lk

R. R. P. van Nooijen
Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands
e-mail: r.r.p.vannooyen@tudelft.nl

J. Gupta
University of Amsterdam, Amsterdam, The Netherlands
e-mail: J.Gupta@uva.nl

A. G. Kolechkina
Delft Center for Systems and Control, Delft University of Technology, Delft, The Netherlands
e-mail: A.G.Kolechkina@tudelft.nl

L. Salamé
Lawyer, specialist in conflict management, Paris, France
e-mail: lenasalame@gmail.com

N. Kumar
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: nkumar@uni-bonn.de

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pressure and water is a close second in a “list” of pre-requisites of human existence. This importance is echoed by the resolutions 64/292 and 70/1 of the UN General Assembly in 2010 (United Nations 2010) and 2015 respectively adopting water and sanitation as human right and the dedicated water goal (No. 6) among the 17 Sustainable Development Goals (United Nations 2015).

While this is a laudable development, people working on water management at any level now find themselves between a rock and a hard place. The rock—planet Earth—is governed by the laws of chemistry, physics and biology (and that of their respective subdisciplines) that cannot be debated or seriously questioned. They must be obeyed, otherwise our dream of sustainability will vanish. The hard place is our governance of water which results from the wide-ranging public debate on our appropriation, use, protection and/or waste and pollution of the world’s water resources. In this debate personal interest, different backgrounds and multiple interpretations of the same words or observations may cloud the real issues. The term “the real issues” stands already for highly debatable and debated ideas, problem interpretations and potential solutions.

Water governance is not a “spectator sport”. Humans from all walks of life are always an active part of the system under study and water management always involves a conscious decision to change or refrain from changing the behavior of humans within the system. In fact, one might see the discourse about a water system, its governance and day-to-day management as an additional feedback loop of such a system. It, in turn, implies that a good understanding of the means that are available to change the system behaviour and their effects is essential to the discussion. This also entails observing and quantifying system behaviour, something that, in an age where weather stations and river gauges providing a significant part of the “ground truth” are being closed down all over the world, seems to have been forgotten. Chapter 13 of this Handbook is dedicated to discussing technical details, governance and other issues related to observation, data archiving and management, thus reminding us that you cannot manage what you do not measure.

The discussion on water and the environment, in general, has many participants. The slogan of the 2nd World Water Forum, held in The Hague in 2000, “Water is everybody’s business” echoes well this necessity (Cosgrove and Rijsberman 2000; World Water Council 2000). Today there is a lively debate where the general public, politicians, water resources professionals, but also representatives of different water users (municipal, industrial, energy, agricultural, recreational, ecological) and representatives of what may be called the “water industry” participate as stakeholders. Specialists and scientists in law, sociology, hydrology, geophysics, geography, ecology, economics, engineering, political science and other disciplines may be involved in these debates out of scientific interest or as advisors.

There is always a risk that such a discussion with participants of very different backgrounds may split into groups along disciplinary lines or, when this does not happen, get bogged down in the discussion of definitions. This may also be happening in the field of water management, where the different discourses, like water and sustainability, the right to water versus water as an economic good to be paid for, water security which is used for the “securitization” of water, water in nexus considerations with (mainly) food and energy but also with health, climate change and waste, ecosystem services versus engineering solutions seem to be drifting apart rather than converging towards implementable, feasible and sustainable consensus solutions. This unwelcome trend is one of the main reasons why this handbook is needed. When conclusions from one discussion forum become dominant there can be undesirable consequences. Major donors of development assistance, for example, may act on these premature or one-sided conclusions without regard for possible undesirable side effects and opinions of other experts. This handbook is conceived to help constructive dialogue among different stakeholders with diverging views, beliefs and disciplinary backgrounds. This handbook aims to facilitate understanding of different concepts, concerns and approaches and ultimately helping integrated management of water to emerge, leading to sustainable consensus solutions.

As in all interdisciplinary problems, constructive work depends critically on the self-reflection of all participating communities. In order to facilitate this, it would be helpful to have a common basis of accepted facts and theories from all professional communities involved in water resources governance, management and use. The professional debate can only be based on mutual respect but also on a certain degree of knowledge of the theories and methodologies of the different disciplines and epistemological communities involved. This implies the need for an inventory of approaches, techniques, methods, laws and principles, together with the critical analysis of their strengths and weaknesses.

Humans are not external masters, but a part of what may be called the global (socioecological) water system. Our behaviour is co-determining the functioning, or malfunctioning of this complex system. This implies that WRM cannot be confined to natural sciences and engineering but needs to rely increasingly on social and behavioral sciences and direct consideration of beliefs, human aspirations and compassion.

This Handbook of Water Resources Management: Discourses, Concepts and Examples provides an overview of ongoing discourses, facts, theories and methods from hydrology, geology, geophysics, law, ethics, economics, ecology, statistics, engineering, sociology, diplomacy and many other disciplines with relevance for concepts and practice of water resources management. It provides comprehensive, concise, but also critical reading material for all communities involved in the different streams of the ongoing water discourses and debate(s). Discourses have manifold impacts as they may evolve towards powerful concepts, help to crystallize principles or can be regarded as the preparatory phase towards the formulation of conventions, treaties and legal frameworks both in national and international contexts.

The term "Examples" in the title of this handbook refers to numerous case studies in the form of boxes, sections, but sometimes as entire chapters. They illustrate success stories, but also show cases to be remembered, thus helping to avoid the same mistakes to reappear in the future. Beyond flagging this explanatory role, the word "Examples" also stands for the implicit acknowledgement that irrespective of its thematic width, not all aspects of water resources management have been dealt with in this handbook with the same depth. Water quality assessment and management, water supply and sanitation, wastewater treatment and urban drainage, but also the water for food or water and health contexts, navigation, industrial water management are rather touched upon than having been discussed in depth.

The name "Handbook" refers thus rather to the style of this publication. Based on consolidated state-of-the-art knowledge, it has been conceived and written to attract a multidisciplinary audience.

The different chapters of the handbook are either "overview" chapters, dealing with the discourse and interactions of different disciplines within water resources management and the role of water in other management and governance efforts, or they are written in more detail showing examples and discussing WRM methods, their merits, multiple interpretations and potential pitfalls.

The fundamental aim of this handbook is to facilitate understanding between the participants of the international water discourse and subsequent multi-level decision making processes. Knowing more about water, its occurrence and movement, vulnerability, but also about the concepts, methods and aspirations of different professional, disciplinary communities, but also that of interest and lobby groups can contribute professionalizing the debate and enhancing the knowledge-based decision-making process.

1.2 Outline and Structure of the Handbook

1.2.1 Part I: Water on Earth: Occurrence, History, Management and Challenges

Part I, which incorporates Chaps. 1–3, is both an introductory part and a summary of many aspects of water and its governance and management which will be discussed and exemplified in the follow-up parts of the handbook.

Part I provides an overview of water as a phenomenon and resource. The origin of water and its history on planet Earth is presented in the first part of Chap. 2. Estimates of different components of the hydrological cycle and subdivisions between sectoral and geographical distribution of water use are presented in the second part of Chap. 2. Part I provides an overview of the unique peculiarities of water as a life-supporting element and resource and the consequences thereof for its governance which is broader than, but includes management.

Water resources management evolved from the classical approaches dealing with surface and groundwater, the two most important components of the terrestrial part of the water cycle. In Chap. 3 the respective overviews are illustrated by examples from different parts of the world. In a nutshell the reader is made aware of the specific aspects of the resource and its management. This part touches upon the state-of-the-art and relevant issues and concepts which influence the ongoing international water discourse including WRM.

Part I includes references to chapters and sections in the forthcoming parts II–IV. In this sense it may be viewed as a "teaser" or/and providing for executive-level readers an overview. This part however, also sets the context for the complex field of (integrated) water resources management (I) WRM. The occurrence and movement of water within the water cycle can be characterized from global to local, at different spatial scales. Consequently, the governance and management of the resource water can also refer to different (vertically interlinked, hierarchical) levels. This implies different scopes and varying resolutions in characterizing the inherent phenomena but also the related governance and management decisions. Simultaneously the horizontal links across disciplines and water (use) sectors and their respective perspectives have to be considered as well. Next to the spatially nested scales the temporal scales add an important further complexity to WRM. Managing water at different spatial and temporal scales means considering both fluxes and stocks and their transitions and interactions within the socio-environmentally defined water cycle. The book aims to capture these complexities and reflect them in the different approaches and methods which may have to be applied at the different spatial and temporal scales of analysis and assessment. No doubt that methodological rigour and analytical depth are both problem and scale-dependent.

1.2.2 Part II: Water and Society

This Part (Chaps. 4–12) summarizes the so-called "non-technical" aspects of WRM. Part II focuses on different water discourses. It outlines our responsibilities for, but also our dependence on water. WRM will be embedded in a broad societal value- and governance-centered framework.

Chapter 4 analyzes the histories of WRM and outlines the evolution of different narratives.

Water ethics provides an important reflection on how to shape our governance and management concepts towards the achievement of sustainable and equitable solutions for the manifold water challenges of our days. Chapter 5 presents principles, concepts and concerns of water ethics.

In Chap. 6 the succinct summary of water law and water right frameworks and mechanisms reflect how decades long discourses evolve towards legal codifications and practice.

Several aspects and issues of the ongoing water discourses are presented and documented with respective case study examples in Chap. 7.

Water security, one of the most debated discourses is presented in the more detailed and focused Chap. 8.

Key issues of water governance and management and the underlying pre-requisites are discussed in Chap. 9. This chapter also refers to the water governance and water management interlinkages.

In Chap. 10 several examples of the economic dimension and methodology (among them the much-discussed water markets) of water resources management, and water use are presented.

Chapter 11 highlights several additional facets of WRM. The duality of human-triggered pressures emanating from the efforts to improve societal well-being and consequent stresses upon freshwater bodies are presented as a key challenge to be dealt with. The interlinkages of water and migration as well as water resources management and (forced) displacement of people are among the most actual problems being feared and referred excessively in the media. The food and health security nexus are further concerns due to the vulnerability of the increasing human population and its exposure to hazard events like the 2020 worldwide outbreak of Covid-19.

Part II is concluded in Chap. 12 on IWRM and adaptive WRM. While IWRM is unanimously recognized as the framework to manage water at various scales real-world examples show the difficulties inherent in the true integration of diverging aspirations to formulate objectives, define constraints and opportunities to achieve sustainable solutions in dealing with water problems.

1.2.3 Part III: Examples of Assessment of Water Resources, Their Protection and Use

The six Chaps. 13–18 in this part deal with various aspects of assessments. The motto "one cannot manage what has not been measured" motivates the overview of available data, the measurement and monitoring methods and the state of matters as far as observation of the different components of the hydrological cycle is concerned.

Chapter 13, while providing detailed technical insights, also highlights the governance questions and social aspects (citizen science) to observe, archive and use data on the water cycle.

The quantitative assessment of water in Chap. 14 covers surface and groundwater resources and addresses the case of desalinization together with other water resources management options. In this chapter, the Nile river basin is introduced as a case study example.

Chapter 15 provides a review of land/catchment use and degradation. This chapter highlights the need for genuine joint management of land- and water resources.

Securing human access to water and its use puts an undeniable pressure on freshwater ecosystems. Dwindling aquatic biodiversity and the fragile nature of water-related ecosystem services and their protection are essential challenges to be addressed in order to assure sustainable use and reliance on these services. Chapter 16 is a succinct reminder that water is as much a resource as a habitat for aquatic flora and fauna. Biodiversity and the sustained provision of water-related ecosystem services are threatened through the ever increasing human pressures on freshwater bodies.

In Chap. 17 the water energy food security nexus is exemplified through a regional case study from the Gulf area.

Finally, with examples of technical options focusing on river and flood management and demand management, Chap. 18 closes the illustrative examples of Part III.

While the aim is to present the state of the art assessment methodologies, the chapters in this part should also remain understandable for readers without a strong natural/technical science background. "Readability" however does not mean oversimplification. This book reveals and explains the complexities and intricacies of water resources assessment (and management) within the interlinked socio-environmental system and its strong links with land use and land cover, water bodies as biotopes next to their role as a resource base and uncertainties inherent in climate variability and change. It should "open doors" for interested readers towards further methodological "depth".

1.2.4 Part IV: Examples of Contexts and Scales: Facets of Water Resources Management and Use, Risks and Complex Systems

In this part the various contexts: water, land and agriculture, forestry, energy and mining are highlighted in several examples. Chapter 19 refers to the close interlinkages between water and land use management, which is highlighted in several examples.

Chapter 20 provides an overview of the multifaceted water/energy context. It discusses hydropower generation in the context of a mix of renewable energy sources. It also considers wave and tidal energy. It places this in the historical context of power generation in general.

Chapter 21 discusses the management and stewardship of water in mining regions showing the efforts within the mining operation proper and the impacts on the surrounding environment.

Part IV deals with yet another emerging context beyond considering water as the source of life and indispensable for manifold economic activities. Water is also associated with a multitude of serious hazards. Determining water-related risks is, therefore, not only a major concern of water resources management but also for the insurance industry. Risk-based considerations, as highlighted in several cases and examples in Chap. 22, are essential in water resources management in particular since the non-stationarity of water-related phenomena becomes more and more evident as climate change evolves.

Chapter 23 provides several examples and a methodological overview of groundwater and the conjunctive groundwater/surface water management.

Chapter 24 is dedicated to discussing the operation and management of storage reservoirs. Providing artificial storage space, while certainly not an uncontroversial means to influence the water cycles, is likely to remain a key element in many adaptation strategies offsetting droughts, increasing the share of renewable energy sources, providing space for flood control and recreation.

Finally, Chap. 25 provides interesting, multidisciplinary insights into and examples of the complexity, uncertainty and dynamics in the management of complex water resources systems.

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Janos J. Bogardi is senior fellow of the Center for Development Research of the University Bonn. where he is also professor for water resources management. He is senior scientific advisor of the Institute of Advanced Studies Kőszeg (iASK) in Hungary and fellow of the Stellenbosch Institute of Advanced Study (STIAS), South Africa. Since 2014 Distinguished Adjunct Professor of the Asian Institute of Technology (AIT, Bangkok). He was executive officer of the GWSP (2009–2012). He served till his retirement from the UN as director of the United Nations University (UNU) Institute for Environment and Human Security 2003–2009 and as Vice Rector a. i. in Europe 2007–2009. He was Chief of Section in the Division of Water Science in UNESCO, Paris (1995–2003) and chair professor of hydrology, hydraulics and quantitative water resources management at the Wageningen Agricultural University in the Netherlands 1989–1995. He was associate professor at AIT between 1985–1988. Between 1969 and 1985 he had research and consulting appointments in Europe and in Africa. He graduated in civil engineering at the University of Technology Budapest in 1969. He holds a doctorate in water resources engineering (Dr.-Ing.) from Karlsruhe University 1979 and three Dr. honoris causa distinctions from universities in Poland, Hungary and Russia.

Tawatchai Tingsanchali is Emeritus Professor of the Asian Institute of Technology (AIT), Thailand. He received his doctoral degree in Water Resources Engineering from AIT in 1975. He received many awards such as Alexander von Humboldt Research Fellowship in 1983–84; Outstanding Hydrologist of Indian Institute of Hydrologists in 1995, Outstanding Researcher of National Research Council of Thailand in 2001 and Honorary Distinguished Engineer of ASEAN Federation of Engineering Organization in 2004. He has 40-year experience in teaching, research and water resources engineering consultancy projects. He published 74 papers in international journals, 200 papers in conference proceedings and 41 research project reports.

Anik Bhaduri is an accomplished leader in the field of water economics, global water policy and water governance with over 20 years of experience. Dr. Bhaduri is the Director of the Sustainable Water Future Programme (Water Future) of Future Earth. Water Future is a global platform facilitating international scientific collaboration to drive solutions to the world's water problems.

Anik is also an Associate Professor within the Australian Rivers Institute, Griffith University. Previously, he served as Executive Officer of the Global Water System Project (GWSP). With a background in environment and natural resource economics, Anik has specialised in water resource management. He has worked on several topics and projects, ranging from transboundary water sharing to adaptive water management under climate change. Anik also serves as a senior fellow at the Centre of Development Research, University of Bonn, Germany.

K. D. Wasantha Nandalal is a Senior Professor at the Department of Civil Engineering, University of Peradeniya, Sri Lanka. He received his Ph.D. in 1995 in the field of Water Resources Management from Wageningen Agricultural University in The Netherlands. His research interests are in the areas of application of soft computing techniques in water resources management, system dynamics modelling and flood modelling.

Ronald R. P. van Nooijen has M.Sc. degrees in mathematics and theoretical physics from Leiden University and a doctorate in Mathematics and Information Science from the University of Amsterdam. After working as a post-doctoral researcher in the field of massively parallel computing applied to fluid dynamics, he switched to research into water management at the Faculty of Civil Engineering and Geosciences of Delft University of Technology. After serving as chair for the IFAC technical committee on modelling and control of environmental systems from 2014 to 2020 he was appointed as member of the technical board of IFAC for the period 2020–2023. He is particularly interested in the theoretical aspects of the application of automatic control and statistics to water resource systems. He serves as an associate editor of the Hydrological Sciences Journal since 2016 and is a member of the Advisory Board for the Springer Water Program.

Joyeeta Gupta is professor of environment and development in the Global South at the University of Amsterdam and at IHE Delft Institute for Water Education. She has been a lead author with the Intergovernmental Panel on Climate Change and the Millennium Ecosystem Assessment and has just completed her role as Co-Chair (2017–2019) of UNEP's Global Environment Outlook-6 published by Cambridge University Press. She is presently the co-chair of the Earth Commission (2019–2021).

Alla G. Kolechkina started out studying electrical engineering with specialization control systems, then obtained a Ph.D. on a topic in automatic control of nonlinear systems with delay. As associate professor she taught control theory to engineering students for 15 years. After a short stint in the private sector, she started participating in research into applications of automatic control in the field of water resources at Delft University of Technology. She was convener of sessions on automatic control in water management at EGU and various IAHS conferences. In 2019 she was chair of the national organizing committee of the IFAC workshop on control methods for water resource systems (CMWRS2019) in Delft. She is primarily interested in real life controlled nonlinear systems, in particular for complex water systems and water/energy systems. She is also active in the field of statistics for water systems.

Léna Salamé graduated from the Sorbonne University in Paris as a lawyer in international public law. She specialized in conflict management and mediation, at a Harvard-MIT-Tufts joint programme and MWI, Boston, respectively. She served in the United Nations' system for 17 years as the strategic and operational coordinator of its programme on water conflict and cooperation.

Lena conceived around a 100 training courses and capacity building activities on international law, conflict management, confidence building and cooperation processes. She trained over 1500 persons on related topics. She also lectured in over 200 international events around the world. Her audiences encompass young, mid and high-level professionals, executive officers, as well as media professionals, decision-makers and the civil society from all continents (i.e. South East Asia, Arab States, Africa, Europe, Latin America, Central Asia). She published a number of scientific articles and scientifically edited over 5000 pages of research related to topics of her competence. Because of this, she is credited for having played a central role in the development and promotion of the modern concept of hydro-diplomacy.

Navneet Kumar (Dr.-Ing.) works as a Senior Researcher at ZEF, University of Bonn in Germany and currently acts as a disciplinary course coordinator for the doctoral program at ZEF. He earned his Ph.D. in Engineering from University of Bonn. His main research themes are water and natural resources management and geoinformatics. Particular topics include hydrological modelling, flood management, climate change, risk and impact assessment, irrigation, remote sensing and GIS applications in water management and agriculture, etc. Dr. Kumar has contributed to several research projects in Africa and Asia (Algeria, Ethiopia, India, Mali, Niger and Uzbekistan). In addition, Dr. Kumar has been involved in a capacity and network building project with PAUWES: Pan African University—Institute of Water and Energy Sciences in Algeria and recently involved in global classroom program with partner institutions from USA and Brazil. He has contributed to the development of e-Learning courses on spatial planning in water management in urban settings and conducted several lectures, summer schools and workshops in Africa, Asia and Germany. Dr. Kumar has presented his work at several international conferences and published his researches in peer-reviewed journals. He is a reviewer for several peer reviewed journals and research grant proposals.

Water: a Unique Phenomenon and Resource

2

Janos J. Bogardi and Balázs M. Fekete

Abstract

This chapter presents water as a major geophysical phenomenon. Based on the paper 'Water balance of Earth' (Kotwicki, Hydrol Sci J 54:829–840, 2009) the role and evolutionary trajectory of water along earth's history is explained. The hydrological cycle is introduced and the corresponding fluxes and stocks are assessed at global, continental, regional and river basin scales. The concept of water cycle, accounting explicitly for the interaction of the natural phenomena and societal demands is introduced. In large-scale overviews the present and expected future water use balances, possibilities and potential reasons of water scarcity are analysed. Interlinkages with population growth, climate variability and change as well as land use/land cover are emphasized.

Keywords

Origin and fate of water • Hydrological and water cycle • Quantitative assessments and trends

Abbreviations

DIA	Domestic, Industrial and Agricultural Water Use
ECMWF	European Centre for Medium-Range Weather Forecasts
GRDC	Global Runoff Data Centre in Coblence, Germany
MENA	Middle East Northern Africa
NCEP-NCAR	National Centers for Environmental Prediction-National Center for Atmospheric Research
PDSI	Palmer Drought Severity Index
RFWR	Renewable FreshWater Resources
RF	River Flow
RTM	River Transport Model
Q	Renewable Freshwater Discharge
WR	Water Recharge

J. J. Bogardi (✉)
University of Bonn and Institute of Advanced Studies Köszeg (IASK), Köszeg, Hungary
e-mail: jbogardi@uni-bonn.de

B. M. Fekete
Grove School of Engineering, The City College of New York, Environmental Sciences Initiative, Advanced Science Research Center at the Graduate Center, City University of New York, New York, NY, USA
e-mail: bfekete@gc.cuny.edu

2.1 Water on Earth

Water is one of the most recognized compound on Earth giving its distinct blue colour in contrast to other celestial objects. On our planet, water can be found in all three phases (solid as ice or snow, liquid in streams, lakes, the soil and deep in the ground and in gaseous phase as water vapour in the air and any pore spaces in soil or snow). The three phases occur in a very narrow temperature range and that is an exceptionally unique property. Transitions between the three phases (freeze/thaw, condensation/vaporization, sublimation) are governed by heat exchanges (absorption or dissipation of energy originated dominantly from the Sun).

Water is present in all living organism (microbes, plants, animals and humans). Approximately two third of the human body consists of water and that should serve as a "constant reminder" of the paramount importance of water, even though this water is hardly the subject of water resources management.

Water played special roles throughout human history manifested by the numerous water deities that are deeply entrenched in many mythology and culture all over the World. Great early civilizations (such as Mesopotamia, Egypt) arose in proximity to abundant freshwater resources. Given its importance, the understanding of how water is

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distributed in space and time and what are the main drivers of its variability are fundamental for humanity.

The narrow temperature range of the water phase changes (Fig. 2.1) alone would not be enough for the presence of water in all three phases on Earth. The distance of our planet from the Sun, its mass and the composition and thickness of the atmosphere dictating the unique combination of atmospheric pressure and average temperature around this narrow temperature range is just as important. The mobility of the liquid and gaseous water in particular—in combination with the spatial and temporal variability of the arriving solar radiation—gives rise to the hydrological cycle, a complex and delicate interaction of hydrological processes. The spatial domain where these interactions occur is called the hydrosphere that encapsulates both the biosphere where living organisms live and the atmosphere that blankets the biosphere.

2.1.1 The Origin and Fate of Water on Earth

The Solar System is estimated to be 4.567 billion years old (Valley 2006). The Sun and its planets accreted from the available material of molecular cloud of gas and dust (Nittler 2003) in a relatively short time of tens of million years. The Sun entered its Main Sequence and started to shine in the first 50 million years (Zahnle 2006). The Earth acquitted 70–90% percent of its current mass in the first 10 million years (Kotwicki 2009).

Theoretically, the Solar System may intercept some astronomical objects containing water from interstellar space, but so far this has not been observed, therefore the Solar System is a closed system in practical terms as far as water is concerned. The absence of gaining additional water as a planetary system as a whole does not rule out the Earth gaining or loosing water from the outer space. During the evolution of our planet, water exchange with the outer space was probably more significant, but exchange rates of water in the present are negligible (Sect. 2.1.2). From contemporary water resources perspective, the Earth, together with its atmosphere is practically also a closed system.

The presence of water on Earth is obvious, but its origin is still poorly understood (Halliday 2006); leaving room for a wide range of plausible reasoning and interpretation. Probably, most of the water was delivered as hydrous silicates (Zahnle 2006) during the Earth's accretion. There is general agreement that the Earth accreted "wet" so the accretion of water and other material occurred simultaneously. The post-accretion influxes of water to Earth from comets were likely limited to less than 20% (Kotwicki 2009) and the Earth dominantly lost water since its accretion as shown in Fig. 2.2.

The likely contributing sources of the otherwise small amount of post-accretion water are ~35% of absorbed water, 50–60% of asteroidal water and 5–15% of cometary water (Izidoro et al. 2013).

From the Solar nebula, the Earth accreted high-temperature (90%) and low-temperature condensates (Ringwood 1975). If the estimated 19.2% water content from the low-temperature condensates were still on Earth, then it should still be covered by an approximately 100 km deep ocean (Kotwicki 1991; Ringwood 1975). The likely explanation of the missing water is that nearly all the water from the huge low-temperature condensates was lost early due to oxidization of iron by water vapour, and the subsequent escape of hydrogen into space.

The water in the primitive mantle of the Earth might have been 10–50 times of the water amount in the oceans today (Abe et al. 2000), but this estimate has not yet been confirmed. Most of the missing water outgassed within 100 million years, with oxygen being absorbed by the lithosphere, and hydrogen escaping into outer space. Oceans existed on Earth already 4.2 billion years ago (Cavosie et al. 2005) and maybe as early as 4.4 billion years ago (Nutman 2006). Their volume have been estimated as possibly twice that of today's World Ocean (Russell and Arndt 2005).

The amount of water on Earth varied over time since its formation. While it would be a difficult exercise yielding inaccurate estimates to assess the volume of the World Ocean at any particular time point in the history of Earth, there are three questions which are worth to be considered in some detail (Kotwicki 2009):

- the quantity of the accreted water during the formation of the Earth;
- total water content of the planet at present;
- the fate of the water over time.

As a conceptual presentation (see Fig. 2.2) of the incidence of water on Earth and the occurrence of water on the surface of our planet shows, the amount of water is related directly to the luminescence of the Sun.

The fate of the Earth's ocean is sealed by external forcing (Bounama et al. 2001). Ultimately, all water will disappear as a result of rising global temperature caused by increasing solar luminosity, with a catastrophic loss of water beginning about 1.3 billion years from now.

When the Sun enters the red giant phase in 5–7 billion years from now, it will swell to a hundred times of its current size, and the luminosity will increase thousands of times. The Earth will literally be scorched, though some water in the mantle may survive.

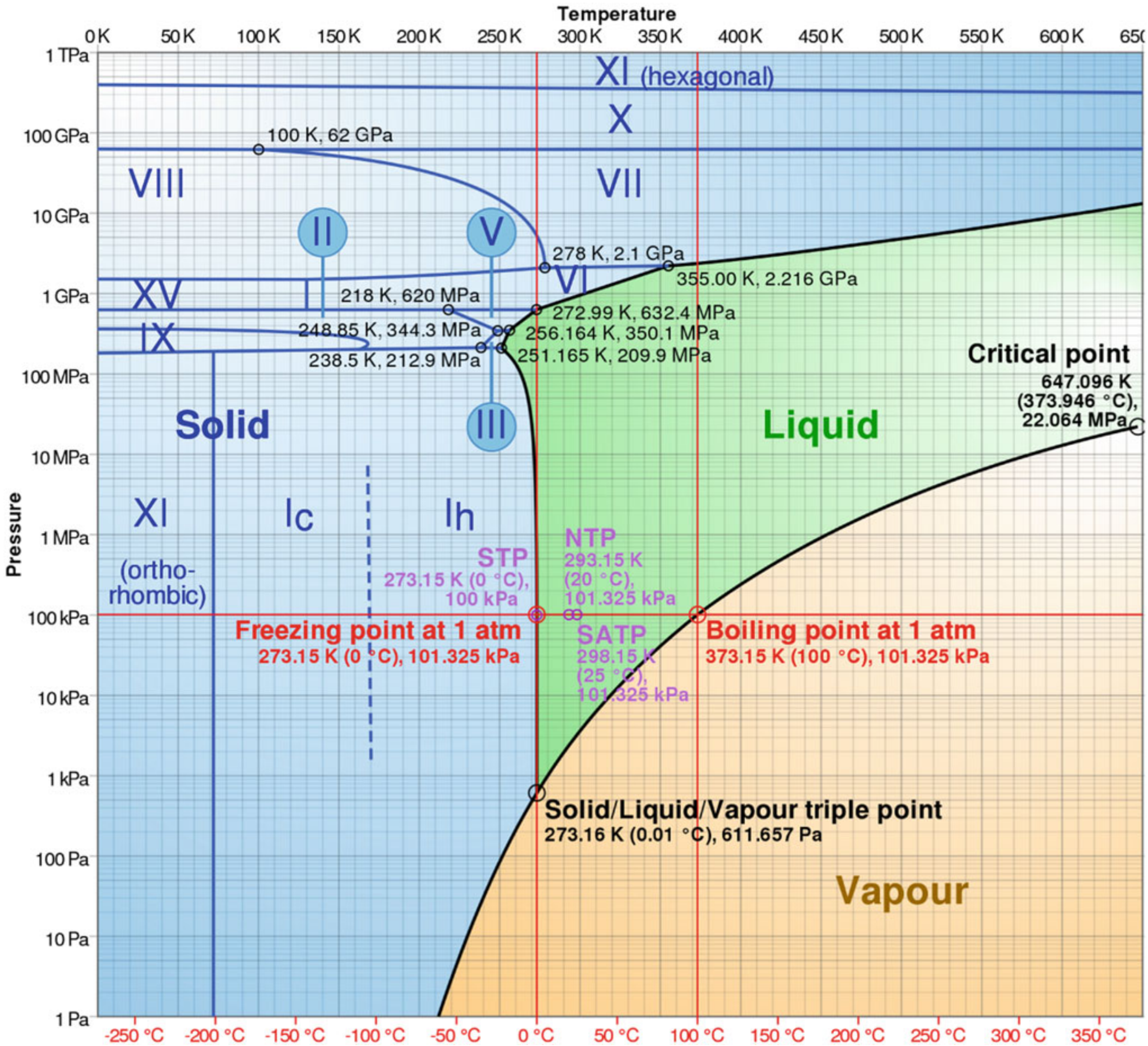


Fig. 2.1 Phase change diagram of water (*Source* https://commons.wikimedia.org/wiki/File:Phase_diagram_of_water.svg)

When the Sun becomes a white dwarf, and subsequently a black dwarf, in the last phase of its lifetime, the Earth will be deeply frozen.

It is not known whether life originated on Earth or was seeded from outer space. Evidences of life on Earth trace back to 3.5–4 billion years (Schopf 2006). Since the emergence of life living organisms co-shaped the atmosphere, hydrosphere and lithosphere of the planet. Ecosystems—even primitive living organisms compared to the present ones—not only relied on the resources of the Earth but played significant roles in shaping our planet (Bogardi et al. 2013).

2.1.2 Water Exchanges with Outer Space and Mantle in the Present

The amount of water in the hydrosphere at any given time is in an equilibrium between water exchanges with the outer space and hydro-tectonic interactions with the interior of the planet. Water exchanges between the hydrosphere and its surrounding is negligible on historical time scales, but it is worthwhile to discuss these water fluxes from geological perspectives where they play important roles in the evolution of our planet.

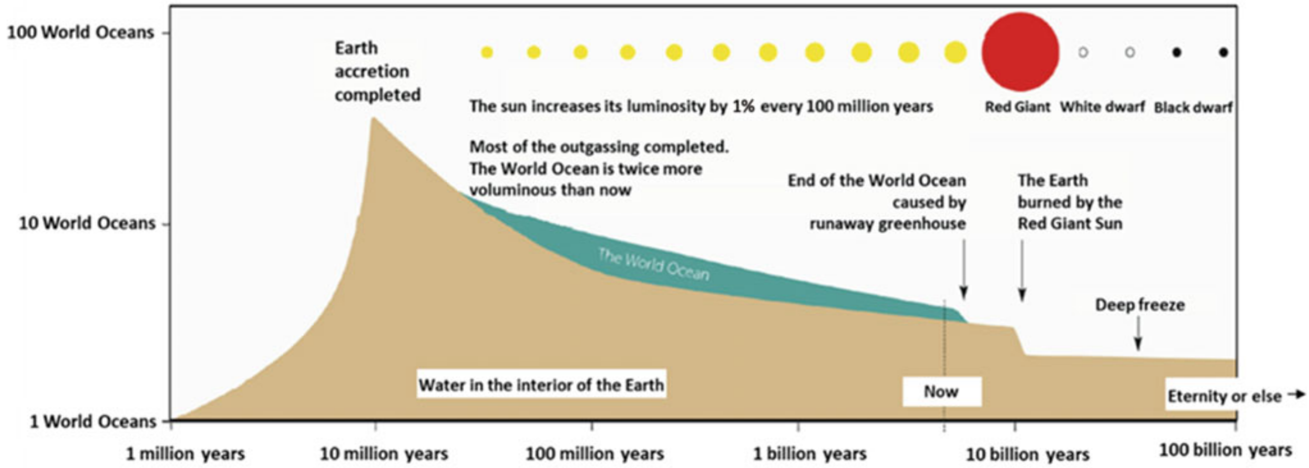


Fig. 2.2 Water on Earth over time (*Source* Kotwicki 2009)

2.1.2.1 Water exchange with outer space

Kotwicki (2009) estimates that the water loss of earth to outer space is about 0.2 km^3yr^{-1}. At this rate, it would take 7 billion years to lose all the World Ocean (Kasting 1988). This is far beyond the 1.3 billion year discussed in the previous section, when the catastrophic losses of water begin due to the increasing luminosity of the Sun that clearly seals the fate of water on Earth (as shown in Fig. 2.2).

The Earth gains water from outer space with volatile accretion rates estimated in a very wide range of between 10^{-4} and 1 km^3yr^{-1} (Bounama et al. 2001). The ± 1 km^3yr^{-1} water exchange with the outer space is well within the rounding error of any water balance estimates and by orders of magnitude smaller than the discrepancies between different assessments of the world's water resources (Fekete 2013a, b).

2.1.2.2 Hydro-tectonic water cycle

Earth's mantle is highly outgassed and presently contains only 1/3 of its initial water (Rupke 2004). Most of the water currently stored in the Earth's mantle is recycled surface water. The Earth's deep and surface water cycles therefore appear to be in close contact presumably through the marine compartment of the hydrological cycle. Possibly, the Earth's surface is losing water to the mantle through subduction of oceanic sediments and crust (Van Andel 1994). Even if this hypothesis can be proved the estimated rate change still would be insignificant in comparison to observational uncertainties.

Besides the unproven hypothesis of losing water through oceanic sediment subduction, water certainly circulates through the mantle. Water trapped in the slabs must be stored mainly in nominally anhydrous minerals that may be transported to the core-mantle boundary region, some 2900 km below the surface of Earth (Ohtani 2005, 2019). Even at the rate as low as one km^3yr^{-1}, the World's Oceans would have been already circulated three times. The strontium isotope ratio ($^{87}Sr/^{86}Sr$) in marine carbonates varies with age. The current $^{87}Sr/^{86}Sr$ ratio of seawater represents about a 4:1 mixture of river water and submarine volcanic water (Condie 1989). The current subduction and spreading rates are only sufficient to recycle the ocean once in roughly 4.5 billion years (Smyth and Jacobsen 2006) suggesting a 0.33 km^3yr^{-1} circulation rate.

The estimates of the present mantle water content from different authors are 1.6 and 20 times of the total volume of the World's oceans, with a mean value of 5 times (Bouwman et al. 2002; Kotwicki 1991) that is the most likely value (Murakami 2002).

2.1.3 The Hydrosphere

In its gaseous phase, water can travel long distances carried by prevailing winds and thermal forces. The significance of water in the atmosphere is often overlooked. Water is the most important greenhouse gas responsible for majority of the greenhouse effect (carbon dioxide only comes as a distant second followed by a host of others). Although, other compounds (e.g. methane) have stronger greenhouse gas effect, but are much less abundant in the atmosphere than water vapour.

Water is constantly on the move in all three of its phases and these movements (fluxes) along temporal stays in various storage compartments (stocks) linked together in a unique, complex and highly interconnected sets of circulations known as the hydrological cycle (Fig. 2.3).

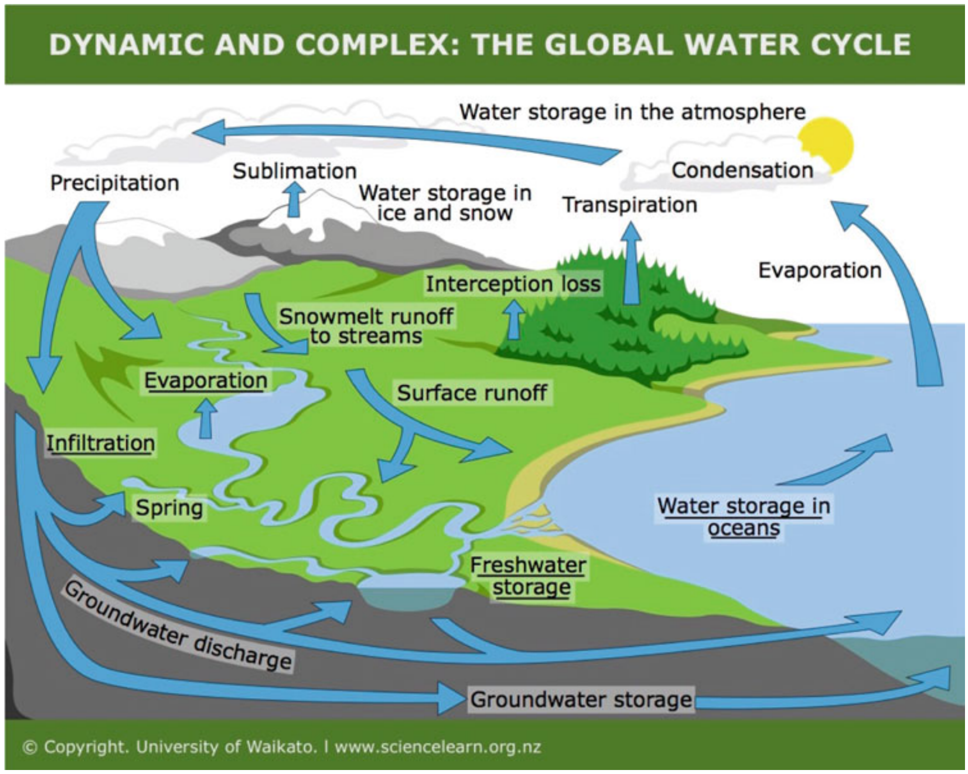


Fig. 2.3 The hydrological cycle and its major components and processes (*Source* University of Waikato)

2.1.3.1 The Hydrological Cycle

This incessant cycle is responsible for the temporary abundance or shortage of the resource water at any given place in the world. Due to this circulatory nature managing water is as much the management of stocks as that of fluxes.

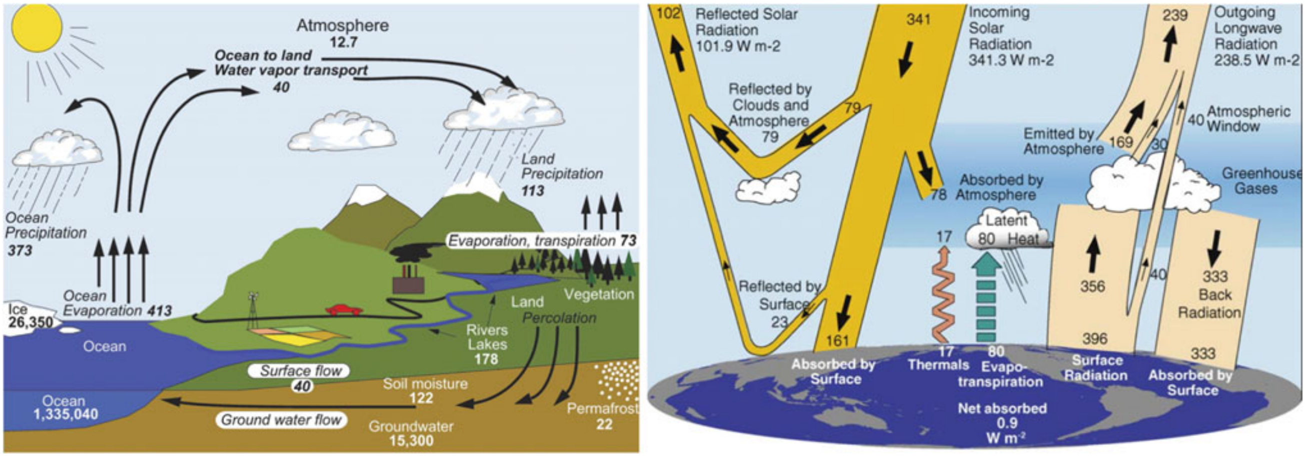
The occurrence and circulation of water on Earth are essential and in many aspects fundamentally important for geophysical processes and life of and on the planet. However, the laws and quantitative details thereof were, and in some cases are still inadequately known and on a global scale poorly measured.

The water balance of the hydrosphere (Trenberth et al. 2007) and the energy balance of the Earth (Trenberth 2009) go hand in hand (Fig. 2.4a, b respectively depicting the last three decades of the twentieth century). The 413,000 km^3yr^{-1} evaporation of the oceans and the 73,000 km^3yr^{-1} evapotranspiration over land (totalling 486,000 km^3yr^{-1}) returning as 373,000 km^3yr^{-1} precipitation over oceans and 113,000 km^3yr^{-1} over land is driven by the 80 W m^{-2} radiation providing the latent heat of the vaporization of water. The 40,000 km^3yr^{-1} imbalance between the evaporation and the precipitation over oceans and the same imbalance between evapotranspiration and precipitation over land are compensated with the same amount of horizontal water vapour transport in the atmosphere and the returning surface and groundwater flow to the oceans and recipient seas.

None of the terms in the water balance nor in the energy balance are known to two digits accuracy with the exception of the incoming solar radiation. Galilei recognised centuries ago that we knew better the movements of celestial bodies than the water in the nearby streams, irrespective that the latter one happened in front of us. Given the considerable differences in scientific publications concerning the main components of the hydrological cycle even at global scale (Syed et al. 2009; Fekete 2013a, b; Haddeland et al. 2011), it is prudent to admit that Galilei's statement did not lose its validity in our days.

The 80 W m^{-2} radiation that drives the hydrological cycle is only the 23% of the incoming solar radiation and 41% of what reaches the Earth's surface. It is also worth noting that the debate over climate change revolves around the 0.9 W m^{-2} net absorbed energy[1] that may go as high as 8.5 W m^{-2} according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Allen et al. 2014).

[1]The four representative concentration pathway scenarios (RCPs) referred as RCP2p6, RCP4p5, RCP6p0 and RCP8p5 in the latest IPCC report do not reflect the concentrations of any substance, but the net absorbed radiation imbalance of 2.6, 4.5, 6.0 and 8.5 in W m^{-2} respectively due to the accumulation of greenhouse gases in the atmosphere.



(a) Source: Trenberth et al., 2007 *(b) Source: Trenberth 2009*

Fig. 2.4 **a** Water fluxes and storage pools (in 10^3 km^{3}yr^{-1} and 10^3 km^3 respectively) of the hydrosphere and **b** the energy balance of the Earth (in W m^{-2})

2.1.4 Estimates of Water in the Different Compartments of the Hydrosphere

Numerous authors attempted to assess the amount of water in the hydrosphere stored in different compartment (Babkin 2003; Gleick 1993; Kotwicki 1991; Pagano and Sorooshian 2002; Shiklomanov 1998; Shiklomanov and Rodda 2003). A comprehensive list of the various storage pools and their estimated volume and area are given in Table 2.1 (Kotwicki 2009) incorporating significant corrections to several terms (Downing et al. 2006; Lehner and Döll 2004; Mitra et al. 2005).

It has to be admitted that none of the terms shown in Table 2.1 are particularly precise. While some of the terrestrial forms of water seem to be less significant in the volumetric sense, they may still cover very significant areas, and, therefore, be important in terms of the atmospheric and land surface water exchange. Their societal significance is also considerable.

2.1.4.1 World Ocean

There are no accurate data on the exact volume of the World Ocean, and various sources present figures ranging from 1.32×10^9 to 1.38×10^9 km^3 (Babkin 2003; Gleick 1993, 1996; Pagano and Sorooshian 2002; Shiklomanov 1998). While this range seems to represent an inaccuracy of less than 5% it should be noted that the sum of all other components in the water balance are much less than the above cited difference of 60 million km^3. The surface of the ocean is by far not the geodesically known zero level but has extensive gravitationally induced “hills” and “valleys” in the order of hundreds of meters. The shape of the hydrosphere is subject thus to astronomic factors, detailed sea-bed topography, temperature and compressibility. Their aggregate influence can affect the ocean volume estimate by millions of km^3. The sea level rose 10 mm since 1950 (Gouretski and Koltermann 2007) due to thermal expansion. Thus, the various effects of climate change can influence both stocks and fluxes within the hydrosphere.

2.1.4.2 Groundwater

Despite the importance of groundwater as a water source, its volume (the value given in Table 2.1 includes Antarctica (Babkin 2003)) is probably the most poorly assessed storage pool in the hydrosphere. Besides the challenges to assess the water stored deep underground, the depth to which to consider water as part of the groundwater is ill-defined. The usual limit of 4000 m excludes groundwater occurring in deeper strata. For example, the Kola Peninsula Superbore found huge quantities of hot, highly mineralized water at a depth of 13 km. There are large aquifers deeper than that. These waters would not only be difficult to access, but expensive treatment would be needed to remove the often harmful mineral content for potential water use.

The groundwater estimates should be regularly revisited in future, if for nothing else but to account for major reduction of groundwater storages due to extensive irrigation from fossil groundwater in India, China, the USA, and other parts of the World. For more detail, see Sect. 3.3 of Chap. 3.

2.1.4.3 Glaciers

Unlike groundwater, glaciers have visible footprint and yet their volumes are almost as poorly known as the groundwater resources and published estimates in the literature are

Table 2.1 Water storages in the hydrosphere

Form of water	Area (km^2)	Volume (km^3)	% of total water (%)	% of freshwater (%)
Salt water	510 065 600	1 350 000 000	97 1	
World Ocean	361 126 400	1 338 000 000	96.3	
Saline groundwater	148 939 100	14 000 000	1.0	
Salt lakes	820 000	85 000	0.006	
Ice	36 821 000	33 400 000	2.40	75.0
Glaciers	15 821 000	33 100 000	2.3S	74.4
Antarctica	13 586 000	30 100 000	2.17	67.6
Greenland	1 785 000	2 620 000	0.19	5.9
Arctic islands	230 000	83 000	0.006	0.2
Mountains	220 000	34 000	0.002	0.1
Permafrost	21 000 000	300 000	0.022	0.7
Freshwater	510 065 600	11 100 000	0.80	24.9
Fresh groundwater	148 939 100	11 000 000	0.79	24.7
Lakes	4 200 000	91 000	0.007	0.20
Soil moisture	148 939 100	16 000	0.001	0.04
Wetlands	5 300 000	12 000	0.001	0.03
Rivers	1 000 000	2 100	0.0002	0.005
Biological water	510 065 600	2 400	0.0002	0.005
Reservoirs	400 000	7 000	0.0005	0.016
Farms	1 377 000	600	0.00004	0.0013
Atmospheric water	510 065 600	13 000	0.00094	0.029
Hydrosphere total	510 065 600	1 390 000 000	100	100
Earth interior		7 000 000 000	approx. 5 World Oceans	

Source Kotwicki (2009)

wildly different. Antarctica alone has considerable contribution to this uncertainty ranging from 22 to 30 million km^3 (Babkin 2003; Siegert 2000).

Glaciers change significantly over time as a result of their retreat from the last glacial maximum that is accelerated more recently as our planet warms. Therefore, reported glacier volumes should be accurately labelled by time. Due to the tendency of past water resources reports underestimating volumes of glaciers, many of them were derived in the 1950s (Kotwicki 2009), so it might be just a matter of time the true glacier volumes approach the values estimated earlier.

NASA (2006) reports that the mass of ice in Antarctica had decreased significantly from 2002 to 2005, enough to raise global water levels by 1.5 mm during this period. This corresponds to a volume of some 20,000 km^3, comparable to the volume of Lake Baikal, the biggest freshwater body on Earth. In addition to that, mountain glaciers lost over 6,000 km^3 of volume between 1960 and 2002 (reflected in Table 2.1).

2.1.4.4 Lakes

Lakes deserve special attention as the most sensitive indicators of climatic changes (Kotwicki and Allan 1998). The literature usually quotes the number of lakes on Earth as 8 million, meaning water bodies with a surface area bigger than 0.01 km^2 (Lehner and Döll 2004). However, there are also staggering numbers of smaller lakes. Downing et al. (2006) estimated that there are 304 million lakes with a surface area greater than 0.001 km^2. This yields an estimated 4.2 million km^2 as total water surface area, more than three times larger than the most often quoted estimate of this area.

There is a special class of lakes, about 145 of them found so far, located on Antarctica, under several kilometres of ice. At some 35 million years of age, they are the oldest lakes on Earth. The largest of them, Lake Vostok is 240 km long, 60 km wide, and over 1 km deep. Its volume is estimated to be 5,400 km^3.

2.1.4.5 Wetlands

Definitions of wetlands, marshes, bogs, fens, swamps and peatlands do vary, as well as their reported local and global coverage (Lehner and Döll 2004; Mitra et al. 2005). There is very likely that the global area of wetlands is underestimated, due in part to many small wetlands which tend to be neglected, but once aggregated would amount to very significant areas. The figure of 5.3 million km^2 quoted in Table 2.1 follows (Mitra et al. 2005), and is more than twice as large as that reported by standard hydrological references. There could be some double counting. The Ramsar Convention (1971) (UNESCO 1971) classifies open water bodies with less than 6.0 m depth as wetlands. Based on this criterion like Lake Balaton in Hungary (the largest lake in Central-Europe) or Lake Neusiedl shared between Austria and Hungary with their 600 and 315 km^2 open water surface respectively are mostly or entirely "wetlands" rather than lakes.

2.1.4.6 Biological Water

The biological water is of obvious interest because living organisms actively participate in the water exchange between the soil and the atmosphere and intensify the vertical water exchange. As an example, forests can evaporate far more than comparable area of open water due to the increased surface by the multiple layers of leaves.

The figure of 1220 km^3 quoted in many references and discussed in (Babkin 2003) is non-representative since it assumes that 90% of the water is in forests, the biomass of which contains 80% water. It is now understood that a large portion of the global biomass consists of unicellular organisms and other microorganisms. Since it is estimated that 10–50% of all biomass on Earth resides deep below ground[2] (Anitei 2006), the figure in Table 2.1 was increased to 2400 km^3 to reflect the upper limit of this range. This is further justified by the fact that wetlands contain much more biomass than was previously thought.

2.1.4.7 Reservoirs and Impoundments

Man-made reservoirs are usually not listed separately in water balances of Earth. Downing et al. (2006) estimate that there are 515 thousand impoundments, with an average area of 0.52 km^2, and a total area of 260 000 km^2. The 25 000 largest reservoirs hold 6815 km^3 of water, out of 7000 km^3 held in all reservoirs, and lose 1–2% of storage capacity annually due to siltation. Babkin (2003) reports that reservoirs of over 1 million m^3 store 5750 km^3, and cover 400 000 km^2.

Due to the reported increase of dam constructions for hydropower development (Zarfl et al. 2015) worldwide the above cited figures are likely to increase considerably. Furthermore, as climate change takes its predicted course the need for more storage space to compensate for the increasing variability of streamflow would simultaneously arise. Growing human population and its undeniably increasing water demand exacerbates the pressure for more storage space. Notwithstanding some negative effects to impound and store water in reservoirs it is very much likely that storage facilities will increase in number and aggregate volume.

Perhaps the oddest impact of reservoirs is their miniscule, but still measurable slowing of the Earth's rotation due to the displacement of water to higher altitude (Chao 1995).

Downing et al. (2006) estimate that worldwide 77,000 km^2 are covered by farm ponds. There are also over 1.3 million km^2 of rice paddies worldwide. Therefore, the open water surface area of agricultural facilities covers around 1% of the total land area, and probably more, due to all the water conveyance facilities and other irrigation and drainage works. Due to the expected increase of droughts and floods as one core manifestation of climate change in the hydrological cycle the proliferation of farm scale storage ponds can be expected during the coming decades.

2.1.4.8 Desalination

Desalinated water is not a storage; however, it is a resource derived from the biggest (natural) water reservoir, the oceans. Kotwicki in 2009 estimated 10 km^3yr^{-1} desalinations and can be considered in conjunction with Table 2.1 to give some perspective to human endeavours. More recent estimate elevated that figure 34.8 km^3yr^{-1} a decade later, thus more than threefold increase (Jones et al. 2019). The by-product of desalinization is the often toxic 51.7 km^3yr^{-1} brine production.

2.1.4.9 Atmospheric Water

As climate warms, the amount of water vapour in the atmosphere is expected to rise faster than the precipitation amount, which is governed by the water holding capacity of the air (Trenberth et al. 2003). This implies that the main changes to be experienced are in the character of precipitation: increases in intensity must be offset by decreases in duration or frequency of events. According to the Clausius–Clapeyron equation, one might expect the global mean precipitation and evaporation to increase at a rate of 7% per 1 °C surface warming (Wentz et al. 2007).

[2]https://news.softpedia.com/news/Natural-Radioactivity-Feeds-Microorganisms-Communties-in-Deep-Biosphere-Deep-Under-Seafloor-41787.shtml.

2.1.4.10 Water not Accounted for

Certain water storages and open water surfaces are usually not considered at all. They include, for example, water stored in sediments, the voluminous difference between ice and liquid water, changes of volume due to temperature and salinity variations, water and wastewater in municipal networks and facilities, water in open irrigation conduits and flooded fields, minor streams, and probably many others.

Some of these amounts are huge, if aggregated. For example, sediments, which average half a kilometre depth over the World Ocean, and sizeable thicknesses under water storages on lands, typically contain plenty of water.

2.1.4.11 Fluxes

Water fluxes are of paramount importance in estimating water resources and many hydrological applications, yet most of them are poorly understood. Furthermore, observational deficiencies constrain their accurate measurement. The two most important fluxes are precipitation and evapotranspiration where the second one is rarely measured, while precipitation measurements have large errors either due to gauge under-catch or the insufficient density of the rain gauge network. Remote sensing techniques even with accurate ground truthing are prone to further errors. The uncertainties in precipitation translate to even greater uncertainties in estimated runoff (Fekete et al. 2004) in relative terms since the runoff sensitivity to changes in precipitation is typically greater than one (Dingman 2015; Yang et al. 2008). The most accurately measured water flux is river discharge (Fekete et al. 2012; Hannah et al. 2010), but discharge measurements practically never used in constraining weather and climate models and as a result they are often in error, by 50–100% (Roads et al. 2003).

These errors manifest in the reality that weather forecast models rarely capture the amount of water circulating through the atmosphere right despite tracking the movement of major air masses fairly accurately. One could recognize this poor performance by following the daily weather forecast that tend to predict the coming storm event quite accurately, but often are wrong about the precipitation amounts. The progress in weather and climate model will need improved global data sets of precipitation and runoff (Widén-Nilsson et al. 2007).

While major storage changes in groundwater can be monitored from space, other specifics of groundwater need to be taken care of too. Direct groundwater runoff to the World Ocean traditionally were assumed to be negligible. Recent estimates of groundwater fluxes as high as 2400 km^3yr^{-1} directly discharging into oceans (Curmi et al. 2013) (see Sects. 2.1.3 and 2.2.2) rectify past assumptions.

While most of considerations of water resources are concerned with and refer to volumes, dominantly open water surfaces rather then volumes are significant for water exchange between the surface of Earth and its atmosphere. The vast majority of this open water surface is over oceans that most textbooks report as 70.84% of Earth's total surface. The correct value is likely to be greater, at least 73.4% for open water surfaces, or 76.5% if the ice covered area were added (Kotwicki 2009).

Estimates quoted by Kotwicki (2009) indicate that this surface area is twice as large as usually acknowledged. Shiklomanov and Rodda (2003) refer to 6.5 million km^2 while Table 2.1 indicates 13 million km^2, an increase well over the extent of two Mediterranean seas.

The higher estimate is 8.8% of the total land area, or 9.8% if glaciers and permanent snow cover areas are included. Open water over land do not necessarily have the highest rate of vaporization among the different land cover types, because the evapotranspiration over forested area under ideal conditions can be higher due to the multiple layers of evaporating surfaces that the leaves form (Federer et al. 1996), but they evaporate steadily only limited by the atmosphere's ability to absorb water vapor and allow its upward movement via turbulent water transfers (Dingman 2015).

2.1.4.12 Temporal variability

The long-term annual average water storages and fluxes in the hydrosphere are useful for the understanding of the overall presence of water on our planet, but the ability to follow shorter variations within the annual cycle is critical for water managers since these average values hide abundances and shortages seasonally or shorter time scales. Prolonged dry spells, droughts leading to water scarcity or excess water leading to floods often cause serious damages including the loss of lives are effectively obscured and "averaged out" in annual water balance values.

Many terms of the water balance of Earth are subject of frequent and substantial fluctuations at least on seasonal, but sometimes also on daily scales. During the winter months at the Northern hemisphere thousands of km^3 water is frozen. Major floods, while of relatively short duration are quite voluminous, and astronomic forcing move huge quantities of water around. It would be desirable to compute the water balances of Earth on a monthly basis to see the variation of these storages and fluxes. For example, there is considerable seasonal variation in the global water balance even at monthly scales (van Hylckama 1970), with 6000 km^3 more water stored on the land in March than in September, 6000 km^3 more water stored in the oceans in October than in March, and 600 km^3 more water stored in the atmosphere in September than in March.

Water on Earth is in a state of constant flux and this fact will be reflected so a dynamic tracking of the water balances of Earth from a combination of sustained observations and data assimilation to coupled hydrological and atmospheric models for both hindcast and forecast are long overdue. Such integrated data assimilation and coupled modelling capabilities exist in many developed countries, but are absent in most part of the world leading to otherwise largely preventable catastrophes (Webster et al. 2011). The static version of the water balance, such as presented in Table 2.1, may serve as an illustration at an introductory level, but the ever increasing need to account for quickly dwindling and qualitatively deteriorating water resources per capita will soon need much more sophisticated estimates and solutions.

Even without predictive capability, providing up-to-date monthly water balances of Earth is an obvious candidate for speedy implementation, and operating such a rudimentary hydrological modelling and data assimilation system is feasible based on the currently available technology and publicly available data sources. A number of prototype implementations of combining real-time observations and modelling were developed in the past (Mitchell et al. 1999; Syed et al. 2008; Wisser et al. 2010) and operating such systems require only a fraction of the resources devoted to long-term weather forecasting, but commitment to turn these prototype system to production quality services is still lacking.

Besides regional water managers who have no access to modern hydrological and meteorological modelling, many international organizations concerned about the sustainable development of our planet are eager to have access to the aforementioned products and anticipate that these capabilities would be extremely handy and invaluable tool for water and related professionals, and contribute to raise the awareness of the public the better appreciation of our most valuable resource—water.

2.1.5 Humans in the Hydrosphere

Recently, questions related to the water availability and its temporal and spatial balance gained importance due to the perceived or real increase of water scarcity, decreasing water resources per capita, and documented water quality deterioration. Water in global and regional circulation models need to be better represented and characterized to evaluate the severity of, what may be called the water crisis situation, and predict more accurately the occurrence and consequences of climate change. Needless to say that the Sustainable Development Goals (United Nations 2015), with their manifold implications for water and its management should rely on as accurate estimations as possible.

There are many reasons for this state of affairs. Among them the declining number of continuously reporting gaging stations can be mentioned (Fekete et al. 2012). Hydrologists can list a series of other causes, starting with the fact that the water is in constant flux, and further pointing out that our measurement devices and methods are still inadequate for the task to capture a resource which, as already ancient Greek philosophers noticed is "panta rhei". Though, increasingly hydrologists can rely on results of advanced space-based observation programs the importance of in situ measurements remains unabated (Fekete et al. 2012, 2015) (see also Chap. 13).

Many people expect that the climate change induced global warming will generally reduce water supplies (Bates et al. 2008), while both the global population and demand for water are increasing. While the amount of water on Earth is practically constant what may well change are the spatial and temporal distributions and occurrence of water, which could feasibly be withdrawn for human consumption and use even at locations of hitherto reliable water availability.

The hydrological cycle, subdivided to its atmospheric, terrestrial and marine compartments forms the most dynamic (and to an extent visible) part of the overall water circulation on planet Earth. While it is the most important cycle of water "at the human scale", other water cycles which operate on geological time scales are also important in visualizing a complete historical and far reaching future water perspectives of Earth.

2.2 Hydrological Versus Water Cycle

The terms "*hydrological*" and "*water*" cycles are normally used interchangeably. The distinction proposed here enables differentiating the context within circulation of the water is investigated. The term "*hydrological cycle*" appears to be better suited for the scientific description of all the processes (fluxes, storages, phase changes, potential gradients and driving forces, etc.) which characterize and quantify the movement and interdependencies of water between phases and compartments of the global cycle. Therefore, in Sect. 2.1 this term was used. The term "*water cycle*" puts more emphasis on the water as a substance in somewhat of an accounting manner that is less concerned about the details of the driving "hydrological processes" and cares more about the flowrates of fluxes and states of the storages. Thus the term "*water cycle*" could be directed more toward the management of water as a resource and associated with its societal value.

This book attempts to apply this distinction between *hydrological* and *water* cycle consistently that the authors believe will help the readers to appreciate the complexity of the *hydrological cycles* while approaching the *water cycles* in more pragmatical terms. The differentiation allows practical simplifications suitable for water managers and policy makers. It recognizes the necessity of approaching water resources assessments with different level of details in representation of underlying processes at different geographical scales like continents, river basins and/or aquifers or even formulating them over man-made jurisdictional areas such as countries.

Water cycle(s) are thus the acknowledgement that the practical management of how we consume, use and utilize water may not be exclusively defined by the principles and laws of nature but substantially motivated by human needs and aspirations. In fact, water withdrawn from its natural cycle could become subject of a strongly human-mediated water cycles either within a municipality or within a manufacturing process (like industrial water cycles). Needless to say that the way humans manage the water cycle(s) have manifold links and feedback to the hydrological cycle, the ultimate, interlinked global circulation of the substance and resource water.

Figure 2.5 underlines the logic behind the suggested distinction. The upper part of Fig. 2.5 shows the global distribution of the origin of continental (local) runoff (Fekete et al. 2002; Vörösmarty et al. 2005). Some areas like the Amazon Basin in South America, Northeast Canada and the Congo Basin contribute substantially to the global water flux from the land mass towards the oceans. Irrespective of their over proportional share in the global resource their role to cover human needs are much less important due to the relatively low population density in these areas as shown in the lower part of Fig. 2.5.

On contrary the Western African coast, South and Southeast Asia and the Indonesian archipelago as well as Western Europe are those areas where the available water supply and demand (due to high population density) correspond well. The juxtaposition of the two parts of Fig. 2.5 reveals the Middle East with the most pronounced discrepancy between the availability of renewable water resources and population density. The bottom map shows the importance of the runoff producing areas in serving human needs (expressed as the number of people within the respective grid area).

2.2.1 Quantification of the Water Cycle at Global Scale

Beyond the understandable scientific curiosity to estimate water and to quantify its occurrence and circulation within the hydrological cycle the increasingly intensifying discourse about regional and temporal water scarcity and the expected deterioration of the status quo (due to climate change and increasing water demands) necessitates an accurate, regionally and temporally distributed assessment of how much water is available in the World. While the quantitative assessment is crucial the qualitative aspects of water resources assessment are gaining considerable importance both with respect to their potential for certain uses, but also with respect to the consequences of these uses to the quality of water resources. As the hydrological cycle is an irreplaceable source, both quantitative and qualitative assessments are needed to determine tolerable thresholds of withdrawals and the consequences of water use (pollution etc.).

While individual human water uses and their provision are usually rather local (or regional) scale activities their proliferating number and intensity as well as their links to the global hydrological cycle make them a global concern (Vörösmarty et al. 2000). Thus in the context of planetary stewardship and with respect to potential planetary boundaries (Rockström et al. 2009b) the first question is how much water do we have on Earth? This is followed by further questions. How much water is in stocks? How much water takes part in the (annual) cycle of global circulation?

As the amount of water to be considered within the perspective of water resources management is practically constant on Earth the different components of the hydrological cycle must balance each other over a certain time period. For the actively circulating amount of water this period is usually the annual cycle. Therefore, the components of the hydrological (as well as water) cycle are expressed in so called water balance equations. These equations may refer to the whole globe, or for a selected part thereof, like continents.

The main elements of a water balance equation are:

- precipitation (as the result of condensation of water in the atmosphere in solid or in fluid phase);
- evaporation (escape of vapor from water bodies or barren ground);
- transpiration (escape of water from plants or other biologically held water);
- sublimation (escape of vapor from solid phase water like ice and snow surfaces);
- percolation or infiltration (seepage of fluid water into the ground);
- surface and subsurface runoff which ultimately links the terrestrial and marine compartments of the hydrological cycle;
- vapor transport as the ultimate closure of the cycle from the oceans towards the land mass.

Due to the extent of certain compartments like the oceans, groundwater aquifers, lakes, glaciers and icecaps etc. the hydrological cycle is a composite of fluxes and stocks.

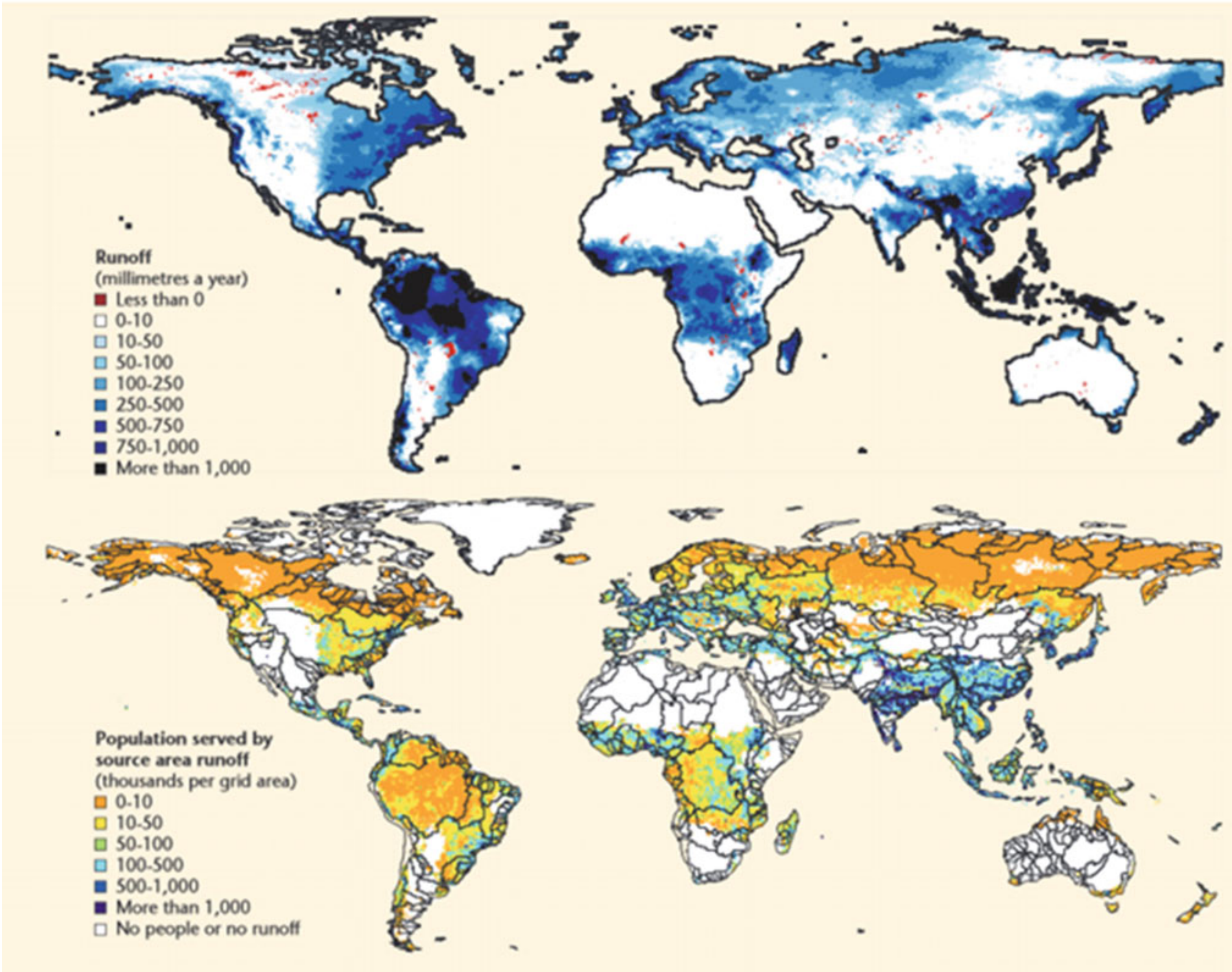
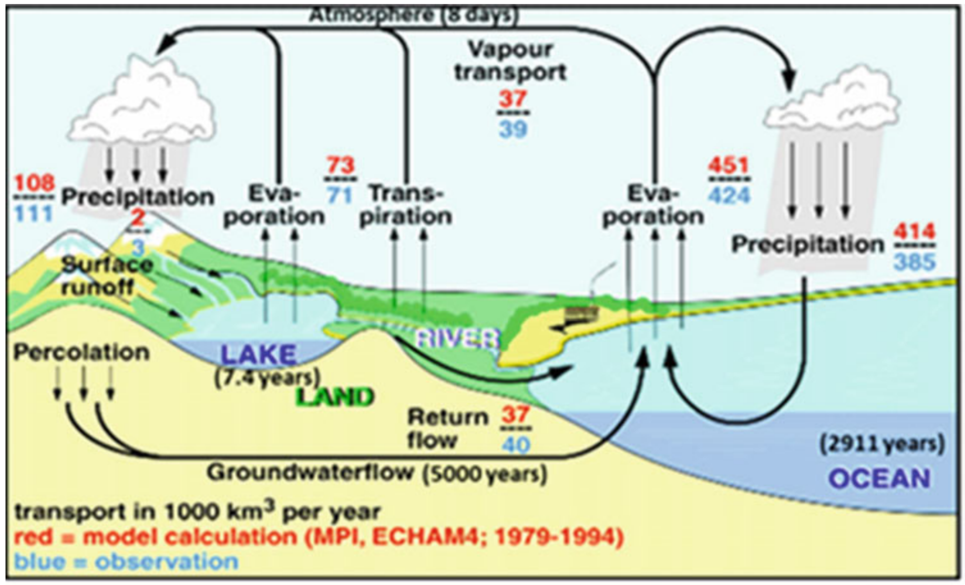


Fig. 2.5 Contrast between the geophysical interpretation and human dimension of the annually renewable water resources (continental runoff) (*Source* UNESCO World Water Development Report 3. 2009)

Figure 2.3 captures these processes without quantifications. Due to the regular annual climatic cycle the hydrological cycle is also subject to an annual "renewal". However, due to the mentioned stocks water stored in these stocks may be renewed over much longer timespans (see Fig. 2.6). Table 2.2 shows the estimated average storage periods in different compartments of the cycle. This table provides estimates of the volume of water bodies stored in the different compartments. It is important to note that the overwhelming part of water on Earth is saline and hence cannot be directly used to cover freshwater demands. A substantial part of freshwater reserves is captured in solid (frozen) form. The remaining freshwater resources can partially be found in uninhabited areas and hence inaccessible for human use. Likewise, soil moisture and biologically bound water, while fulfilling essential life-supporting functions are not readily available to be allocated for whatever water use people may have in mind.

It is worth mentioning that estimates presented in Tables 2.1 and in Figs. 2.4a and 2.6 somewhat differ. It is to be emphasized that these estimates are based on combinations of measured and model calculations. Data assimilation techniques allow the incorporation of observations into atmospheric (typically weather forecast) or hydrological models in a manner that ties down model simulations closer to reality while the model acts as a means to interpolated spatially and temporarily amongst the sparse observation data points (Harding et al. 2011). Irrespective of the ever improving measurement techniques (see Chap. 13 for more detail) the observational accuracy of the components of the hydrological cycle and of course also for the water cycle is notoriously low.

Fig. 2.6 Comparison of the estimated components of the water cycle, size of water stocks and estimated storage periods



Source: Lozán et. al, 2007

Table 2.2 Mean duration of storage of water in the different compartments of the hydrological cycle

Component	Mean residence time	Total water stored (thousands of cubic kilometres)	Freshwater stored (thousands of cubic kilometres)
Permafrost zone, ground ice	10,000 years	300	300
Polar ice	9,700 years	24,023	24,023
Oceans	2,500 years	1,338,000	na
Mountain glaciers	1,600 years	40.6	40.6
Groundwater (excluding Antarctica)	1,400 years	23,400	10,530
Lakes	17 years	176.4	91.0
Swamps	5 years	11.5	11.5
Soil moisture	1 year	16.5	16.5
Streams	16 days	2.1	2.1
Atmosphere	8 days	12.9	12.9
Biosphere	Several hours	11.2	11.2
Total		1,385,985	35,029

na is not applicable.

Note: Components may not sum to total because of rounding. Reservoirs of water that respond slowly to change have long residence times. The atmosphere exhibits huge variability, its dynamics changing over very short space and time scales, whereas permafrost is sluggish and would be expected to respond slowly to forced changes such as those associated with global warming. Residence time also has an enormous impact on water quality. Streams and river waters, with their generally short residence times, are able to respond relatively quickly to pollution control measures, whereas groundwater can remain polluted – and taken out of the resource supply pool – for centuries unless costly remediation measures are applied.

Source: Based on Shiklomanov and Rodda 2003.

Source UNESCO World Water Development Report 3. (2009)

Table 2.3 Summary of estimates of the global water balance by different authors. Data is given in 1000 km^3

		N_L	V_L	A_L	V_M	N_M	$N_E = V_E$
E. Brückner	1905	122	97	25	384	359	481
R. Fritzsche	1906	112	81	31	384	353	465
W. Schmidt	1915	112	81	31	273	242	354
G. Wüst	1922	112,1	75	37,1	304,2	267,1	379,2
A. A. Kaminskij	1925	81	51	30	337	307	388
W. Meinardus	1934	99	62	37	449	412	511
W. Halbfass	1934	100	52	48	458	410	510
G. Wüst	1936	99	62	37	334	297	396
W. Wundt	1937	99	62	37	383	346	445
F. Möller	1951	99	62	37	361	324	423
E. Reichel	1952	100	70	30	345	315	415
M. I. Budyko u. a.	1956	105,1	67	38,1	407,9	369,8	474,9
M. I. Budyko u. a.	1963	107	61	46	450	404	511
J. Marcinek	1966	100	63,5	36,5	411,2	374,7	474,7
M. I. L'vovič	1967	108,4	71,3	37,1	448	410,9	519,3
M. I. Budyko u. a. (bei Dyck 1968)	1968	107	61	46	449	403	510
M. I. L'vovič	1972	113,5	71,8	41,7	-	-	-
J. Marcinek (extended)	1975	100	62,5	37,5	411,2	373,7	473,7
V. I. Korzun u. a.	1974	119	72	47	505	458	577
M. I. L'vovič	1974	113,5	72,5	41	452,6	411,6	525,1
A. Baumgartner u. E. Reichel	1975	111,1	71,4	39,7	424,7	385	496,1
R. K. Klige (für 1894–1975)	1982	119,8	69,9	50,2	507,1	457,2	Δ 0,3
R. K. Klige u. a. (actualized)	1998	119,83	69,91	50,53	507,15	457,23	577,06
M.T. Chahine	1992	107	71	36	434	398	505
I.A. Shiklomanov	1998	119	74	45	503	458	577
T. Oki	1999	115	75	40	431	391	506
K.E. Trenberth et al.	2006	113	73	40	413	373	486
Mean value		107	69	38	411	373	480
Standard Deviation		9,2	9,6	6,3	60,8	56,5	60,6
Maximum		122	97	50	273	242	354
Minimum		81	51	25	273	242	354
Range of variation in % of the mean value (of) 38		68	67	57	58	46	
Model calculations with ECHAN4_OPYC [3)]							
1990–1999 according to IPCC- scenarios IS92A[4)]		118	78	46	453	411	529–531
2090–2099 according to IPCC- scenarios IS92A[4)]		127	82	51	459	411	531–541

Source Marcinek (2011)

It is not surprising that the different estimates of global scale water balance elements made in the last hundred years varied considerably as shown in Table 2.3 (Marcinek 2011), but the lack of convergence in more recent studies (Haddeland et al. 2011; Fekete 2013a, b) is concerning. Some of the early estimates were very close to modern estimates and yet sometimes newer estimates diverge considerably (Syed et al. 2010; Haddeland et al. 2011). One might note that global scale hydrological models show wide spreads even with identical climate drivers (Haddeland et al. 2011) that are strictly due to the uncertainties in hydrological modelling.

N_l and N_m in Table 2.3 represent the precipitation over the landmass and the oceans respectively, whereas V_l and V_m stand for the evaporation from land and oceans. A_l represents the sum of continental runoffs. Finally, the equality of N_e and V_e (global aggregate precipitation and evaporation) indicates the necessary balance between the atmospheric, terrestrial and marine components of the cycle.

Scientific methods and database certainly improved over time. However, with few exceptions, estimated precipitation over land are quite similar. In contrast runoff estimates that is more relevant for water resources management appears to be more uncertain (Fekete 2013a, b). Table 2.4 refers to estimated aggregated discharge to the oceans and hence comparable with values for A_l in Table 2.3. It is worth to note that the two tables show differences even for the same author and source. Even more interesting to note that the global terrestrial runoff estimates made in the 1930s (Table 2.3)[3] often do not differ much from most of the more recent results as shown for example in Table 2.4.

The estimates of Table 2.4 vary relatively widely. Some of them were calculated by models relying on reanalysis data, but the differences between the model assumptions (global land surface versus global hydrological models) led to significant deviations in the terrestrial runoff (discharge) results, irrespective that the same meteorological forcing data was used. Fekete et al. (2002) articulated that the

[3]Table 2.3 Footnotes:(1) The table has been extended by M. Quante and J. Marcinek.(2) Not considered in the statistics.(3) Remains as it is as these are the names of two institutes (in German).(4) The scenario IS92a considers further greenhouse gas emissions in the twenty-first century.

Table 2.4 Estimates of the annual global discharge to the oceans in km^3yr^{-1}

Source	*Discharge*
Baumgartner and Reichel (1975)	37 713
Korzoun et al. (1978)	46 900
L'vovich et al. (1990)	39 700
Oki et al. (1995)	22 311
Postel et al. (1996)	40 700
Grabs et al. (1996)	42 700
Nijssen et al. (2001)	36 103
Fekete et al. (2002)	38 320
Dai et al. (2009)	37 288
Schlosser and Houser (2007)	36 000
Syed et al. (2010)	32 851
Wisser et al. (2010a)	37 405
Haddeland et al. (2011)	42 000–66 000

Source Fekete (2013a)

plausible estimates need to lie between 28,700 and 41,000 km^3/a based on the recognition that measured discharge leaving the land mass (at the most downstream discharge gauges) is approx. 20,700 km^3/a that originates from half the total continental land mass (sum of the catchment areas of the most downstream discharge gauges) that is 72% of the actively contribution land since approx. 30% is too dry to contribute to riverine runoff. Apart from a number of outliers most of the estimates in Table 2.4 are between 36.000 and 40.000 km^3/a, a range estimated based on gaged river discharges (Fekete et al. 2002), which corresponds well with estimate of Trenberth et al. (2007) and with the estimates shown on Fig. 2.4a.

Numerous authors argued that the most reliable estimates of global freshwater availability and distribution are based on in situ observations (Fekete et al. 2002; Dai et al. 2002; Hannah et al. 2010; Fekete 2013a). This fact however does not mitigate the importance of model-based estimates. The calibration of the so called Water GAP (Global Assessment and Prognosis) model shows remarkable success (Alcamo et al. 2003). Models like Water GAP, but also other model exercises (Hanasaki et al. 2008a, b; Gerten et al. 2011; Haddeland et al. 2011; Wada et al. 2014) enable comparison of the different models but also to simulate water distribution and use in a refined resolution at global scale. Without these models it would be impossible to draw a comprehensive picture of the availability and use of water. It has to be added that the global data sets are based on the less than optimal set of observations and thus products of data time series extensions and extrapolations. Unavoidably, the reliability of these (reanalysis) data sets, irrespective that they provide and input data point at every calculation node of the model, cannot be better than what is provided by the historical records.

The approx. 40,000 km^3yr^{-1} horizontal water fluxes (Trenberth et al. 2007) from land to oceans (discussed in Sect. 2.1.3) is a good approximation of the available "renewable" water resources that can be contrasted with freshwater use. Planetary boundaries (Rockström et al. 2009a, b) are widely used metrics to express the sustainable anthropogenic appropriation of various earth resources. The proposed limits for consumptive freshwater range between 4,000 km^3yr^{-1}–6,000 km^3yr^{-1} (Rockström et al. 2009a; Steffen et al. 2015), that are mere 10–15% of the annually renewable freshwater resources of the world.

The water withdrawals for irrigation (that is the most significant form of consumptive water use) range has a wide range 2500–3200 km^3yr^{-1} (Döll 2002; Vörösmarty et al. 2005; Wisser et al. 2008), but some of the withdrawn water finds its way back to surface or subsurface water pools resulting in a much lower consumptive water use ranging 1200–1800 km^3yr^{-1} (Hanasaki et al. 2008b; Döll et al. 2009; Wisser et al. 2010). The distinction between withdrawal and actual consumptive use is not always clear. So the estimate of 2,600 km^3yr^{-1} from Steffen et al. (2015) represents either a substantial upward adjustment of the previous estimates if it truly meant consumptive water use or could be just as well within past assessments if it was based on water withdrawal.

At global scale, consumptive freshwater use is still within sustainable boundaries, but once regional differences are factored in there are growing number of regions where the local thresholds are already passed. The areas where the planetary threshold for freshwater use is violated are associated with high population density, intensive agriculture and scarce, highly variable water resources (discussed in the Sect. 2.2.2). With the exception of South Africa most of these hot spots in the world can be found in the "dry belt" of the Northern Hemisphere.

The planetary boundary for freshwater use is an essential, however relatively simple threshold as it refers only of water quantity (so called "blue water" withdrawal, see Sect. 2.2.2), while water quality considerations may impose additional and even more severe constraints to water consumption and use. Application of wastewater treatment technologies may help, but water quality is threatened from non-point pollution from intensive agricultural using fertilizers, pesticides and altering the landscapes (especially wide scale deforestation). Excessive use of phosphorus and nitrogen fertilizers corresponds with the prime agricultural areas of intensive land use.

Both Rockström et al. (2009a, b) and Steffen et al. (2015) classify the nitrogen and phosphorus cycles as violating the proposed respective planetary boundaries (see Table 3.1). Undoubtedly, water is the transport medium carrying nutrients from fields to the recipient water bodies and hence ultimately the oceans. Therefore, the appropriate planetary boundary would be better defined as a function of the available water carrying away the excess nutrients that otherwise impose stress on the aquatic ecosystems leading to eutrophication.

2.2.2 Estimates of Water Resources and Their Use at Continental and Regional Scales

While the quantification of the global hydrological (and water) cycle is an important scientific exercise and certainly will remain in the focus of researchers to prepare more accurate estimates, to reflect the impacts of global environmental change and to assess the limits of a global resource, the use and management of water is not happening at the global scale. Abundance of water in a certain geographical location is usually little consolation for people facing consequences of drought just on the opposite side of the planet. Discussion of global water governance by defining general principles may guide practitioners, but their practical implementation as well as the management of water resources happens on smaller scales like national jurisdictions, river basins or even at the level of a single municipality.

Water use and water demand for the different sectors are primarily driven by density of human population and intensity of their agricultural or industrial activities to grow crops, generating energy, operate manufacturing facilities and other economic and social activities. Satisfying these water demands reliably and preferably from local sources is often a great challenge especially while sustaining fundamental and vital planetary and ecosystem services. Thus, the subdivision of the hydrological cycle to continental scale as well as its routing through different land form and cover/land use systems as parallel water cycles is of importance to understand the interrelationships between water and land, nature (ecosystems) and human use.

Figure 2.7 indicates that next to the continental runoff to the oceans (37,200 km^3/annum discharged to the oceans through so called exorheic river basins as estimated by Vörösmarty and Meybeck (2004) about 940 km^3/a is discharged into internal recipient water bodies like the Caspian Sea, Aral Sea, Dead Sea in Eurasia, to the Okawango Delta in Africa or Lake Eyre in Australia. The respective basins are called closed, or endorheic ones. Further to this distinction (Vörösmarty and Meybeck 2004) estimated the origin of these two flow categories according to their origin from different land forms. They also compared the renewable freshwater availabilities for the then 6.5 billion inhabitants of Earth. While the average annual water availability was 6,200 m^3yr^{-1} per capita in the exorheic part of the world the inhabitants of closed basins faced already in the early 2000′s the meagre average of 2,100 m^3yr^{-1} per head and year. These values continuously and substantially deteriorated ever since due to the increasing population in particular in water scarce regions of the world.

Two interlinked Sankey diagrams Fig. 2.8a, b visualizes the continental distribution of the renewable precipitation, surface and ground water fluxes and the services (Curmi et al. 2013, 2014). The total precipitation over the land mass (approximated as 110,000 km^3yr^{-1}) subdivided among the

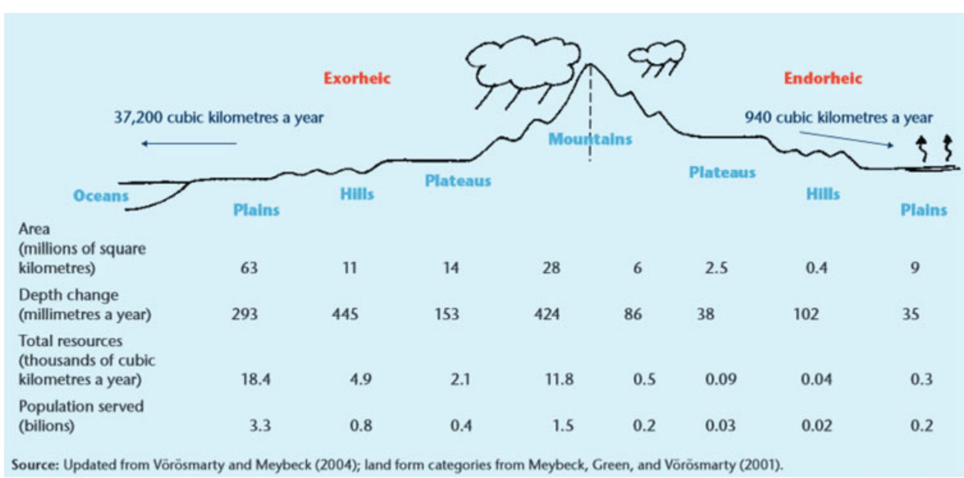


Fig. 2.7 Exorheic and endorheic continental runoff from different landforms and the number of people relying on these flows (*Source* UNESCO World Water Report 3. 2009)

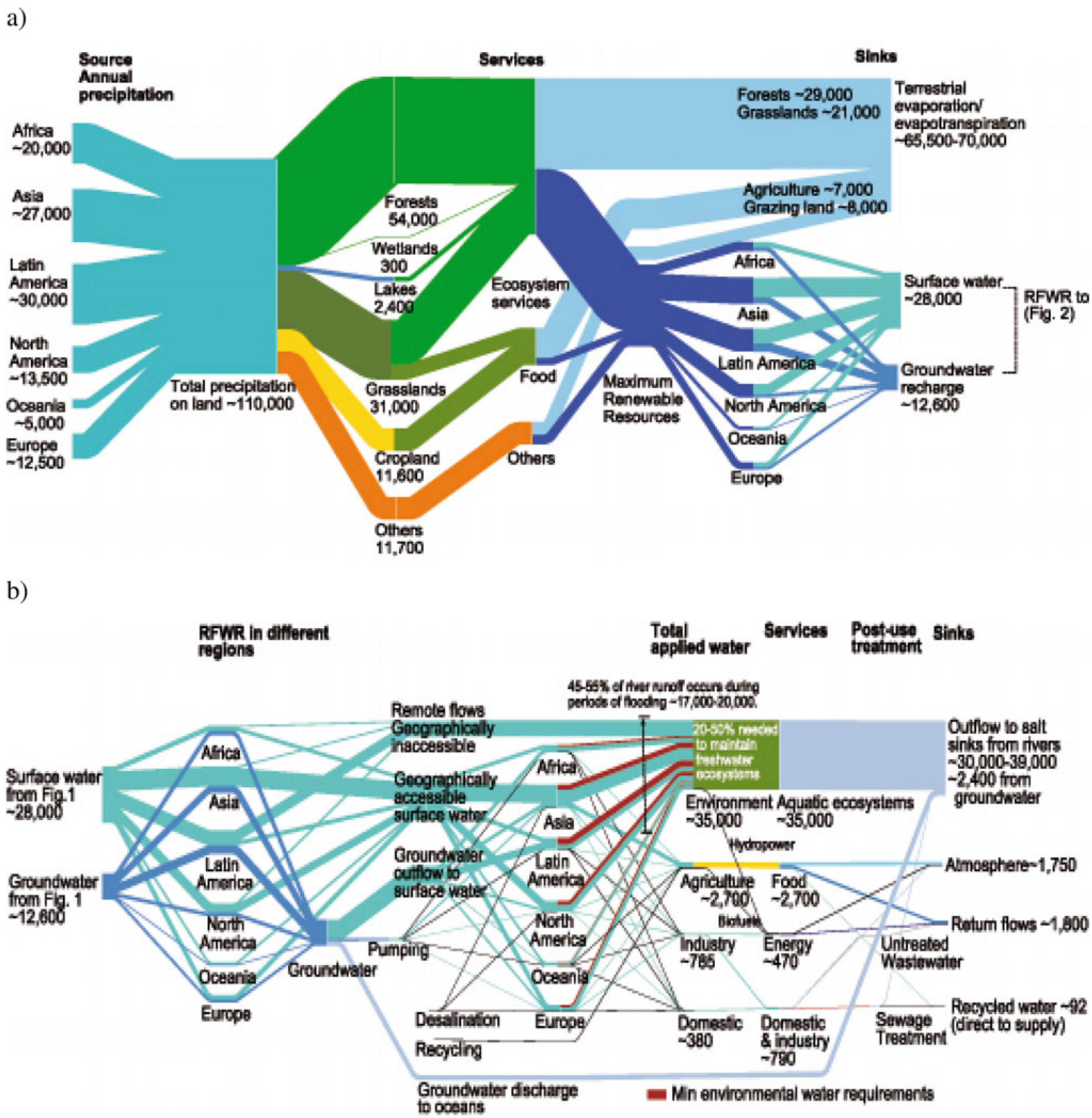


Fig. 2.8 Continental distribution of precipitation, surface and groundwater flow and the services they provide (*Source* Curmi et al. 2014)

continents represents the "input" to the terrestrial phase of the water cycle is routed through the various ecosystems like forests, wetlands, lakes, grassland, cropland and other land cover/land forms. The upper part of Fig. 2.8 shows major part of the precipitation absorbed by forests and croplands and partially by grasslands and other landforms returns directly to the atmosphere as terrestrial evaporation and evapotranspiration. Up to 70% of the precipitation thus short-circuits the water cycle without reaching the marine compartment.

The excess precipitation is estimated as 40,600 km^3yr^{-1} sometimes referred as "*blue water*" (Falkenmark and Rockström 2006) is subdivided between the continents and distinguished whether they occur as river flow (RF) or water recharge (WR) to the aquifers. It is worth to mention that the estimated 12,600 km^3yr^{-1} annual WR will contribute to the river flow as base flow component and only approximately 2,400 km^3yr^{-1} groundwater outflow reaches the oceans directly. The management of the excess precipitation ("*blue water*") component of the renewable resource (flux) predominantly driven by gravitational forces was subject of the traditional engineering based water resources management. Needless to say that water use (and hence water resources management) heavily relies on and have to consider the so called "*green*" water component of the continental precipitation (Falkenmark and Rockström 2006), which bypasses the marine compartment of the hydrological cycle. Green water movement in the hydrological cycle is governed predominantly by molecular forces. Traditionally "green water management" (though historically this term was never coined) was an implicit by-product of agricultural, forestry and land use management activities. While the use of the "blue and green water" terminology has been firmly established in the international water discourse, its usefulness in water resources management and planning is debated (Jewitt 2006; Hoff 2009; Gerten et al. 2011; Curmi et al. 2013).

Parts (a) and (b) of Fig. 2.8 are connected through the two components of "RFWR". These two components are subdivided among the continents. The two main fluxes then subdivided between categories like remote, geographical inaccessible flows (approximately 7,700 $km^3 yr^{-1}$), geographically accessible flows (roughly 20,000 $km^3 yr^{-1}$), groundwater outflow to surface water bodies (estimated as 10,000 km^3), and direct groundwater outflow to the oceans (2,400 $km^3 yr^{-1}$). The continentally distributed fluxes are expected to deliver services like maintaining terrestrial and aquatic ecosystems, to provide water for agricultural, industrial, energy and municipal (domestic) purposes. As far as human mediated services (water uses) are concerned they usually imply withdrawal either from rivers, lakes or by pumping of groundwater.

Figure 2.8 refers also to unconventional water resources like recycling and desalinization of saltwater. Figure 2.8 reveals the fluxes appropriated by humans for their various activities are seemingly minor compared to other fluxes. Thus, the water cycle(s) seem to have reserves even to accommodate the expected increases of water demands. However, as Fig. 2.8 indicates roughly half of the global surface runoff occurs as flood flows. Furthermore, a vaguely estimated 20–50% of the streamflow is needed to maintain aquatic ecosystems. The minimum environmental flows (Smakhtin et al. 2004) are indicated with red colour in Fig. 2.8.

According to Postel et al. (1996), 54% of the geographically accessible runoff is used already in human-related services. Thus beyond the geographical inaccessibility, major components of the RFWR flux are beyond the sustainable threshold for human appropriation, or being already being appropriated. In light of these constraints the present freshwater use (withdrawal from the annually renewable surface and groundwater fluxes) is close to 4,000 $km^3 yr^{-1}$. Curmi et al. (2014) refers to an estimated global groundwater depletion of almost 300 $km^3 yr^{-1}$ (Wada et al. 2012, 2014). This "mining" into the groundwater stock of de facto fossil groundwater increases marginally the water circulating in the hydrological cycle, but leads to massive drawdown of the water table of aquifers. Figure 2.9 clearly shows that diffuse groundwater recharge is minimal in most arid parts of the globe.

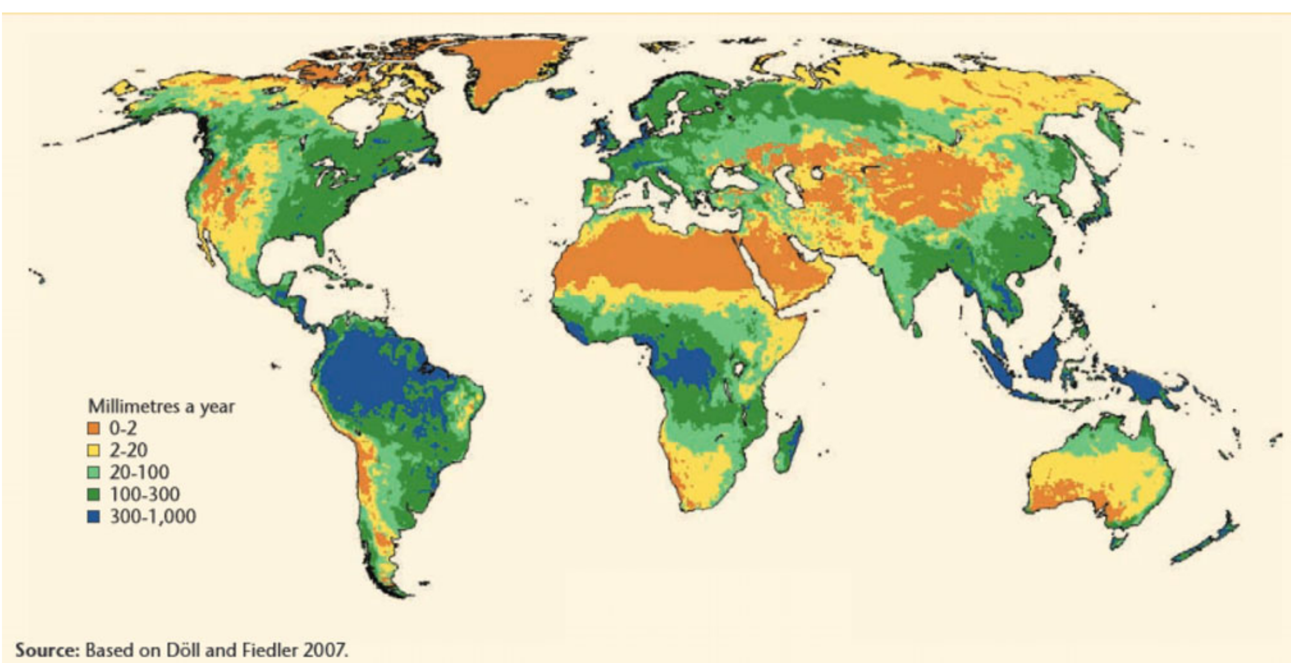


Fig. 2.9 Long-term average annual diffuse groundwater recharge (1961–1990) (*Source* UNESCO World Water Development Report 3. 2009)

Beyond the quantity-based limitations of water use, it is certainly important to notice the estimated annual 1,800 km^3 return flow, which carries pesticides and nutrients from agricultural fields, treated and untreated sewage from settlements and industrial residues including new, artificial compounds, cosmetic and pharmaceutical, usually nanoscale substances or single molecules which pass unabated through traditional wastewater treatment facilities. Ultimately, water quality deterioration is a stronger constraint for water use than quantitative limits.

Table 2.5 reveals that in some regions of the world like in Eastern Europe and Central Asia as well as in Latin America and OECD countries substantial percentage of the renewable water supply is not accessible for humans. Regionally this can lead to scarcity especially in the Eastern European—Central Asian region as this area commands only 10% of the total renewable water supply of the world.

Based on data collected till the end of the twentieth century Shiklomanov (2000) estimated the continental distribution of renewable water resources and their average availability per unit area and per capita and contrasted them with water estimate during the twentieth century and forecasts into the future up to 2025. The contemporary population estimates were based on figures from 1994, thus accounting "only" with 5.63 billion people. Ironically, due to the low population number the annual per capita availability of freshwater in Australia and Oceania is not only the highest but with (then) 83,700 m^3yr^{-1} per capita annually more than twice as high as in South America. Further it is interesting to note that the annual global renewable resource estimate of Shiklomanov (2000), which he indicated to be between 39.780 and 44.750 km^3 is rather high in comparison with later estimates (Fekete 2013a; b).

Table 2.6 shows a more recent estimates of annual discharge from the different continents totalling to 37,786 km^3yr^{-1} annual discharge (Fekete et al. 2002; Fekete 2013a, b). By a large margin South America is the most water-endowed continent. The runoff depth is more than

Table 2.5 Estimates of regional distribution and accessibility of renewable runoff (blue water flows)

Indicator	Asia	Eastern Europe, the Caucasus and Central Asia	Latin America	Middle East and North Africa	Sub-Saharan Africa	OECD	Global total
Area (millions of square kilometres)	20.9	21.9	20.7	11.8	24.3	33.8	133.0
Total precipitation (thousands of cubic kilometres a year)	21.6	9.2	30.6	1.8	19.9	22.4	106.0
Evaporative returns to atmosphere (percent of precipitation)	55	27	27	86	78	64	63
Total renewable water supply (blue water flows; thousands of cubic kilometres a year) [% of global runoff]	9.8 [25]	4.0 [10]	13.2 [33]	0.25 [1]	4.4 [11]	8.1 [20]	39.6 [100]
Renewable water supply (blue water flows accessible to humans; thousands of cubic kilometres a year) [percent of total renewable water supply]	9.3 [95]	1.8 [45]	8.7 [66]	0.24 [96]	4.1 [93]	5.6 [69]	29.7 [75]

Note: Means computed based on methods in Vörösmarty, Leveque, and Revenga (2005). Estimates are based on climate data for 1950-96, computed using estimates of population living downstream of renewable supplies in 2000.
Source: Fekete, Vörösmarty, and Grabs 2002.

Source UNESCO World Water Development Report 3. (2009)

Table 2.6 Continental discharge and runoff variability

Region	Discharge ($km^3 yr^{-1}$)	Runoff ($mm yr^{-1}$)	Normalized minimum (%)	Normalized maximum (%)
Africa	5557	185	72	125
Asia	11 932	268	80	120
Australia	1144	139	65	209
Europe	2041	201	69	136
North America	5693	232	84	120
South America	11 419	636	80	113
Global	37 786	278	88	110

[a]Annual discharge from continents along with average annual runoff is given in the first two columns along with normalized range of discharge/runoff fluxes referenced to the 1901–2002 long-term average.

Source Fekete (2013a, b)

twice as much as from the second best water-endowed continent, Asia. Due to the water rich South America the average annual global runoff, 278 mm yr^{-1}, is higher than for any other continent. It is also important to point out that the size of a continent and its aridity play an important role concerning the variability of the annual discharge (and runoff). Australia is not only the smallest, but also the driest continent with the highest interannual discharge variability. Irrespective that Europe is considered to have very moderate climate and flow regimes the interannual variability of the surface runoff (and interannual discharge) at continental scale is higher than in Africa. While, as expected, the global discharge shows the most moderate variability, this is an additional hint that global views (and numerical estimates) hide the potentially extreme manifestations of the water cycles at smaller scales.

Even continental values can be misleading. The water abundance of South America notwithstanding the Atacama Desert is considered of being one of the driest spot on Earth or Northeast Brazil, which is also notoriously dry in an otherwise water rich continent. With 185 mm annual runoff Africa seems to be the second driest continent behind Australia. Irrespective of hosting with the Sahara, the Kalahari, the Namib Desert and the extended drylands of South Africa huge and extremely dry areas, the equatorial part of Africa is explicitly rich in rainfall and the discharge of the Congo river cis second only to the Amazon River (Dai and Trenberth 2002).

Table 2.7 illustrates the uncertainties inherent in different model or data based estimates of what is called (interchangeably) renewable water supply, or freshwater discharge to the oceans or continental runoff (if expressed in mm water depth). The continental/regional scale estimates show considerable spread while the variability of the estimated global value, as expected, is significantly less. Table 2.7 presents also the mean regional/continental water crowding, by providing the estimate of the number of people to be served by 1 million m^3/year regionally available freshwater. In this respect the Middle East—Northern Africa (MENA) region can be identified not only as a regional, but even as the global hot spot by a large margin, having approximately eight times higher water crowding than the global average. This regional focus of concern on the MENA region is justified in addition to the high water crowding (as indicator of latent scarcity) also by the extreme variability of freshwater discharges. This includes also big deviations of low flows from the regional mean. Figure 2.10 reveals among some other spots scattered worldwide the entire MENA region is characterized by the highest class of deviation of low flows from the mean. This includes also the relative frequency of the ephemeral flow phenomenon, when rivers fall dry for extended periods.

Table 2.7 Indicative range of uncertainty in regional estimation of the annually renewable water resources and water crowding

Region	Renewable water supply (cubic kilometres a year)	Mean water crowding (people per million cubic metres a year)
Asia	7,850-9,700	320-384
Former Soviet Union	3,900-5,900	48-74
Latin America	11,160-18,900	25-42
North Africa and Middle East	300-367	920-1,300
Sub-Saharan Africa	3,500-4,815	115-160
Organisation for Economic Co-operation and Development	7,900-12,100	114-129
Global total	38,600-42,600	133-150

Note: Supply here refers to global total renewable runoff, both accessible and remote from human population and croplands.

Source: The ranges reported here are from three global-scale water resources models, two of which were used in the *Millennium Ecosystem Assessment*: Vörösmarty, Federer, and Schloss (1998); Fekete, Vörösmarty, and Grabs (2002) and Federer, Vörösmarty, and Fekete (2003) for the Condition and Trends Working Group assessment and Alcamo et al. (2003) and Döll, Kaspar, and Lehner (2003) for the Scenarios Working Group. A third model from Dirmeyer, Gao, and Oki (2002) and Oki et al. (2003) was also compared.

Source UNESCO World Water Development Report 3. (2009)

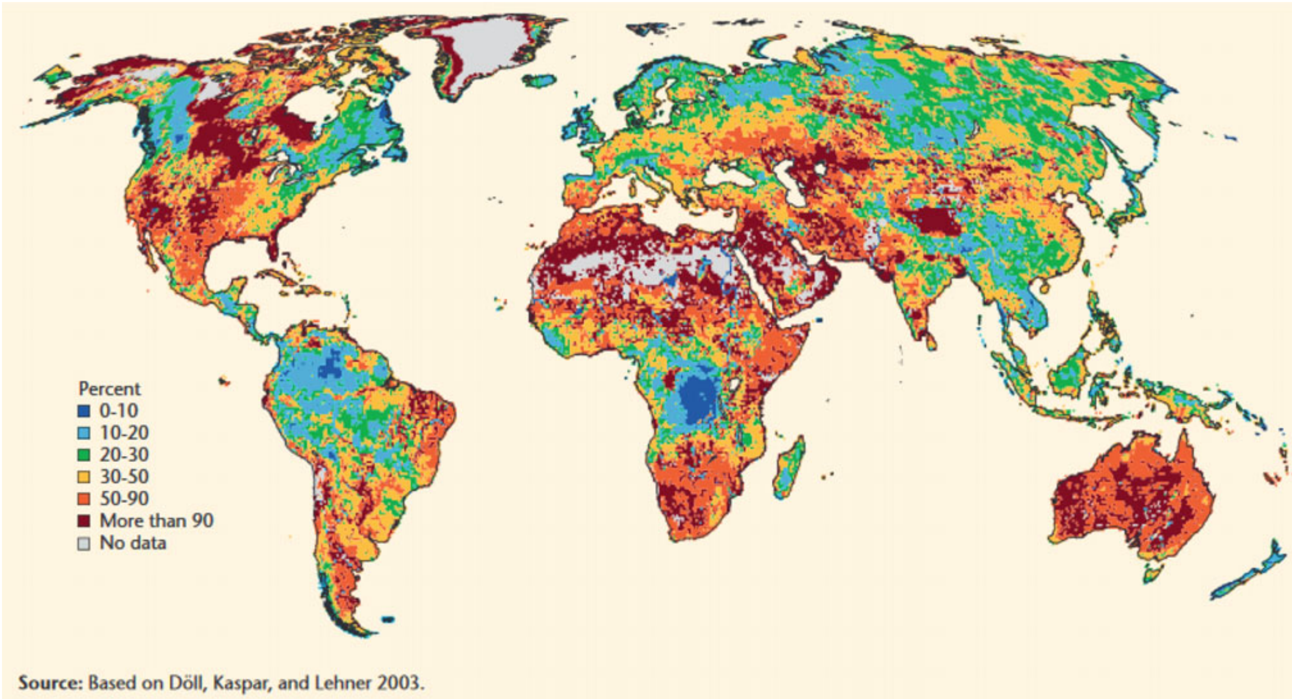


Fig. 2.10 Variation between low flows and mean flows (percentage deviation of the 1 in 10 year low flows from the mean flows measured over 1961–1990) (*Source* UNESCO World Water Development Report 3. 2009)

Next to the continental (spatial) distribution Dai and Trenberth (2002) estimated the annual and monthly mean values of continental freshwater discharges into the different oceans. Several assessment methods were used in a one-degree resolution mask. Similar to the conclusion of Fekete (2013a; b) the most accurate estimate is based on streamflow data, supplemented with estimates of discharge from unmonitored areas based on the simple ratios of runoff and drainage area between the unmonitored and monitored regions. Discharge records of the 921 largest rivers of the world have been used. Simulations using a river transport model (RTM) forced by a runoff field were used to derive the river mouth outflow from the farthest downstream river gage records. Separate estimates are also made using RTM simulations forced by three different runoff fields:

- Observed streamflow and a water balance model, and from estimates of precipitation minus evaporation computed as residuals from the atmospheric moisture budget using atmospheric reanalyses;
- The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) data set, and
- The European Centre for Medium-Range Weather Forecasts (ECMWF) data set.

Compared with previous estimates, improvements were made in extending observed discharge downstream to the river mouth, thus accounting for the unmonitored streamflow, in discharging runoff at correct locations, and in providing an annual cycle of continental discharge. The use of river mouth outflow increases the global continental discharge by 19% compared with unadjusted streamflow from the farthest downstream gaging stations. The river-based estimate of global continental discharge presented here is 37,288 ± 662 $km^3 yr^{-1}$) which corresponds with a 35% share of the precipitation over the landmass. This number is comparable with, and thus confirms earlier estimates. Dai and Trenberth (2002) extended their estimate by partitioning it into different receiving oceans (Table 2.8).

The information communicated by Fig. 2.11 provides probably the most justified reason for concern. The Global Runoff Data Centre (GRDC) reportedly receives less data in the early twenty-first century than in the 1980s. The lack of accessible data weakens scientific estimates and makes the observation-based assessment of runoff changes (due to climate change or other reasons) almost impossible. Recent observational data seems to be missing from large parts of Africa, a continent widely referred as the part of the world to expect the worst impacts of climate change and yet, it is the least monitored one.

Table 2.8 Comparison of estimates of the mean annual discharge into the different recipient oceans and seas. Data in km^3/a

	Arctic	Atlantic	Indian	Mediterranean Sea[c]	Pacific	Total[d]
Largest 921 rivers[a]	3658	19 168	4532	838	9092	37 288
Fekete runoff	3263	18 594	5393	1173	10 420	38 843
ECMWF *P–E*	3967	20 585	4989	1144	7741	38 426
NCEP–NCAR *P–E*	4358	16 823	3162	909	7388	32 640
Fekete et al. (2000)	2947	18 357	4802	1169	11 127	38 402
Korzun et al. (1977)[b]	5220	20 760	6150		14 800	46 930
Baumgartner and Reichel (1975)	2600	19 300	5600		12 200	37 713
Oki (1999)	4500	21 500	4000		10 000	40 000

[a] Largest 921 rivers are scaled up by accounting for the unmonitored areas and the runoff ratio at 4° lat resolution.
[b] Korzun et al. (1977) include groundwater runoff (2200 km^3 yr^{-1} globally) and iceberg runoff (2700 km^3 yr^{-1} globally).
[c] Mediterranean Sea includes the Mediterranean and Black Seas.
[d] Total excludes discharge into inland (besides Black) seas and from Antarctica, which puts ~2613 km^3 yr^{-1} freshwater into the ocean (Jacobs et al. 1992).

Source Dai and Trenberth (2002)

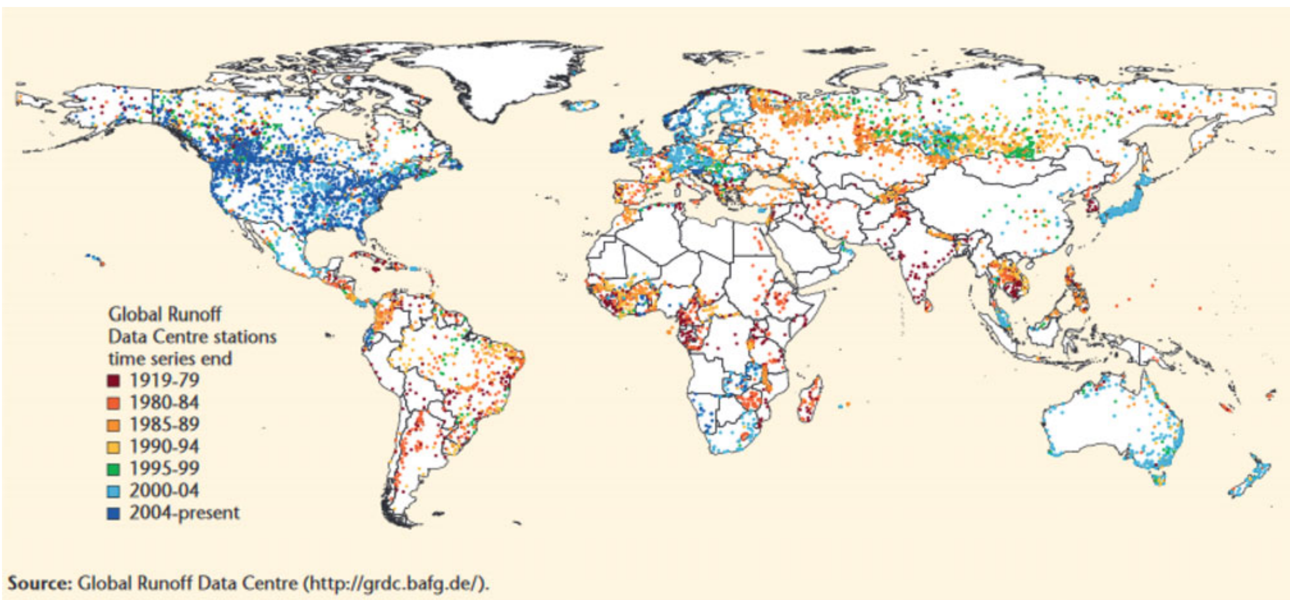


Fig. 2.11 Distribution of Gages reporting to the Global Runoff Data Centre (*Source* UNESCO World Water Development Report 3. 2009)

2.2.3 Estimates of Water Resources at Sub-Continental, National and Basin Scales

Beyond the continental/regional distribution of continental runoff, or assessing the freshwater discharges into the different recipient seas and oceans a more accurate geographical assignment reveals that the latitudinal distribution of discharge differs from earlier studies (Baumgartner and Reichel 1975; Fekete et al. 2002) as shown in Fig. 2.12. The fact that the land mass of the world is located overwhelmingly in the Northern Hemisphere is well documented by the relatively even distribution and higher share of runoff than from the Southern hemisphere.

By evaluating the discharge statistics of the 50 and 200 most water rich rivers of the world (Dai and Trenberth 2002) showed that the 50 largest river (by the token of their discharge) see Fig. 2.13, which drain together about 50.4 million km^2 (33.8% of the land mass of the world) discharge 21,152 km^{3}yr^{-1} water into the oceans. This is almost 57% of the entire discharge from the land mass to the oceans. By extending the statistics to cover the 200 largest rivers their share in the total discharge volume increased to slightly over 67%, which was obtained from the aggregated drained area of 73.65 million km^2 (49.5% of the land mass). These statistical comparisons illustrate the very uneven distribution of water resources in the world. For example, the Amazon River, the largest river of the world alone discharges about 17.8% of the entire terrestrial

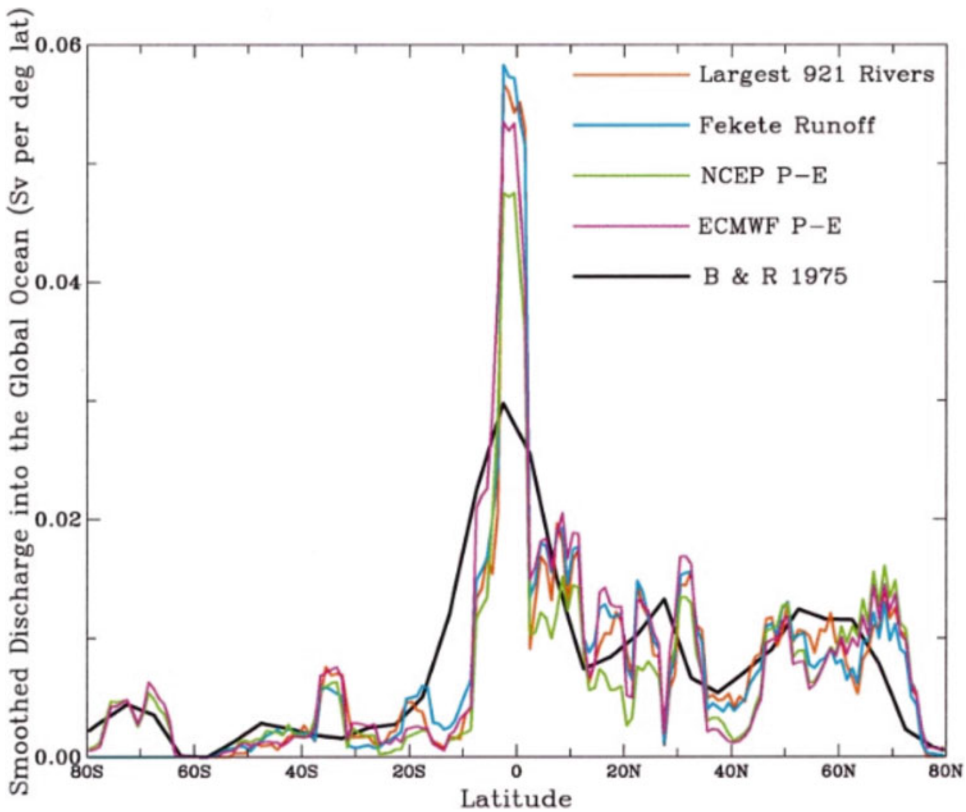


Fig. 2.12 Estimated latitudinal distribution of the annual discharge into the oceans compared with the result of Baumgartner and Reichel (black line) (1975) (*Source* Dai and Trenberth 2002)

runoff into the Atlantic Ocean from a basin of 5.85 million km^2 (3.9% of the global land mass).

As far as temporal distribution of the flows is concerned the peak discharges into the Arctic, the Pacific, and global oceans occur in June, versus May for the Atlantic and August for the Indian Oceans. Snow accumulation and melt are shown to have strong effects on the annual cycle of discharge into all oceans except for the Indian Ocean and the Mediterranean and Black Seas. For the ten largest rivers (by the token of their discharge) the monthly distribution of discharge and precipitation over their basins is shown in Fig. 2.13.

As a side note, it is worthwhile to discuss discharge into the Arctic that rarely gets much attention in water resources studies, but plays pivotal role in Arctic ice formation that ultimately has far reaching impact on the Earth's climate. None of the large rivers (Amazon, Congo, Ganges, Brahmaputra, etc.) affect the currents of the receiving oceans—since the water fluxes from these rivers pale compared to the water volumes in the oceans—except the Arctic flowing rivers (Ob, Lena, Yenissei, Mackenzie, etc.) because the Arctic ocean is the only place in the world where the total area of the watersheds is comparable to the receiving ocean and the freshwater fluxes can affect ocean salinity (see Fig. 2.14). Arctic flowing rivers originate from temperate climate zones well inside the continental landmass. The ocean salinity partly dictated by the freshwater inflows affects ice formation, which further affects the surface reflectance (albedo) leading. The salinity gradient between the Arctic and the Atlantic Ocean is a key driver of the Gulf current that is part of the Global thermohaline circulation.

Increasing freshwater input into the Arctic oceans due to climate change—since the Arctic is warming faster than the tropics—raised concerns about the slowing or potentially completely halting of the Gulf current (Peterson et al. 2002, 2006). Since, the Gulf current is responsible for the relatively mild climate of Northern Europe (Ireland, Scotland, Sweden, Norway, etc. compared to other places on Earth at the same latitude), therefore climate change was feared paradoxically to cause severe cooling in this region.

2.2.4 Trends of Water Availability and Water Use at Different Spatial and Temporal Scales

Almost without exceptions most predictions, referring to climate change and variability, or/and to increasing human water demand, conclude increasing water stress and scarcity. Climate change is singled out to cause increasing variability of precipitation and consequently that of discharge. Dai et al. (2009) report the increasing frequency of very dry and very wet years within a generally "drying" trend. Even if the total annual renewable resource base remains unchanged, floods

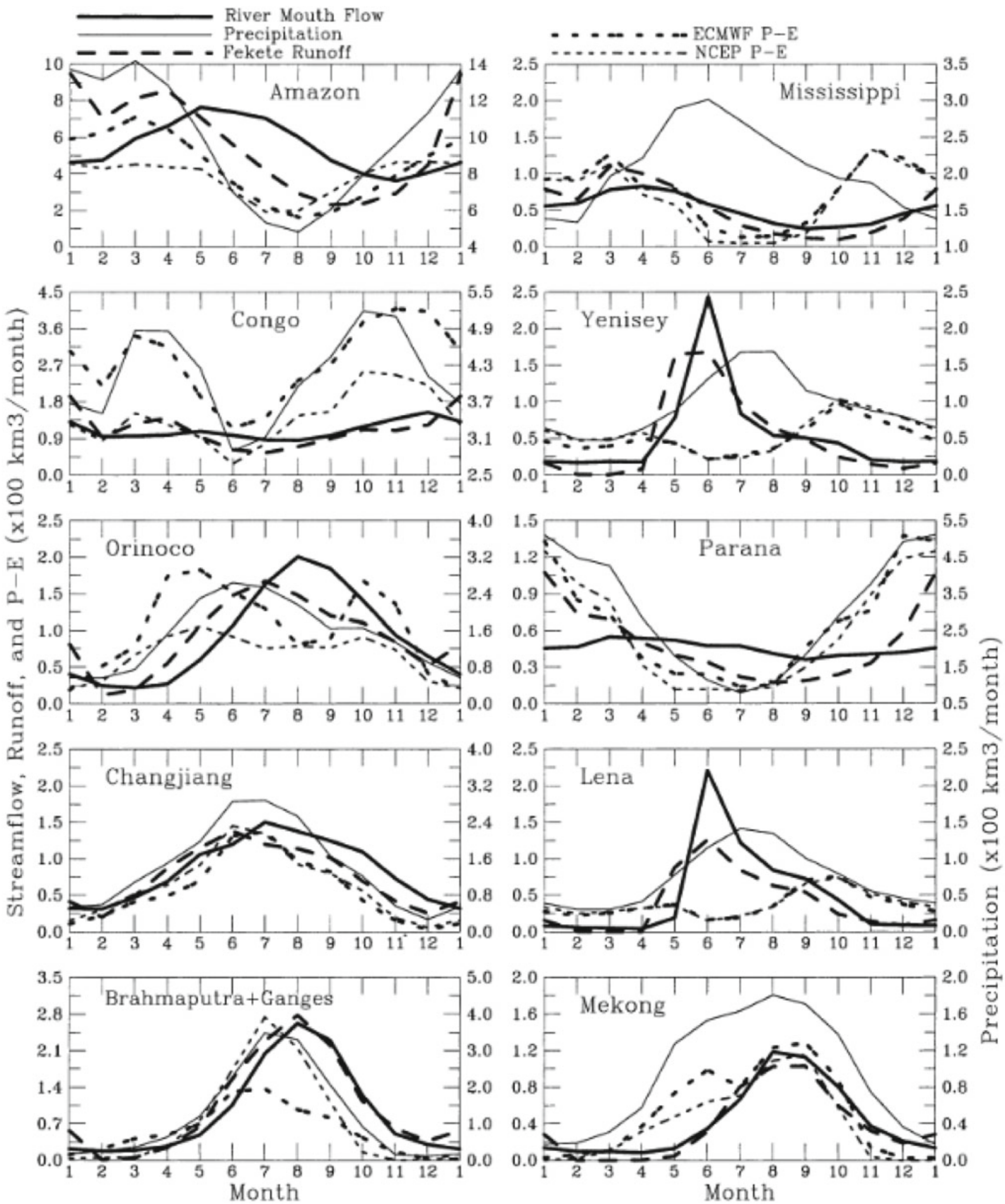


Fig. 2.13 Monthly distribution of the mean annual river discharge and basin precipitation for the 10 largest rivers of the world (*Source* Dai and Trenberth 2002)

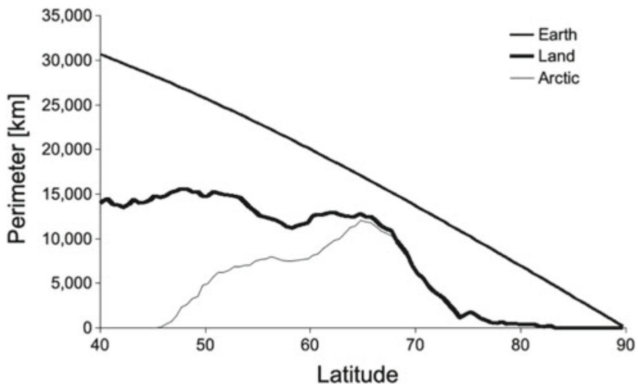


Fig. 2.14 Latitudinal extent of the watersheds flowing into the Arctic Ocean (thin line) in contrast with the land extent (thick line).and the earth circumference (medium thick line)

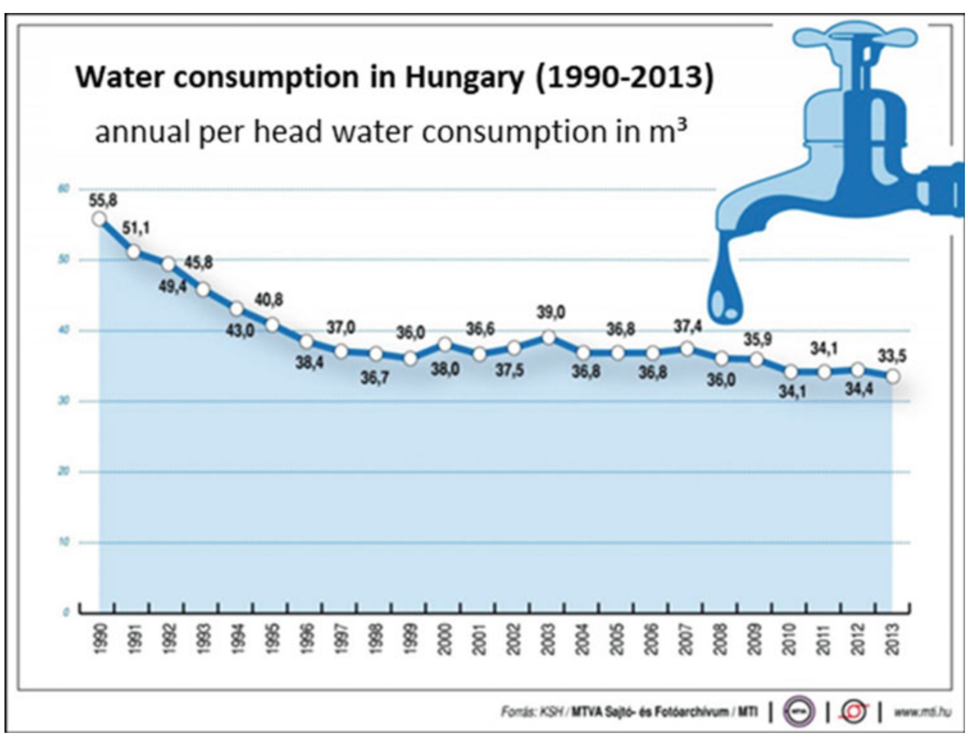
and droughts are both expected to increase in magnitude and frequency. Consequently, the inaccessible component of the annual renewable discharge increases (increased portion of flow in form of excessive flood flows) and the periods of shortage to match water demands adequately will become more frequent and more prolonged.

Two decades ago Shiklomanov (2000) assumed uninterrupted increase of water withdrawals deep into the twenty-first century. No doubt, that increasing population and better standard of living for more and more people unavoidably lead to increasing water demand. However, the earlier predictions could not reckon with improved water use efficiencies, especially in the sector of industrial use.

Water use forecasts are highly unreliable as they cannot capture adequately potential improvements in use efficiency and changing value systems in decades ahead. Dieter et al. (2018) report for example that the self-provided water withdrawal for industrial use in the US declined from $170 \times 10^6 m^3 day^{-1}$ in the 1970s and 1980s to $56 \times 10^6 m^3 day^{-1}$ in 2015. This is less than 1/3 of the consumption which might have been used for extrapolation of the observed trends of the last century by earlier predictions. By assuming 300 working days in a year the annual industrial water withdrawal in the US fell in approximately three decades from 51 $km^3 yr^{-1}$ to 16.8 $km^3 yr^{-1}$. It can be expected that at least in other developed countries the industrial water use also declined without reduction of the industrial output. Due to the lack of reliable global statistics about water uses, it is difficult to judge how far the decoupling of increasing GDP from increasing water use can already be seen as a global phenomenon.

Drinking water demand is certainly to grow with increasing population and with the provision of safe drinking water to all, as stipulated by SDG 6. However, drinking water use shows, within a reasonable range substantial price flexibility. The substantial increase of the cost of drinking water in Hungary after 1989 led to a steady decline of per capita use as shown in Fig. 2.15. The water use in 2013 was 92 l day^{-1} per capita, 40% less than it was prior to the introduction of "market prices" for drinking water. Interesting to note that in Cape Town, South Africa during the 2017/2018 drought and water crisis the daily allowance of

Fig. 2.15 Annual water consumption in Hungary ($m^3 yr^{-1}$ per capita) https://www.mti.hu/mti/Default.aspx and https://mtva.hu/



about the same amount of water corresponded to an elevated water saving alarm level. For more detail of the Cape Town water crisis see in Sect. 3.2.5 Box 3.2). Saving on drinking water has a strong potential. Beyond the enormous losses due to leakage of water pipes of the conveyance and distribution system, sensible water tariffs can "guide" the consumption towards more sustainability.

Agricultural water withdrawals are approximated on global scale to be about 70% of all water withdrawn (with up to 90% share in arid countries). Fighting hunger in the spirit of SDG Goal No. 2, providing food for the expected population growth by 2050 (roughly 2 billion more people) and countering the expected vagaries of climate change and variability (more frequent and longer droughts and dry spells) all imply increasing water use in agriculture (both green and blue water use). How far drought tolerant cultivars, improved agricultural technics (soil preparation etc.) and irrigation technologies, drainage, waste water use and recycling can limit this growth is very much an open question. The more so as hitherto rural development and agriculture development experienced much less investment and official development aid than other sectors.

As the transition to renewable energy is gaining momentum, hydropower is increasingly seen as a viable energy source (Muller 2019) that is already leading to a new boom in hydropower dam constructions (Zarfl et al. 2015). Besides being renewable energy source, hydropower is particularly attractive because it can be turned on and off on demand therefore it is often used for load balancing. Hydropower generators are rarely designed for 24/7 operation (Fekete et al. 2010) and hydropower stations often have more built-in capacity than the available continuous hydropower demand. The access capacity is used during peak hours and the generators sit idle when the electricity demand is low allowing the reservoir to recover (Fekete et al. 2010).

The total hydropower potential can be computed by multiplying the 40,000 km^3yr^{-1} access water dominantly entering to the World's oceans as river discharge by (a) the 275 m runoff weighted average elevation to account for the spatial variability of runoff, (b) the density of water and (c) the gravitational acceleration on the Earth surface yielding 3.5 TW (Fekete et al. 2010) that is already a fraction of the ever growing energy demand that was 16TW in 2010 (Fekete 2013a, b). Evidently, this is the potential energy in the access water on the land and only a fraction of this power is available for energy production. In contrast, the built-in reservoir capacity was 0.7 TW at the time of Fekete et al. (2010) publishing their total hydropower estimate. Prior to Fekete et al. (2010), potential hydropower capacity was estimated to be 4.8 TW (Resch et al. 2008) or higher. The two likely sources of the over estimations are (a) extrapolating from the built-in capacity as if those were the actual hydropower generation capacities and (b) using the mean global elevation that is around 500 m instead of the lower runoff weighted elevation (indicating that high elevation regions are more dry than low elevation areas).

The intentional, intermittent operation of hydropower leads to low load factors (the ratio of the generated power and the built-in generator capacity), but unlike solar and wind power, the low load factor actually reflects the flexible operation to follow demand (Waldman et al. 2019). The low load factor of solar and wind power stations poses challenges in their integration into the power grid because their power generation rarely coincides with the power demand. Jacobson et al. (2015) anticipated hydropower to provide solution to overcome the problem of intermittency of other renewables and allow rapid transition to 100% renewable energy, but Clack et al. (2017) severely debunked the overly optimistic assumptions of Jacobson et al. (2015) that would have led to extreme diurnal fluctuation of river discharge downstream from the hydropower stations.

The limits of hydropower as a means of storing energy can be easily understood by contrasting the heat capacity of water (4.2 kJ kg^{-1} $°C^{-1}$) with the potential energy (9.81 J kg^{-1}) of a unit amount of water lifted by 1 m. Based on these two numbers, one has to realize that either the water needs to lifted very high or lot of water needs to be lifted just for the sake of making one litre (1 kg) coffee (heating the water from room temperature to boiling). Hydropower has low "energy density" and solar and wind can produce the same amount of energy on a fraction of the land occupied by reservoirs (Waldman et al. 2019). One could safely state that hydropower will not play significant role in the world energy system and only viable in exceptionally fortunate conditions such as the Cielos de Tarapacá solar project in Chile combining solar power generation with pumped hydro energy storage utilizing the unique coastal terrain allowing the utilization of ocean water.[4]

In their seminal paper Vörösmarty et al. (2000) estimated that the total annual water use will decrease from 640 to 580 m^3yr^{-1} per capita between 1985 and 2025. Therefore, the absolute increase in water use reflects population growth and migration rather than intensification of water appropriation by humans. In their global analysis, three scenarios were developed to estimate whether, how much and where the ratio between DIA (domestic, industrial and agricultural water use) and Q (renewable freshwater discharge) would change between 1985 and 2025 if we consider:

[4]https://futurenergyweb.es/en/valhalla-seeks-build-largest-latin-american-solar-project.

– Scenario 1 (Sc1): changing climate (estimated state as of 2025) but unchanged magnitude and distribution of the human population as of 1985;
– Scenario 2 (Sc2): using projected water demands and population size for 2025, but considering unchanged climate (thus water availability and distribution as of 1985);
– Scenario 3 (Sc3): using projected water demands and changing climate driven hydrological situation, both as of 2025.

Vörösmarty et al. (2000) use the DIA/Q = 0.4 threshold value to identify 30′ times 30′ pixels in a world map where severe water scarcity situation prevails. Using more than 40% of the available freshwater resources is considered as severe scarcity situation (United Nations 1997). Vörösmarty et al. (2000) and a series of other publications, among them the recurring World Water Development Reports refer to the threshold of 40% as an indicator of serious water scarcity. While setting a clear limit is a persuasive mean of communicating the need of behavioural change and policy actions, the scientific justification of this single value is somehow underargued and underrepresented in the literature.

No doubt that the ultimate height of a recommended annual threshold depends on the distributions and discrepancies between the within-year time series of water availabilities and needs. These are clearly climate dependent phenomena. Furthermore, the availability and management of storage facilities can substantially influence which percentage of the annual renewable resource could be relied on. Thus using one single threshold for the whole world does not seem to be justified.

Important to notice that due to the refined 30′ pixel resolution water stressed regions can even be identified within water rich countries like Brazil or Canada. The role of resolution in problem identification can be stunning. Vörösmarty et al. (2000) compared the results of the then usual country level statistics with their pixel-based analysis identifying the number of people living in different water stress categories as defined by United Nations (1997).

The country level statistics have about 200 entries whereby the pixel (grid–based) analysis relies on several ten thousand entries. The population values used refer to 1995. While there are relatively minor differences between the country level statistics and the aggregation of grid-based results at country scale (except between the low and moderate water stress categories) the juxtaposition of the country scale statistics with the grid-based analysis shows a completely different picture.

Contrary to expectations the distribution of the population among the four water stress categories indicates that already at the turn of the millennium roughly 2 billion people lived in a “pixel” where more than 40% of the available renewable freshwater resources were used. Interestingly, but actually quite logically over 3 billion people lived in a “pixel” of abundant water supply (less than 10% of the available freshwater resources appropriated. Astonishing this double peaked distribution with the relatively low population (less than 800 million people worldwide) in moderate and medium–high water stress pixels. As Vörösmarty et al. (2000) show the aggregate country-scale classification completely blurs these results. The country-scale statistics indicated approximately 3.5 billion people living in moderately and medium–high water stressed countries and indicated less than 500 million people in high water stress countries.

In the course of the scenario analysis based on the above described three scenarios deviations are considered significant if the value of the DIA/Q quotient for each pixel changed more than plus minus 20% compared to the reference situation. Sc1 (impact of climate change) provided mixed results. Some parts of the world would experience easing the potential water stress situation while some areas will have to face increasing water scarcity. Sc2 implies heavy and quite widely distributed deterioration of water stress. Sc3 indicates that the sparsely populated grid cells, which might become more humid due to climate change would not change this status because the driver of increasing water stress is predominantly the increasing population and its increasing water demand. By 2025 the global renewable freshwater discharge may diminish by approximately 5.6% (from the estimated 39,300 km^3 annual renewable freshwater discharge to a predicted 37,100 km^3 in 2025) but the then predicted population growth between 1985 (4.83 billion people) and 2025 (8.01 billion people) implies an increase of over 65.8%. This population growth with its inherent growing water demand is mainly responsible for the increase of the water stress between 28% (in North America and 121% (South America). The other continents are within this range (Vörösmarty et al. 2000). These increases at continental or global scale do not push the planet as a whole into a severe water stress situation. However, two things became very clear: the main driver of future water stress is population growth and its concentration to locations where water stress is already experienced.

Like the global circulation model based estimate of future hydrology with decreasing runoff discharge values (Vörösmarty et al. 2010) the use of the Palmer Drought Severity Index (PDSI) and its change over more than 100 years of observed precipitation time series can be used to document increasing aridity in many parts of the world. As Fig. 2.16 shows very high (and increasing) drought severity can be expected first and foremost in areas already subject of arid climate and water scarcity.

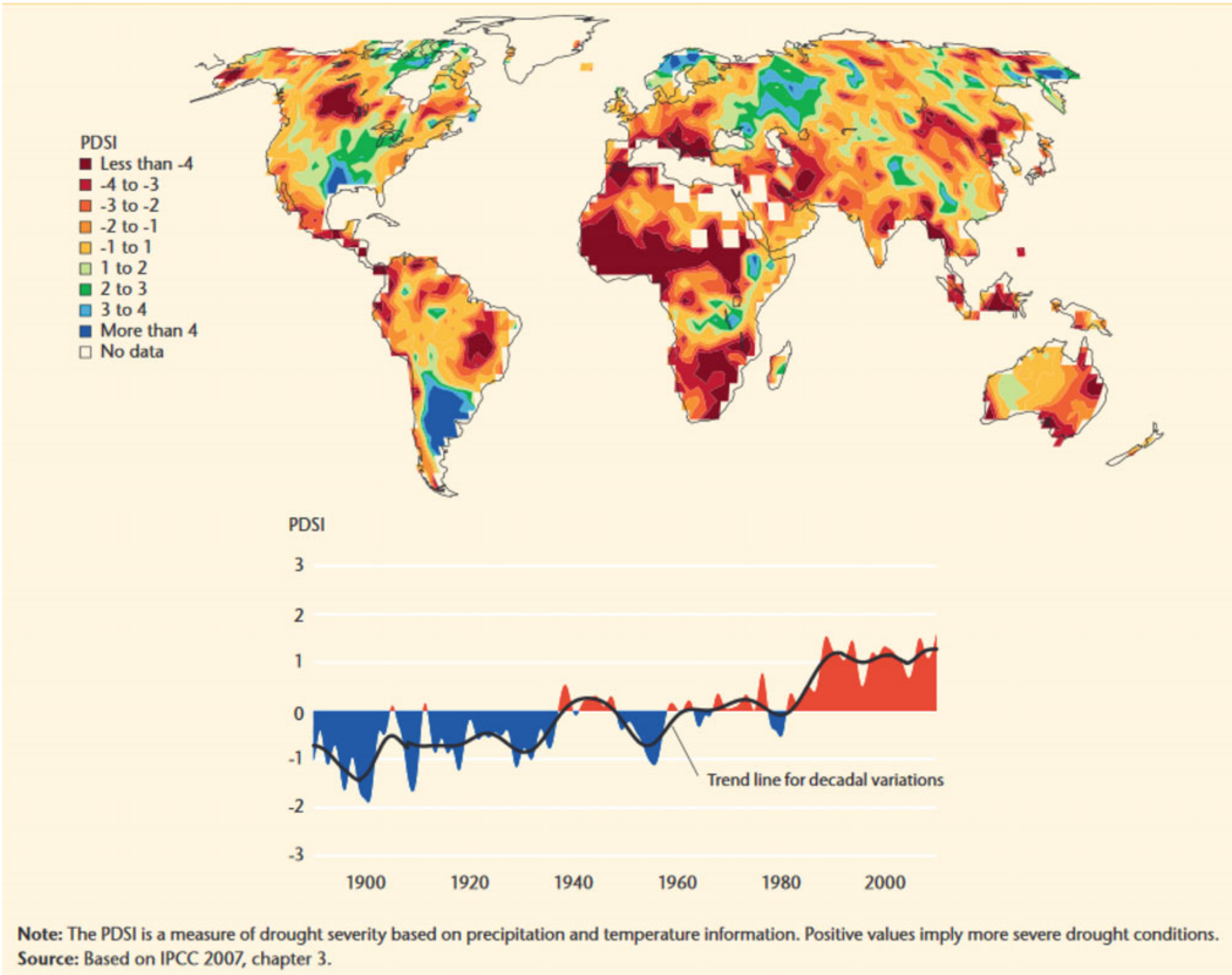


Fig. 2.16 Geographic distribution of the trend of the Palmer Drought Severity Index (PDSI) and annual variation of the averaged global PDSI (1900–2000) (*Source* UNESCO World Water Development Report 3. 2009)

An important aspect of the global hydrological cycle should be further discussed. As Fig. 2.4 reveals the annual moisture flux from the oceans towards the land mass is about 40,000 km^3yr^{-1}, thus equal to the aggregate continental runoff towards the oceans. While the marine and terrestrial water balances are thus linked adequately, Fig. 2.4a indicates that the continental precipitation is about 113,000 km^3yr^{-1}.

The discrepancy between the moisture flux of maritime origin and the precipitated amount of water indicates that a major component of the observed precipitation is of continental origin. As moist air is carried by major wind systems across the continents the moisture content of the air is replenished by the evaporated/transpired water. Thus in areas far away from the maritime source of vapour the observed precipitation is increasingly "recycled" precipitation. (van der Ent et al. 2010; van der Ent and Savenije 2011) estimated in a global modelling study both the precipitation and evaporation recycling ratios as shown in Fig. 2.17. According to their findings the overwhelming part of the precipitation in Eastern Siberia, Mongolia, Northern China and Tibet, but also in Western Africa and in the central part of South America is recycled from evapotranspiration along the route of prevailing winds. Eastern Europe, Western Siberia, Central and Western Asia, but also East Africa and the Amazon basin could be identified as the major sources of this recycled moisture. This water based interdependency is a strong reminder how far land use and land cover along the routes of prevailing wind systems co-determine water availability and distribution in faraway places. The value of standing forests with their elevated evapotranspiration versus deforestation and replacement by cropland is impressively demonstrated. The integration of land use planning with water resources management, while

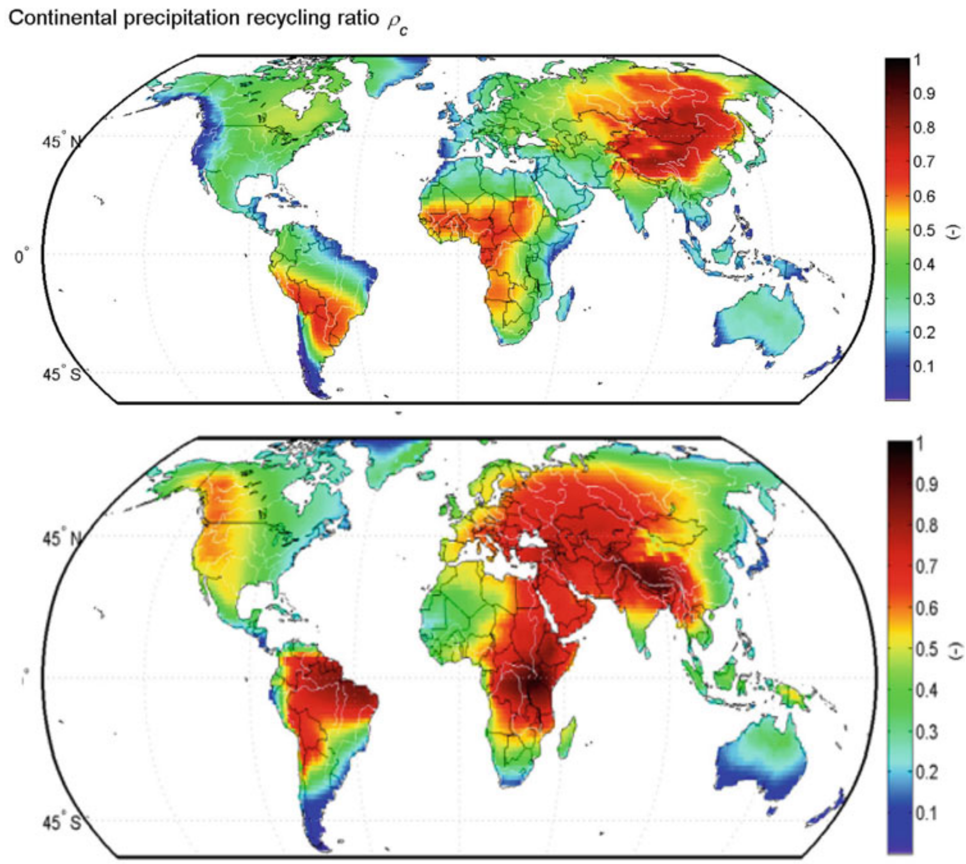


Fig. 2.17 Average continental precipitation recycling ratio (1998–2008) (above) and evaporation recycling ratio (1998–2008) (below) (*Source* van der Ent et al. 2010)

an acknowledged principle, receives additional arguments well beyond the frequently emphasized river basin scale considerations.

The systematic overview of the quantitative assessment of the water resources of the world is provided in Chap. 14.

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Janos J. Bogardi is senior fellow of the Center for Development Research of the University Bonn. where he is also professor for water resources management. He is senior scientific advi-sor of the Institute of Advanced Studies Köszeg (iASK) in Hungary and fellow of the Stel-lenbosch Institute of Advanced Study (STIAS), South Africa. Since 2014 Distinguished Ad-junct Professor of the Asian Institute of Technology (AIT, Bangkok). He was executive of-ficer of the GWSP (2009–2012). He served till his retirement from the UN as director of the United Nations University (UNU) Institute for Environment and Human Security 2003–2009 and as Vice Rector a. i. in Europe 2007–2009. He was Chief of Section in the Division of Wa-ter Science in UNESCO, Paris (1995–2003) and chair professor of hydrology, hydraulics and quantitative water resources management at the Wageningen Agricultural University in the Netherlands 1989–1995. He was associate professor at AIT between 1985 and 1988. Between 1969 and 1985 he had research and consulting appointments in Europe and in Africa. He graduated in civil engineering at the University of Technology Budapest in 1969. He holds a doctorate in water resources engineering (Dr.-Ing.) from Karlsruhe University 1979 and three Dr. Honoris causa distinctions from universities in Poland, Hungary and Russia.

Balázs M. Fekete earned his M.Sc. in civil engineering with specialization on water resource at the Technical University of Budapest and Ph.D. in Earth Sciences at the University of New Hampshire. He worked as research scientists in various ranks at the Water Resources Research Center, ISTER Environmental Research, University of New Hampshire and City College of New York. He joined the faculty of the Department of Civil Engineering at the City College of New York of the City University of New York in 2012 and he has affilated faculty status in the Advanced Science Research Center at the Graduate Center, CUNY. Dr. Fekete's primary scientific interest is hydrological modeling and data assimilation at various scales for water resources assessments and the integration of modern spatial data management with modeling frameworks to integrate the available data into hydrological analyses.

Water and Its Management: Dependence, Linkages and Challenges

3

Janos J. Bogardi, Luna Bharati, Stephen Foster, and Sanita Dhaubanjar

Abstract

This chapter highlights the key dependences, linkages and challenges of water resources management. (Many of these issues discussed are revisited and illustrated in the following chapters.) The first part introduces surface and groundwater management in the terrestrial part of the water cycle. Comprehensive presentations of key hydrological phenomena and processes, monitoring, assessment and control are followed by overviews of dependences, linkages and challenges. The manifold facets of intensive human/resource interaction and inherent threats to the resources base are exposed. Both sections present examples illustrating differing contexts and options for solution. The second part summarizes the main drivers and challenges of contemporary water resources management and governance. It provides a critical overview of different water discourses in recent decades. The role of benchmark and recurring water events, their declarations and intergovernmental resolutions are analyzed, and the key concepts and methods of implementation are discussed.

Keywords

Surface water • Groundwater • Availability and uses • Challenges of water resource management

J. J. Bogardi (✉)
University of Bonn and Institute of Advanced Studies Kőszeg (IASK), Kőszeg, Hungary
e-mail: jbogardi@uni-bonn.de

L. Bharati
International Water Management Institute, Bonn, Germany
e-mail: l.bharati@cgiar.org

S. Foster
University College London, London, UK
e-mail: DrStephenFoster@aol.com

International Water Association-Groundwater Management Group, Den Haag, The Netherlands

International Association of Hydrogeologists, Reading, UK

S. Dhaubanjar
Utrecht University, Utrecht, The Netherlands
e-mail: sdhauban@gmail.com

ICIMOD, Patan, Nepal

3.1 Introduction

Water is more than a common, yet fascinating substance to be found in the atmosphere, on land, underground, in seas and oceans and in the mantle of Earth. It is the source and an indispensable component of all forms of life. This is true not only for the biological processes of ecosystems, including humans, but also applies for economic metabolisms. As a key factor in all human activities water is simultaneously a production resource, transport agent, cooling medium and ultimately as water body recipient of sediments, debris, byproducts and waste from human settlements, agricultural land, industrial estates, mines and infrastructure. Water resources are finite and can easily be subject to quantitative or qualitative deterioration.

This chapter aims to summarize the key challenges and opportunities water and its management faces at present and in the foreseeable future. The motto of the 2nd World Water Forum (WWF) (2000) "Water is Everybody's Business" aptly coins the complexities, but also the importance of managing and safeguarding water. What had been once conceived as a straightforward engineering approach has been becoming a rather complex, transdisciplinary, multi stakeholder, multiple level, collaborative, but also confrontational exercise. Decisions, concerning water resources are made within new, still evolving, formal and informal institutional frameworks. As a corollary of the motto of the 2nd WWF, all water stakeholders should know more about

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water, its governance and management, and about the role different stakeholder groups may play in these processes.

This chapter starts with an overview of the interdependences, linkages and challenges we face in the domains of surface- and groundwater and their respective managements. Sect. 3.4 of this chapter provides an overview of the challenges faced by the contemporary concepts and practice of water resources management. The broad international and interdisciplinary debate, what may be called the water resources management discourse and its evolution will be introduced. While it is widely acknowledged that water resources management is integrative and focusing on thematic subdivisions may narrow the scope, it has to be acknowledged that water use and management historically evolved with surface and groundwater management pursued largely in separate "silos". Although, surface and groundwater are part of a continuum, due to the profound differences between these forms of occurrence of water and the different expertise and technologies needed to utilize surface or groundwater respectively, different professional communities have emerged. Even at present the overwhelming part of water demands are covered either from surface- or/and from groundwater bodies. While the conjunctive use of both resources (see Sect. 23.3 for more detail) is becoming more and more commonplace, proactive water resources management, especially at project scale still frequently refer either to surface or to groundwater. Hence highlighting the differences and peculiarities is not only warranted, but necessary to recognize the opportunities and constraints an integrated approach may face.

3.2 Surface Water Resources

The beginning of life on Earth has been linked to water. Modern humans (Homo sapiens) have inhabited this earth for some 300 000 years (Hublin et al. 2017; Richter et al. 2017), most of that time as hunter-gatherers. Some 10000 years ago, when people adopted an agrarian way of life, humans started establishing permanent settlements. All early civilizations were established close to large water bodies-rivers, lakes and seas. Over 70% of the surface area of our planet as well as human bodies consists of water. Therefore, water is literally life.

Water is not only a part of our constitution but plays a key role in promoting our livelihood practices by supporting agriculture, industries, energy production, recreation, domestic use such as drinking, cooking and bathing etc. The match or the mismatch between water availability and its uses leads to water scarcity issues and adds stress to human societies. In this section the availability of surface water resources and the water cycle will be discussed, followed by an overview of surface water management. Finally, we will present some future challenges and risks for water management.

3.2.1 The Hydrological Cycle

About 71% of the Earth's surface is covered with water. The *oceans* hold about 97.5% of the earth's water resources as saline water. Therefore, only 2.5% of all the water on earth is fresh, making it a relatively limited resource. Furthermore, of this 2.5% of fresh water, more than two-thirds (68.7%) is frozen as snow and ice, and more than one-third is stored below the surface as ground water. This means that only 0.3% of all fresh water on the planet is readily available as surface water in lakes, swamps, rivers and streams (Gleick 1996). Freshwater is millions of years old and is continually circulating in the hydrological cycle, which basically consists of flows (fluxes) of water between various stores or storages. Water is stored in the atmosphere as vapor, in liquid states in the oceans, rivers, lakes, reservoirs and wetlands as well as in the surface in soils and plants and beneath the surface in underground aquifers. Water exists in solid states in ice shields and glaciers and snow packs as well as in permafrost soils.

All this storage is temporary as water is always in flux, moving from and into the various storages. Precipitation is the process of water falling from the atmosphere to the earth surface. Precipitation can take many forms such as rain, snow and hail. When precipitation hits the land surface, some of it will be intercepted by vegetation and evaporated back into the atmosphere. Precipitation which reaches the ground will run-off if it hits impermeable surfaces such as built up areas or concrete roads. The precipitation which reaches the soil surface, infiltrates into the soil until the soil reaches saturation, then the rest flows as overland flow into streams and rivers and lakes. The water which infiltrates into the soil eventually percolates into the bedrock and underground aquifers. Groundwater is also moving laterally towards rivers and contributes to river flow as baseflow. Groundwater movement is very slow in comparison to surface water flow and could take thousands of years to reach rivers or other surface outlets (springs, oceans) as shown in Table 2.2 in Sect. 2.2.1.

Water returns to the atmosphere through evaporation caused by the heat of the sun. Water can also evaporate from humans and animals in the form of respiration and perspiration. Plants draw water from the soil and evapotranspire it back into the atmosphere. Water vapor in the air then condenses to form clouds and when oversaturated, cooled or triggered by the presence of condensation nuclei, falls back again to the earth surface through precipitation. The water cycle consisting of fluxes and stores is shown in Fig. 3.1. The total quantity of water on earth therefore does not change but is in a permanent state of flux. A water balance equation can be used to describe and quantify the flow and storage of water within the hydrological cycle.

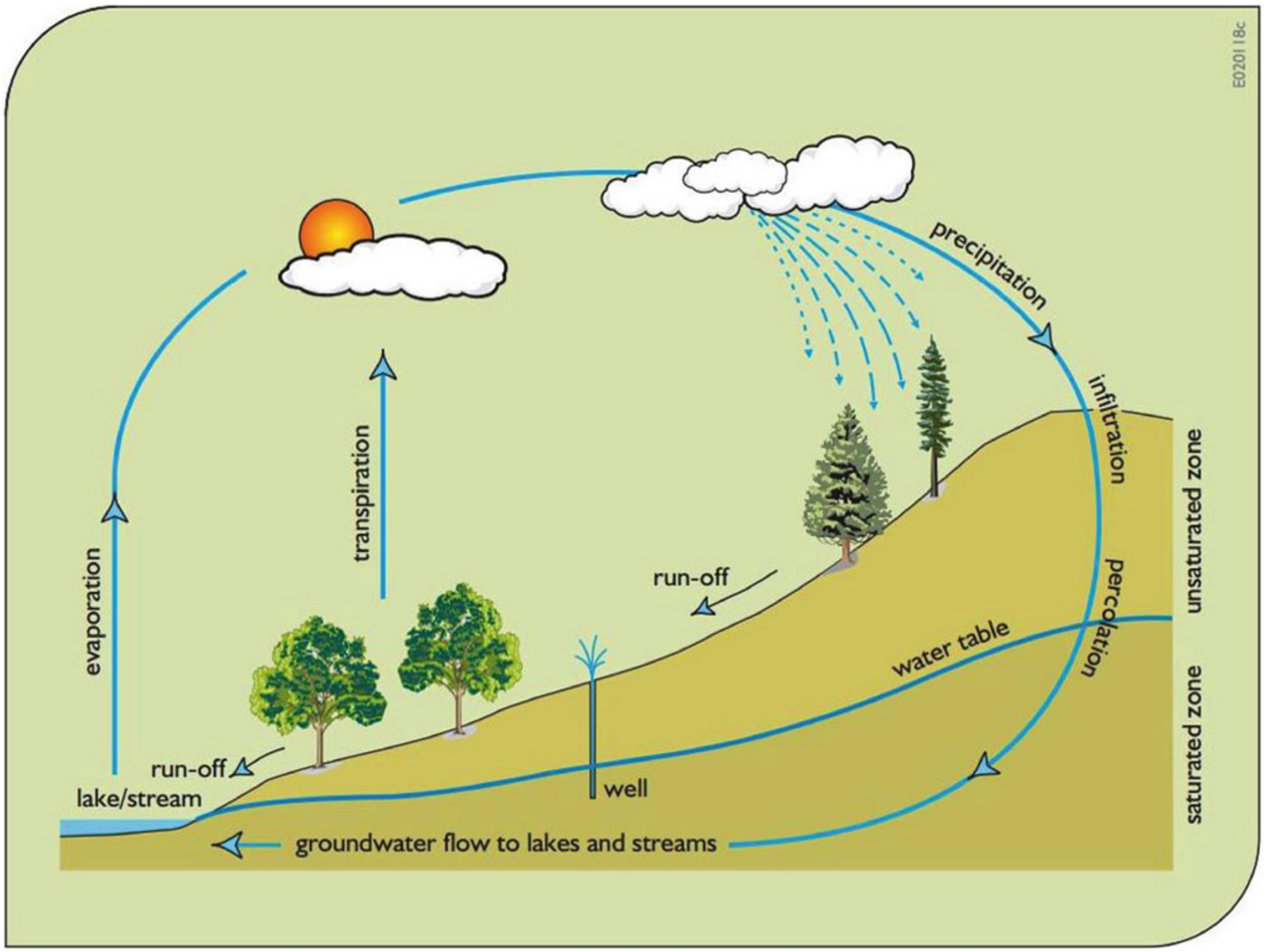


Fig. 3.1 The hydrological cycle. Reproduced from: Loucks et al. (2005)

3.2.2 Surface Water Systems: Some Essential Concepts

As Sect. 3.2 focuses on surface water hydrology, understanding runoff generation processes is very important. Hillslope hydrology is concerned with the partitioning of net precipitation passing through the vegetation coverage into several runoff components (Bogena 2001). Runoff is the total amount of water flowing into a stream/river, evaluated as the sum of direct runoff and base flow. Direct runoff is the sum of surface runoff and interflow. The surface runoff component is the sum of the so called Horton overland flow and saturation excess overland flow. In the following sections, the individual terms contributing to total runoff will be discussed. Total runoff comprises generally, of a combination of various runoff processes. One exception is during dry periods where the stream is recharged by the groundwater system (baseflow) alone (Bogena 2001). During a storm event, several runoff processes may be involved and the importance of each process depends on climate, type and state of the soil or surface cover, slope, geology, and vegetation.

3.2.2.1 Surface Runoff—Overland Flow

When rainfall reaches the land surface it can infiltrate into the soil. Most of this infiltrated water percolate vertically. However, soil has a finite capacity to absorb water. The maximum rate at which infiltration can occur under specific conditions of soil moisture is referred to as infiltration capacity (Fetter 1994). The infiltration capacity varies not only from soil to soil but is also different for dry versus moist conditions even for the same soil (Fetter 1994). As the capillary forces diminish with increased soil-moisture content, the infiltration capacity drops. Eventually, the infiltration capacity reaches a more or less constant, or equilibrium value. If the precipitation rate is lower than the equilibrium infiltration capacity, then all the precipitation reaching the land surface will infiltrate, but when the precipitation rate is greater than the initial infiltration capacity, the overland flow process, sometimes called Horton overland flow after Robert Horton (1933, 1940) occurs (Fetter 1994; Bharati et al. 2002). Therefore, Horton overland flow is the portion of rain, or snowmelt that moves laterally across the land surface and enters a wetland, stream, or other body of water. Horton overland flow is rarely observed in the field, except after very heavy precipitation events or where the soils are very fine textured, hydrophobic, heavily compacted, bare or frozen. A further mechanism producing overland flow is called return flow (Dunne and Black 1970). Return flow occurs when subsurface flow emerges as seepage at the foot of the slope and enters the stream or other water body as surface flow.

3.2.2.2 Interflow

If the unsaturated zone is uniformly permeable, most of the infiltrated water percolates vertically. However, if layers of soil with a lower vertical hydraulic conductivity occur beneath the surface, then infiltrated water may move horizontally or laterally in the unsaturated zone without reaching the water table and discharge directly into a stream or other body of water. This is referred to as interflow and can have a significant contribution to total stream flow (Fetter 1994).

During the 1960's and 1970's, increasing evidence of the complexity of flow generation and the impact of subsurface flow on storm hydrographs began to appear (e.g. Whipkey 1965; Hewlett and Hibbert 1966; Kirkby and Chorley 1967; Betson and Marius 1969; Dunne and Black 1970; Bryan and Jones 1997). This coincided with increasing reports of subsurface erosion features in many different materials and climatic zones (Bryan and Jones 1997). The field hydrologists then realized that stormflows could take place where overland flow was completely missing e.g. in forest catchments (Tani 2011). Many observational studies studying this problem have emphasized role of macropores (Mosley 1979; Tani 2011). Tani (1998) has observed that major stormflows are produced by a system of fast lateral saturated flow within macropores receiving vertical quick propagations of rainwater within unsaturated soil matrix. This effect can occur at rainfall intensities below those required for a Hortonian overland flow (Bogena 2001).

3.2.2.3 Baseflow

Baseflow is the sustained flow in a stream that comes from groundwater discharge or seepage. Days, weeks or even years may pass before water that seeps to the water table eventually reaches a stream. Some groundwater can, however, reach a stream during or shortly after an input event via translatory flow i.e. when a belt of antecedent water is forced by new seeping water or when there is a perched groundwater below the slope (Lawrence 1994). In humid regions, streams receive much of their volume from the groundwater system. These streams are gaining or effluent streams. In arid regions the groundwater table is very low and most streams lose volume to the groundwater system. These streams are then referred to as losing or influent streams (Fetter 1994). Baseflow will be further discussed in Sect. 3.3.2 in a groundwater perspective.

3.2.3 The Water Balance

The main water balance components are Precipitation, Runoff, Evapotranspiration, and Water Storage in various forms. A general water balance equation can be written as:

$$P = R + E + \Delta S$$

where, P is precipitation
E is evapotranspiration
R is runoff
ΔS is the change in storage (eg. in soil or groundwater).

Water balances can be calculated for land areas such as watersheds, river basins and countries as well as for surface and subsurface water bodies such as lakes and reservoirs, swamps, groundwater bodies, glaciers, ice sheets and inland seas. The water balance may be computed for any time interval such as a year, season, month or number of days (UNESCO 1974).

At the global scales, there are already several international initiatives that aim at developing water resources assessments and water balances, such as the activities of the UNESCO- International Hydrological Programme (IHP). Under the UNESCO-IHP Programme, an Atlas of World Water Resources was developed already in the 1970s, followed by guidelines for conducting water resources assessments (Godwin et al. 1990; UNESCO-IHP 1999; United Nations 2014). A compilation of water balances have also been produced by FAO/AQUASTAT (Food and Agriculture Organization of the United Nations 2016). The World Meteorological Organization (WMO), Commission for Hydrology has also worked on hydrology and water resources assessment (World Meteorological Organization 2008). These form the core of water balances thinking, as we know it today (European Commission 2015). New methods to improve water balance calculations continue to be developed. Use of satellite data, remote sensing tools and hydrological modeling are developing novel methods to calculate water balances (Sood and Smakhtin 2015, Daniel et al. 2011, Singh and Frevert 2002a, b).

3.2.3.1 Overview of Hydrological Modeling

Modeling is the process of organizing, synthesizing, and integrating component parts into a realistic representation of the prototype (Bouraoui 1994). The reliance on models in carrying out water balance assessments is increasing because models enable us to study very complex problems and to synthesize different kinds of information (Sorooshian and Gupta 1995; Singh and Frevert 2002a, b). Due to the increasing capability and widespread availability of computers, the development, acceptance and use of computer models has increased. However, model results are only as reliable as the model assumptions, inputs and parameter estimates (Sorooshian and Gupta 1995). Therefore, before being able to move any further, there are three major hurdles. The first is to select a suitable model to simulate the processes and management goals of the study area. The second is to select values for the model parameters so that the model closely simulates the behavior of the study site (Sorooshian and Gupta 1995). The third is the fundamental need of reliable data to run the model.

3.2.3.2 General Categorization

Since the development of the Stanford Watershed model (Crawford and Linsley 1966), there has been a proliferation of watershed models (Renard et al. 1982; Singh 1995; Singh and Frevert 2002a, b; Sood and Smakhtin 2015). At present, a large number of models of different types and developed for different purposes exist. In general, these models can be categorized into three classes (Bouraoui 1994): 1. Empirical models 2. Conceptual models 3. Physical models.

Empirical models or black box models contain non-physically based transfer functions to transform input data to output data. These models are often referred to as cause and effect models where the physical processes taking place are not simulated (Bouraoui 1994). This type of model is relatively simple, requires little data and can be used for statistical extrapolation. However, extrapolating beyond the range of available information especially for an outlier, or extreme events, may lead to highly erroneous results. Examples include simple regression models or water-balance/water-quality spreadsheet models. Conceptual models can be defined as semi-physical models since they simulate physical processes using major simplifications. This approach is used when information or general knowledge of the processes taking place is lacking (Bouraoui 1994). Examples of conceptual models are Hydrologiska Byråns Vattenbalansavdelning—HBV (Bergström 1976, 1992) and QUAL-2 K (Chapra and Pelletier 2003). Alternatively, physically based models simulate the internal mechanisms of the system using a theoretical approach. These models use physical parameters that can be either measured or determined using appropriate equations. Examples of such models are: the MIKE- Système Hydrologique Européen (SHE) model (Jayatilaka et al. 1998), the Precipitation Runoff Modeling System/Modular Modeling System—PRMS/MMS model (Leavesley et al. 1983), the Soil and Water Assessment Tool—SWAT (Arnold et al. 2012), and the Hydrological Simulation Program-FORTRAN—HSPF (Bicknell et al. 1997).

3.2.3.3 Lumped and Distributed Models

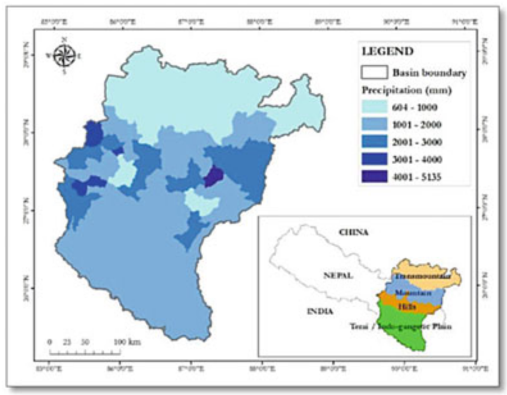
Hydrologic assessment models can also be divided into lumped and distributed models. A lumped model, is in general, expressed by ordinary differential equations taking no account of spatial variability of processes, input, boundary conditions and system (watershed) characteristics (Singh 1995). The whole catchment is assumed to be homogenous, and all the potential variations are lumped (averaged) together. Thus, the degree of accuracy of the model is expected to vary with the degree of non-homogeneity of the catchment. Lumped models provide a unique output for the whole watershed, however, they do not provide any information regarding the spatial behavior of the outputs (Bouraoui 1994).

Distributed models take into account the spatial variability of processes, input, boundary conditions, and/or system (watershed) characteristics (Singh 1995). Distributed models discretize the watershed into subunits (cells), which are assumed to be homogenous. All the hydrologic climatic and management parameters are then assumed homogenous within each cell, but may vary from cell to cell. The dynamics of the simulated processes are then described at each point within the watershed, and the outputs from each cell are routed to the watershed outlet (Beven 1985; Bouraoui 1994). Distributed models can either be conceptual in their model structure or physically based. For example, a GIS-supported and grid-based calculation of soil erosion with the simple regression equations (e.g. Universal Soil Loss Equation—USLE) can, in principle, be described as a distributed model (Bogena 2001). Box 3.1 presents an example of water balance assessment for Koshi basin in Nepal (Bharati et al. 2012) using SWAT (Arnold et al. 2012), a semi-distributed physically based model.

3.2.3.4 Time-scale Based Classification

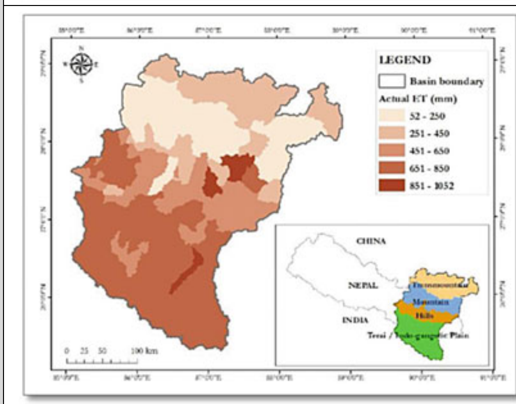
The hydrological models can also be classified based on the time scale of models (Singh 1995). Based on this description, the models can be distinguished as (a) continuous-time or event based, (b) daily, (c) monthly, and (d) annual models (Singh 1995). This classification depends on the interval of computation and the input data. The choice of a time interval is also often a function of the models intended use.

Box 3.1 Spatial Distribution of Precipitation, Actual ET and Water Yield in the Koshi Basin, Nepal using SWAT



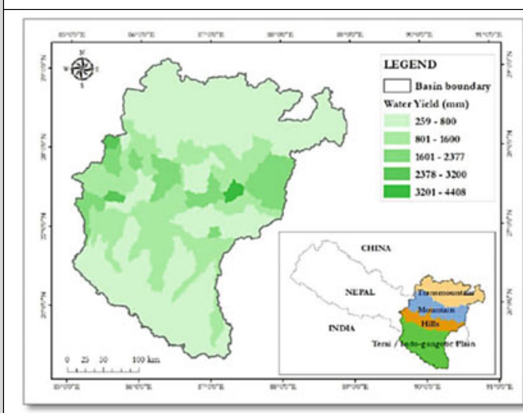
Precipitation

- The precipitation is lowest in the trans mountain region in the Tibetan plateau and highest in the mountains followed by hills in Nepal.
- Maximum precipitation (5,135 mm) occurred in a sub-basin in the mountain region and minimum precipitation (604 mm) in the trans mountain region in the Tibetan plateau.



Evapotranspiration (ET)

- As ET depends largely on precipitation, land cover and temperature, it was found to be high in forested areas in the hill regions of the basin and agricultural areas in the plains of Nepal and India.
- The maximum ET (1052 mm) occurred in a sub-basin, in the Indo-gangetic Plains of India, while the minimum (52 mm) occurred in a sub-basin in the Trans-mountain region.



Water Yield

- Similar to precipitation, the net water yield is lowest in the trans mountain region and highest in the mountains followed by hills in the Nepal part of the basin.
- Water yield is maximum (4,408 mm) in a sub-basin in the mountain region of Nepal and minimum (259 mm) in a sub-basin of the trans-mountain region.

Source: Bharati et al., 2019

Bharati L., Bhattarai U., Khadka A., Gurung P., Neumann L. E., Penton D. J., Dhaubanjar S. & Nepal S. (2019). From the mountains to the plains: impact of climate change on water resources in the Koshi River Basin. IWMI Working Paper. 187, 49

Understanding of the hydrology has traditionally been established through measurements of climate and various water balance components at point locations. Such direct measurements are often gathered and protected by national authorities, with limited public access. Point measurements are also hard to upscale rapidly over time and space. Remote sensing, the indirect measurement of physical parameters based on electromagnetism and signal processing theory, has emerged as a promising alternative, overcoming these limitations. Sensors deployed onboard unmanned-aerial vehicles (UAVs), airplanes or satellites, are used to remotely measure parameters affecting the water cycle based on signal responses over a grid (for observations and hydrological data management, see also Chap. 13).

For instance, satellite based global precipitation is estimated using radar and microwave imaging by Tropical Rainfall Measuring Mission (TRMM), Integrated Multi-satellitE Retrievals for Global precipitation measurement (IMERG) and Global Satellite Mapping of Precipitation (GSMaP). Advanced SCATterometer (ASCAT) and European Remote Sensing—2 (ERS-2) satellites remotely monitor soil moisture based on radar measurement of emissivity and reflectivity. Radar interferometry (e.g. Shuttle Radar Topography Mission—SRTM, TerraSAR-X add-on for Digital Elevation Measurement—TanDEM-X) is used to developing elevation models while radar altimetry (e.g. CyroSAT, Synthetic Apeture Radar—SAR, Altimeter Corrected Elevations, Version 2—ACE2) is being explored to measure water levels. Thermal and multi-spectral imagery can be used to distinguish different surface land covers (e.g. LandSat) and snow cover (e.g. Moderate Resolution Imaging Spectroradiometer—MODIS). Multi-spectral imagery can also be used to measure evapotranspiration. Gravimetry can provide estimates for total water storage, including sub-surface water (e.g. Gravity Recovery and Climate Experiment—GRACE). These examples present satellite-based products, but the sensors can be installed on ground-based or air-borne carriers for localized measurements. The rapid adoption of remote sensing techniques has also fueled the development of models and data assimilation methods that combine traditional point based measurements with gridded remote sensing datasets (Liu et al. 2012).

Remote sensing provides an opportunity to develop globally standardized data sets (among them also the so-called reanalysis data, see also Sect. 2.2), often accessible publicly. However, their application in sub-continental and local scale analysis is debatable (McCabe and Wood 2006; van Dijk and Renzullo 2011). The spatial resolution of satellite-based products and their performance is inherently poor in areas with complex topography. Interference in data due to cloud cover is another major issue for satellite-based products. Use of ground-based or air-borne carriers, such as Unmanned Aerial Vehicles (UAVs), gliders, helicopters etc., can overcome the issue of clouds and provide data with finer resolutions; but the cost of such endeavors can be high. On-the ground validation of remote sensing products is also challenging, requiring comparisons of grid-based and point measurement. Processing of geophysical signals actually measured by these sensors to physical hydrological and climatic parameters requires rigorous processing algorithms that can be computationally intensive. Nonetheless, remote sensing is already revolutionizing the measurement and modeling of the hydrological cycle as the technology becomes more reliable, efficient and cost effective. For more detail see Chap. 13.

3.2.4 Water Availability and Uses

Flows and storages described in the previous section are due to natural phenomena. Human activities also influence components of the water balance equation. This can be through building large artificial storages such as reservoirs, abstractions for water supply or water transfers to other areas and by transferring return flows from various uses such as irrigation areas back into the hydrological (or water) cycle. Land use changes, such as increase in agricultural area, deforestation, or imperviousness on urbanized areas can also influence the processes of evapotranspiration, infiltration, soils storage, and runoff. Therefore, water balances can also be calculated to capture the equilibrium in the physical system between inputs and outputs modified by the human intervention (European Commission 2015).

Once water balances have been established for a certain land area such as a river basin or even country, water availability can then be estimated. Water availability calculations are usually done to manage current water resources against the various anthropogenic demand/uses and for designing future water resources development through infrastructure projects such as dams, reservoirs and diversions canals. All developed countries and many developing countries regularly carry out such assessments and maintain databases. However, the level of detail and precision may vary. There are wide variations in water availability vs. use among the different regions in the world. Water scarcity problems arise when water availability of an area is lower than the water demand or use. Water available in a certain country may or may not be generated within its own borders. For instance, upstream countries like Bhutan, Nepal and China generate all their water within its geographical boundary, while a downstream country like Bangladesh receives over 90% of its water from across its geographical boundaries. Figure 3.2 shows a global map identifying areas of physical and economic water scarcity in varying degrees of severity. Water scarcity is often divided into physical and economic water scarcity (Molden et al. 2003) as in certain

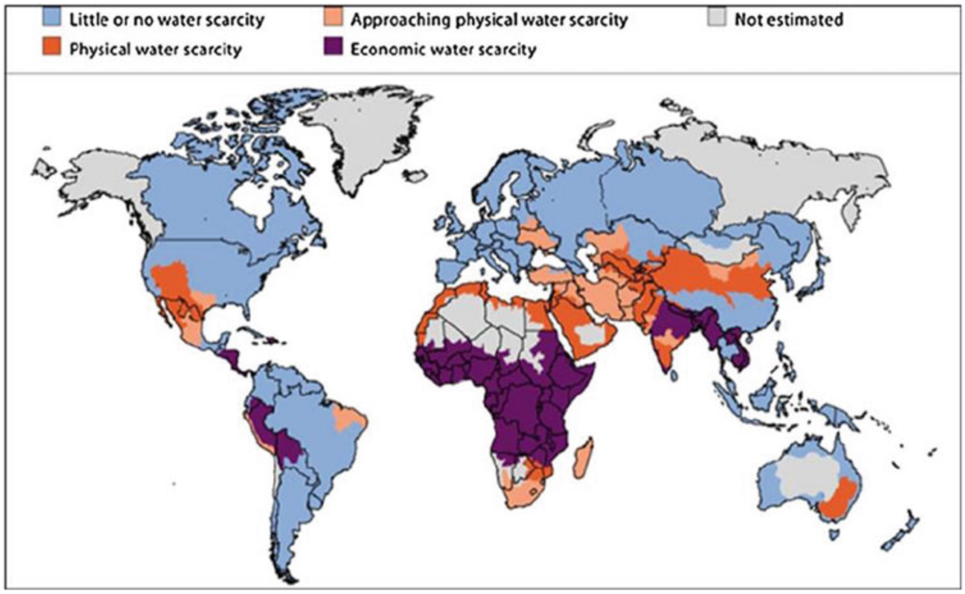


Fig. 3.2 Areas across the globe with physical and economic water scarcity in varying degrees of severity reproduced from Comprehensive Assessment of Water Management in Agriculture (2007)

places, such as in upland areas, water availability might be low although a large river is flowing a few hundred meters below in the valley. In such cases, if the upland areas have the economic means to access the river water through pumping, they do not have water scarcity issues. Similarly, groundwater or even shallow ground water might be available but due to lack of investment in infrastructure to pump ground water, many countries esp. in Africa and South Asia face economic water scarcity.

3.2.4.1 Water for Human Use and Consumption

Figure 3.3 shows the global water use differentiated as "blue water" and "green water". Blue water refers to naturally available freshwater found in rivers, lakes, reservoirs, and aquifers. Within the hydrological cycle the movement of 'blue water' is predominantly governed by gravitational forces (runoff, infiltration, seepage etc.). Due to this feature the management of 'blue water' can rely on hydraulic engineering techniques. Of the total renewable blue water resources available globally, 9% is used annually. Cities and industries extract 1200 km^3 of blue water per year but most of this water (90%) is returned to the sea (Comprehensive Assessment of Water Management in Agriculture 2007). Green water refers to soil moisture available to plants. 'Green water' is moved predominantly by molecular forces (capillary rise, evapotranspiration etc.). Consequently 'green water' management is overwhelmingly done by agricultural practices (selection of crops, change of soil structure etc.). Rainfed agriculture depends on green water, whereas irrigated agriculture depends on blue water, usually transferred from lakes and rivers. Of all the water uses, agriculture is the largest water user (See Fig. 3.3). Through the process of evapotranspiration, both green and blue water are consumed by the vegetation and not returned to the immediate water bodies as in the case of other use (Comprehensive Assessment of Water Management in Agriculture 2007).

3.2.4.2 Environmental Water Demands

Increasing demands for water to fulfill the diverse societal needs within the domestic, agricultural, industrial and commercial sectors is leading to plans to develop and exploit rivers and streams. The term "environmental flows" (EFs) is now commonly used to refer to a flow regime designed to maintain a river or stream in acceptable ecological conditions, balanced with water use for human needs. All components of the natural hydrological regime have ecological significance. In regulated basins, the magnitude, frequency and duration of some or all flow components is modified and the suite of acceptable flow limits for such modifications can ensure a flow regime capable of sustaining some target set of aquatic habitats and ecosystem processes (Poff et al. 1997). EFs can therefore be seen as a way to balance river basin development and maintenance of river ecology. According to the definition from the Brisbane Declaration (2007), environmental flows (EFs) describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. The Science of EF is a rapidly advancing field with new concepts, methods and tools being added to an ever-expanding knowledge base. Several reviews of the tools and concepts of EF are currently available (e.g. Tharme 2003; Acreman and Dunbar 2004; Poff and Zimmerman 2010; Pahl-Wostl et al. 2013; Acreman 2016).

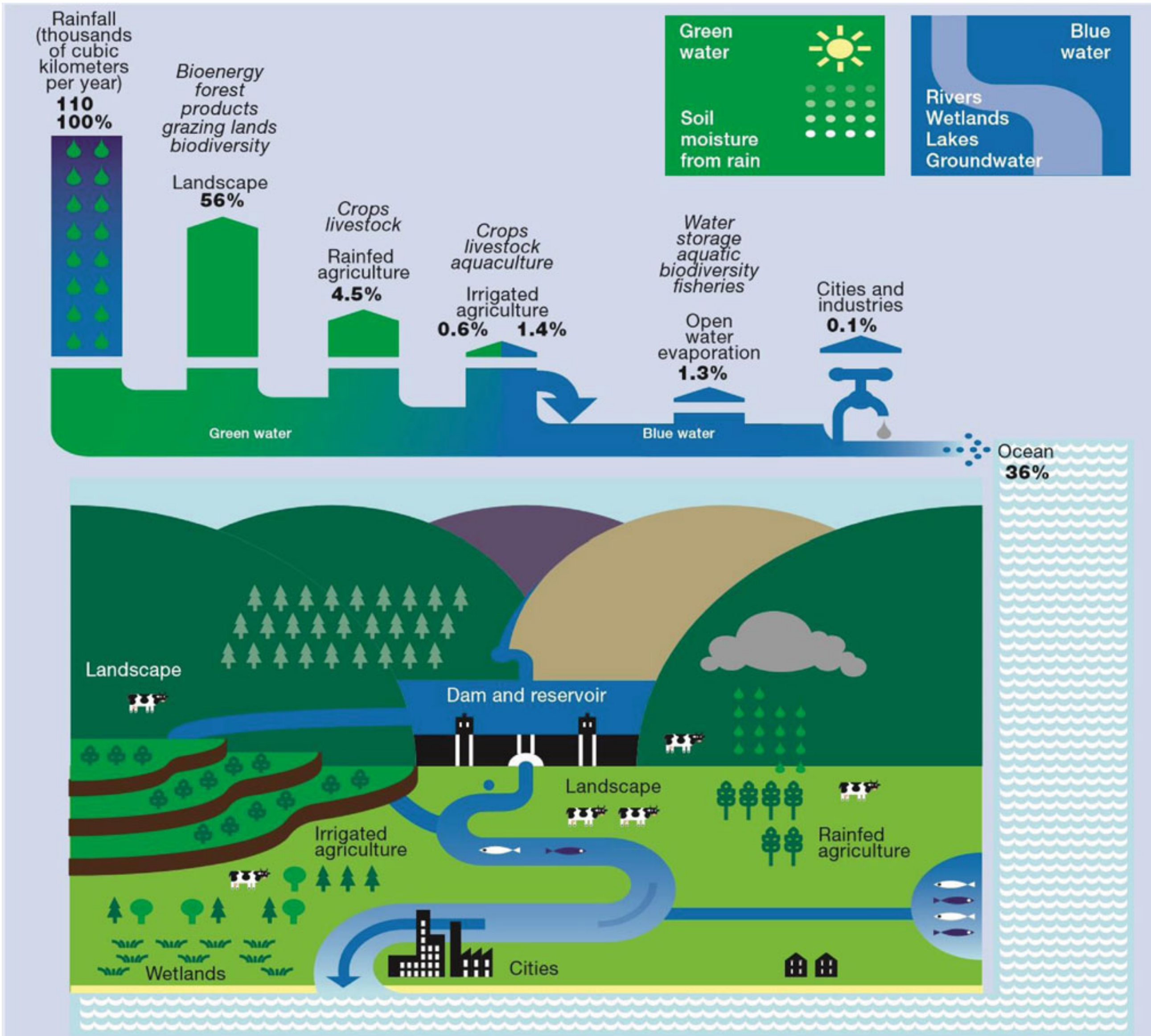


Fig. 3.3 Global water use reproduced from Comprehensive Assessment of Water Management in Agriculture (2007)

3.2.4.3 Water Accounting

Water balance calculations, usually focus on the physical processes in quantifying water fluxes and stores. Water accounting has therefore been in use to quantify/take stock of water use by natural and anthropogenic processes. The main objective is to understand weaknesses, strengths, and opportunities in existing water management practices. Water accounting therefore provides practical decision support tools that systematically links water balance, land use and water use, enabling users to understand implications of water and land management interventions. These methods categorize all water usage in the system as consumptive/non-consumptive, beneficial/non-beneficial, committed/non-committed or recoverable/non-recoverable, shifting the focus to the level of productivity in water management (Molden et al. 2003). To a certain extent, water accounting frameworks respond to the call for a globally consistent standardization of terminologies and methods in water management similar to that in finance (Karimi et al. 2013). These frameworks also promote that better management of existing water resources is key to address water scarcity in the twenty-first century (Fig. 3.4).

Different frameworks exist with varying levels of rigor in tracking the fate of every water drop in the system. AQUASTAT, developed by the FAO, represents one of the first attempts that compiled national data on water inflows and outflows. The United Nations' System of Environmental

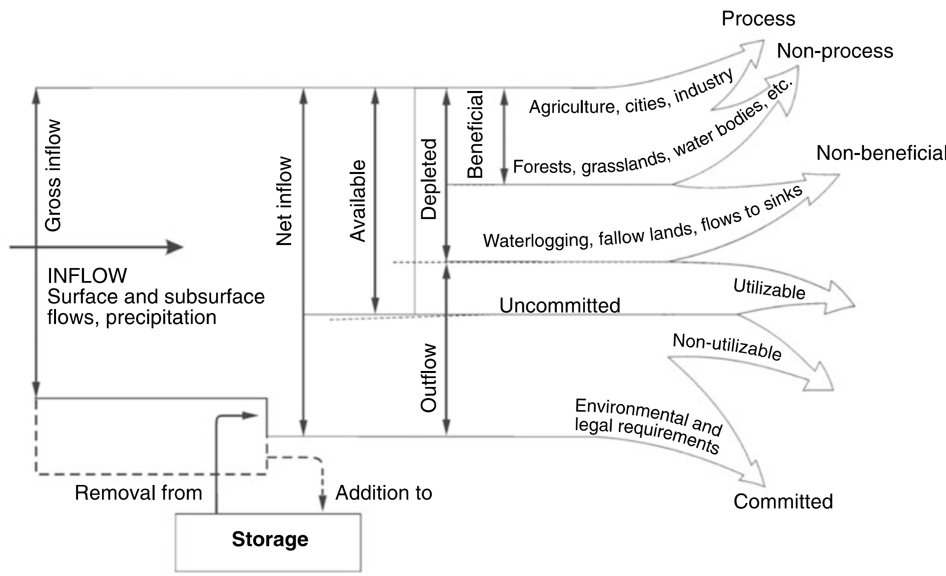


Fig. 3.4 Generalized diagram for water accounting. Reproduced from: (Molden et al. 2001)

Economic Accounting for Water (SEEA-Water) (United Nations et al. 2014) and the Australian general-purpose water accounting report (GPWAR) represent more comprehensive but data intensive efforts following financial accounting models (Burrell et al. 2018). Both SEEA-Water and GPWAR focus on accounting water flows and actual abstraction, leaving out evapotranspiration—one of the major processes leading to water loss in a river basin. Depletion based water accounting methods overcome this by considering processes that lead to depletion of water available in the system. Such methods are desirable when data on sector-wise withdrawal is not publicly available for most basins.

Water Accounting Plus (WA+) represents the state-of-the-art in depletion-based water accounting by utilizing freely available satellite based datasets for evapotranspiration to identify processes that lead to beneficial and non-beneficial water depletion in a basin (WA+ 2016). WA+ uses gridded evapotranspiration datasets to quantify water depletion from natural processes, as well as anthropogenic processes based on the land use class in each grid. As such, the water balance used in WA+ directly links water depletion with land and water management practices (Karimi et al. 2013). Figure 3.5 presents a surface water balance for the Nile river basin conducted using WA+ (Karimi et al. 2012, 2013; WA+ 2016). WA+ is especially useful in a trans-boundary basin like Nile where field data collection and sharing is limited but satellite data is readily available.

3.2.5 Global Changes and Future Risks

3.2.5.1 Water Quality and Reuse

The problem of water quantity is most often also accompanied by the problem of water quality. Water quality is closely linked to human and environmental well-being. Contaminated waters are a threat to human health and to the sustenance of aquatic biodiversity. Many natural processes in the water cycle and symbiotic relationship between water bodies and their ecosystems provide water resources an inherent ability to self-regulate their quality, for example, removal of pollutants in runoff through soil infiltration, dilution of pollutants in large quantities of water. However, in many places dilution is not resolving pollution problems anymore as human activities have exhausted and saturated the natural capacity of surface water resources to maintain their quality. As freshwater resources become over-allocated and stressed by demands from multiple sectors, interventions to maintain water quality and subsequent reuse of water will be inevitable.

The quality of water is determined by its physical, chemical and biological composition commonly quantified in measures of turbidity, pH, temperature, dissolved oxygen, bacteria, ionic and organic content. Pure water, comprising strictly of hydrogen and oxygen seldom exists naturally. Surface water contains suspended solids, dissolved gases, minerals and organic and inorganic compounds accumulated

	Kagera	Lake Victoria	Victoria Nile	Semliki -Lake Albert	Albert Nile Bahr al Jabal	Sudd	Baro-Akobo-Sobat	Bahr el Ghazal	Lower White Nile	Blue Nile	Main Nile 4	Tekezze -Atbara	Main Nile 3	Main Nile 2	Main Nile 1	Total
precipitation	57	247	102	79	88	144	418	210	102	300	3	114	48	2	1	1914
Evapotranspiration	48	188	89	70	93	190	442	220	137	192	5	89	70	12	16	1861
Incremental Evapotranspiration man-made	0.001	0.007	0.04	0.00	0.11	0.3	0.1	0.3	5.1	2.5	0.5	0.9	7.5	10.3	10.4	38
Virginal flow	8.4	59	12.4	8.7	-4.0	-46.0	-24.4	-10.5	-30.0	110.8	-0.9	26.7	-14.9	0.2	-5.1	90
Man made withdrawals	-0.4	-1.1	-0.6	-0.4	-0.6	-1.2	-3.0	-1.5	-8.8	-5.4	-1.0	-2.6	-39.8	-17.2	-15.5	-99.1
Returnflow	0.3	1.0	0.4	0.4	0.4	0.8	2.7	1.1	3.5	2.7	0.4	1.6	32.0	6.8	5.0	59.1
Storage	0	-2.6	-0.7	0	0	0	0	0	0	-2.1	0	0	8.19	0	0	3
Inter-subbasin exchange	0	-14	-8	0	0	16	16	3	15	-21	0	-4	-2	0	-1	
Mean annual riverflow per subbasin	4	30	28	3	37	16	0	18	36	52	81	10	59	45	41	-
Mean annual riverflow collected	4	30	28	32	37	16	16	34	36	88	81	91	59	45	41	-
Environmental flow	1	7	7	8	9	4	4	8	9	21	19	22	14	11	10	-
Committed flow	0	0	0	0	0	0	0	0	0	8	0	0	56	0	0	-
Reserved flow	1	7	7	8	9	4	4	8	9	21	19	22	56	11	10	-
Direct downstream allocated	1	1	0	1	1	3	2	9	5	1	3	40	17	15	0	-
Further downstream allocated	0	0	12	20	19	16	14	5	0	14	11	0	8	0	0	-
Total downstream allocated	1	1	12	21	20	19	16	14	5	15	14	40	0	15	0	-
Utilizable flow	6	43	36	34	30	6	9	-2	-14	49	50	44	33	53	52	-
Actual flow	8	50	54	63	59	28	28	20	0	85	84	105	89	79	62	-

Fig. 3.5 Annual surface water inflow and outflow from different tributaries along the Nile River in km^3 using WA+ for 2010. Reproduced from (WA+ 2016) accessed on 25.09.2018

overtime as water moves through its surroundings. The composition of water can thus be considered an indicator of its origin and history of travel through the water cycle. Discharge of unwanted physical, chemical or biological contaminant and pollutants degrades the quality of water. These include for example: dissolved organic carbon, ammonia, phosphorous, pesticides, pathogens, organic micro pollutants, as well as heavy metals and unnatural trace elements. Such dissolved pollutants in water can be major health hazards while pathogens in water can cause water-borne diseases. Poor water quality can lower oxygen content in water or cause bloom of invasive aquatic species degrading the native aquatic biodiversity. Decline of ocean water corals is also attributed to pollutants in water.

Non-consumptive usage of water, where all or a fraction of the water is returned to the system, often alter its quality. For instance, excess water applied for irrigation that exits the farmland soaks away the surplus of fertilizers and pesticides used to enhance agricultural productivity. In various industries and in energy production, water may not be a direct ingredient but an aid for different processes, such as heating, cooling or transportation. Water discharged after such usage may contain dissolved organic or inorganic contaminants such as heavy metals, harmful gases and toxic substances. The returned water might also have substantially higher temperatures, posing an additional environmental hazard. Acid mine drainage, water used for hydraulic fracturing (fracking) and water for cooling of power plants are some controversial industries that discharge poor quality water. Babel and Wahid (2008) found that 70% (~300–500 million tons) of heavy metals, solvents, toxic sludge, and other wastes from industrial activities were discharged untreated alone into the Ganges–Brahmaputra-Meghna River Basin. Diffuse sources of pollution are considered a major threat to more than 40% of Europe's rivers (European Environment Agency 2016). Discharge of such pollutants to natural rivers, stream and lakes can result in rapid degradation of surface water quality. These diffuse and point sources of polluted water are caused by active anthropogenic usage of water.

Many other human activities generate liquid wastes that make their way into surface water resources. Sewage, municipal wastes and storm water containing unwanted sediments, debris, chemicals and disease causing pathogens can also end up in surface water bodies. In rural landscapes, open defecation and excretion are big threats to surface water quality. Direct dumping of solid and liquid wastes into flowing water is also a practice of serious concern plaguing waters in the global south. Karn and Harada (2001) found that municipal sewage contributed to nearly 85% of pollutants in river waters in Kathmandu (Nepal), Delhi (India), and Dhaka (Bangladesh) while infiltration of urban stormwater, leakage of wastewaters and septic reservoirs, and improper industrial activities were other sources of pollutants. Unmanaged solid waste and dirt from urban landscapes also make their way into rivers and the ocean as heavy rains wash them away and flood the sewers. In Kabul (Afghanistan) for example, over 70% of the city's solid waste is accumulated at the roadside, drains, and open places, ready for storm water to push them into open drainage pits and sewage channels (Scott et al. 2017).

Poor water and waste management at local scale ultimately affect our oceans as rivers transport polluted waters downstream. The great pacific garbage patch is a visible example of the intensity with which our surface waters are being infested (Eriksen et al. 2014; The Ocean Cleanup 2018; Lebreton et al. 2018). Scientists are studying this growing amalgamation of floating plastics and other wastes pushed from all over the world into the center of the Pacific Ocean by global ocean currents and wind patterns in hopes to reduce its impact on water quality. New water quality threats, such as microplastics and residues of medicines, have also emerged in recent decades as new industrial processes and new wastes are being developed.

The open and accessible nature of surface water resources makes them more vulnerable to water quality degradation through human interference than groundwater resources. Various sub-surface dynamics that provide natural filtering and purification of groundwater in underground aquifer are entirely missing for surface water. The constant flow of river waters through various terrains provides some grounds for filtration and oxidation of water to improve its physical and chemical composition. However, such natural carrying capacity is governed by the geomorphology of the river. Water quality control measures need to be put in place to control point and diffuse sources of pollution into water bodies. Impact of point sources can be reduced through complete or partial treatment of wastewater, sorting and selective removal of solid wastes prior to their release into natural water bodies. Control of diffuse pollutant sources such as agricultural leachates require interventions to reduce chemical applications in agricultural practices. Better solid waste management, including better designs of septic systems and landfill are also important for curbing water pollution. Policies and regulatory institutions need to be strengthened to support such measures for improving water quality.

While water quality degradation is an important issue on its own, its impacts will heighten under increasing water demand and water scarcity. Creative use of low or poor quality water for non-consumptive use is important to ensure water for various anthropogenic needs and equity in water allocation under socio-cultural hierarchies (Comprehensive Assessment of Water Management in Agriculture 2007). For example, in Hanoi (Vietnam), irrigation of 80% of vegetables are supplemented with wastewater, while and in Kumasi (Ghana), wastewater is potentially incorporated for irrigating a third of the country's irrigated areas. Channeling of water through non-consumptive usage requiring varying quality of water can also help propagate circular economies by closing the loop of water demand across various sectors. Countries like Cyprus and Malta already reuse over 90% and 60% of their wastewater respectively, while the European Union (EU) is pushing to increase wastewater reuse potential (estimated as 6 km^3 annually) across all member states (European Commission 2018). Low quality water can be an important resource if it can be improved to acceptable standards for indirect usage in certain applications.

3.2.5.2 Impact of Climate Change

According to the World Economic Forum's Global Risks Report, Climate Change (CC) threats dominate the list for the third year in row (The World Economic Forum 2019). Climate change directly impacts the water cycle. The magnitude and seasonality of water availability in any surface water follows the changes in weather patterns, both local and global. While the hydrological cycle largely revolves around local patterns for temperature, precipitation and relative humidity, these local climate parameters are linked to global fluctuations in temperature and wind patterns. These linkages between global and local climate patterns are best demonstrated during the El Niño and La Niña or the El Niño-Southern Oscillation (ENSO) phenomenon, whereby warmer or colder than average surface temperatures in the Pacific ocean shifts the direction of atmospheric circulation inducing changes in weather patterns and consequently precipitation globally (NOAA 2016).

There is scientific consensus (IPCC 2013) that the planet is warming due to greenhouse gas emissions, which will impact the climate system. The fifth Intergovernmental Panel on Climate Change (IPCC) assessment reports projected change in global mean surface air temperature for the mid- and late twenty-first century relative to the reference period of 1986–2005 will likely be from 0.4 to 2.6 °C for 2046–2065 and 0.3 to 4. 8 °C for 2081–2100, under various levels of anthropogenic emission scenarios.

The IPCC warns that though projected changes in precipitation are not uniform globally, extreme precipitation events will become more intense and frequent in many regions. Figure 3.6 visualizes the potential shifts in probability distribution of climate variables under climate change (Stocker et al. 2013; IPCC 2014a, b).

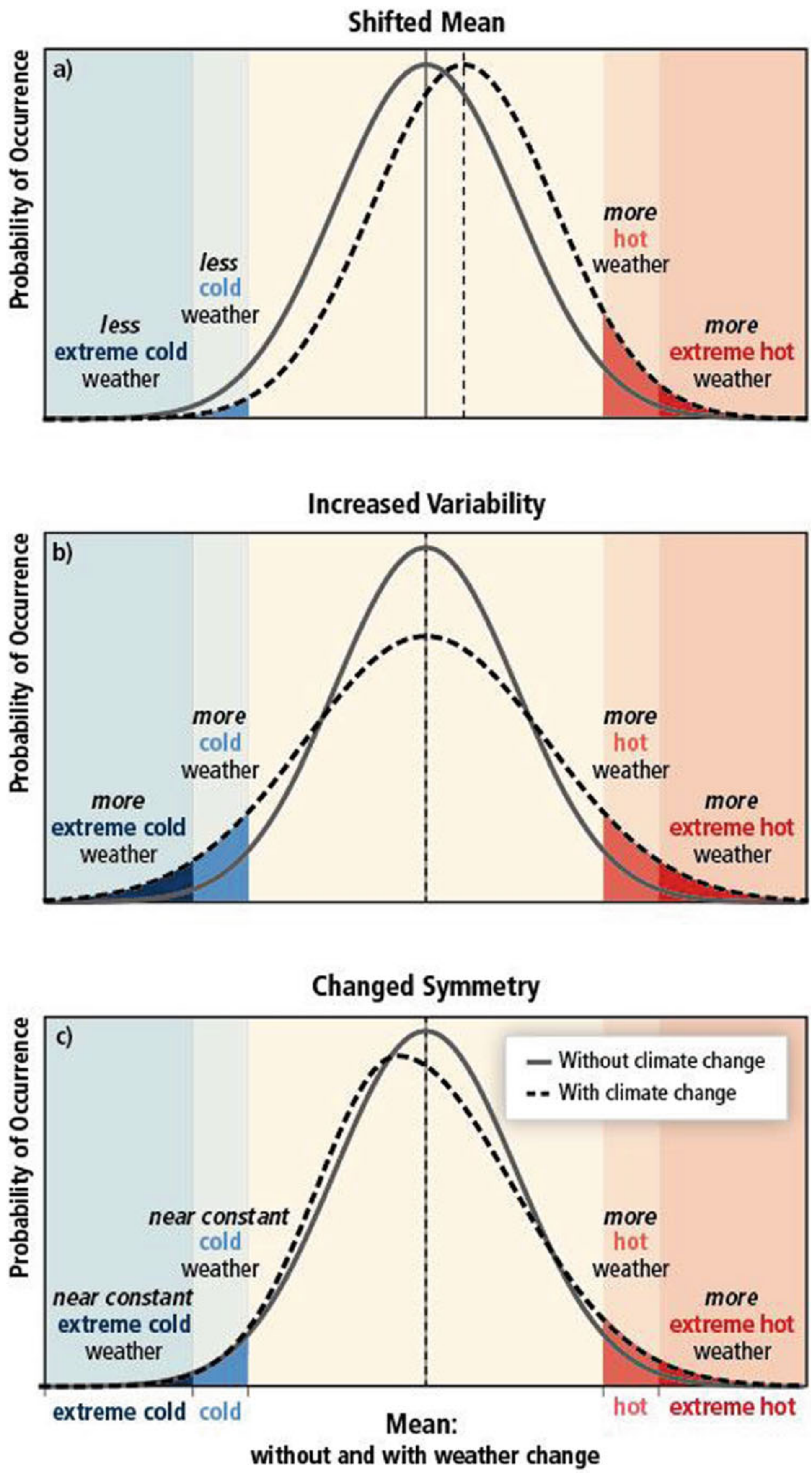
Such projections for global climate change are bound to alter the state of water resources in terms of both quality and quantity. A warming atmosphere holds more water vapor. Increasing temperatures will increase glacier and snow melt as well as evapotranspiration. Shift in precipitation will cause a shift in direct runoff contributions.

In the long run, temperature and precipitation changes will also induce changes in land cover as vegetation zones shift. Climate change induced desertification is gaining recognition as an important issue with its addition to the scope of sixth IPCC assessment (IPCC 2017). The threat of climate induced disasters such as hurricanes, floods, landslides and severe droughts are also imminent (IPCC 2014b). The impacts of climate change on water resources will be further multiplied by the domino effect on the various other sectors interlinked by the water-energy-food-environment-livelihood nexus. Climate inducted change in water availability will not only affect production of food, energy and nearly every other manufactured commodity, but it will affect human lives every day. Water infrastructure and management intervention decision makers should therefore be particularly wary of selecting designs and pathways that are climate-resilient. Coordination between management and governance systems is key challenge to ensure water resource management is done with the purview of balancing benefits across various stakeholders and future climate risks. The IPCC points out that future risks are higher for disadvantaged communities across the globe because of higher vulnerabilities (IPCC 2014b). According to IPCC vulnerabilities are not just a function of sensitivity and exposure to the bio-physical parameters but also very dependent on social and economic adaptive capacity, which includes structural inequities in the society related to gender, class, race, ethnicity etc. Many good adaptation strategies therefore might come from the non-water sector such crop insurance schemes or index based insurances, livelihood diversification, linkages to markets etc.

The future is also still uncertain. The multitude of regional and global circulation model (RCM and GCM) projections indicate change however; especially for precipitation there is sometimes no agreement on the magnitude and direction of this change (IPCC 2014a). Therefore, future water resources planning and adaptation strategies should not focus too much on future changes in averages and certain trends (increase and or decrease in precipitation) but plan for uncertainty and increases in variability of the system.

The example of the water shortage in Cape Town in 2018 aptly demonstrates that the projected dryer future might already be happening. Box 3.2 summarizes the dramatic situation in the first half of 2018.

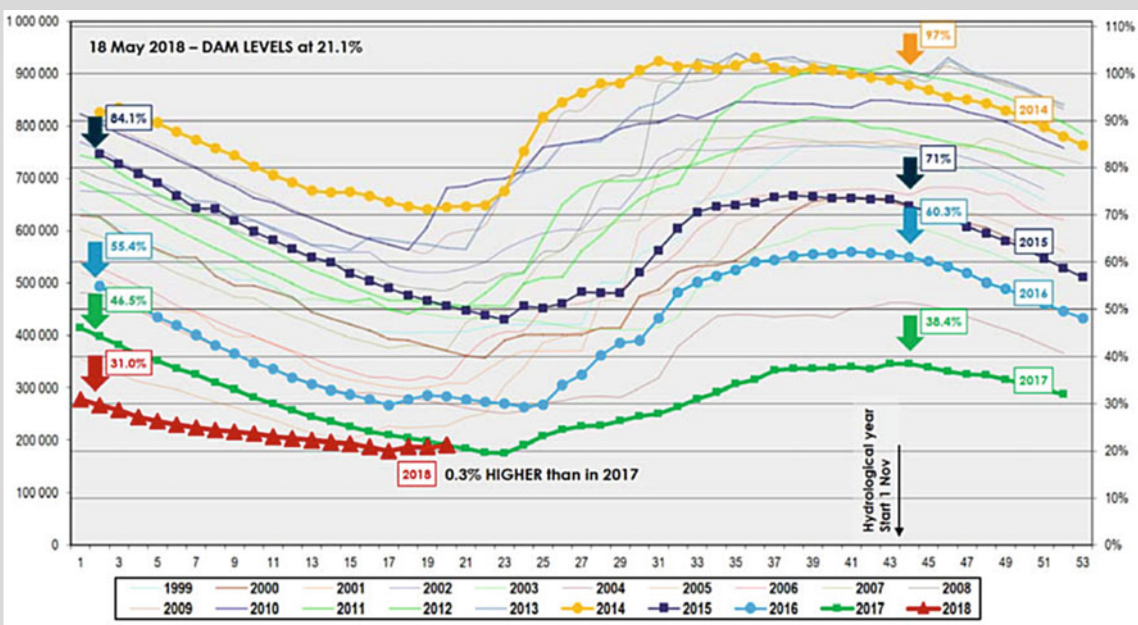
Fig. 3.6 Shift in climate patterns. Reproduced from: (IPCC 2014a)



Box 3.2 Day Zero in Cape Town, South Africa

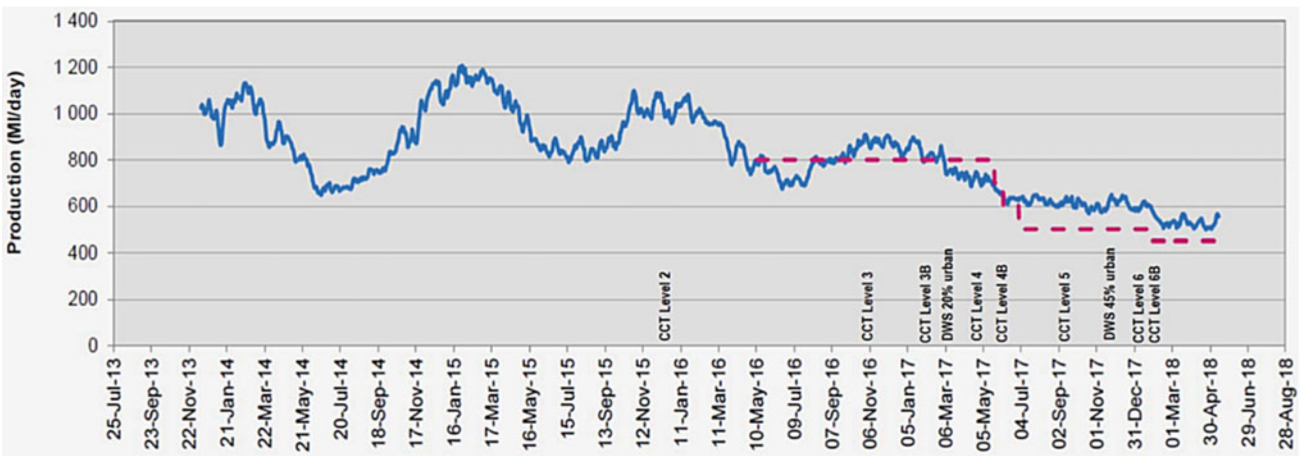
Year 2018 saw the City of Cape Town (CCT) reduce municipal water allocation to as low as 50 liters per day per person (lpd). The CCT forecasted several dates for the approaching Day Zero, when the city's major dams would reach the critically low supply level of 13.5%, forcing the CCT to stop all municipal water supplies. Residents would then collect their allocation of 25 lpd per person from the 149 municipal water collection points. This water crisis is a harbinger of the severe water scarcity that can impact many other urban centers in the world. For the majority of cities, current water resources and management measures are not in line with expected increases in anthropogenic water demand due to consumerism, urbanization, industrialization, and population growth. Indeed, by 2025, over 3.5 billion people are projected to live in water-insecure regions worldwide.

Six major dams that harness streamflow dominate the CCT's water supply system. The total yield of the dams is 1500 million liters per day (MLD), augmented by over 200 MLD of groundwater. Very little treated wastewater is reused to supplement industrial demands, though there is potential to reuse over 200 MLD. An additional 350 MLD is required to make Cape Town sufficiently water secure. Diverse sources such as groundwater, desalination, and wastewater re-use are being explored by CCT. But augmentation projects have been slow under political and financial tensions. The climate-sensitive water supply system was thus hit hard by severe drought from 2015 to 2017. The drought is one of the worst the city has seen, a rare event occuring once in 300 years, resulting in some of the lowest water levels recorded for the city's dams.



Decline in dam water supply due to the 2015–2017 drought in the City of Cape Town compared to water levels over the decade. Reproduced from: City of Cape Town Water Outlook Report 2018.

Given the drought conditions, CCT launched aggressive demand management strategies to ensure the available water in the dams could be stretched until the end of the persisting drought. Water saving infrastructures were applied, pressures in the system reduced, detection and repair of leakages prioritized, and installation of water management devices was ramped up. Progressive tariffs were also applied to penalize water usage above 50 lpd per person February 2018 onwards. Communication campaigns warned citizens against the looming crisis and drive behavioral changes. An online dashboard enabled citizens to monitor dams and changes in sector-wise consumptions. Adherence to daily allocation was incentivized while those exceeding CCT's allocations were subject to public shaming. By May 2018, the CCT more than halved the unconstrained daily demand from 1346 MLD to 681 MLD. Such aggressive demand management, combined with heavier rains in May and June and donation of farmer's irrigation water to the city, allowed CCT to push back the imminent Day Zero to 2019. However, households in poorer neighborhoods, who cannot afford to have a private supply well bore the weight of the CCT's restrictions. Affluent households often exceeded their restricted allowances, as the higher tariffs were not a financial burden. For long-term reduction in domestic water demand, CCT needs to consider measures that impose restrictions that weigh evenly on all households.



Change in annual daily average water demand in the City of Cape Town (CCT) with restrictions placed on sector-wise water allocation by the city. Reproduced from: City of Cape Town Water Outlook Report 2018.

While Day Zero was narrowly avoided in 2018 in Cape Town, CCT continues to pursue measures to build water security. Many other cities in South Africa and beyond are functioning below the 50 lpd minimum allocation defined by the World Health Organization. Managing water, particularly in water-insecure areas, will require an integrated, targeted and aggressive approach. Day Zero is a much-needed reminder that addressing water insecurity needs to consider technical, institutional, economic, social and behavioral factors that affect water availability, water access and climate resiliency for all stakeholders.

Sources

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3.3 Groundwater: Dependence, Linkages and Challenges

3.3.1 Human Dependence on Groundwater

3.3.1.1 A Brief Historical Evolution

Since earliest times humankind has met much of its need for good quality water from subterranean sources. Springs, the surface manifestation of underground water, have played a key role in social development. The earliest waterwells were rarely more than 50 m deep, deployed manual or animal water-lifting and were sunk in Asia and the Middle East. But it was not until the nineteenth century that the foundations of modern hydrogeology were laid in Western Europe, by Henry Darcy and William Smith.

During the twentieth century, there was an enormous boom in waterwell construction for urban water-supply, agricultural irrigation and industrial processing. This was facilitated by major advances in waterwell drilling, pumping technology and hydrogeologic knowledge, which allowed deep boreholes to be drilled relatively quickly and extract large volumes. Groundwater became a key natural resource supporting human well-being and economic development—but one that continued to be widely misunderstood, under-valued, poorly managed and inadequately protected (Burke and Moench 2000).

Comprehensive statistics on groundwater pumping are not available, but global withdrawals are estimated to have reached 900 km^3/annum in 2010, providing some 36% of potable water-supply, 42% of water for irrigated agriculture and 24% of direct industrial water-supply (Dőll et al. 2012). The highest withdrawal intensity currently occurs over large areas of India, China, Pakistan, Bangladesh and Iran, and more patchily in North America, Southern Europe, North Africa and the Middle East. The social value of groundwater should not be gauged solely by volumetric withdrawals, since its use often brings major economic benefits per unit volume, because of local availability, scaling to demand, high drought reliability and generally good quality (requiring minimal treatment). The dependence of innumerable urban areas on groundwater is intensifying (for example, it provides the public water-supply for 310 and 105 million people respectively in the EU and US), and the contribution of groundwater to irrigated agriculture is high in terms of crop yield and economic productivity (Llamas and Martinez-Santos 2005).

3.3.1.2 Importance of Hydrogeological Understanding

Groundwater systems constitute the predominant reservoir and strategic reserve of freshwater on our planet, but calculating their huge volume is not straightforward. Indeed, the precision of any calculation will inevitably be open to question, since major assumptions about the effective depth and porosity of the freshwater zone will be involved. If only relatively shallow groundwater in ‘active circulation’ is considered (some 5–8 million km^3) then groundwater would amount to 95–97% of total freshwater stocks (UNEP 1996), with only 2–3% being held in lakes, reservoirs, rivers and swamps, and with soil-moisture storage representing about another 1%.

Groundwater normally moves very slowly through the myriad of pores and/or fractures in aquifer systems, from areas of recharge to areas of discharge (determined by the geologic structure). If not intercepted by waterwell pumping, tens, hundreds or thousands of years can elapse until eventual discharge to a spring, river, wetland or the coast (Fig. 3.7). Understanding groundwater also requires knowledge of the near-surface (unsaturated) ‘soil-moisture regime’, which plays an important role in the hydrologic cycle.

The characterization of groundwater systems requires an interdisciplinary approach, and must integrate geology, hydrology, physics, chemistry and biology. Being the study

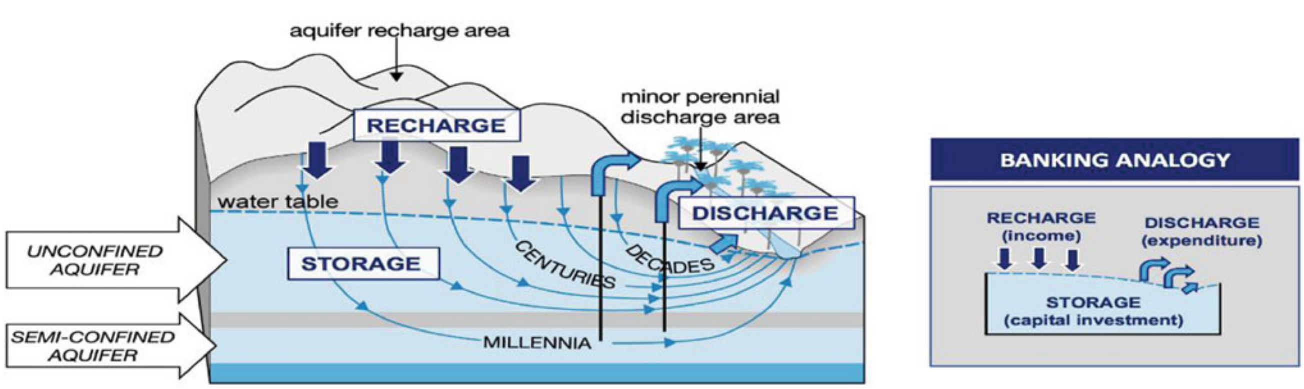


Fig. 3.7 Typical groundwater flow regime with the ‘banking analogy’ for aquifer storage

of geological environments that control groundwater occurrence, the physical laws that describe groundwater flow and the (bio)chemical processes occurring during this flow determine groundwater quality. It is also essential to assess the influence of mankind on the natural groundwater regime and the influence of the natural groundwater regime on mankind. Groundwater science therefore has to incorporate consideration of the socioeconomic dimensions and embrace facets of engineering and ecology.

3.3.2 Groundwater Systems: Some Essential Concepts

3.3.2.1 Nature of Groundwater Storage and Flow

All aquifers have two fundamental characteristics: a capacity for 'groundwater storage' and a capacity for 'groundwater flow'—but different formations vary considerably in their properties, for example:

- unconsolidated deposits—such as sand and gravel, with porosities storing water in as much as 30–35% of their total volume and permitting significant groundwater flow
- consolidated rocks—such as some limestones storing water only in micro-fractures rarely occupying more than 1% of rock volume, but limestones can enlarge markedly by dissolution forming so-called 'karst systems' which transmit groundwater very rapidly.

The vast storage of many groundwater systems is their most distinctive characteristic, but can result in the false impression that 'groundwater resources are inexhaustible' (Foster et al. 2013). Whilst this storage provides an effective 'natural buffer' against climatic variability, contemporary recharge is finite and controls the long-term physical sustainability of groundwater resources (Fig. 3.7).

Groundwater bodies are naturally recharged by rainwater and snow-melt where they infiltrate through the soil zone and drain by gravity to the water-table. It usually takes various years for infiltrating water to reach the water-table. Assessing the relationship of surface water to underlying aquifers is important, and it is essential to distinguish between:

- streams and lakes on which an aquifer is dependent for significant recharge
- rivers that in turn depend significantly on aquifer discharge to sustain their dry-weather flow.

Slow flow rates and long residence times, consequent upon large aquifer storage, are another distinctive feature of groundwater systems, and they naturally transform highly variable recharge regimes into more stable discharge regimes. Groundwater flow regimes are shaped by geologic structure—with some formations of low permeability ('aquicludes') virtually blocking all groundwater flow and others ('aquitards') only allowing limited movement.

3.3.2.2 Evaluation of Groundwater Recharge and Balance

The evaluation of contemporary recharge rates to aquifers is of fundamental significance when considering the sustainability of groundwater resources. With increasing aridity, direct rainfall recharge generally becomes progressively less significant than indirect recharge from surface runoff and incidental artificial recharge from human activity. However, there is often substantial scientific uncertainty in quantifying individual recharge components due to the inherent geo-complexity of natural systems, and the wide spatial and temporal variability of rainfall and runoff events (Scanlon et al. 2002). Figure 2.9 in Sect. 2.2.3 shows the long term average groundwater recharge worldwide.

Understanding the intimate linkage between land-use and aquifer recharge is an essential basis for integrated water resources management (Foster and Cherlet 2014). The common paradigm of 'constant average groundwater recharge rates' is false and leads to serious 'double resource accounting', especially in more arid regions. Recharge rates vary considerably with:

- changes in land use and vegetation cover—notably the introduction of irrigated agriculture, but also vegetation clearance and soil compaction
- urbanisation processes—in particular the level of water-mains leakage, proportion of unsewered sanitation and degree of land-surface impermeabilisation
- widespread water-table lowering by groundwater abstraction and/or land drainage—leading to increased areas and/or rates of infiltration in some aquifer systems
- changes in surface water regime—especially diversion or canalization of river flow.

All waterwell pumping results in a decline in water-table over a certain area. Some decline may be desirable, since it improves land drainage and maximizes groundwater recharge by providing additional storage space for excess wet-season rainfall. But all groundwater flow is discharging somewhere, and extraction from waterwells reduces these discharges. Any attempt at defining some form of 'acceptable aquifer yield' must thus make value judgements about the importance of maintaining (at least a proportion of) 'natural beneficial discharges' from the aquifer system, and also clearly distinguish consumptive use and catchment export of extracted groundwater from non-consumptive uses which generate return water.

Past episodes of natural climate-change have transformed some large land areas (which formerly had much wetter climates) into deserts, and virtually eliminated all contemporary groundwater recharge, although some discharge to oases is often still occurring. Groundwater reserves which are not being actively recharged are known as 'fossil groundwater'. These reserves can be, and are being, tapped by waterwells but once pumped out may never be replenished—they are thus termed 'non-renewable groundwater resources' and as such merit special governance provisions (Foster and Loucks 2006). The large non-renewable groundwater resources of some major aquifers can provide very reliable sources of water-supply, which are completely resilient to current climate variability. However, in the end their use will be time-dependent and as such deserves careful consideration in terms of efficient utilization, ecological impacts and inter-generational equity. It should always be considered a strategic development subject to special investigation, monitoring and management.

3.3.2.3 Consequences of Excessive Aquifer Exploitation

Prior to large-scale anthropogenic activity (mainly pre-1950 but in some places 1920) human capability to abstract groundwater was tiny in comparison to available resources, and most groundwater bodies (outside hyper-arid regions) were in physical equilibrium. In subsequent years rapid (and often uncontrolled) expansion in groundwater exploitation generated major socioeconomic benefits, but encountered some significant problems. In many locations, abstraction rates are now not physically sustainable in the long-term (Foster et al. 2013).

While it is accepted that over-drafting aquifer storage can be a legitimate strategy during social transformation to a less water-dependent economy, large overdrafts can have various consequences whose implications must be weighed against the socio-economic benefits of resource development. These include waterwell yield reductions and/or increased pumping costs; degradation of groundwater-dependent ecosystems; saline water intrusion or up-coning; and in certain settings land subsidence causing extensive and expensive damage to urban infrastructure and increased flood risk.

There are numerous examples of major aquifer depletion from groundwater use for agricultural irrigation with water-table lowering over extensive areas. Cumulative resource depletion from 1900 to 2008 (but mainly since 1950) has been estimated to be at least 4,500 km3 (mainly in India, USA, Saudi Arabia and China) (Konikow 2011), although estimates are subject to uncertainty over the average specific yield of strata dewatered. More localised depletion occurs around some major urban conurbations, especially where the main aquifer is semi-confined. Aquifer depletion contributes indirectly to sea-level rise by creating a water transfer from long-term terrestrial storage to active surface circulation with net water transfer to the oceans. A volume-based assessment for depletion during 2000–08 gave a minimum estimate of 106 km^3/a, equivalent to 0.3 mm/a (or 18% of current sea-level rise).

3.3.2.4 Processes of Groundwater Quality Degradation

Groundwater, for the most part, is naturally of excellent microbiological and chemical quality. The underlying reasons for this are:

- capacity of subsoil profiles to filter-out faecal micro-organisms pathogens, and all suspended solids and organic matter, from percolating recharge
- long sub-surface residence time (decades to millennia) compared to the environmental survival of pathogens (usually <50 days and rarely >300 days)
- relatively low solubility and non-toxic nature of the matrix of most aquifers.

There are, however, some important exceptions to this since some aquifers exhibit both natural groundwater contamination with trace elements that create a health hazard (arsenic and fluoride) or nuisance (dissolved iron and/or manganese) and elevated vulnerability to pollution from the land surface due to their thin vadose zone and/or the presence of highly-preferential pathways to the water-table. Moreover, all aquifers are vulnerable to pollutants that are resistant to subsurface adsorption and/or biodegradation such as nitrate, salinity and numerous man-made organic chemicals. Sustainable development is thus not only constrained by resource availability, but also by quality deterioration.

Globally, significant non-coastal areas are suffering serious groundwater salinization (Foster et al. 2013, 2018) as a result of various processes (Fig. 3.8) including principally:

- fractionation of salinity into irrigation water returns to groundwater—especially in situations where groundwater is main source of irrigation-water
- natural salinity being mobilized from the landscape—consequent upon natural vegetation clearing for farming development with increased rates of groundwater recharge
- excess infiltration causing rising groundwater tables—usually associated with inefficient irrigation using imported surface water in areas of inadequate natural drainage

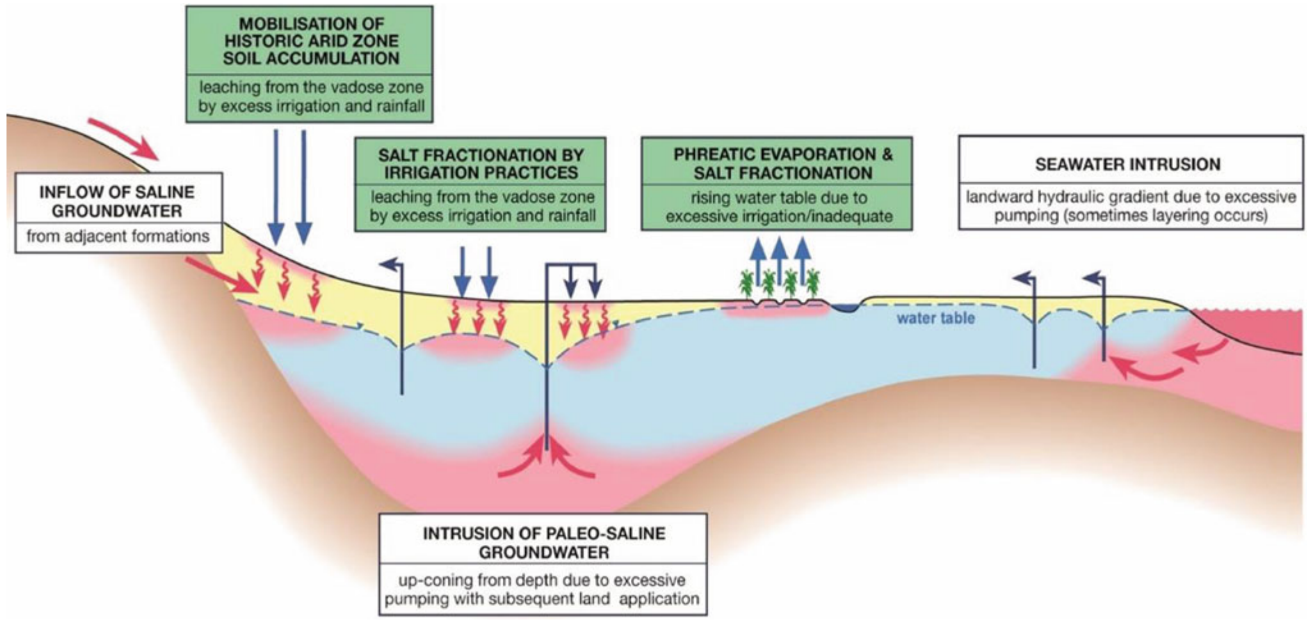


Fig. 3.8 Schematic representation of salinization of groundwater recharge by irrigated agriculture and other mechanisms (modified after Foster et al. 2018)

- excessive disturbance of natural groundwater salinity stratification—through uncontrolled waterwell construction and pumping.

The above mechanisms are in addition the intrusion of saline water in coastal aquifers due to excessive groundwater abstraction. Groundwater salinization is very costly to remediate and often quasi-irreversible, since the saline water which invades macropores and fissures diffuses rapidly into the matrix of porous aquifers, and then can take decades to be flushed out even after flow of freshwater has been re-established.

An important characteristic of porous media is their natural potential for contaminant attenuation. Since not all subsurface profiles are equally effective in this regard, the (albeit simplified) concept of aquifer pollution vulnerability is useful (Foster et al. 2006)—with vulnerability being expressed as a function of the intrinsic properties of the unsaturated (vadose) zone (or confining beds) separating the aquifer from the land surface. An important factor, especially in consolidated strata, is the possibility of downward contaminant transport via preferential pathways, which will greatly increase aquifer vulnerability to pollutants that would otherwise be retarded by adsorption and/or eliminated by biodegradation.

The location and evaluation of pollution incidents, and pollution prevention, monitoring and remediation, are all much more challenging for groundwater than for surface water. Pollution from human activity, especially agriculture at the land surface has been increasingly reported since the 1970s in industrialized countries, and from somewhat more recently in industrializing and developing nations, due to absence of proactive aquifer protection policies. Many more pollution incidents are likely to be occurring unreported (because of inadequate groundwater monitoring) and incidents that occurred decades ago may still be threatening groundwater quality, with the legacy being detectable around industrially-contaminated land.

Spectacular groundwater pollution incidents with large plumes can be associated with industrial point sources from major spillage or casual discharge in vulnerable areas, but much more insidious and widespread problems arise:

- if urban sanitation is achieved by on-site arrangements—leading to major increases in recharge rates but deterioration of recharge quality (nitrate, organic carbon and possibly of toxic synthetic compounds)
- where mains sewerage delivers minimally-treated wastewater used for flood irrigation of agricultural crops—incidentally resulting in the augmentation and contamination of local groundwater
- if small-scale industries (notably textile manufacture, leather processing, garment cleaning and vehicle maintenance) dispose of liquid effluents (including spent oils and solvents) to the ground
- from intensification of irrigated and rainfed agricultural cultivation sustained by ever-increasing quantities of inorganic fertilizers and a wide spectrum of synthetic

pesticides—with close correlation of high nitrate in shallow groundwater being widely reported, together with soluble and mobile pesticides whose degradability decreases markedly once leached below the soil zone.

Whilst groundwater is much less vulnerable to anthropogenic pollution than surface water, once polluted aquifers are very difficult to clean-up given their inaccessibility, the large volume of groundwater usually involved and the very slow rates of diffusion of contaminants out of the finest pores and fractures.

3.3.2.5 Approaches to Groundwater Pollution Protection

Groundwater pollution is usually insidious and invariably expensive. Insidious because it often takes many years to become fully apparent in waterwell abstraction, by which time it will normally be too late to have prevented serious contamination. Expensive because of the high cost of providing an alternative water-supply and of remediating polluted aquifers. Indeed, restoration to drinking-water quality standards is often impractical.

The 'polluter-pays-principle' should thus be interpreted to require all potential point-source polluters to pay for adequate groundwater protection, and the 'precautionary principle' applied to pollution control. In the case of groundwater this approach is essential because determining who is to blame for actual pollution is made difficult by both the hydraulic complexity and the large time-lag in pollutant transport (even in some cases just to reach the water-table).

Since groundwater is a very important source of water-supply for public use, sensitive industrial production, terrestrial ecosystems and river baseflow, it is essential that its quality be protected for present and future use. This requires mapping of high pollution vulnerability and drinking-water source protection zones, with application of appropriate controls on hazardous activities corresponding to each zone so as to reduce the risk of major groundwater pollution (Foster et al. 2006). More targeted groundwater monitoring is required in most countries to establish quality status reliably, and identify trends in any quality degradation, as an iterative feedback to proactive aquifer protection.

3.3.3 Linkages to Social and Environmental Sustainability

3.3.3.1 Food Security and Groundwater

Groundwater proved to be a critical input for enabling food production to increase by 250% during the 'Asian green revolution' (1970–2000). This witnessed a remarkable investment in private waterwell construction for agricultural irrigation, because groundwater is more reliable than surface water, and guarantees higher crop yields and economic returns to farmers. Current withdrawal rates for irrigated agriculture in more arid areas, however, are not physically sustainable, and are resulting in long-term depletion of aquifer reserves. Elsewhere, widespread waterlogging and salinization of shallow groundwater is an insidious menace resulting from inadequate surface-water irrigation management. The implication of both of these threats is that at least 15% (and perhaps more) of current global food production may not be sustainable (IAH 2015a).

Agricultural land-use practices also exert a major influence on aquifer recharge rates and quality, although the impact varies with hydrogeological setting (especially water-table depth) and whether groundwater or surface water is the irrigation water-supply. Changing from flood irrigation to precision drip or sprinkler technology can reduce the volume of water applied to a specific crop and thus energy use for pumping—but this (so-called) 'efficient irrigation' is not usually a significant 'water-resource saving measure', and its introduction often has negative consequences for groundwater (Foster and Perry 2010). Intensification of agricultural cropping also widely leads to groundwater resource depletion and diffuse pollution of groundwater by plant nutrients, salinity and some pesticides—and improved land management measures need to be promoted so as to provide farmers with incentives to enhance groundwater recharge and reduce agrochemical leaching (Foster and Custodio 2019).

3.3.3.2 Urbanization and Groundwater

Groundwater is a major source of urban supply worldwide, and aquifer storage represents a key resource for water-supply security under extended drought and climate change scenarios. To achieve this, groundwater must be managed more effectively through promoting as 'best engineering practice' (IAH 2015b):

- establishment of more water-utility wellfields outside cities, with their 'capture areas' as drinking-water protection zones
- more widespread use of groundwater and surface-water resources conjunctively
- adoption of 'adaptive management strategies' recognising that aquifers are in continuous evolution, with some uncertainty over their precise behaviour.

Private waterwell construction for in-situ self-supply has 'mushroomed' in many developing cities as a 'coping strategy' during periods of inadequate utility water-service, and continues for years after as a 'cost-reduction strategy'. These unregulated private wells often draw water from shallow aquifers which have already been polluted by local urban or industrial waste disposal. Broad groundwater quantity, quality and economic assessments of current and likely private waterwell use need to be undertaken to allow the public administration to formulate balanced urban water policy (Foster and Hirata 2011).

In-situ sanitation practices and wastewater handling/re-use from mains sewerage provide a component of urban groundwater recharge but simultaneously pose a serious threat of shallow groundwater pollution (including pathogenic micro-organisms, ammonium or nitrates, toxic community chemicals and pharmaceutical residues) (Fig. 3.9). The pollution risk varies widely with the local hydrogeological setting, density of population served, design of in-situ sanitation units or the level of wastewater treatment, and location/mode of wastewater reuse. Thus it is critical that groundwater vulnerability and dependence are taken into consideration in the planning and implementation of sanitation investments however—the governance and operational arrangements for this to occur are still widely lacking.

3.3.3.3 Human Health and Groundwater

The naturally excellent quality of most groundwater bodies has long been a vital factor for human health. A prerequisite for preserving this quality is that potable groundwater sources must be carefully sealed to prevent direct entry of pollutants, such as pathogenic organisms and hydrocarbon fuels or lubricants, from the land surface. All waterwells and springs used as drinking-water sources require quality surveillance in relation to perceived pollution risks—and if used untreated those at serious risk (or already impacted) should be clearly marked as suitable only for non-potable uses. Aquifers exploited for drinking-water supplies should be subject to systematic assessment of both actual polluting processes and potential pollution vulnerability from pathogenic microorganisms (which present an acute health risk) or chemical pollutants (which constitute a chronic health risk) (IAH 2016c). These risks can then be managed by designating land protection zones of appropriate dimensions to the local hydrogeological conditions in which potentially-polluting activities can carefully vigilated and controlled.

The most widely-distributed threat to potable groundwater quality comes from land-cultivation for intensive agriculture, which employs heavy applications of nutrients and pesticides that can be leached from soils to the underlying aquifers. Some synthetic organic chemicals of widespread industrial and community use (including the so-called 'emerging contaminants' with endocrine-disrupting or carcinogenic implications) are resistant to degradation in the subsurface and constitute a long-term health hazard. However, currently the most serious groundwater contamination hazard and health threat at a global scale comes from excessive arsenic and fluoride concentrations, which arise naturally through sediment or rock dissolution under certain hydrochemical conditions (IAH 2016c).

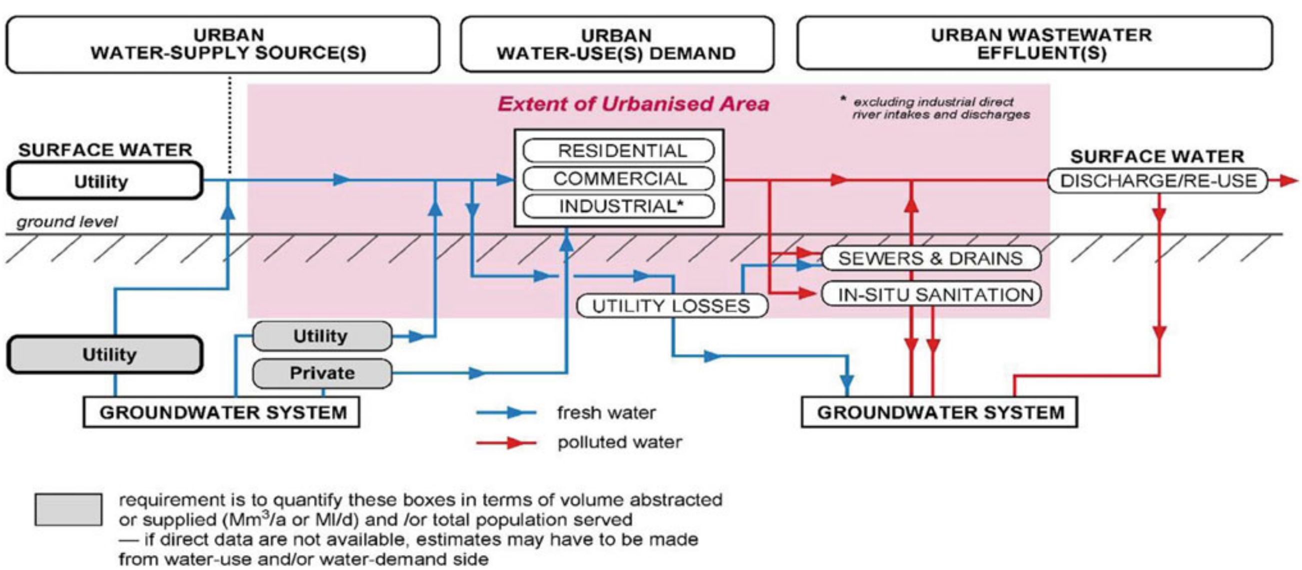


Fig. 3.9 Schematic representation of urban groundwater processes in cities underlain by unconfined aquifers (modified after Foster and Hirata 2011)

3.3.3.4 Ecosystem Conservation and Groundwater

Groundwater-dependent ecosystems (GDEs) comprise a complex subset of ecosystems of major significance in the conservation of biodiversity (Fig. 3.10), including many vital sites covered by the RAMSAR Convention (IAH 2016b). Such ecosystems are usually characterized by phreatophytic plants which derive most of their water needs from saturated soils, and long-term groundwater depletion will eliminate these species and their ecosystem function. GDEs also have direct value for the human population from fish and plant production, water storage and purification, and indirect value in terms of landscape and habitat. There is a pressing need to identify GDEs according to type (aquatic, terrestrial or subterranean) and improve understanding of their relationship with underlying groundwater.

Degradation of GDEs can occur because of anthropogenic modifications to aquifer flow regimes and salinization or pollution of their groundwater. Potentially negative ecological impacts, with the extermination of key species, can arise from uncontrolled groundwater withdrawals for irrigated agriculture or urban water-supply and/or modest increases in groundwater salinity and/or pollution (with nutrients and pesticides). Social awareness of the importance of groundwater for sustaining viable ecosystems must be promoted to mobilize appropriate stakeholders for GDEs such as conservation NGOs and local land authorities. GDEs can be conserved by integrating their protection into basin and aquifer scale water-resource planning and management, or at least acting selectively to incorporate GDE protection zones into overall groundwater resource use and land-use control policy (IAH 2016b).

3.3.3.5 Extractive Industries and Groundwater

On-shore hydrocarbon exploitation requires full hydrogeological risk assessment, appropriate environmental regulation, diligent operational control and secure management of subsurface waste injection. In non-renewable hydrocarbon development the principal concern is to prevent shallow aquifer pollution with formation brines, hydrocarbon compounds, fracking fluids and 'stray gas', and much improved hydrogeological monitoring of such activities is needed (IAH 2015c). Applied hydrogeological science is also required for:

- development of hydrogeothermal energy (particularly of 'very low enthalpy' for space cooling or heating), with long-term monitoring and modelling of groundwater system response being required to assess sustainability and improve design
- the nuclear power sub-sector in power station siting and radioactive waste disposal, so as to build political and public confidence in selection of safe geological repositories for radioactive waste.

Mining enterprises also present a significant risk of perturbing groundwater flow and polluting groundwater quality (IAH 2018), and in particular:

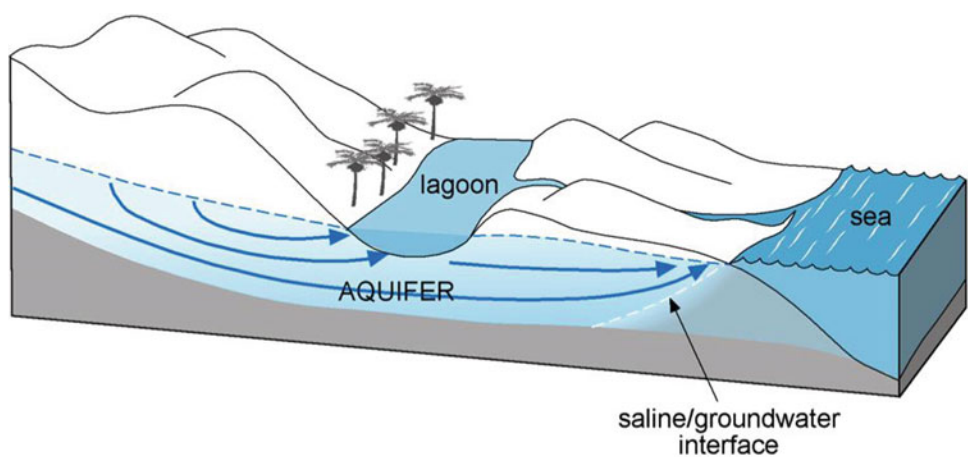


Fig. 3.10 Coastal freshwater lagoons—an example of a widespread groundwater-dependent ecosystem

- open-cast extraction of sand-and-gravel or coal/lignite usually produces a significant disturbance of the local groundwater regime and can be a groundwater quality hazard
- deeper mining activities (for coal, metals, salt/potash, precious minerals, etc.) often involve pumping large groundwater volumes for drainage, modifying the flow and quality regime, and on abandonment with water-table rebound can lead to the discharge of highly-acidic and polluted groundwater.

Cross-sector regulation planning of such activities is required to facilitate harmonization, with long-term provision for environmental management throughout the entire mining 'life-cycle' (for the mining and water nexus, see Chap. 21).

3.3.3.6 Geotechnical Hazards and Groundwater

Groundwater plays an important role in various geotechnical processes—constituting a serious geotechnical hazard whose presence reduces the engineering strength and slope stability of many soils. Of particular concern here are the potential impacts of either falling or rising water-table as a result of changes in groundwater resource extraction (or other processes).

- falling water-table—which can lead to significant land subsidence (consequent upon dewatering and settlement of aquitards) and result in serious damage to urban infrastructure (such as building foundations, sewer lines, tunnels, etc.) with increased flood risk
- rising water-table (or water-table rebound)—which can lead to inundation of subsurface structures (such as basements, car parks and subways) and structural damage of 'watertight subsurface structures' due to uplift.

Some construction activities can also perturb groundwater systems and create a potential groundwater quality hazard including the emplacement of buried fuel tanks and pipelines, underground railways and roads, car parks and deep basements.

3.3.4 Global Change and Groundwater

3.3.4.1 The Need for Adaptive Management

Groundwater management to confront situations of excessive and unstable resource exploitation will require demand-side management interventions (such as restricting waterwell use at certain times, reducing consumptive use by irrigation or industry) and in-situ supply-side engineering measures (such as rainwater harvesting, management or aquifer recharge enhancement). It is important to stress that constraining demand for groundwater abstraction will normally be essential to achieve groundwater balance, irrespective of what local supply augmentation measures can be economically undertaken.

The large natural storage of aquifer systems means that they play a vital environmental role in 'buffering' rainfall variability—receiving recharge seasonally (or only in years of exceptional rainfall in arid terrains) but generating a more uniform water discharge back into the surface environment and thus, even during drought, maintaining the baseflow of lowland streams and sustaining many aquatic ecosystems. In low-flow periods the groundwater contribution to river flow widely rises to 90% or more. The natural resilience of groundwater systems to drought is also of major significance (IAH 2016a) for securing drought-reliable low-cost water-supplies for the human population generally and providing a reliable water source for agricultural irrigation during periods of more extended drought (particularly valuable in assuring yields of high-value crops). These functions will be critical in adapting to climate change.

In view of the uncertainties associated with both climate change and groundwater system behavior, adaptive management is needed. It will be necessary to maintain a reasonable balance between the costs and benefits of interventions, and thus take account of the susceptibility of the system in question to degradation and the legitimate interests of water users. And where groundwater quality is concerned, preventive management approaches will be far more cost-effective than purely reactive ones.

3.3.4.2 Impact of Global Warming

Climate change (with increasing ambient temperature, variation of rainfall rate and intensity, modifying the vegetation cover and its evapotranspiration) will eventually impact groundwater resources (Taylor et al. 2012). Graphic evidence of this exists in the paleo-hydrological record of aquifers containing groundwater at depth which is up to 20,000 years old, and which originated as recharge in past wetter and colder millennia. However, given the large volume of many aquifer systems, only marked climatic change will have measurable influence on groundwater resources overall. Global warming is likely at many latitudes associated with an increasing incidence of high-intensity rainfall episodes, it is also likely to result in increased preferential flow through the vadose zone and thus increased leaching of agrochemicals. It may also result in peak water-table levels higher than previous maxima and cause 'groundwater flooding'.

3.3.4.3 Impact of Land-Use Change

In contrast, major land-use change is capable of exerting a marked impact on both the amount of recharge and quality of groundwater within decades. Most groundwater originates as excess rainfall infiltrating the land surface. Thus land-use has a major influence on both groundwater quality and recharge. Every land-use practice has a 'water resource footprint', and may result in diffuse groundwater pollution. Similarly, land-use practices will influence groundwater recharge rates considerably, especially under more arid conditions.

Some of the more significant changes for underlying groundwater include clearing natural vegetation, converting pasture to arable land, extending irrigated agriculture, intensifying dryland and irrigated agriculture, introducing biofuel cropping, and reforestation and afforestation with commercial woodland (Foster and Cherlet 2014), but extending irrigated agriculture using surface-water has the greatest impact—significantly increasing groundwater recharge but degrading its quality.

Globally there is a need to increase production of staple grains (such as maize, rice, and wheat), whose yields are generally only 30–50% of those in 'more advanced' agriculture, but concerns are growing about its impact on groundwater recharge due to increasing consumptive water-use, and excessive nutrient and/or pesticide leaching. For the intensification of vegetable and fruit cultivation, farmers tend to use 'precision irrigation' (such as pressurised drip and micro-sprinkler systems), which markedly decreases recharge rates. In some senses the large-scale introduction of solar panels is a welcome development, since it reduces land-use pressure on groundwater, but the energy generated is required to be incorporated into the 'national or local grid' and not used directly for powering waterwell pumps.

3.4 The Main Challenges of Water Resources Management in the 21st Century

3.4.1 Drivers and Constraints

There are good reasons to debate what are the major, globally relevant issues which bear upon how the water resources of the world should be used and safeguarded. With this utilitarian concept, but also through the necessary stewardship, water has been put in a direct human- resource context. This context is shaped by drivers. Drivers can be interpreted as events, development processes or the likes emanating predominantly from within societal realms. They are taking place irrespective of the human-resource context and its potential limitations. Drivers can also be associated with aspirations of society. Availability and quality of the resource constrain the feasible decision space for solutions accommodating the respective achievement levels of the drivers. No doubt that once certain levels are reached, drivers may directly redefine constraints. Achievement on one account can limit the feasible space for other drivers.

Drivers thus may exert pressures on resources. As long as the respective service provision expected to be provided by a certain resource can continue virtually indefinitely, pressures may not impair the resource base. However, extreme pressure levels, or the combination of various pressures may accumulate and can become stressors. Stressed water resources systems may gradually, or even precipitously lose their sustainable service function. (For more detail see Sect. 11.2).

Drivers and constraints are thus directly associated with human demands and aspirations, but can also be the consequence of malfunctions of society. These may be explicitly formulated by societal actors, or emerge indirectly and sometimes unnoticed as the consequence of societal activities, human behavior and their change and interactions with other natural or/and socioeconomic processes.

3.4.1.1 The "Immediate" Drivers: Population Dynamics, Poverty and Pollution

The most direct drivers and constraints in the context of human society and water resources are associated with the three "P"s: Population dynamics, Poverty and Pollution.

Population dynamics encompasses more than population growth. While the rapid increase of population, especially in water scarce regions represents by far the biggest challenge to cope with (see Sect. 2.2.4), the decrease of population can also imply water management problems, for example in form of underutilized (and underfunded) water infrastructure in economically shrinking areas.

Population dynamics includes also vertical (upward) mobility, the increase of the standard of living with its consequences manifested in increasing demands, consumption and resource use. However, vertical mobility can also refer to downward movement of impoverishment and other forms of decline.

Finally, population dynamics accounts also for "horizontal mobility", displacement (forced or voluntary), including the exodus from rural livelihoods towards urbanized areas and different forms of temporary or permanent (including trans-border) migration.

The most momentous manifestation of population dynamics is the ongoing rural migration towards urbanized settlements. Already more than half of humanity lives in urban areas and this percentage is expected to grow rapidly. By 2050 the world population is projected to reach about ten billion people with nearly seventy per cent of the population living in cities (UN DESA 2017 and 2018 resp.). Most of these people will be born in developing countries where drinking water and adequate sanitation are still to be provided. Burgeoning cities also present challenges because of their demand for water and pollution of rivers, lakes and aquifers. Losses from municipal water supply systems and seepage from sewers can reach alarming proportions as maintenance is often neglected (Sewilam and Rudolph 2011). The rapid, and to a large extent disorganized, influx of rural population creates an enormous stress on water in the recipient urban spaces. The existing urban water infrastructures are usually insufficient to provide adequate service for the newly arrived people and rehabilitation and/or extension may not be able to keep the pace with the population increase.

The more and more concentrated demand centers and consequently pollution sources are challenges, but also an opportunity to tackle the problems "at the source" with appropriate and efficient technological and "soft" solutions. In spite of these challenges, cities provide also opportunities for improvements in water supply and sanitation because concentrations of people and wealth in cities can enable the deployment of efficient technical solutions that are unaffordable or/and infeasible in rural areas. The other side of the coin is the relative depopulation of rural areas. Labor shortage could precipitate in declining maintenance of rural water infrastructure (wells, irrigation and drainage canals etc.). However, like urban challenges, the rural ones could also be regarded as opportunities for ecologically sound rehabilitation and redefinition of water resources management in rural contexts.

The threefold increase of the global population during the twentieth century has coincided with a six-fold increase in water use (FAO 2009). Widespread water pollution has made good-quality freshwater scarce. Human health and biodiversity are among the first affected (Vörösmarty et al. 2010). The magnitudes of environmental transformations, including climate change, are signs of unsustainable socioeconomic activities at global scale. Number and intensity of these transformations raise the question, well beyond the strict realm of water management alone, how the planet will be able to accommodate the achievement of the (sometimes contradicting) goals summarized in the Sustainable Development Goals (SDGs) (United Nations 2015). As the consequence of the population dynamics, by 2050 an additional two to three billion people will increase the number of inhabitants of the world to around ten billion (UN DESA 2017). All SDGs, irrespective of their time horizon till 2030, should consider the additional needs and impacts of the burdening population.

Water resources management of areas with large human population concentration is a special challenge. Many urban agglomerations, even megacities are located in explicitly water scarce areas. Providing water services to these urban centers implies water transfers from remote, and frequently multiple sources. Coastal settlements, mainly in developing countries are among the fastest growing urban spaces.

Population dynamics ultimately also includes large scale (international) migration. Permanent, but even temporary displacement of people creates new demand (and pollution) centers in virtually unexpected places. Migration can also be triggered by water-related disasters and consequences of both land degradation and climate change.

Poverty is frequently the underlying driver of many manifestations of population dynamics (different migratory responses). But poverty can also be defined as an unwanted consequence of population dynamics. However, it is also a fairly static state, frequently called the "poverty trap". Poverty hampers pro-active participation in efficient use of water resources, but also in resource protection.

Even without poverty-triggered displacement extreme economic stratification within societies poses a major hindrance to meet water related humanitarian and political objectives, like the Millennium Development Goal 7 Target 7c, or the Sustainable Development Goal No. 6 targets 6.1 and 6.2.

Sustainable water provision and resource management cannot take place without overcoming poverty and many facets of poverty cannot be eliminated without sustainable provision of safe water supply and sanitation services. Additionally, fighting other attributes of poverty like hunger, malnutrition, lack of energy access and decent housing all have implications for water demand and water pollution. Breaking through this vicious cycle is the paramount pre-requisite of sustainable water resources management.

Pollution is a widespread phenomenon as far as water is concerned. Increasing resource use, lack of resource protection and meager investment in waste water collection and treatment technologies are the sad consequences of unregulated population dynamics, but also that of political short-sightedness and carelessness. In this respect providing water supply without simultaneous solutions for wastewater disposal and treatment is unfortunately an often repeated bad example. As the consequence roughly twice as many people have no access to adequate sanitation than to safe water supply. This uneven situation threatens to undermine the sustainability of achievements in the field of improved and safe water supply. As of 2017 an estimated 80% of all wastewater of the world is discharged without treatment into recipient water bodies. The municipal wastewater problems are becoming increasingly vicious. Population growth and mushrooming urban agglomerations, especially the so called informal settlements, are causes for fundamental concerns. They are exacerbated even by otherwise positive trends like improving health care provision and higher standard of living for an increasing number of people. These lead to increasing wastewater volume, but also to substances in it (pharmaceutical and cosmetic residues, nanoscale pollutants etc.) which may not be removed by traditional state-of-the-art wastewater treatment technologies. Increasing number of people and consumer behavior drives industrial production (and automatically pollution) as well as more food production with corresponding pesticide and fertilizer use (and respective residues in receiving water bodies). Increasing water use may indicate the achievement of societal aspirations for better service provisions and increased human well-being. However, these developments will not prove being sustainable if the resource pollution will not be controlled swiftly and effectively, preferably at the source of pollution.

Due to humanitarian but also socioeconomic imperatives associated with the main driver, the increasing world population both agricultural and industrial activities are expected to increase (Vörösmarty et al. 2000). Economic development—without adequate water treatment or/and recycling—inevitably perpetuating pollution that endangers ecosystem and human health (Vörösmarty et al. 2010). Residues of hundreds of pharmaceutical and cosmetic products enter fresh water bodies through municipal sewage. Even if treated, these substances are slipping through state-of-the-art biotechnological treatment plants unabated. Their long-term environmental consequences are still not understood well (Howard et al. 2006; Frimmel and Müller 2006).

Population dynamics, poverty alleviation and pollution elimination and control are powerful drivers. However, without addressing them head on, they can turn into imminent stressors of the socioecological systems in our planet, of which water is a crucial component. No doubt that these drivers affect much more aspects and human resource contexts than water alone. However, their manifold effects can propagate through different socioecological pathways and causing additional, indirect impacts on water.

3.4.1.2 "Slow" Drivers: Climate Change and Land Use/Land Cover Change

Successes in addressing the immediate ("P") drivers, but also tragedies and exigencies related to these unfold literally "on line". The three "P" drivers are potent stressors affecting water resources in many parts of the world and ultimately can impact the complex global socioecological system. Irrespective of this perspective, climate change is certainly more present both in the political and in the natural science dominated discourses than any of the above outlined challenges. Climate change can already be seen as a stressor of its own. However, its potential implications as far as the hydrological cycle is concerned are well pronounced even if uncertain in their magnitude and occurrence. Shifting hydrological regime (more and stronger floods and droughts, see Sect. 3.2.5) is considered indicating a more unstable world in the future. Global warming may imperil agricultural production levels, thus the need for more water storage and irrigation-supported agriculture can be expected. Climate change can trigger further migratory waves. Thus taking into account of the climate change related consequences is wise. It follows the precautionary principle.

However, at least at present, climate change is rather an "add on" amplifier factor for the challenges contemporary water resources management is facing. Climate change, but also the less discussed land use/land cover change are eminently associated with population dynamics and inherent pursuance of societal aspirations "at the lowest price", thus without using environmental friendly technologies, remedial actions as piece and parcel of comprehensive and sustainable development. Exploitation of environmental resources and disregard of the consequences, should they remain unaddressed, would further aggravate the seriousness of the very pressing, immediate triple "P" challenges.

These are not only very much contemporary challenges, but also latent problems inherited from the twentieth century. They are manifestations of the 'business as usual' attitude. Even in the most developed countries where environmental rehabilitation started a few decades ago the old "impair first and then repair" mentality as the resource development paradigm can still be traced (Vörösmarty et al. 2010).

This concern is more than justified as far as SDG 6, the dedicated water goal and its targets, the products of intergovernmental agreement (see Box 3.5), are concerned. Water is irreplaceable and non-substitutable. Where and when it is in short supply (droughts) or in excess (floods), it is a major source of risk, strife and insecurity. Even where water is in abundant supply, its quality may compromise its use by humans and its ability to sustain aquatic biodiversity. Water is a universal solvent and, hence, is a vector of compounds and transport medium, a climate regulator, a carrier of energy, and cooling and heating agent.

By token of its occurrence phase in the terrestrial compartment of water cycle as a fluid, and hence gravity driven downwards flowing resource, water bodies, including groundwater aquifers usually occupy the lowest parts of a landscape. Therefore, they accumulate naturally all substances being released from whatever socioeconomic activities or/and natural processes take place in the respective landscape and carried by free flowing streams or by seepage towards these recipient sinks. This is evident from the presence of high concentration of nutrients, agrichemicals, industrial wastes and persistent organic pollutants in many water bodies, high nitrate levels in subsurface waters, heavy metals in river and lake sediments, and algal blooms and depleted oxygen that lead to fish death.

Along this voyage from source to sink river deltas are of particular importance. They are the transitional zones between the freshwater and saline water (marine) compartments of the water cycle. As such they are both coveted economic spaces and valuable ecosystems. They are being threatened by human activities, especially by storage facilities and increasing withdrawals. In addition, to climate-change induced sea-level rise, many river deltas are subsiding due to upstream dams and reservoirs trapping sediments. Missing this recurring sediment deposits deltas further subside and could become increasingly vulnerable for coastal erosion. Overexploitation of coastal aquifers are a further reason of subsidence (Syvitski et al. 2009). Abstracting water from fossil groundwater bodies further aggravate sea level rise (see Sect. 3.3.2). Upstream modifications of river flows and dam construction obstruct migratory routes for fish and limit the transfer of nutrients that would enhance agricultural productivity in flood plains and in deltas. Environmental flow allocations can be planned to protect ecosystems including sensitive deltas, but implementation remains a concern (Poff et al. 2010).

Water is a renewable and revolving resource. This renewal cycle is visualized by the water cycle (see Figs. 2.1, 2.4, 2.5 and 3.1). The expected effects of climate change (more liquid than solid precipitation, faster melting glaciers and snow, more intensive rains and longer lasting dry spells and droughts) imply the loss of natural storage capacities and more variable sequences of water availability and shortage. This could lead to a vicious cycle, whereby in some areas new dams may be needed to replace the lost and increase the water storage capacity to alleviate droughts, and control floods. The construction of new dams and their operation to meet societal demands could cause further deterioration of aquatic ecosystems and disturb the delicate sediment balance along the watercourses.

Through the unique hydrological cycle water is globally interconnected. Irrespective of the less than global scale of water resources management in the practice (basin or aquifer, or national, regional, municipal scales) its consequences propagate much beyond the given geographical demarcation. Water flows across jurisdictions and management spaces. Terrestrial water evaporates and transpires into a common atmosphere. There it may be carried as vapor across oceans and continents before precipitating again (see Fig. 2.17 in Sect. 2.2.4). Finally, it may even be traded as the "virtual water content" of exported agricultural or industrial products. Water thus connects several, interlinked, geophysical, socio-ecological and economic systems and, in this sense, constitutes a "global water system" (Global Water System Project, GWSP 2005). Since the industrial revolution humans have been changing the global water system in globally significant ways without adequate knowledge of the system and its response to change (Alcamo et al. 2008). There are also important uncertainties over the state of global water resources as well as the dynamics and interconnections of water, nutrient and material cycles.

Land use and land cover are subject to both rapid and relatively slow changes. Rapid changes are associated with the main (immediate) drivers, while natural vegetation succession and climate change are associated with the slower pace changes. Achieving legitimate goals (among them the key SDGs) will unavoidably accelerate land use/land cover changes. Increasing, partially unexpected stresses may occur.

This is problematic due to two reasons. Land tenure and ownership of water follow different governance systems. Furthermore, the state of the world's fresh waters (both "blue" and "green" water fluxes but also its stocks, see Sect. 2.2) are not adequately monitored, creating significant obstacles to management and mitigation or prevention of water scarcity and water quality degradation. Impacts of changes on biodiversity and ecosystems will also be hard to predict, given that, for example inventories for freshwater fauna are very incomplete globally, particularly in the tropics (Balian et al. 2008).

3.4.2 The Water Discourse: An Overview and Trends

'Water discourse' can be defined as the ongoing, multifaceted, recurring discussion and search attempting the identification of the most urgent problems and the formulation of (preferably) consensus concepts, methodological approaches and ultimately solutions. It reflects the problem perception(s) of the participating actors. While in Sect. 3.4.1 the three "P"s, climate change and land cover change have been identified as the key drivers (and inherent potential stressors), this conviction and narrative might not be shared by all participants (and moderators) of international water debates. Water discourse is heavily influenced by beliefs and ethical imperatives and the respective knowledge base of the participants (for more detail, see Chap. 5). Water discourse (s) are increasingly influenced by representatives of the civil society, but also some governments are active in the water discourse, either in the political arena or in the NGO-IGO-national governments discourse. Ironically, and regrettably some, mainly disciplinary, professional and scientific associations are almost entirely absent especially from the public and transdisciplinary debates. While stakeholder involvement is, in what used to be an exclusively professional domain, a difficult exercise, there is no other option than involving all interest groups in the search for sustainable, negotiated solutions.

The advent of the water discourse can be seen as coinciding with the wake of environmental awareness. This is frequently pegged to the UN Conference on the Human Environment, held in Stockholm in 1972. As far as the contemporary water discourse is concerned it is worth to review the evolution and key milestones starting from the United Nations Conference on Water held in 1977 in Mar del Plata, a mere five-year long time lag after the Stockholm conference. The International Drinking Water Decade 1981–1990 (United Nations 1980) was initiated at the Mar del Plata conference. As part of an international awareness raising drive 22 March was declared as World Water Day and it is observed worldwide since 1993 (United Nations 1992).

The International Conference on Water and the Environment, held in Dublin in January 1992 was not only an important preparatory meeting of the UN Conference of Environment and Development (Rio 1992) but with its "The Dublin Statement on Water and Sustainable Development" shaped for decades the water discourse. This conference and the "Dublin Principles" are also discussed in Sect. 8.1.2. The four principles formulated in Dublin (see Box 3.3) triggered much debate, especially over Principle 4, defining water as an economic good.

Many organized international meetings and conferences with explicit water focus emerged in the 1990s. First and foremost, the annual Stockholm water events (at present called Stockholm World Water Weeks) since 1991 and the triannual World Water Fora since 1997. These events are frequently copied mainly with a more explicit regional or national foci. A number of recurring water weeks and other platforms proliferate and serve as regular opportunities to pursue the water discourse like the Singapore or Amsterdam water weeks. Besides frequent, but standalone water events, the international water decades or recently launched water conference series (like the triannual Budapest Water Summits since 2013) two other mechanisms can be mentioned.

At a larger decennial scale, environment, development and sustainability oriented intergovernmental events like the United Nations Conference on Environment and Development in 1992 in Rio de Janeiro, the World Summit on Sustainable Development in Johannesburg in 2002 and the United Nations Conference on Sustainable Development (Rio +20) in 2012 which was held again in Rio de Janeiro took place. Water played an ever increasing role in these high level events. A further sign of the increasing political prominence of water is reflected in the proliferation of high level panels and working groups initiated by politicians or by the UN Secretary General. Several examples can be mentioned. The UN Secretary General's Advisory Board on Water and Sanitation (UNSGAB 2004–2015) had a prominent membership. Activities of UNSGAB are summarized in its final report UNSGAB 2015).

Box 3.3 The "Dublin Principles" Guiding Principles

Concerted action is needed to reverse the present trends of overconsumption, pollution, and rising threats from drought and floods. The Conference Report sets out recommendations for action at local, national and international levels, based on four guiding principles.

Principle No. 1:

Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment. Since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems. Effective management links land and water uses across the whole of a catchment area or ground water aquifer.

Principle No. 2:

Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels. The participatory approach involves raising awareness of the importance of water among policy-makers and the general public. It means that decisions are taken at the lowest appropriate level, with full public consultation and involvement of users in the planning and implementation of water projects.

Principle No. 3:

Women play a central part in the provision, management and safeguarding of water. This pivotal role of women as providers and users of water and guardians of the living environment has seldom been reflected in institutional arrangements for the development and management of water resources. Acceptance and implementation of this principle requires positive policies to address women's specific needs and to equip and empower women to participate at all levels in water resources programmes, including decision-making and implementation, in ways defined by them.

Principle No. 4:

Water has an economic value in all its competing uses and should be recognized as an economic good. Within this principle, it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failure to recognize the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources.

UNSGAB and the UN-led International Strategy for Disaster Reduction (ISDR) addressed the ever increasing loss issue of water related disasters (UNSGAB and ISDR 2009). Further, the High Level Expert Panel on Water and Disaster, a multi-agency initiative produced the report Water and Disasters (Delli Priscoli and Hiroki 2019) which put additional emphasis on a specific, transdisciplinary concern area. The Global High Level Panel on Water and Peace, an initiative of 15 nations (2015–2017) with its final report "A Matter of Survival" (Global High-Level Panel on Water and Peace 2017) and the High Level Panel on Water, established by the UN Secretary General and the President of the World Bank in January 2016 with its outcome document "Making Every Drop Count" (High Level Panel on Water 2018) are further examples of the efforts bringing water issues into the political conscience of the world.

Besides these political and public awareness raising efforts other intergovernmental initiatives focused on formalizing the global governance of water with special concern on its international dimension. Significant, legally relevant achievements of this, several decade long process and engagement are the Convention on the Protection and Use of Transboundary Watercourses and international Lakes of UN Economic Commission for Europe (UN ECE 2004). It was in force for regional parties since 1996 and became global in its scope in 2013. It can be acceded by member states outside of Europe since 2016. The global UN Convention on the law of non-navigational use of international watercourses from 1997 entered into force only in 2014 (United Nations 2014) after its ratification by the 35th party of the convention, though its principles guided the transboundary water discourse since its inception.

Two other institutionalized initiatives deserve to be mentioned for their role in contributing to and moderating the international water discourse. Both the World Water Council (legally an association according to French law) and the Global Water Partnership (operating in an intergovernmental setup) were initiated in 1996. Their respective key contributions like the triannual World Water Fora and guides, toolboxes, promotion of integrated water resources management (IWRM) are discussed in the respective chapters, in particular in Chaps. 7 and 12.

Water featured relatively modestly in the Millennium Development Goals (MDGs) as the water related targets 7c in MDG Goal 7 Ensure Environmental Sustainability (United Nations 2000), see Box 3.4.

However, this impressive list of actions and successes should not strengthen the temptation of complacency. Water problems are neither solved universally nor sustainably and there is ample reason to believe that the tasks ahead are increasingly difficult. As Box 3.4 reveals the water supply target is formulated as "safe" drinking water, while the reporting refers to "improved" sources of water, thus leaving certain concern unanswered, whether the water supply target has indeed been reached, or not. Therefore, the ongoing and future water discourse has the essential task to moderate the process and helping the emergence of consensus concepts and unbiased reporting to tackle the un(re)solved and emerging water problems.

Box 3.4. The Water Related MDG Targets and their Achievement Goal 7: Ensure environmental sustainability

Target 7.C: Halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation

The world has met the target of halving the proportion of people without access to improved sources of water, five years ahead of schedule.

Between 1990 and 2015, 2.6 billion people gained access to improved drinking water sources.

Worldwide 2.1 billion people have gained access to improved sanitation, Despite progress, 2.4 billion are still using unimproved sanitation facilities, including 946 million people who are still practicing open defecation.

Source: http://www.jn.org/millenriumRoal5/ enviror.shtm.

As far as water was concerned the explicit targets in MDG 7 specified to halve the number of people without access to safe drinking water and adequate sanitation. These targets were to be achieved by 2015. There is still fierce debate whether these targets were met. By changing the term "safe" to "improved" as 2015 approached there were justifiable comments claiming that not even the drinking water target was achieved. It was unanimously acknowledged that the sanitation target was clearly missed. Even if, by 2015, all water-related MDG targets would have been achieved, major water challenges would have remained:

How could access levels be made sustainable?
How could water services be provided for an ever-growing human population?
How could be ensured that provision of drinking water and sanitation did not endanger freshwater biodiversity and

threaten the ecosystem goods and services that underpin human livelihoods?

Needless to say that these challenges still exist and the same questions can be asked as far as the present water related targets of SDG 6 are concerned.

One of the most important (and somehow underestimated) milestone of "putting water on the international agenda" was The Ministerial Declaration of the 2nd World Water Forum in 2000 (World Water Council 2000a; b) which called for water security by:

> …ensuring that freshwater, coastal and related ecosystems are protected and improved; that sustainable development and political stability are promoted, that every person has access to enough safe water at an affordable cost to lead a healthy and productive life and that the vulnerable are protected from the risks of water-related hazards.

To achieve these goals, seven challenges were formulated (World Water Council 2000a; b):

- Meeting basic (human) needs;
- Securing the food supply;
- Protecting ecosystems;
- Sharing water resources;
- Managing risks;
- Valuing water; and
- Governing water wisely.

These seven challenges put three water demand categories in a clear hierarchy to satisfy as paramount aspect of water security. The water use category, direct human needs, was clearly given the highest priority. Further the role of water in food security was emphasized. In this list ecosystem needs were mentioned at the third place. Interestingly neither industrial nor energy related water needs were mentioned explicitly. Relatively strong emphasis was put on the remaining four challenges which described the recommended "how" to achieve water security. It distinguishes between governance and management, though does not mention explicitly integrated water resources management. It underlines water as a shared resource and valuing water implies, though implicitly, that water services come at a price. Valuing, however, is not meant as endorsement of an exclusive monetarization of value judgement. While pioneering on its own right, this list does not identify water as the key factor binding nature and society. The Ministerial Declaration, while product of high level negotiation of governmental actors was not a formal intergovernmental process. Ever since the 2nd WWF in The Hague, subsequent World Water Fora are gradually becoming broad multiple stakeholder events. While the size of World Water Fora (in terms of participant numbers) increases unabated, due to the multitude of various water events, high level committee reports, conference declarations, UN resolutions and conventions their impact on the water discourse remains rather disproportionate.

The momentum which prevailed in the early years of the present millennium is well characterized by the declaration of 2003 as the International Year of Freshwater (United Nations 2000) and the International Decade for Action "Water for Life" 2005–2015 (United Nations 2003).

Human water security, irrespective of the controversies associated with this terminology (Bogardi et al. 2016) is a major political issue. Chapter 8 presents an in-depth analyses of the water security discourse and its main actors.

Broadening water security in the water, energy and food security (WEF security nexus) context came by not earlier than 2011 (Bonn Conference on WEF) (Hoff 2011). Deliberations of the World Economic Forum, held prior and after the Bonn Conference on WEF were instrumental to trigger very broad and still intensive WEF discourse. Chapter 17 presents the WEF nexus in context of the Gulf region.

The UN resolution 64/292 declaring water and sanitation as human right (2010) and the appointment of a Special rapporteur for the Human Right to Water and Sanitation elevated the water issue into a new ethical level, irrespective of the fact that these human rights are legally not enforceable. Chapters 5 and 6 address these issues in more detail.

The latest, most comprehensive and intergovernmental binding agreement the Sustainable Development Goals (SDGs) (United Nations 2015) call for eliminating completely by 2030 the proportion of people without sustainable access to safe drinking water, and have been extended by adding the same requirement for sanitation. UN resolution 70/1 on the Sustainable Development Goals (SDGs) includes with SDG 6, the dedicated water goal (United Nations 2015). The SDGs (see the list of associated 8 targets of SDG 6 in Box 3.5) made the historical step by going beyond the hitherto exclusive intergovernmental praxis addressing only "WASH" (water supply, sanitation and hygiene) objectives and targets. SDG 6 is addressing water quality, freshwater ecosystem related targets and specifying the application of integrated water resources management (IWRM) and other implementation means and targets. In addition to the dedicated water goal SDG 6, freshwater issues are embedded, at least implicitly, in nearly all other SDGs. Hence the critical role of good water stewardship is essential not only for the achievement of the water goal but for the entire SDG architecture.

Of particular concern is the likelihood that the water-related Sustainable Development Goals (SDGs) targets may not be achievable not only due to lack of good governance, professional capacities and funding commitments, or a failure of delivery mechanisms but also due to some inherent conflicts between the achievements of competing targets. Eliminating hunger can hardly be achieved without additional water and fertilizer use. Improved health services likely to imply more pharmaceutical residues in receiving water bodies. Constraints on water availability and reductions in water quality jeopardize secure access to this resource for all legitimate stakeholders, including aquatic and terrestrial ecosystems. Thus the implementation of the SDGs, next to a sustained political will, needs to rely on adaptive approaches and consideration of interdependencies and tradeoffs between goals and their respective targets. The SDGs from the water perspective are highlighted in Bhaduri et al. (2016).

Water problems in the public perception and discourse are first and foremost related to direct human needs and use. Despite this decades long focus, approximately one billion people still lack access to safe drinking water and about two billion people live without basic sanitation (Water Supply and Sanitation Collaborative Council 2011). Depending on the consideration of the ever increasing human population, especially in water sector and least developed countries, as well as more rigorous estimations (High Level Panel on Water 2018) refer to rather 2 billion people without access to safe drinking water and 4 billion people (more than 50% of humanity) without adequate sanitation.

Box 3.5 The dedicated water goal no. 6 of the Sustainable Development Goals and its targets (Source: United Nations 2015) Goal 6. Ensure availability and sustainable management of water and sanitation for all

6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all.

6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.

6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.

6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.

6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.

6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.

6.a By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies.

6.b Support and strengthen the participation of local communities in improving water and sanitation management.

Irrespective of this state of "unfinished business", improvement of access to water and sanitation is one of the successful examples of global water governance. Significant progress has been made during the last decades. However, the proclamation of access to water and sanitation as a human right by the UN General Assembly Resolution in 2010 underscores the point that the then valid MDG targets such as stipulated in MDG 7, that is to halve by 2015 the number of people without access to safe drinking water and sanitation, which left many people without water services and adequate sanitation were ethically not justifiable, even if they represented commendable development milestones. Similar success of water governance cannot be reported for another global water target, the institutionalization of integrated water resource management (IWRM), irrespective that the Plan of Implementation of the Johannesburg Summit in 2002 called for IWRM and water efficiency plans by 2005 in all countries (Johannesburg Plan of Implementation of the World Summit on Sustainable Development 2002). Sectoral fragmentation and institutional inertia still impedes effective implementation of integrated water governance and sustainable management practices at global, regional and national levels. Chapter 12 addresses IWRM in more detail examples.

Given its global scope and interconnectedness water must be a priority on all political agendas. In spite of the importance of water to climate change, it has been largely ignored in the climate debate. Water tends to be considered as one of the "sectoral adaptations" which overlooks its central role in the interlinked socio-ecological system, and the ethical imperative espoused also by the UN General Assembly's resolution RES/64/292 (United Nations 2010) which declared access to water and sanitation a human right.

Although accurate forecasts are elusive, trends that will carry into the future are clear: human populations and the demand for water are increasing, and this is occurring also in the context of anthropogenic climate change (Gedney et al. 2006). Climate change should be seen as a catalyzer for long-overdue water governance reforms, and improved integration in water resources management. First steps in this context should be "no-regret" measures, so that uncertainties in climate-change projections cannot be used as excuses for postponing action.

Aspirations for "water security" involve protecting and living with the water cycle. It includes safeguarding the service function and relying on engineered storage facilities and protection infrastructure, developing risk awareness and preparedness, in combination with a coordinated legal framework, implementing policies and better operational water management directed by effective governance. An additional challenge is that provision of water and its management and governance must be applied in conjunction with other processes shaping societies, economies and the environment (World Economic Forum 2011). This implies the societal endorsement of new water use concepts, valuation, and readiness to change and to share.

Political stability, economic equity and social solidarity are much easier to maintain if supported by good water management and governance. The future should therefore be viewed through a "water" lens and implications of the complexities, role and intricate feedbacks of the global water system fully considered at all levels of the interlinked socio-ecological system. Oversimplification may yield one-sided, unsustainable solutions; overcomplicating could lead to inaction (Bogardi et al. 2012).

The connections between nature and engineered water infrastructure, the high rates of freshwater biodiversity loss, and the linkages between water and land use must all be addressed in the quest for sustainability (Alcamo et al. 2008).

A sustainable "water world" must reflect social and political dynamics, aspirations, beliefs, values and their impact on human behavior, along with physical, chemical and biological components of the global water system at different spatial and temporal scales. One thing is certain: development of a sustainable "water world" requires innovative, interdisciplinary science and will need the engagement of all stakeholders. The development and presentation of what may be called the common knowledge base of the participants of the water discourse is the aim of the present handbook.

The water discourse can hardly be separated from the broader, presumably all-encompassing sustainability discourse. While the concept of planetary boundaries is not without controversies and scientific debates (Blomquist et al. 2012) it contributes undeniably to the visualization of the prevailing problems and hence to awareness raising. The assessment of whether the planet is on a sustainable trajectory has indicated that three consensus-based "planetary boundaries" (see Table 3.1) have already been significantly transgressed (Rockström et al. 2009a; b). There is the need to improve the scientific knowledge on the interdependency of planetary boundaries, including the understanding of how many and which planetary boundaries can be transgressed and how long, before system collapse would occur.

There is clear evidence that human activities at present are on an unsustainable trajectory. Freshwater use, at least at global scale, is not yet among the most critical threats for global sustainability. The proposed planetary boundary for global water consumption by humans and for human use was estimated as 4000 km^3 annually (or about 10% of the annual freshwater flows to the oceans; see Fig. 2.4). As of 2009 an estimated 2600 km^3 was "consumed" before returning as waste water or via evapotranspiration to the hydrological cycle (Rockström et al. 2009a). Given the expected increase of population and better nutrition as stipulated by the SDGs the need to improve water use efficiency is evident. While present water consumption is below the critical threshold proposed in Table 3.1, this does not imply that withdrawals could increase indefinitely. Furthermore, global values do not account for local conditions. Many watersheds and aquifers are significantly overstressed with water withdrawal for agricultural use alone close to or exceeding locally available renewable water resources (UNESCO 2006). The respective scientific community drafted a road map to refine planetary boundaries for freshwater use, accounting for different scales (Gleeson et al. 2020; Zipper et al. 2020).

Through its interconnecting functions, water has a role to play in many planetary boundaries. For instance, the unsustainable loss of global biodiversity in Table 3.1 appears to be far higher from freshwater ecosystems than from the marine or terrestrial realms (Strayer and Dudgeon 2010). Furthermore, changes in land use and water availability are intricately intertwined. Water vapor plays a crucial role in all atmospheric processes and is a potent greenhouse gas affecting climate change. Should "business as usual" continue then transgression of the planetary boundary for water can be anticipated within this century as human population growth continues.

Table 3.1 Planetary boundaries proposed by Rockström et al. (2009a, b)

PLANETARY BOUNDARIES

Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis		To be determined	
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof		To be determined	

Boundaries for processes in red have been crossed. Data sources: ref. 10 and supplementary information

3.4.3 Concepts and Issues in Water Governance and Management

3.4.3.1 Ecology Centered Versus Utilitarian Considerations

Human water security implies the provision of quality drinking and domestic water, water for energy generation, industry, and transport, maintenance of ecosystems and biodiversity and water for food security. Tradeoffs and potential for considerable conflict exist. Over 70% of "blue" water withdrawal is used for food production (Cosgrove and Rijsberman 2000), and the links between water security and food security will become increasingly evident as the demand for food grows in parallel with increased water requirements for industry and energy generation (Hoff 2011) In addition, biodiversity in freshwater and terrestrial ecosystems also depend upon provision of adequate quantities and quality of water. Meeting the future needs of growing human populations will have major implications for maintaining adequate quantity of water for ecosystems. In a global analysis addressing 23 threat factors or stressors for human water security and freshwater biodiversity (Vörösmarty et al. 2010) shows that, threat to human water security and biodiversity frequently coincide (red shaded areas in Fig. 3.11) but, in many places—especially in the developed world—human water security is achieved at the expense of freshwater biodiversity (yellow shaded areas). There are virtually no places where a high degree of water security for humans has been achieved without considerably impacting biodiversity. This result reflects the "traditional" management mentality "impair, then repair". Tolerating

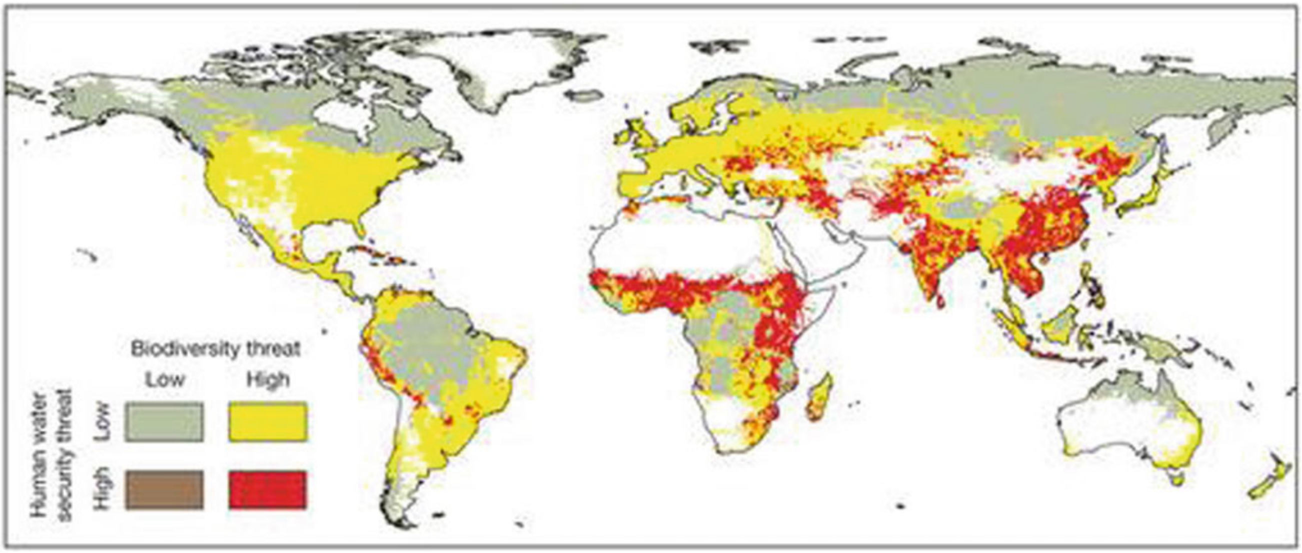


Fig. 3.11 Prevailing patterns of threat to human water security and biodiversity from Vörösmarty et al. (2010)

degradation of ecosystems and then applying expensive remediation strategies (if at all) after the damage has been done is not only costly but likely to be infeasible as well. The more so, as the robustness and resistance of the impacted socioecological systems cannot be easily assessed whether and how long they would endure increasing deteriorations without local, regional or even larger scale collapse. Competition for water between humans and nature will intensify in the future. New approaches, aiming to satisfy human demands while, at the same time, securing biodiversity and ecosystem services are urgently needed. It is perceived that compromises would be unavoidable. Yet, we still have knowledge deficits to propose sustainable tradeoffs at various scales and in different contexts. Chapter 16 discusses in more detail the global distribution of water as resource and biotope, as well as the status of freshwater biodiversity, ecosystem services and the impacts through human induced pressures and stresses.

3.4.3.2 Socioecological Interconnections: Virtual and Physical Water Transfer

Economy and trade create spatial interconnectivities for water. Water circulates in the global economic system as an embedded ingredient. It is the so called "virtual water", incorporated in or/and used to grow food and manufacture other internationally-traded products (Oki and Kanae 2004). Arid countries may compensate for national water scarcity by importing water-intensive commodities. These water fluxes, which are entirely mediated by societal needs expose important international or inter-regional water dependencies that should be considered in governance discussions (Oki and Kanae 2004) but also in the general water discourse.

The physical transfer of water between basins is a direct interconnectivity that sometimes triggers conflicts due to its high economic and ecological costs, and competition among potential users (UNESCO IHP 1999). Despite these controversies, large-scale transfers are ongoing or planned (Shumilova 2018). Moreover, as climate zones may start to shift, interbasin water transfers might have to be considered in the future as adaptive measures.

Changes in land cover and use have a major influence on water movement and consumption, and through changing land–atmosphere feedbacks, affect precipitation patterns. Deforestation of the tropical rain forest, and the expansion of commercial and energy crops, depletes terrestrial biodiversity, and the resulting monocultures are more vulnerable to pests and climate vagaries than the natural vegetation (Marengo 2010). As noted earlier, the unique role of water as connecting medium among ecological and social systems mandates that water must be managed in a multisector environment. Conversely no socioecological system can be sustainably managed without adequate consideration given to water. Joint development strategies, especially for land and water management are needed. It can be concluded that in light of these strong interconnection, further development of integrated water resources management (IWRM) towards a truly integrated land and water resources management paradigm seems to be an important and urgent scientific/professional development issue. IWRM is addressed in several of the following chapters, especially in Chaps. 9 and 12.

3.4.3.3 Water Governance, Security and Conflicts

Sustainable and, equitable allocation and protection of water resources must occur within the framework of integrated management and embedded in a conducive water governance framework. While these principles are likely to be widely endorsed implementation remains problematic. Ongoing global climate change, increasing population, urbanization, and aspirations for better living standards present a challenge which cannot be ignored. While water use at global scale currently seems to be within its proposed planetary boundary, shortages already prevail in several water-scarce and over-populated regions (see Sect. 2.2.4). All signs and trends seem to project shortages to increase (see Chap. 16). Furthermore, the ongoing large scale impoverishment of aquatic biodiversity, ecosystem degradation and reductions in water quality are unaddressed "side effects" even in areas where water can be secured for municipal and economic uses.

Water connects several socio-ecological, economic and geophysical systems at multiple scales and hence constitutes a "global water system". This must be considered both in technical interventions and governance frameworks. How to govern the water system with hierarchically structured, yet interdependent scales is still more a research question than implemented praxis. Chapter 9 provides an overview about water governance issues and recommended solutions.

Water security in the twenty-first century will require direct linkage of science and policy, as well as innovative and cross-sectorial initiatives, adaptive management and polycentric governance models that involve all stakeholders. Consensus solutions will need to be achieved by evidence-based mediation within multiple stakeholder processes. Chapter 9 highlights the inherent key governance and management issues in more detail.

Ensuring that no one remains without access to adequate water and sanitation should be a core aim of global water governance. Securing water for other vital human needs such as food and energy production, as well as safeguarding the quality and quantity of water for nature should not be neglected in pursuance of the undoubtedly primary water supply and sanitation goals. If existing governance structures are not adequate to address water problems in an integrated way what kind of new institutions are required? Will greater efficiency arise from a worldwide, uniform approach to water governance, or from a diversity of regional and local approaches? How far could polycentric governance models be successfully adopted? In short, the global "water crisis" is ultimately a "governance crisis" extending from the local to the planetary scale (Bucknall et al. 2006).

Constraints slowing the achievement of water security can arise from a lack of local knowledge, and institutional, professional and vocational capacities, shortage of funding and delivery capacity, including a lack of legislation or limited implementation of rules and regulations at all levels (UN-Water Decade Programme on Capacity Development 2011). During periods of water scarcity, these constraints can accentuate the conflict potential among water users at local, basin and international scales. Thus far, however, sharing water of transboundary rivers and lakes has been relatively successful (Wolf 2010). Although wars triggered by water conflicts between sovereign states are unlikely to occur, the potential for violence in water disputes at lower than the sovereignty level increases with the extent of dependence of livelihoods on water (Wolf 2010) and the increasing human demand for a finite resource. Emerging tensions in shared river basins could be reduced or deferred by use of more water efficient irrigation techniques, alternative land management, and new water use and purification technologies. Adopting common governance principles and sharing benefits derived from water at all levels and implementing efficient water management practices will help facilitating cooperation on water issues. Chapters 7, 8 and 11 addresses several aspects of this discourse.

Research on water governance is a relatively new interdisciplinary field. Comparative analyses of water governance systems around the globe reveal that their performance is context sensitive but not context specific. Good water governance is achievable in most countries although financial resources help. Funding is a necessary but by no means sufficient condition for efficient and effective improvement. Improved water governance can be realized through polycentric governance, effective legal frameworks, reduced inequalities, open access to information, and meaningful stakeholder participation (D'Haeyer et al. 2011). The water sector needs institutional reforms towards effective and adaptive governance and management systems. This will require multi stakeholder debates at national and international levels placing water at the center of social and economic development including energy, food, climate change and biodiversity issues. Neither markets, nor governments nor civil-society movements can provide water security alone, on their own (Pahl-Wostl 2009).

3.4.3.4 Integrated, Adaptive and Nexus Management of Water Resources

Integrated water resources management (IWRM) is an internationally accepted framework (Global Water Partnership 2011; Ibisch et al. 2016). However, IWRM is far from being a simple and universal panacea. Its practices must be adapted to changing conditions with testing and long-term monitoring of their performance (Pahl-Wostl et al. 2013). IWRM cannot deliver the promised results unless it is embedded in an adequate governance framework and guided by political will (Ibisch et al. 2016). Chapter 12 provides additional in-depth analysis of IWRM along with examples.

The management of water cuts across multiple sectors such as agriculture, industry, sanitation, health, energy, etc. and several concern areas such as governance, equity, well-being and economic development. Thus water resources management activities that are too narrowly defined to suit one use of water inadvertently affect water availability for other usages. The boundaries or river basins can also cut across administrative and country boundaries thus providing the potential for conflict between the riparian countries or other jurisdictionary entities. The connectivity of surface and groundwater resources across the basin adds further complexity. River basin boundaries are more visible, while transboundary aquifers have still not yet been extensively mapped in many parts of the world irrespective of their importance and inherent conflict potential. Hence calls for a ‘unified’, ‘comprehensive’ or ‘holistic’ approach integrating multiple water sources and usage, in a framework where river basin is considered the spatial unit of analysis has been made repeatedly (Molle 2006).

Global discussions to formalize an integrated approach to water resources management initiated at the first global water conference in Mar del Plata in 1977, followed by the Agenda 21 and the World Summit on Sustainable Development in 1992 in Rio de Janeiro. The Global Water Partnership (GWP) popularized the concept of Integrated Water Resources Management (IWRM) with the formal definition —“a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (Global Water Partnership 2011). The IWRM aimed to bridge fragmented sectorial approaches to water management by bringing all stakeholders to the discussion table to set policies that balance and coordinate between various water users, including the ecosystem.

Alongside, the integrated river basin management (IRBM) gathered momentum in the twentieth century as large-scale water infrastructure development, such as dams and water diversion projects, highlighted the need for considering upstream and downstream linkages in a river basin (Molle 2006; Benson et al. 2015). The “ecosystem approach” introduced by the Secretariat of the Convention on Biological Diversity (2004) as “a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way” is similar to IWRM in its end goals but further highlights the interdependencies between biodiversity and natural resources, including water.

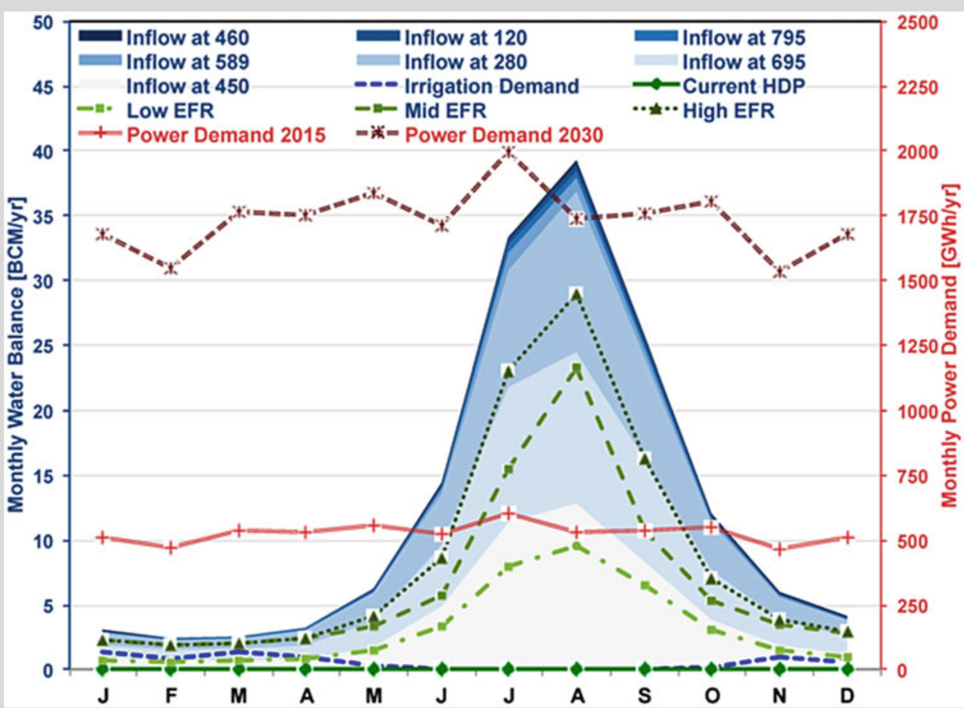
Nevertheless, the concept of IWRM needs be extended towards a broader integrated and context-specific resource management accounting framework for a wide range of ecosystem services, which can differ widely within and between countries (Vlek et al. 2017). Research results (Vörösmarty et al. 2010) imply that integrated land and water management are crucial to achieve human water security while preserving ecosystems (See Sect. 3.4.3.1 and Fig. 3.11).

While many tools and guidance for implementation of IWRM have emerged over time (NeWater Project 2006, 2009), the discourse on implementation of various approaches is still evolving. In essence, all approaches are univocal that sustainable growth across the globe is only possible through integration of policy and practices governing resource allocation between water, energy, food, environment and other related sectors. Many institutions and practitioners have developed their own qualitative frameworks based on problems at hand. System analysis based tools such as optimization and simulation models, hydroeconomics etc., can provide quantitative basis for integration of water management policies and practices (Bazilian et al. 2011; Brown et al. 2015). Representing complex interconnected systems within a framework that is easy to adopt and scalable across spatial scales and management context is a formidable challenge (Bazilian et al. 2011), Opinions are divided on best practices and best decision-making platforms for operationalizing the various integration approaches. Demarcating “boundaries” for integrated systems assessments can also be problematic as cross-cutting areas such as health or gender should also be incorporated.

Furthermore, despite the abundance of integrated water management frameworks and assessment tools, few examples of their application are found in the real world. The actual management of water, especially in developing countries is still very fragmented and sectorial, leading to tension and conflict between various sectors and countries rather than synergies and collaboration (Hellegers et al. 2008; Biswas 2008; Suhardiman et al. 2015). Some of the main barriers for implementing integrated water management approaches include neglect of existing political structure and processes within and beyond the water sector (Allan 2003), inadequate inclusion of tradeoff assessments between the various objectives (Molle 2006) and a lack of data and information necessary for planning. The ministries and implementing agencies under them often compete for resources so there is lack of incentives to cooperate. These criticisms recommend an explicit recognition that decisions related to water resource management are political choices (Wester et al. 2003). It is imperative to shift from unrealistic blueprint institutional arrangements to adaptive, flexible and inclusive approaches such as polycentricity (Blomquist and Schlager 2005; Suhardiman et al. 2015).

More recently, the increasing human demand for water, energy and food under the pressures of globalization, urbanization, adoption of resource intensive lifestyles has stressed the need to build resilient societies that are water, food and energy secure even in the face of societal and environmental crises (Hoff 2011). The World Economic Forum Annual Meeting in 2008 introduced the Water-Energy-Food-Climate Nexus from the perspective for water security. The Bonn 2011 Nexus conference formalized the Water-Energy-Food (WEF) security nexus as an approach to "enhance water, energy and food security by increasing efficiency, reducing trade-offs, building synergies and improving governance across sectors" (Hoff 2011). The nexus approach fosters sustainable economies built by maximizing efficiency in resource use and productivity across all sectors by closing resource flow loops and capitalizing on existing synergies. The concept has also been expanded to include environment and livelihood in the nexus framework recognizing that "security" depends not only on resource availability but also on access of individuals to resources and their ability to utilize these under the dynamics of existing social power relations and institutions (Biggs et al. 2015). The nexus approach, based on analyzing trade-offs and synergies across sectors in an integrated framework, has also proven useful for streamlining sustainable development goals, often operating in sectorial silos, to fulfill multiple objectives concurrently (Weitz et al. 2014). Chapter 17 provides further insights into the implementation of the nexus concept. Box 3.6 presents an application of multi-objective optimization to operationalize the WEF nexus.

Box 3.6 Multi-Objective Optimization for Quantitative Analysis of the Nepalese Nexus To unleash the estimated hydropower potential of over 43,000 MW, the Nepalese government plans to increase hydropower capacity from current levels (~790 MW) to 37,628 MW by 2030. Achieving this will require altering natural flows through construction of many dams, with implications for water availability for irrigation, fisheries and environmental services as well as water-induced disaster management. Multi-objective optimization can provide a systematic basis for assessing tradeoffs across the various water-energy-food-environment nexus linkages under hydropower infrastructure development. Monthly average water and power demand in Nepal as well as water availability across the major basins are shown in the following figure. While water is clearly abundant, nearly 80% of river flows arrive between June-September. Irrigation water demand is high in the dry period when rain-fed agriculture is not possible. The power demand doesn't vary significantly within the year, but low water levels in the dry period result in frequent power outages. Trade off exists not only in when and how the available water is allocated but also where the benefits are reaped.

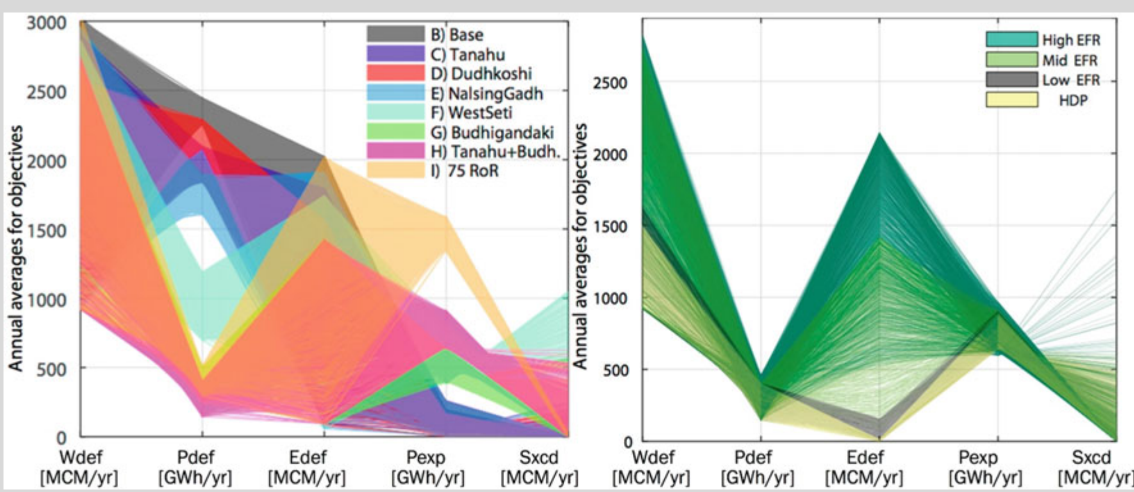


Average monthly water demands, power demand and inflows across seven major basins of Nepal. Reproduced from Dhaubanjar et al. (2017).

Dhaubanjar et al. (2017) used multi-objective optimization to couple two water and power system models in a single objective function to represent the linkages in the water-energy-food-environment nexus. The national scale optimization model compared how eight Nepalese power development scenarios affect five management objectives: minimization of power deficit, maintenance of water availability for irrigation to support food self-sufficiency, reduction in flood risk, maintenance of environmental flows, and maximization of power export. It is important to consider these objectives jointly, because prioritizing some may undermine others. For instance, storage reservoirs provide an opportunity to stock up excess wet period flows to minimize deficits in power and irrigation water demand in downstream basins during dry periods; however, this decreases year round environment flows and reservoir flood storage capacity. For each hydropower development scenarios, 1500 different weighted combinations of the five objectives were run. Such variable weighting allows for simulation of real life scenarios where stakeholders would prioritize the objectives differently.

The figure below shows the range of possible annual tradeoffs under each scenario with medium environmental flow requirements (EFR) and for scenario H) under varying levels of EFR. It is clear that prioritization of different management objectives can impact the level of fulfillment of other objectives. Some pathways offer a better balance between the objectives. Generally, environmental deficit, power deficit, and power export are in relative harmony, as all require higher reservoir releases. The trade off in annual power and water deficit indicates that seasonality and the spatial distribution of power and water demand should be further analyzed. Prioritization of power production can have large impacts on the water objectives. Higher EFRs can support more power exports but may increase flood risks as wet period reservoir storage may be increased to ensure dry period EFR. Multi-objective optimization provides a quantitative basis to understand the trade-offs and synergies across different objectives.

Source Dhaubanjar S, Davidsen C, Bauer-Gottwein P (2017) Multi-Objective Optimization for Analysis of Changing Trade-Offs in the Nepalese Water–Energy–Food Nexus with Hydropower Development. Water 9:162. doi: https://doi.org/10.3390/w903016.



Range of possible annual average tradeoffs across five management objectives in the Nepalese nexus: minimization of irrigation water deficit (Wdef), environmental deficit (Edef), power deficit (Pdef) and flood storage exceedance (Sexcd) and maximization of power export (Pexp). Each line indicates combinations for one model run. Subfigure a) shows tradeoffs across 8 hydropower development scenarios under mid EFR and power demand for 2015. Subfigure b) shows tradeoffs for scenario H) under varying levels of EFRs. Reproduced from Dhaubanjar et al. (2017).

Nexus planning does not always lead to win–win situations. Tradeoffs also need to be calculated and assessed in designing nexus solutions. It is known that taking a systems view increases efficiencies and optimizes the production value. On the other hand, it is often not possible to optimize all components in the system equally, because there are synergies as well as tradeoffs. Discussions between Nepal and India on the development of large dams in the upper Ganges basin have also been ending in a deadlock because India wants larger dams for energy as well to store water for downstream irrigation requirements. However, Nepal is not in favor of large dams as large reservoirs consume prime agricultural land and have long-term ecological impacts (Bharati et al. 2016). Gaining efficiency in one sector could also lead to waste or inequity in another; e.g., when electricity becomes cheaper it is typically used more, which may have unintended consequences such as unsustainable extraction of groundwater for irrigation. Therefore, understanding the connections among the water, energy, food and land nexus within a broader context perspective can help promote efficiency, manage trade-offs and could lead to sustainability, greater equity in their distribution and greater food, water and energy security (Vlek et al. 2017).

Chapters 9 and 12 go in more detail as far as IWRM is concerned, whereas Chap. 17 provides a detailed regional example of the application of the nexus concept.

One billion people suffer hunger; two billion people exist on inadequate diets and approximately one billion people do not have access to adequate energy resources while the global population is still rapidly increasing. To meet the nutritional needs of all food production will have to double in the next 25 years (Kendall and Pimentel 1994). Consequently, agricultural water use will increase, unless potentially offset by improvements in water and land use efficiency. Chapter 19 provides several examples of interconnected land and water management.

There is much scope for such improvement: globally, at least half of the water withdrawn for irrigation does not reach the crops for which it is intended (Food and Agriculture Organization of the United Nations 2016). The recent increase in growing energy crops may supplement rural incomes, but it creates competition for water and land with food crops, and thus between food and energy security.

Hydropower is an important source of energy globally, and its share of the energy sector will increase at the expense of fossil fuels. The benefits accruing need to be compared with the loss of biodiversity and vital ecosystem functions that accompany dam construction and modification of flow regimes to generate electricity (World Commission on Dams 2000). Hydropower is certain to remain part of the global energy mix, the more so as substantial dam constructions are undertaken to increase hydropower generation worldwide (Zarfl et al. 2015). Thus policies and practices need to be put in place to mitigate impacts on freshwater ecosystems. Science-based compromises will have to be found and hydropower generation managed adaptively to account for environmental flow requirements (Pahl-Wostl et al. 2013).

Even water resources management itself consumes energy. Water purification and desalination are very energy intensive, and energy is needed to pump and distribute water from rivers and aquifers. Saline groundwater or seawater has to be desalinized to meet water demands in arid areas, and this consumes substantial energy. Microfiltration and membrane technologies used in sewage treatment also have high energy consumption (Frimmel and Niessner 2010).

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Janos J. Bogardi is senior fellow of the Center for Development Research of the University Bonn. where he is also professor for water resources management. He is senior scientific advisor of the Institute of Advanced Studies Köszeg (iASK) in Hungary and fellow of the Stellenbosch Institute of Advanced Study (STIAS), South Africa. Since 2014 Distinguished Adjunct Professor of the Asian Institute of Technology (AIT, Bangkok). He was executive officer of the GWSP (2009–2012). He served till his retirement from the UN as director of the United Nations University (UNU) Institute for Environment and Human Security 2003–2009 and as Vice Rector a. i. in Europe 2007–2009. He was Chief of Section in the Division of Water Science in UNESCO, Paris (1995–2003) and chair professor of hydrology, hydraulics and quantitative water resources management at the Wageningen Agricultural University in the Netherlands 1989–1995. He was associate professor at AIT between 1985 and 1988. Between 1969 and 1985 he had research and consulting appointments in Europe and in Africa. He graduated in civil engineering at the University of Technology Budapest in 1969. He holds a doctorate in water resources engineering (Dr. Ing.) from Karlsruhe University 1979 and three Dr. honoris causa distinctions from universities in Poland, Hungary and Russia.

Luna Bharati has 15 years of post Ph.D. experience as a senior scientist and research program manager. She is currently a principal researcher of hydrology and water resources at the Inter-national Water Management Institute (IWMI). The key areas of her interests and expertise are in water resources assessment and management. She has also worked extensively in assessing climate change risks and impacts on the hydrological cycle in large river basins to small mountain watersheds and farming systems. She has provided direct input into two national policies of the government of Nepal e.g. Irrigation Master Plan and the Nepal Water Resources Strategy. Her work on Environmental Flows has also been incorporated into the Clean Ganga Mission from the Government of India. She has recently provided input to the Government of Nepal's position on Climate Change and River Basin Strategy and the Government of Myanmar's Nationally Determined Contribution Report. Prior to joining IWMI, Dr. Bharati worked for the Center for Development Research (ZEF) in Bonn, Germany on the Global Change and Hydrological Cycle (GLOWA) project in the Volta Basin, Africa.

Dr. Bharati has a multidisciplinary background with a Bachelors majoring in Environmental Sciences-Biology and a minor in Economics from Luther College, USA and a Masters in Water Resources from Iowa State University, USA. She conducted her doctoral research at the Dept. of hydrological modeling at the Helmholtz Center for Environmental Research- UFZ in Germany focusing on catchment modelling of surface hydrology, erosion and NPS pollution from agriculture. She has authored over 100 publications including edited 1 book and 40 articles in peer reviewed scientific journals. Dr. Bharati has been involved in capacity building programs all throughout her career. She is involved in teaching Masters and Doctoral courses at the University of Bonn. She has worked in projects in North America, Europe, South Asia, South-East Asia and West Africa.

Stephen Foster has British chartered status as an Environmental Engineer and Applied Geologist, with major international experience in groundwater Assessment and management. Senior posts held include: World Health Organisation Groundwater Advisor for Latin American and Caribbean (1985–89), British Geological Survey Divisional Director (1990–99), World Bank Groundwater Management Team Director (2001–12), International Association of Hydrogeologists President (2004–08), Global Water Partnership-Senior Adviser (2012–15) and International Water Association Chair Groundwater Management Group (2018–22). Stephen received a DSc in 1983 for published work and various professional awards including: Institution of Water & Environmental Management Whitaker Medal (1975), International Association of Hydrogeologists-Presidents Award (2004) and Geological Society of London William Smith Medal (2006).

Sanita Dhaubanjar is a Water Resources Engineer. She is currently a SustaIndus Ph.D. Fellow at Utrecht University in The Netherlands and ICIMOD, Nepal. Her research topic is on envisioning hydropower development under the water-energy food nexus in the Indus. She has previously served as research officer for Water Futures at the International Water Management Institute. She is passionate about the use of novel tools and integrated methods for evidence-based water resources management. She focuses on quantitative assessments, environmental modeling, climate downscaling, data analysis and visualization.

Part II

Water and Society

4 A Drop in the Ocean. On Writing Histories of Water Resources Management

Maurits W. Ertsen and Ruth A. Morgan

Abstract

This text builds on the shared focus of historians and engineers to understand how particular circumstances came to be. In their endeavours, engineers regularly turn attention to the past, many times with the explicit aim to build on the past. In this chapter, it is discussed why these water histories written by engineers are vulnerable to being less correct. Using a range of scholarship on water history and shared experiences within the International Water History Association, we discuss the core of any historical scholarship: a drive to demonstrate and understand the complexity of the past. As such, this chapter wants to warn against the engineering drive to use (water) history as a guide towards the future. Instead, we propose a perspective of history as a way of reading and understanding the complex paths we have travelled until now.

Keywords

Historiography • Grand narratives • Deserts • Colonial irrigation • Climate change

4.1 Introduction

Historians and engineers have at least one thing in common: they try to understand how particular circumstances came to be. Where historians aim for explaining how human past(s) can be understood, either on their own or in relation to the present, engineers aim for understanding particular issues or problems and providing solutions to ameliorate them for the future. Both endeavours require data of different kinds, and an engagement with processes, or perhaps more specifically, both create processes. For instance, the historian discerns processes of the past based on (always limited) archival and other sources, the engineer shapes the future based on (always limited) expectations and data. In their work for the future, more often than not, the engineering profession turns its attention to the past. Sometimes this is undertaken with the explicit aim to build on the past, while at other times, this is performed with the explicit aim that "the past is the key for the future" (Angelakis et al. 2012). According to this perspective, studying historical technologies would reveal their "apparent characteristics of durability, adaptability to the environment, and sustainability", and is often accompanied with the idea that such "technologies are the underpinning of modern achievements in water engineering and management practices" (ibid).

Without suggesting that these aims are problematic in themselves—an issue we will discuss in more detail later in the chapter—we would suggest that these water histories written by engineers are vulnerable to at least one risk. Where professional historians and archaeologists continuously discuss new findings and contrast these with existing empirical and theoretical claims—in similar ways that other scholars practice, including engineers—the historical work that engineers undertake is often based on secondary publications, ignores recent studies, and can rehearse well-worn narratives of triumphant progress. Furthermore, with engineering publications on historical issues typically focussed on descriptions of technologies—again, an issue we will return to later—it is the contextual and more socio-political material that tends to be repeated. Let us briefly review the topic of "qanats" to illustrate why this observation would be problematic—benefitting from a recent thematic issue in *Water History* on this technology (Issue 1, 2018).

M. W. Ertsen (✉)
Water Resources Management Group, Delft University of Technology, Delft, The Netherlands
e-mail: M.W.Ertsen@tudelft.nl

R. A. Morgan
School of History, Australian National University, Canberra, Australia
e-mail: ruth.morgan@anu.edu.au; ruth.morgan@monash.edu

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The term ‘qanat’ refers to the technology of subterranean galleries tapping groundwater, specifically in the Near East and western/central Iran. The technology is known elsewhere as “Mina de aqua”, “viajes de agua” or “galería drenante” in Spain, “khattāra” in Morocco, “foggāra” in the northern Sahara, “kārēz” in Iraq, Eastern Iran and Pakistan, “kan’erjing” in China, and “falaj” in Oman and the UAE (Charbonnier and Hopper 2018). Environments, length, depth and levels of investment of these structures are highly variable, but their purpose is always to “drain groundwater resources in their upstream section and channel the water to the surface by gravity” (Charbonnier and Hopper 2018).

Despite this diversity, one of the more persistent narratives within archaeology in the twentieth century has been that the origin of qanāts (always using that term) had to be sought in Achaemenid Persia in the sixth century BCE—modern Iran. The spread of qanats would have gone hand in hand with the expansion of the Persian Empires—and beyond, when, for example qanat technology would have moved from Spain to the Americas. Even when qanats were found in Oman that predated the Achaemenid period, this was explained by processes of technological diffusion (Potts 1990). Apparently, the option that the technology had moved from Oman to Iran was not taken seriously. Much of the claims of Persian qanat origin are based on the idea that the technology could only have been developed by particular civilizations, such as Ancient Persia. When qanats were in use elsewhere, in seemingly less developed societies, populations would only have maintained pre-existing Persian structures (Charbonnier and Hopper 2018). Such claims were also clearly suggesting that the large number of water tunnels in Iran, with their relative length and discharges, were the result of a long trajectory of development—with the assumption that this long trajectory meant that the Iranian plateau was the single region of origin.

Such a claim is not as straightforward as it appears. As Charbonnier and Hopper (2018) indicate, evidence suggests that this technology is more ancient than previously thought, and originates in many diverse environments. This new evidence brings these authors to suggest a polycentric origin of qanāt technology, mainly grounded in the observation that the societies with early examples of qanāts would not have had cultural ties. Despite this new evidence (see Yazdi and Khaneiki 2017; Boucharlat 2016 for further discussion), the popular narrative that qanats originate from (what we now call) Iran, and have been disseminated from there, remains strong. Such a narrative is problematic, as it suggests that a certain water capturing feature would be more unique than others (tunnels versus dams for example) without clear explanation why that would be the case. It is also problematic because a single origin still does not clarify why the technology could spread so successfully. Actually, the different types of groundwater tapping systems firmly indicate that the origin of the technology was more diverse than previously understood. Furthermore, although some qanat tunnels are impressive in scale, most qanats are rather short, and could have easily resulted from communities originally following a drying well into a hillside. With mining technologies also widely available among ancient human societies, the idea that qanats arose from a single origin is not as straightforward as many authors suggest.

In this chapter, we draw on a range of scholarship on water history, including our own and the manuscripts that have featured in the journal *Water History*—established in 2009—and on shared experiences within the International Water History Association to survey the field of water history. Nearly a decade of publication has introduced readers to a wide range of themes within water history, with contributions on rivers, urban water systems, irrigation, health, water quality, and state-led engineering, just to name a few. Meanwhile, case studies have focused on regions as far-flung as the southern United States, the North China Plain, Iran, and central Europe. Among the approaches to studying these relationships, there has been a particular focus on the importance of water technologies, which bring human desires, ideas, and expertise into relationships with physical possibilities and material limits. These relationships, as we show in this chapter, can be extremely complicated: it is the water historian’s task to disentangle these relationships between people and water over specific time periods.

In this regard, the water historian’s task is not unique: at the core of any historical scholarship is a drive to demonstrate and understand the complexity of the past. History is comprised of a confluence of specific contexts, causation, and contingencies that shape human relations and experiences over time. Writing history requires explicit historical analysis of the particular society, place or issue under examination, while avoiding neat and over-generalized linear trajectories of change over time. Although the past might point us in particular possible (future) directions, historians are mostly suspicious of the direct applicability of such lessons to the concerns of the present. This chapter does not make a case for water history as a “roadmap for the future” (Sabin 2010) that will show us the best way out of our current planetary predicament, but rather, a way of reading and understanding the complex paths we have travelled until now.

We continue the discussion by examining the grand narratives of water history, including those that are popular in works on water technologies and the work of one of the earliest water historians in the 1950s. We contrast this work to what had been published in the journal *Water History*, with a brief overview of the themes, periods, and regions that have been discussed. While on the one hand we argue that the grand narratives that purport to tell the story of water and society are not fit for purpose, this does not mean we think it is not possible or useful to discuss water histories in a comparative perspective. In the three sections of this chapter, we offer the reader three different historical narratives, that each show specific ways of historical actors engaging with water. We have selected three themes that will interest readers: deserts and water use, colonial irrigation, and water and climate change. We have drawn these examples from our own work on the intersections of agriculture, colonialism, and water in historical moments as varied as the ancient Hohokam culture of the American southwest to the climate anxieties of twentieth-century Australia. Finally, we conclude by reflecting on the relationships between small stories and great histories.

4.2 Grand Narratives

Water has been a key concern to human societies throughout history. Whether used for domestic, economic, or spiritual purposes, water has historically played a valuable role in processes of production, health, transport and communication (Boomgaard 2007; Collins 1990; Gill 2000; Hundley 1992; Lansing 1991; Lucero and Fash 2006; Marcus and Stanish 2005; Magnusson 2001; Pietz 2002; Rortajada 2000; Scarborough 2003; Steinberg 1991; Worster 1985). These processes depend on a reliable and predictable water supply: too much or too little water can wreak devastation, as catastrophic floods and famines have shown (Bankoff 2003; Davis 2000). In some cases, the human hand in such "natural" disasters is evident—secondary salinity, desertification, and dam failure are all consequences of water and land "management" (Reisner 1986; Davis 2007, 2016).

As a result of humans' material and spiritual dependence on water, the ways that human societies harness, access, and use water have significant implications for their organization. The importance attached to the availability of water tends to give rise to highly regulated water flows and access arrangements, which depend on particular rules, institutions, and hierarchies to mediate social relationships. Some scholars in the social sciences refer to such relationships as "hydro-social" in nature (eg. Swyngedouw 2009; Linton 2014). Whatever the concept applied, human-water relations also have implications for the ways that humans in societies make meaning out of water. For example, ideas about water often relate to its purity and transformability, which are expressed in Hindu rituals near the river Ganges, baptism rituals of Christian conversion, and ritual cleansing before Muslim prayer (Strang 2004, 2015; Morgan and Smith 2013).

The wide literature on the history of water and human societies tends to emphasise the centrality of water to the many environmental problems that face the world today—climate change, natural resource scarcity, pollution, and habitat destruction. How should water resources be developed and distributed? Who decides? Neither of these questions are new. Historicising a society's relationship to water is crucial to understanding our contemporary concerns, as it can invite more creative approaches to water management in the present. Yet we encourage water managers to be wary of certain historical accounts of the hydro-social relations of the past. 'Grand narratives' of water history often fall into one of two camps: either triumphalist stories of Western technological progress, or declensionist tales of mismanagement and ruin. In this section, we critique these approaches to water history and suggest that they fall short of helping us to understand the complexity of hydro-social relations in different cultures, places, and time periods. Their tendency towards simplification and narrative linearity misrepresents the past, and as a result, curtails their usefulness to understanding our current environmental crisis.

A significant early example of such grand narratives of the relationship between human societies and water is the work of the German-American historian Karl Wittfogel. In his book *Oriental Despotism: A Comparative Study of Total Power*, Wittfogel (1957) put forward a 'hydraulic hypothesis' to account for the development of different forms of political organisation. Absolutism, he argued, was the product of the ways that societies managed their particular hydrological endowments. In the so-called "hydraulic civilisations" of Egypt and Mesopotamia, for example, political power was in the hands of those who controlled water. The expansion of irrigation infrastructure in these arid and semi-arid climes (and the mobilisation of labour for its construction) facilitated the consolidation of the elite's power and their increased control over both people and the environment. This centralisation of power fostered what he called 'Oriental despotism', in contrast to the representative political systems that developed in the more well-watered lands of Western Europe. Wittfogel's hypothesis continues to provoke debate on the grounds of environmental determinism, the extent to which authoritarianism is inevitable in such conditions, and the Eurocentric assumptions that underlie his argument (Bichsel 2016, 359–60; see Harrower 2009, Wilkinson and Rayne 2010).

Many decades later, the association of water with political power, civilisation, and the essence of life continues. Anxieties about water scarcity and the prediction of water wars have produced a new generation of writers, who seek to navigate the history of humankind through water (eg. Scarborough 2003; Solomon 2010; Fagan 2011; Sedlak 2015). Many claim that the water crisis of today can be—and needs to be—explained in relation to global water history. Some go as far to suggest that "water is calling us to learn its lessons so that we can grow and prosper" (Priscoli 1998: 628). Certainly, the importance of water for societies from ancient Mesopotamia to twenty-first century China calls for the study of hydro-social relations through both archaeological and historical perspectives. Water history can reveal the structural foundations of material and social conditions today, such as the ongoing challenge of subsidence in Amsterdam that is the product of historic drainage works (Van Dam 2000; De Bruin and Schultz 2003). These experiences show how a particular intervention in the past continues to shape the hydro-social relations of the twenty-first century. Nevertheless, we encourage readers to approach such accounts with caution. Many authors of grand narratives appear to misconstrue the methods and aims of contemporary historical research and writing, in favour of their teleological ends.

We consider grand narrative approaches to water history to have four main failings. First, these histories often universalise the historical relationships between people and water, such that these become histories not of individuals, groups, and societies, but of humanity as a whole. Claims such as the declaration by archaeologist Fekri Hassan in his UNESCO study that the "history of water management is nothing less than the history of humankind" (Hassan 2011: 5) are symptomatic of this tendency. Second, a singular water history is depicted as a stream of linear events—a "series of stages" or "successive transformations" (Hassan 2011: 22, 23). These stages are defined as "those that have been adopted by the majority of human societies" (Hassan 2011: 24).

Third, this progressive version of water history favours the telling of ecological morality tales—of the centrality of water to the ultimate success or failure of societies. Take journalist Steven Solomon, for example, for whom the lesson is clear: "Repeatedly, leading civilizations have been those that transcended their natural water obstacles to unlock and leverage the often hidden benefits of the planet's most indispensable resource" (2010: 14). The last of the grand narrative failings is that, the progress or evolution of humankind through these stages is often depicted as logical, natural, and inevitable, overlooking the role of contingency and context in shaping the hydro-social relations of the past. The advance of a society through each stage is characterised as the result of a 'turning point' or 'breakthrough' on the march towards Western modernity (Solomon 2010). Elsewhere, Solomon describes societies as having 'failed' in their (progressive) relations with water, which seems at odds with the reality of their continued existence in the present. Similar stories of progress and decline can be found in many works on the history of engineering technology.

In Juuti et al. (2007), several historical situations concerning water and sanitation services are discussed, in order to show that history of water and sanitation is strongly linked to current and future water management and policy issues. The book is structured along a timeline of 'early systems' through a 'period of slow development' to 'modern urban infrastructure' and finally 'future challenges'. As the book does not specifically provide thematic cross-cutting discussions of the various chapters, the different cases remain relatively isolated from each other. Interestingly, the chronological structure of the book suggests a certain "order of development", but chapters dealing with comparable issues appear to be set in different timeframes. In other words, the overview does suggest a certain timeline of developments, but does not provide any further discussions of the cultural construction of this trajectory.

The historical overview of wastewater technologies provided by Laureano et al. (2014) is again interesting, as it offers evidence of human ingenuity and arrangements, and can serve as sources for inspiration. However, here the suggested chronological arrangement of the book might suggest that there is a logical order of these water-related applications. Such a claim, however, would have to be explained, at least as to how different parts of the globe would be connected over time—an issue we already encountered in the discussion on qanats, where the absence of evidence of such relationships was explicitly mobilized to refuse to acknowledge a connected and dynamic history of the technology. Fortunately, Laureano and colleagues do have something more to say about the relevance of their collection on issues of relations and chronology compared to Juuti et al. (2007).

Take, for example, their suggestion that "the history of wastewater offers the possibility to study the history of mankind from a very unique perspective" (Laureano et al. 2014). Indeed, many histories tend to ignore dirty subjects—with the possible exception of environmental history, possibly the closest to water history within the larger historical discipline. They suggest, however, that the technologies in question are direct proxies for the wealth and prosperity of a society. We would agree that investment opportunities should relate to technologies that have been applied, but we would also suggest that there are other issues to consider, such as cultural preference, climate, and political realities. As such, we do not consider that the concept of "technological improvements" should be used so loosely. Who decides what an improvement is? Applying an uncritical chronology of unrelated wastewater technologies in several regions ignores standard historical questions of power, environment, and influence. Instead, the book suggests a rather linear idea of progress of wastewater technological development, interrupted now and then by "barbaric raids and invasions" (ibid), as if without such raids there could not have been changes and interruptions. Both World Wars in the twentieth century may have been rather strong interruptions, but did not seem to have changed wastewater technologies. This uncritical idea of historical change is only highlighted by the authors' use of phrases, such as "a timeline about historical development of sanitation and wastewater management".

Another engagement with histories of water management establishes a series of stages through which a city's water management proceeds over time. According to a linear 'Urban Water Management Transitions Framework', a city's infrastructure develops from 'water supply' to sewers, drainage, waterways, and ultimately, to the water sensitive city (Brown et al. 2009). Although the original figure explicitly represented how these 'transitions' unfolded in the particular context of settler Australia (post-1788), subsequent iterations posited its stadial representation of progress towards a 'water sensitive city' as a more general depiction of how "how urban water management in cities generally transitions when moving towards sustainable urban water conditions" (Hoekstra et al. 2018, 9). Likewise, the aspirational 'water sensitive city' is the (ideal) "result of the several stages transited by the cities when looking for sustainability" (Rodriguez et al. 2014, 174). Excised from its original context, the figure has been interpreted as a means by which to "benchmark a city's progress (either forwards or backwards) at a macro scale" (Fisher-Jeffes et al. 2014, 1029). This representation of a smooth continuum from past to future states (however originally framed as not so linear in practice) flattens and erases the dynamism, agency, historical context, and material conditions that shaped the ways in which cities have historically managed water.

Using the past as a linear laboratory of technological progress suggests that particular historical developments are both normative and certainties. If there is anything that the historical discipline shows, however, it is that progress and linearity are very problematic terms. Just as current engineers deal with uncertain futures, so did our historical actors. In their times, it was not clear at all what "progress" would look like, let alone how it could be achieved. Apart from robbing historical actors of their agency, a linear idea of progress suggests not only that a single idea of progress exists, but also that that idea of progress can be found in historical and archaeological sources. However, as soon as we accept that historical actors would have had differences of opinions—just as we have in the twenty-first century—it would be strange that historical analysis could reconstruct a single timeline of development. The difficulty of doing so is highlighted by the partial nature of historical knowledge, drawn from archives that reflect the views of particular social groups.

Overviews such as the example provided by Rossi et al. (2009) offer a more careful approach to histories of water technology. Even though the term "ancient" is taken rather loosely—given that descriptions from the seventeenth, eighteenth and nineteenth century are included—the authors provide several interesting remarks about how they address concepts of historical development and progress. They start with the observation that the idea that "our generation has invented and discovered almost everything" is not correct (Rossi et al. 2009). Rather than viewing progress as "sudden unexpected spurts of individual brains", they view such change as a "limitless progression of experiments" (ibid). Without providing too much historical context, the book focuses on artefacts and the persons who first designed or described them. This is done, however, without any strong claim of linearity in the artefacts' development themselves. The authors mainly show the wide variety of technologies that all deal with the basic premise of providing water to society.

Similarly, more modest approaches in general overviews also steer away from claims of grand narratives and/or overarching chronologies. Archaeologist Steven Mithen, for instance, present a series of case studies from antiquity in his 2012 work, *Thirst: Water and Power in the Ancient World*. Although the book opens with the Hoover Dam as a symbol of the dependence on the modern world on "hydraulic engineering", this example is in this case a framing device to examine the extent to which this dynamic also characterised the hydro-social relations of the distant past. *Thirst*'s narrative is not a linear tale of technological progress, but rather a survey of the water management and hydraulic systems in the ancient world (Mithen 2012). The author also highlights a significant limitation of the study, which is relevant to the more ambitious studies we have already discussed—the difficulty of accessing "individual lives and experiences" beyond those of the elite that figure most in recorded history. The book's modest approach extends to the policy relevance of the hydro-social relations of the ancient world: *Thirst* concludes with the observation that the water challenges of the twenty-first century are unprecedented in their scale. Nevertheless, Mithen argues, "understanding the past enables us to see the present more clearly" (Mithen 2012; 296). As historians, we share this inclination toward the social and political value of water history, while cautioning against simplistic attempts to map our current sense of crisis onto those of societies past.

4.3 Towards Water Histories

The formal establishment of the International Water History Association (IWHA) in 2001 has helped to invigorate the study of water history on local, regional, and global levels. Increasing interest in water history was given further momentum in 2009 with the launch of IWHA's journal *Water History*, with the support of publishing house Springer. The new journal wanted to offer a message to its audience of readers and authors of inclusiveness—in the sense that the editors encouraged all kinds of water histories (not only those that examined European or modern contexts), and from all areas of scholarship (Tempelhoff et al. 2009). As water has been such an essential resource for human communities throughout the world, its study contributes to our understanding of economic, political, social, and environmental history, the history of science, medicine, technology, environmental sciences, and geography. Scholars from the humanities, social sciences, sciences, and engineering disciplines have all contributed to the field of water history. The coherence of water history as a subfield arises from its commitment to the disciplinary characteristics of history. Through their formulation of research questions, theoretical approaches, analytical methods, and use of sources, water historians can "transcend disciplinary boundaries" (Sewell 2005, 3) precisely when they remain true to the discipline of history, more precisely, "its careful use of archival or 'primary' sources, its insistence on meticulously accurate chronology, and its mastery of narrative" (Sewell 2005, 3).

The editors also sought complexity, in the sense of a historical narrative that delineated relations between various actors, settings and problems, which would require a high level of detail in the papers. In its 10 years' existence, *Water History* has managed to cover a diversity of topics—ranging from transportation and sanitation to water supply and issues of energy and governance. Given the multitude of possible topics, one of the policies of the journal has been to encourage the publication of thematic issues. The themes of these issues have included methodologies and interdisciplinarity, indigenous histories, Roman canals, and big dams. In addition to the thematic issues on Vienna and the Danube in 2013 and on urban cases in 2016, contributors to *Water History* have published widely on urban water histories in general. This is not unusual, given that water in cities is a major topic in current academic and policy circles. The increasing—real or perceived—water problems in urban areas, the trend of urbanization itself, and the theoretical question as to the extent to which the urban differs from the rural are topics of these historical studies—suggesting again that the history we write is strongly influenced by our own ideas, contexts, and interests.

Despite efforts from the outset to define 'water' as broadly and as inclusively as possible, *Water History* is yet to engage closely with salt water (although the thematic issue of June 2015 on writing water histories includes some articles on sea-related topics). As Rila Mukherjee argued in her 2015 paper, water history encapsulates the "connectedness" of "oceanic, riverine, deltaic and estuarine histories" (Mukherjee 2015, 172). In terms of time periods, contributions to *Water History* are predominantly about the Ancient world (that is, archaeological) and the Roman Empire, or focusing on the nineteenth and twentieth centuries. The term "Dark Ages" may no longer be in vogue among historians, but the scholarship on water history on what is generally labelled as the (European) medieval period is definitely scarce. In terms of regional focus, the majority of published articles in *Water History* discuss water issues in either Europe or Asia. This probably reflects two different realities: USA-based water historians find options to publish within the USA, and there are few water histories of Africa, given the challenges for scholars in terms of budgets, archival access, and publishing options.

The journal is not alone in these specific focus points and gaps. We find a comparable—although not completely similar—composition in terms of book and chapter titles when taking a look at the nine volumes that shape the book series *A History of Water*, which was initiated by Norwegian geographer Terje Tvedt in 2001. The first volume was published in 2006, the last in 2016. The series aims to provide "a long-term historical and comparative perspective to the understanding of the complex relationship between water and society".[1] In contrast to the monographs we discussed above, however, the series aims to analyse "history and societies' development—from the birth of civilization to the present day" by bringing "the myriad confluences between water and society into the picture". In order to do this, Tvedt and his co-editors have brought together 255 scholars from many disciplines and close to 100 countries. As such, the series may claim to provide a universal history of water, but the multitude of voices and accounts needed to do this in fact reinforce our position—that the study of the relations between water and societies requires an engagement with many empirical areas, and does not favour the imposition of a single global (or "grand") narrative.

Taken together, such published water histories provide a rich and varied set of case studies that illustrate the breadth of this growing field. This wealth of topics, time periods, and places indicate the difficulty of forming any overarching history on the relation between water and society. That does not mean, however, that we would argue that all arguments on more general issues or concepts are to be resisted. We do think that it is both possible and fruitful to discuss water histories in a comparative or general perspective. In the following sections, we will offer three of those perspectives, drawn from our own research. We chose these case studies for the mundane reason that we are familiar with our work, have easy access to it, and appreciate the opportunity to reflect on these interventions. The drawback is that we remain within most of the temporal and geographic boundaries we have identified as characteristic of the field. For instance, we discuss ancient and modern times, with little much in between, and we focus on fresh water (or lack of it), ignoring the vast tracts of salt water on planet Earth. Despite these limitations, these examples present opportunities for

[1] https://terjetvedt.w.uib.no/a-history-of-water/.

further discussion about the possibilities of water history in water resource management.

The first case study explores a landscape that seems almost the antithesis of water—the desert—and shows why deserts are relevant to water history. In the second, we focus on colonial irrigation engineers, how they altered the hydrology of landscapes, and how they constructed their professional identity in doing so. Finally, we extend our narrative about engineers into the late twentieth century, shifting to how they deal with and discuss issues of climate and climatic change.

4.4 Deserts and Irrigation

Water is often portrayed as the source of life. On the other end of the spectrum, deserts—or arid landscapes in general—are often portrayed as uninhabitable and useless, barriers instead of bridges. Just as elsewhere, human survival in arid regions depends on human ability to adapt to the natural environment. A major instrument in reshaping arid environments for human prospering is irrigation. The role of irrigation in intensifying production, allowing societies to grow and thrive, is well studied. Much of the available scholarship is produced in the light of a typical image of a full-scale, well-watered agricultural system—as if all irrigation is similar to a Chinese or Balinese terrace system. The stark binary between desert and irrigation system plays on the desire to use irrigation to transform harsh environments into an anthropogenic version of the Garden of Eden. Irrigation as the antidote for deserts has served, and perhaps still serves, the defenders of irrigation as a major symbol of civilization and progress against the marginality and backwardness of aridity. For emerging colonial societies, such images were valuable as they justified state initiatives to develop irrigation. For anthropologists, geographers, and engineers making careers in colonial circles, stressing the marginality of the arid lands to be cultivated and exploited was normal. Here, we show how this narrative of irrigation 'redeeming' the desert is indeed too simplistic (see also Davis 2007, 2016).

Certainly, dry conditions do provide societies challenges to overcome, but there have been many different ways of responding to these pressures. In some well-known irrigation-based societies such as the Hohokam in the Southwest of the United States of America, irrigation seems to have been of a supplemental nature—occasionally bringing water to fields in a growing season. Instead of meeting the demands of crops, as in rice systems where ample water is available, the Hohokam system stored moisture in the soil. Furthermore, Hohokam irrigated agriculture provided roughly 50% of food production, suggesting that exploiting the desert environment was at least as important as watering fields.

The Hohokam is an archaeological culture found along the middle Gila and Lower Salt rivers in the Phoenix basin in the Sonoran Desert—the following discussion is based on the Middle Gila area (Ertsen et al. 2014). The Hohokam culture is renowned for two things: its extensive irrigation canals, which were discovered by European colonists, and the apparent disappearance of Hohokam society after roughly 1450. The Hohokam occupied that area roughly between 0 CE and the middle of the fifteenth century CE.

Originally, as the name suggests, the Classic period (1150–1450 CE) was seen as the core period of a flourishing Hohokam civilization. However, flourishing may be an optimistic way of describing the way that Hohokam society dealt with the challenges of their environment. The Hohokam did develop monumental architecture and extensive hydraulic infrastructure, but life was likely harsh along the Salt and Gila Rivers, with overpopulation, environmental degradation, resource stress, and poor health. We can speculate that social fragmentation was a result of this. The story of the Hohokam is a popular fable for the risks that societies run when they rely on a single source of food production and when they overstress that system. However, the situation was more nuanced and complex than such accounts suggest.

First, even though irrigation was important for the Hohoham, it was not everything. Hohokam people also relied heavily on harvesting wild plants, and they hunted animals as well. At the moment, the best estimates suggest that about 50% of calorie contribution came from irrigated agriculture. The principal irrigated field crops were maize, beans, squash, and cotton. Agave was an important wild plant, used for both fiber and food, but it seems to have been grown within irrigated systems along canal banks as well. Mesquite was a very important wild plant, both for food and wood. Wild mammals were hunted, including rabbits/hares, rodents, antelopes, and mountain sheep, besides birds and fish. Second, in terms of water use, maintenance, and other tasks within the larger agenda of food production, recent research suggests that within the yearly labour and irrigation cycle, several production bottlenecks (in terms of activities to be performed) can be found, related to winter floods, summer monsoons, dry periods, maintenance, planting, harvest, gathering, hunt and the available workforce (Zoric 2015).

The largest bottleneck was in the harvest and planting transition period (late June—early August), as this overlapped with activities like gathering, canal cleaning, and irrigation. Another potential bottleneck was the period of harvesting, where winter floods might arrive to interrupt this activity. The last major bottleneck was the start of a new agricultural cycle in March/April, when floods could destroy both canals and the young crops on the fields. These floods appear to have occurred more frequently than was hitherto assumed. Flood events—very wet conditions—would have been a very critical factor for Hohokam desert agriculture.

The changes in Hohokam society in the second half of the Classic period (1150–1450 CE)—both in terms of lower population numbers and its ultimate disappearance—are often attributed to increasing aridity, but something else may have been happening. Researchers have recently found that the Hohokam area had relatively low ('apparent') water scarcity together with a low runoff variance between 750 and 1000 CE. This moderately dry and relatively calm period may have led to changing dietary contributions from gathering and sedentary (irrigated) farming, with irrigation becoming more important. Around 1150 CE (the beginning of the Early Classic era), increased water scarcity might have resulted in a larger, perhaps more hierarchical cooperative structure in the area.

The period between CE 1275 and 1350 shows the highest incidence of both droughts and floods, compared to the previous two centuries. During these same years, the Hohokam seemed to have witnessed a dispersal of the larger cooperative networks. Although it is not really possible to generalize for the whole Hohokam area, there is evidence that in wet periods people moved away from settlements; many people would have moved back in dry times. These movements might have led to the dispersal of population centers as the Hohokam sought better areas settle elsewhere. A community dependent on irrigation would need to repair the canal systems after a flood, but the higher flood frequency might have demanded more energy to keep the systems working than the gains from cooperative irrigation could sustain.

These specific interactions between humans, water and climate have made and changed the Hohokam and their irrigated landscape over time. One of the striking observations of Hohokam society could be that although the elements that support hydraulic states all appear to be present in the Salt and Gila basins—arid lands, single rivers, people—Hohokam society does not appear to have grown into such a complex state. The danger of a grand narrative approach to the Hohokam may be, however, that it aims to explain precisely why the Hohokam did not develop into a complex society, as if that is something problematic. In a way, such an approach ignores the need that all situations of state development and water need to be explained, whatever state formation process and hierarchical societies one encounters in the archaeological and/or historical record. Building a society is hard work. In the specific case of the Hohokam, recent work by Zhu et al. (2018) shows that the growing irrigation systems would have created problems that could not be solved anymore in ways that created equal options for all members of Hohokam society. With irrigation systems becoming larger, with higher numbers of people being involved, opportunities to keep the costs and benefits of irrigation disappeared. These processes of change in irrigation-based groups need to be understood in detail before one can assess its course of development. One cannot take the outcomes of processes of water-related societal development for granted just like that (Ertsen 2016).

4.5 Modern Water Knowledge: Colonial Irrigation

Irrigation was an important field for most major European colonial powers during the nineteenth and twentieth centuries, especially in areas that were considered as deserts or wasteland, such as parts of Africa, India, and Australia. Even in non-desert areas (with desert defined as arid land), like in the Netherlands East Indies, colonial powers stressed that they had to improve these territories. Engineers especially highlighted the inadequate nature of indigenous irrigation structures, and articulated the import of their own expertise to the civilizing mission in order to strengthen their position within the colonial bureaucracy. In quite a few colonial settings that heavily exploited irrigation, like in the Netherlands East Indies, French North Africa and the British Sudan, a change in colonial policy occurred in the late nineteenth century, moving from mere exploitation to a policy of productive imperialism, in which the colonies' productive capacities should be improved (Bolding 2004; see also Diemer 1990). Irrigation development in the colonies did not only serve the colonial powers, but also had to serve the needs of the colony itself, whether in terms of agricultural needs or environmental conditions.

Most irrigation systems developed by the British in British India were aiming to maximizing economic profit for the state through an increased land tax. Irrigated land was taxed higher than "dry" land, no matter the size of the harvest. The British irrigation approach employed the principle that 'water follows irrigated surface'. Especially after 1860, this policy was developed, when the British introduced the concept of protective irrigation. Protective schemes provided lower amounts of water to large numbers of acres. This water was not enough to realize maximum yields, but was assumed to be enough to produce a crop and especially save food crops during droughts—an assumption that had to be confirmed in actual practice. Water from the subcontinent's rivers was brought to large tracts of land through long canals with many outlets. In order to minimise operation costs, these schemes needed to function with a limited workforce. The schemes also needed to produce a fixed, predictable supply to the land and to be secured against human interference.

The colonial objective for an almost autonomous irrigation system required engineers to adapt to local conditions across the environmentally diverse sub-continent. In the Bombay Agency, British engineers designed structures that could discharge a constant volume independent of changes in canal flow (Bolding et al. 1995); in the Punjab, the translation was sought in an artefact delivering a fixed proportion of the canal flow (Van Halsema 2002). In 1922, engineer Crump introduced new proposals for outlets in the Punjab: The Open Flume and the Adjustable Proportional Module (APM). These basically similar structures consisted of a narrow throat with a sloping sill. Crump had designed his devices in such a way that they could deal with fluctuations in canal water levels and seasonal changes of water levels due to silting or scouring of canal beds (Van Halsema 2002). Crump's artefacts could maintain the delivery of a relatively stable water flow to fields within wide fluctuations of upstream water levels. This success was recognized: in 1944, Open Flume and APM outlets covered 67 percent of all outlets in the Punjab (Van Halsema 2002).

In West and North Africa, French engineers endeavoured to overcome what they saw as a degraded and unproductive landscape. One of their more challenging plans for irrigation had to be realized in the old inner delta of the Niger River (modern Mali). The delta region actually had been and still was an important area for the cultivation of cereals like millet and sorghum, using the soil moisture that was available after the flood season. Nevertheless, the French stressed its desolate character and compared its potential to the Nile—as early as 1899, when Emile Zola expressed the hope that the Niger could be supported in its conquest of the desert and creating a fertile valley to make the river the Nile of the French Empire. Creating the vast scheme proved difficult (Spitz 1949; Diemer 1990). In North Africa, however, French engineers had more success. There they aimed to return the region to its mythical past as the "Granary of Rome", which would cement themselves as successors to the Roman Empire (Davis 2007). Even in Northern Africa, however, the Roman ideal was initially challenged by an Egyptian image: Morocco's rivers would have to be converted into Niles, with the Sebou Plain under cotton generating as much wealth as the Nile Delta.

Around 1930, 'la politique des grands barrages' was formulated, the first irrigation development program for Morocco and indeed North Africa (Swearingen 1984). Another crucial colonial decision was a focus on high-value crops, such as citrus and other fruits, and vegetables. By this time, the rapidly developing agricultural economy of California had replaced Ancient Rome and Egypt as the model to emulate. California also inspired other countries, including Spain, South Africa, Argentina, Russia, Canada, Australia, and other French colonies such as Tunisia and Algeria.

Like their French counterparts, the agents of the Dutch empire were also interested in maximizing crop yields. As the Dutch colonial state levied taxes on actual harvests per unit of land, its aim was to maximize productivity of land. In contrast to the British in India, who tried to maximize the land area under irrigation, the Dutch colonial officials were more interested in maximizing labour inputs on agricultural land to maximize crop yields (Djuliati Suroyo 1987). For Dutch colonial irrigation water followed the irrigated crop: the appropriate amount of water should be distributed when the crop actually needed it. These ideas were translated into design requirements for water distribution structures, which resulted in very different structures compared to those devised in British India. In the Dutch East Indies, the ability to adjust and measure water flows was key. Irrigation management on Java had to be able to adjust to the different crop demands and available flows in the dry East Monsoon or the wet West Monsoon.

The cultivation of peasant crops with commercial crops was a particular issue for Dutch water managers. Peasant crops included rice, and non-irrigated crops such as *polowidjo*, while the commercial crop was sugar cane. Private sugar estates produced the sugar from the cane. They did not own the land to grow the sugar cane. Instead, they rented the land for a period of three years from the Javanese owner. In any other year, the same fields were used to grow rice in the West Monsoon or dry crops in the East Monsoon. With sugar factories renting new land and returning other land back to rice every year, each year the mosaic of fields with cane and rice changed. Furthermore, although rice and sugar cane were irrigated, their different requirements and rhythms created another complex water demand pattern. Rice needed water in the West Monsoon, but sugar cane needed its highest irrigation water gifts in the East Monsoon.

In Dutch colonial irrigation, water was distributed to rice and sugar cane through the same canal system—as the fields for both crops were the same over time—but at separate times. Sugar cane could be irrigated during the day in the East Monsoon, which meant that peasant crops had to be irrigated at night (or from late afternoon onwards). In order to assess the water delivered, which was crucial to determine whether the crop potential could be reached, water distributed for sugar cane was measured with moveable measuring weirs just before the water entered the field(s). This general description already reveals the two pillars of Dutch East Indian water management: (1) water measurement (although in the beginning only for sugar cane) and (2) the need to adjust water distribution over the years. In summary, the main difference between Dutch and British approaches regarding discharge structures in irrigation is a matter of adjustability (see Ertsen 2007, 2010 for further detail).

After World War II, the new political realities of independence for many former colonial areas caused a major shift in context for Dutch and other colonial irrigation activities. For Dutch engineers Indonesia had disappeared as secure field of practice. This new reality led many Dutch irrigation engineers to seek work in other countries, while engineers from other former colonial powers began working in independent Indonesia. These new working realities for Dutch irrigation engineers were explicitly taken into account to defend continuous attention for irrigation in Dutch engineering training programs at the universities of Delft and Wageningen. In Delft especially, irrigation engineering education continued to be an application of design prescriptions developed in the Netherlands East Indies. Until the 1980s, all irrigation professors in Delft had gained their working experience in the Netherlands East Indies. As a consequence, until the 1980s the Delft university irrigation approach reads like a collection of Netherlands East Indian design tools and artefacts. They may have been stripped from their original political, economic and even natural context, but remained firmly grounded in colonial practice. New engineers applied the well-known design practices of their respective colonial practices, which were treated as 'the best possible method' (Dahmen 1997).

Elsewhere, colonial irrigation practices also persist in post-colonial engineering activities (Van Halsema 2002; Mollinga 1998; Bolding et al. 1995; Pritchard 2012). Colonial British irrigation concepts, for instance, continue to influence irrigation in Pakistan and India to a large extent, while French engineers continue to build on the colonial lessons of the Maghreb. The colonial influence on irrigation methods similar informs the definition of different 'schools' or approaches: The Dutch in the former Netherlands East Indies, and the British in South Asia and Britain's former African territories, the French in north-western Africa (Ertsen 2010; Dahmen 1997). Although the activities of international bodies such as the World Bank and the International Commission on Irrigation and Drainage suggest the existence of an international, homogeneous body of engineering knowledge, these separate approaches to irrigation continue to pervade the practice of water resource management (Plusquellec et al. 1994).

4.6 Water and Climate

As the Hohokam and the approaches of European empires to colonial irrigation suggest, how a society understands its climate (and the extent of climate variability) influences the ways that society manages its water resources. This understanding of climate is inherently historical, drawing directly on past experience or through information transmitted by oral and written cultures. The implication of such thinking is that humans have experienced the full range of climate extremes of a particular place, and that future conditions will not exceed these expectations. The principle of stationarity enshrines such an approach and provides the foundations for planning, designing and operating water infrastructure (Jones and Brooke 2005). It assumes that neither the prevailing extent of climatic variability nor the relationships between the major climatic variables, such as rainfall and temperature will change. Yet this basic principle of water management is being undermined by climatic change in a warming world—researchers at the US Geological Survey even declared "stationarity is dead" in 2008 (Milly et al. 2008). For water managers, the past is no longer a guide to the future. This shift indicates the extent to which historical thinking has been a part of water management over the last century (Morgan 2011a). In this section, we examine the Australian experience of coming to terms with this shift in perspective during the 1980s.

By the end of the 1980s, the increasing scientific and political concern about anthropogenic climate change and its likely impacts had begun to seriously challenge conventional approaches to environmental management. Although scientists had made significant advances in their understanding of the greenhouse effect in the 1970s and early 1980s, the potentially harmful effects of increasing atmospheric carbon dioxide levels were yet to stimulate political action. But a small group of scientists endeavoured to inform Western nations about the growing scientific knowledge of the enhanced greenhouse effect (Bodansky 2001, 27). The well-publicised Villach meetings of the mid-1980s proved to be especially influential for the ways in which scientists and policymakers imagined and planned for a greenhouse future.

At a joint meeting of the United Nations Environment Program, World Meteorological Organization (WMO), and International Council of Scientific Unions in 1985, participating scientists presented their findings on the emerging climate question. They agreed that increasing concentrations of greenhouse gases would lead to an unprecedented rise in global mean temperature in the first half of the twenty-first century. In the preface to the conference proceedings, the editors presented what is referred to as the 'Villach Statement'. It read:

> Many important economic and social decisions are being made today on long-term projects … all based on the assumption that past climatic data, without modification, are a reliable guide to the future. This is no longer a good assumption since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century (WMO 1985).

Climate data from the past could no longer provide a reliable guide to future conditions—the future was uncertain (Morgan 2011a, 162).

This developing climate change agenda prompted Australia's peak scientific body, CSIRO (the Commonwealth Scientific and Industrial Research Organisation), and the federal government to convene the Greenhouse87 conference in late 1987 (Morgan 2011b, 99). Greenhouse87 was the first national meeting of scientists and resource managers to discuss the potential socioeconomic and environmental effects of anthropogenic climate change for Australia. The basis of these discussions was a CSIRO climate scenario for the year 2030, by which time the concentration of carbon dioxide in the atmosphere was expected to have doubled. The resulting changes in the atmospheric circulation would cause a decline in the rainfall of the southwest region of Western Australia, which extends from Geraldton to Esperance and is home to the overwhelming majority of the state's population (Pittock 1988, 42).

With less frequent rainfall and higher temperatures, this scenario depicted a significantly drier and warmer future for the southwest in the twenty-first century (Pittock 1988, 43). What made the prospect more alarming was that the southwest region had a reputation for having the most consistent and reliable rainfall in the nation. The rest of the continent is more susceptible to the effects of the El Nino-Southern Oscillation and other global climatic processes, which leads to extremely variable rainfall from year to year (Nicholls et al. 1997, 66). The southwest's renown for reliable rainfall had therefore played an important role in attracting colonists to the region and influenced the dryland agricultural practices that farmers had developed there since the early twentieth century (Morgan 2014). According to CSIRO's scenario, however, the region's future climate might be less suitable for prevailing practices of land and water management. Although this was not the first time that the declining rainfall of the southwest had been linked to anthropogenic climate change, Greenhouse87 altered the landscape for decision-making about the region's water resources (Morgan 2011a, 163).

Water managers from the state's water utility were invited to respond to this projection of a drier future for the southwest. The findings of the Villach meeting had resonated closely with their observations of a period of dry years since the 1970s with lower than normal winter rainfall (May, June, July). The contrast of this trend with the region's reputation for reliable rainfall had made the pattern all the more apparent to them. The local reservoirs were especially affected: at the time they provided seventy per cent of the region's potable water supplies (Mauger 1989, 16). To supplement the dams, the water utility relied increasingly on the groundwater reserves beneath the Swan Coastal Plain, but these too were susceptible to the drier conditions that were underway (Morgan 2015).

Three Western Australian water managers attended Greenhouse87 to present their utility's position on the implications of a changing climate in the southwest. Comparing the recent rainfall records to the trend identified in the Greenhouse87 scenario, they suggested that the expected drop in rainfall might have already commenced in about 1970 (Sadler et al. 1988, 299). As a result of the Greenhouse87 prediction, they assumed that the drying trend already underway would continue to the middle of the twenty-first century, leading to a twenty per cent reduction in rainfall and an even greater decline (over forty per cent) in the average streamflow of the region's rivers, due to the relationship between soils, climate and vegetation in catchment areas (Sadler et al. 1988, 299–300). With lower rainfall and streamflow, they expected that demand for potable water would surpass the available supplies more quickly than they had previously expected. This revised forecast suggested that water supplies could be insufficient by as early as 2020, rather than lasting until nearly 2040. Other sources of scheme water would have to be found and demand for water would have to be curtailed as soon as possible.

Planning for drier conditions in a warmer future required water managers to reconsider one of the very basic assumptions of water management, that of stationarity. Stationarity assumes that the climate conditions of the past will continue indefinitely. This relationship between the past, present and future was a comforting prospect for water managers who had to contend with other variables, such as water demand and water quality. But neither the drying trend since the 1970s nor the Greenhouse87 scenario suggested a stable, static or predictable climate. Instead, the local water managers saw that the southwest's climate could be variable and uncertain, with no guarantee that future climatic or hydrological conditions would reflect those of the past. They could no longer rely on the historical record alone to determine their planning for the future (Morgan 2015).

The Greenhouse87 prediction of a drier future thus led local water managers to reconsider the trends and fluctuations of rainfall and streamflow within the data set (Ludwig 2009, 80). Until the late 1980s, their planning had considered the entire meteorological record in the southwest region. But wetter conditions in the earlier half of the twentieth century had obscured the below average rainfall that had prevailed since about the drought of 1969. Restricting the historical record to the more recent past gave water managers what they believed to be a more realistic view of the future, given their new expectation of drier greenhouse conditions. Excluding the statistics from the wet 1930s and 1940s "reduce[d] the estimated yield of river resources by about 13 per cent", producing a vision of the past that was more congruent to the possibility of a drier southwest (Mauger 1989, 30). No longer were the run of dry years from the 1970s only temporary. Instead, these drier conditions were permanent and worsening as part of a broader trend of a changing global climate.

This new interpretation led water managers to dismiss an alternative climate scenario for the southwest region. At the Greenhouse88 Conference in November 1988, the Perthoffice of the Bureau of Meteorology presented a second scenario that considered the impact of a larger increase in greenhouse gas emissions than the Greenhouse87 option

(Hille 1989, 12). Higher greenhouse gas emissions, the meteorologists suggested, would affect the winter atmospheric conditions of the southwest and actually produce a slight increase in rainfall (Hille 1989, 13). But the lower rainfall levels since the 1970s suggested to water managers that an increase of rainfall in the future would be unlikely. Furthermore, the coincidence of the Greenhouse87 meeting with two winters of below average rainfall in the southwest reinforced their conviction that dry conditions could continue (WAWA 1987, 27). Their decision-making reflects the view that "environmental claims are most often honoured when they can piggyback on dramatic real-world events" (Ungar 1992, 483). Their position also reflected an adherence to the precautionary principle, which was later elucidated at the Rio conference in 1992 (Dovers and Handmer 1995, 92–93). The choice between the two scenarios was especially significant, as the different futures they presented would require very different planning strategies and investment in water infrastructure. If the water utility invested in infrastructure for lower winter rainfall but the predictions were not fulfilled, the consequences would be less disastrous than if they had invested for higher winter rainfall but received less.

The prediction for the future also altered the way water managers interpreted the past: no longer were the dry years of the 1970s and 1980s a temporary drought, but rather part of a long term, permanent and worsening trend, which required accelerated development of other sources of water supply for the thirsty region. This new understanding changed the way the historical data was incorporated into planning decisions Instead of utilising the entire historical record, the water managers took a much shorter excerpt of more recent data, which excluded earlier periods that did not conform to the emerging pattern of a drying region. Their pragmatic approach to the past suggests that both water managers and historians have a shared interest in exploring how the past can shed light on the circumstances of the present and the future.

4.7 Drop in the Ocean…

Whether drawing on the knowledge of past climates, emulating ancient civilisations, or perpetuating colonial irrigation methods, these case studies suggest that historical thinking has long permeated water management. Implicitly or otherwise, water managers turn to the ways that other peoples have addressed their own water challenges—challenges that are inherently about the relationships between society, water, and the environment more generally. We have critiqued grand narratives of water history especially for this reason. Grand narratives overlook how water histories are neither universal nor stable and neutral entities. Instead, water histories are mobilized for many different visions of the relationships between people and place.

As we have shown, European colonial powers portrayed themselves as the successors of earlier empires—if not Roman then certainly Mesopotamian or Egyptian. But they were not the first to position themselves in this way—the Assyrian empire likewise stressed the benevolent role of the imperial state in converting arid desert to irrigated paradise. Indeed, many early civilizations seem to have used irrigation agriculture to feed their (growing) population, including Mesopotamia, Egypt, the Indus Valley, China, Mexico and Peru. These ancient examples have encouraged scholars to interpret irrigation as fundamental to the growth of urban elites, forming the basis for grand narratives such as Wittfogel's model of hydraulic civilizations.

When the first issue of *Water History* was in preparation, the editors faced the task of identifying an appropriate symbol or image to encapsulate its vision. The editors sought to represent the field's unity and unique identity, without suggesting the existence of a single, overarching narrative, nor the impossibility of bringing different voices together (Tempelhoff et al. 2009). What would be a suitable picture for the first issue of a new journal? From the start, the editors agreed that an image that would reflect the grand narratives of water—like an aqueduct, huge canal or impressive dam—would be less desirable. Eventually, the editors selected a tide mill from Île de Bréhat in western France, constructed in the first half of the seventeenth century. As the name suggests, such structures generated energy from the tide.

> Often referred to in the past as 'salt mills', 'salt water mills' or 'sea mills', tide mills worked, on the simple principle of impounding water at high tide behind a barrier (or dam) on the foreshore. As the tide rose, water entered a tidal millpond through a sluice gate in the dam which closed at high water. When the tide dropped sufficiently to leave the waterwheel free of the water that would impede its rotation, the impounded water in the millpond was released to turn the wheel to allow milling to start. Milling ceased when the rising tide reached the waterwheel again or when the millpond was empty (McErlean and Crothers 2008, 16).

Selecting a tide mill for the journal's cover, the editors hoped, would encourage readers to reflect on *Water History*'s aims, the historical analysis of the material and cultural uses of water, and the meanings attached water in particular places. Tide mills operate in particular physical contexts, in terms of location, flows, and rhythms. The ideal location of a tide mill is on coasts with sufficient tidal range, preferably with small inlets or estuaries that can be easily blocked with a dam to provide the mill with its pond. In this sense, the cover image served an important purpose—to remind readers that seas and saltwater were as relevant to water history as freshwater. Studying a map of Europe reveals a concentration of mills in southeast England, the French west coast (where the Île de Bréhat example is located), Belgium, the Netherlands, north and southwest Spain, and southwest Portugal (McErlean and Crothers 2008; Minchinton 1979; Charlier et al. 2004; Van der Veur and Van Wijk 1999). From Western Europe the technology was exported to the Americas (Newman and Holton 2006) and Australia (Preston 2001). The discovery of seventh-century tide mills in Northern Ireland and a Roman tide mill on London's Fleet River in the past two decades suggests that tide mills have been in use in Europe for centuries (McErlean and Crothers 2008; Spain 2002).

The analysis of a tide mill also requires attention to its social position and the many ways relations were built with other agents in the wide society. Why would people be prepared to invest considerable amounts of labor and material to build and maintain such a structure? What forces drove the industries supported by the mill? Perhaps using the tide was their only choice, but it could also have been the best option for certain groups. The tide mill typically operates in salt water environments and only under particular conditions (such as storm swells, etc.). There is also a temporal dimension to the operation of the mill: as the tidal sequence shifts in time, milling operation times shift as well. Occasionally, mill operators had to work during the night to sustain production. How was the labor needed to maintain the mill organized? Who was responsible for organizing and managing this labor? Keeping the mill working was a clearly challenge, but the yields must have warranted the effort. Which products were made in the mill? How was the production transported to consumers or users, and over what distance?

The tide mill's technical features also require analysis. These include the tidal range, the resulting forces on the mill, and the energy required and delivered for particular uses. The engineering aspect of these structures is intriguing, as Spain's (2002) study of the possible Roman tide mill near London suggests. Studying such a structure, or finding one, also raises new questions about the social context in which it functioned. The discovery of the remains of two tide mills at the site of Nendrum Monastery (Northern Ireland) has stimulated reinterpretations of earlier ideas about the development of the monastery (McErlean and Crothers 2008). Excavations have shown that the reservoir that was once thought to be a fish pond, was in fact a mill pond for a tide mill. The monastery's resources, including its capacity for food production, the availability of labour and timber, and its willingness to invest these in the mill, had to be reconsidered.

All societies know spirituality, liberty, rationality, history, but in different ways that are continuously negotiated and contested over time. As such, all water histories are local and constructed, crafted in response to the changing relationships between people and water. Consequently, we encourage closer methodological attention to the agency of historical actors and to the specificity of the historical and environmental contexts. The wealth of water histories available points to the opportunities for more diverse and comparative studies of how people have understood and managed water in the past. Further still, they show how water histories are fundamental to the practice of water management, then, now and in the future.

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Maurits W. Ertsen is associate professor within the Water Resources Management group of Delft University of Technology, the Netherlands. Maurits wants to know how irrigation realities emerge from short-term actions of (non-)human agents. Sustainable water management, closely associated with success and collapse of human civilizations, has become crucial given cur-rent climate variability. Maurits studies how longer-term water practices emerge from short-term actions of human and non-human agents in current, historical, and archaeological periods in places ranging from Peru to the Near East.

He holds a M.Sc. degree in Irrigation Engineering from Wageningen University and a Ph.D. degree in History of Technology from Delft University of Technology. His two books discuss colonial irrigation in Sudan and Indonesia. He has co-edited a volume on human niche construction in the Rachel Carson Center Perspectives Series.

His 60+ book chapters and journal articles range in terms of topics from building interdisciplinary understanding of irrigation and survival strategies of ancient communities to developing methods to study relations between humans and hydraulics through modeling.

Dr. Ertsen has been one of two main editors of Water History, the official journal of the Inter-national Water History Association (IWHA), since its inception in 2009 until December 2020. He has been involved in the leadership of that same association between 2003 and 2017. Cur-rently, he is council member of the International Consortium of Environmental History Organ-izations (ICEHO). In the Netherlands, he is coordinating editor of the Dutch journal of Water History.

Ruth A. Morgan joined the School of History at the Australian National University in July 2020. She is an environmental historian and historian of science with a particular focus on Australia, the British Empire, and the Indian Ocean world. Her research focuses on the changing relationships between people and their environments, with a particular interest in water resources and climate variability.

She is a co-investigator on an Australian Research Council (ARC) Discovery Project on the water history of urban Australia. She is Lead Author for the IPCC Sixth Assessment Report, Working Group II (2021). She has held an ARC Discovery Early Career Researcher Award and a Postdoctoral Research Fellowship from the Alexander von Humboldt Foundation.

In addition to over 25 refereed journal papers and book chapters, she has authored or co-edited five books. She has had nearly 50 papers accepted for international conferences including events of the American Society for Environmental History, American Historical Associa-tion, European Society for Environmental History, and International Conference of Historical Geographers.

She is a member of the executive committees of the Australian Historical Association, the International Water History Association, the International Commission on the History of Meteorology, and the International Consortium of Environmental History Organisations.

5 Water Ethics

David Groenfeldt

Abstract

The growing appreciation for the diversity of water values—ranging from the spiritual to the economic—highlights the challenge of making water management decisions that do justice to different and often conflicting values. Water ethics offers a systematic approach to making water management decisions consistent with society's values, while at the same time holding up the values themselves for critical examination. While the term "water ethics" is rarely encountered in the water literature, water governance best practice reflects key normative value principles including integrity, stewardship, social and environmental justice, ecosystem services and rights of nature. The added value of a systematic approach to water ethics is to render existing norms of water governance more explicit and identify value gaps and synergies. This has been the focus of a recent initiative to formulate a Water Ethics Charter, building on earlier work by UNESCO and the Botin Foundation, and a parallel campaign by Indigenous water protectors to elicit international recognition of culturally diverse ontologies of water. As climate change brings keener awareness of values-based water conflicts, there will be a growing need for new tools of mediation and resolution. The developing field of water ethics can contribute to new solutions.

Keywords

Water values • Water ethics charter • Indigenous water protectors • UNESCO

D. Groenfeldt (✉)
Water-Culture Institute, Santa Fe, NM 87505, USA
e-mail: dgroenfeldt@waterculture.org
URL: http://www.waterculture.org

Department of Anthropology, University of New Mexico, Albuquerque, NM, USA

5.1 Introduction

Ethics refers to the broad value principles and rules, whether tacit or explicit, that provide guidance about the proper course of action. Decisions about water management and policy cannot *not* reflect underlying principles embedded in society and culture. While individual psychology also matters, the field of ethics focuses attention on collective standards of behavior. By understanding what we value about water and the natural ecosystems where water is found, and what we value for our own lives as members of multilayered human communities, we can assess, or "reflect upon" the wisdom of a potential course of action. Ethics is our platform for judging whether a potential action would be desirable or not, and for guiding our vision for what the UN Sustainable Development Goals refer to as, "The World We Want".

Ethics, in other words, provides a framework for considering the implications of our values, and helping us to assess whether the values we hold are actually the values we wish to keep holding. If I place a strong value on the rights of companies to dump their manufacturing waste into the nearest river, the ethical implication is that government should not regulate water pollution. But if an implication of this value (the right to pollute) is that children are dying from carcinogenic contaminants in their drinking water, I might be motivated to revise my values and adopt the value proposition that human health is more important than the freedom of companies to pollute. The ethical implication following from my re-prioritized values is that water pollution should be regulated after all.

Values cannot protect our water supplies; values can only theorize that clean water is a high priority. The ethical implication of the high value placed on clean water is that we should regulate water pollution, or we should impose stringent drinking water standards, or the city should provide free bottled water to all residents whose tap water does not meet drinking water standards, as was ordered by a judge in Flint, Michigan for several months during the Flint water

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crisis (Clark 2018). There can be many alternative responses to a situation of water-related harm, defined as a violations of values (Ziegler et al. 2017). But identifying the situation as a problem (e.g., lead levels in Flint children should not be so high) depends on having values about the importance of children's health and the equal rights of people regardless of race or class to enjoy safe and affordable water. Without strongly held values about human welfare, water regulators in Flint ascribed the high lead readings to other environmental factors (leaded paint) or sampling errors (Clark 2018). Having the right values is essential to formulating ethical principles that align with those values, though ethical reflection is still needed to guard against perverse outcomes of bad values being reinforced by bad ethics.

5.1.1 Recognizing Values

Values about water, beyond the usual economic values, are finally getting serious attention in many venues: the UN High Level Panel on Water's "Bellagio Principles" on valuing water (HLPW 2017); the Vatican conference on water values on World Water Day in 2017 (worldwatervalues.org), and American water utilities sounding the alarm for greater investments in urban water infrastructure (thevalueofwater.org). Water is increasingly recognized as something more than a factor of economic production, and rivers are viewed as more than nature's plumbing systems. Managing water effectively entails addressing the complex range of cultural, social, and psychological values embedded in water policies, projects, and investments.

Values are resources that, like water itself, can help us attain our broad social, economic, and environmental goals —the well-known "triple bottom line". Values operate at a foundational level where we formulate the specific goals and objectives to be achieved through water policies. This relationship was laid out by Ralph Keeney (1992) in his book, *Value-focused Thinking: A Path to Creative Decision-Making* and later elaborated by management guru, Richard Barrett (2014), in his notion of "values-driven organizations". It is not money, fame, or even sex that directly motivates people; rather, people are motivated by their values about the importance of attaining these (and many other) goals. Values are powerful but messy. Our values, goals, and specific objectives need to be sorted out carefully and deliberately. This is where ethics, and specifically "water ethics," comes into play. Ethics is the art of deciding what action should be taken in light of one's values, while at the same time holding up the values themselves for critical examination. Will the expression of these values lead to good outcomes?

Ethics, in other words, should be part of our decision support toolbox. Should the proposed dam be approved, modified, or rejected? Cost–benefit analysis cannot deal with intangible values very well. Legal arguments about the dam might invoke moral arguments, but legal decisions are based on existing laws, which usually reflect old ethical assumptions. The growing interest in water values is framed as a way of bringing a broader and more contemporary perspective to bear on water decisions. But then what? Where does the path of values-analysis lead us? Are we simply enlarging the chorus of values-driven special interests? How can we promote water decisions that respond to the greater societal good, rather than to the strongest pressure group?

While it would seem that an ethics perspective would offer a valuable complement to conventional water decision-making methods, it is almost never used in any systematic way. Very few analytical reports on water use the words, "ethics," "ethic" or "ethical" even in the context of discussing water values, the building blocks of ethics. For example, a recent Science Magazine article on "Valuing water for sustainable development" (Garrick et al. 2017) does not mention ethics. The final report of the UN High Level Panel on Water (HLPW 2018) presents five principles for valuing water "in all its dimensions….which may be cultural, spiritual, emotional, economic, environmental, or social" but without any mention of ethics. The UN report suggests that reconciling conflicting values be done "in ways that are equitable, transparent and inclusive." But with no reference to ethics, what would be the basis for prioritizing some values over others? How will allowable pollution levels be decided? What does it mean to "protect" water sources or to provide "equitable" access to safe water?

5.1.1.1 Money Isn't Everything: The Case of the Orme Dam

In the simpler era of the late 20th Century, conflicts over water values were typically settled by economic cost–benefit analysis, based on monetizing the value of various costs and benefits. This approach assumed that different sorts of values were somehow commensurable and could be expressed on a monetary scale. The Orme Dam, proposed in the 1970s to be built on the Verde River near Phoenix, Arizona, would have inundated nearly two-thirds of Yavapai Indians' territory. Along with their land, their ancestors' graves would be lost, as well as the nesting area for several bald eagles. The Yavapai perceived that their entire culture was at stake. The tribe had suffered a history of hardships during nineteenth-century conflicts with the US military; their lands had been reduced, but their legal rights to their remaining lands, on the Fort McDowell Reservation, were secure; the Yavapai tribe could take a lucrative settlement and move to another location, or they could stay on their land and forgo the money. In a 1976 referendum, the tribal community voted against selling their land for the dam. The tribal chairman accepted their vote: “I have heard my people's answer. I don't care if you give a million dollars to each and everyone of us. Our answer will still be no” (as cited in Espeland 1998, p. 208). November 12th, the day the US secretary of the interior officially withdrew the dam proposal in 1981, has since become an occasion for celebration: the Orme Dam Victory Days, an annual event of the Fort McDowell Yavapai Nation.[1]

5.1.1.2 Ethics of Water Quality

The topic of Water Ethics takes on a fundamental importance in dealing with the ethical principles underlying the use and protection of the essential basis of life itself: water. What could be more important than the ethical principles by which life itself is protected? There is an intuitively obvious need for assessing whether a proposed drinking water standard for a particular class of chemicals—Let's take the case of PFAS-related chemicals—strikes the right balance between what is possible and what is desirable. An ethicist might ask why the maximum PFAS level recommended by the US government's public health agency[2] is seven times lower than the level recommended by the policymakers at the US Environmental Protection Agency. What value principles are being expressed in the divergent recommendations?

An ethicist would consider society's responsibility to protect public health, potential effects on natural ecosystems, and implications for the industries using these chemicals. Sadly, but not surprisingly, “ethicist” is not part of any job description that I am aware of within the water sector. While ethics are always operating, albeit tacitly, to guide water decisions, analysis of those ethics is rarely conducted. We are quite literally managing our water—the basis for all life—without considering the ethics of what we are doing. Should we adopt EPA guidance on PFAS levels, or the far more stringent levels proposed by ATSDR?

The ethical tools that we have developed within the water sector revolve around a few basic principles that are non-controversial, such as transparency and anti-corruption, the human right to water and sanitation, and the importance of sustainability, participation, and social justice, including gender equity. These issues can be addressed within the dominant water paradigm of Integrated Water Resources Management (IWRM) which views water as a resource that needs to be managed in an integrated way. So long as we can continue to live within the established liberal world order (Ikenberry 2018), we can settle our disputes the way we always have done, but our days may be numbered. Whether for reasons of feeling drawn to a different world, or pushed out of our old world, we will need to confront bigger water-related controversies: Should we be building more mega dams (already in the pipeline) or decommissioning existing dams? Under what conditions should mining be carried out? Should nuclear power be part of our future? Can we create a different food system based on agroecology and plant-based proteins? Will the oceans become our gardens or our waste stream? Will rivers become cleaner or dirtier? Will they flow more or flow even less?

5.1.2 The Emergence of Water Ethics

The formal study of ethics applied to water owes its establishment largely to the 1998–2004 UNESCO-COMEST initiative on Water and Ethics (Delli Priscoli et al. 2004). A background paper on “Ethics of Freshwater Use” (Selborne 2000, pp. 7–8) presented six universal ethical principles “directly applicable to the issue of water”: (1) human dignity, (2) participation, (3) solidarity, (4) human equality, (5) common good, and (6) stewardship. The initiative produced a series of fourteen reports on various aspects of water ethics, ranging from gender to groundwater to environment, plus an integrative report, *Best Ethical Practice in Water Use* (Brelet and Selborne 2004). A few years later, the Bangkok office of UNESCO produced a report on *Water Ethics and Water Resource Management* (Liu et al. 2011) as part of the project on “Ethics and Climate Change in Asia and the Pacific.” And just recently, UNESCO-COMEST undertook a broader assessment of water ethics, including the oceans, under the title “Water Ethics: Ocean, Freshwater, Coastal Areas” (COMEST 2018).

The UNESCO initiatives had the dual purpose of highlighting how ethics plays a role in decisions about water use and management and in prescribing what that role should be. These themes were continued by the Botin Foundation in Spain, which sponsored two seminars on water ethics in 2007 (Llamas et al. 2009) and 2010.[3] Independent from this “UNESCO lineage” is the work of David Feldman whose book, *Water Resources Management: In Search of an Environmental Ethic* (Feldman 1991), pioneered the application of environmental ethics to water management within the United States, and Sandra Postel, who demonstrated the relevance of ethics to water with her book, *Last Oasis: Facing Water Scarcity* (Postel 1997).

The field of Water Ethics today is still in a state of emergence, and can be described as a main stem of “water

[1] https://www.fmyn.org/event/orme-dam-victory-days/.

[2] The Agency for Toxic Substances and Disease Registry (ATSDR), a division of the Centers for Disease Control and Prevention at the US Department of Health and Human Services.

[3] See Llamas (2012) and Delli Priscoli (2012) for an overview of the 2010 seminar.

ethics" proper, complemented by a number of new branches addressing normative dimensions of water governance, but without using the ethics label. These branches of water ethics do not self-identify as "water ethics" but promote strong norms that are ethics-like in character: (1) Water integrity, (2) Water stewardship, (3) Water justice, (4) Ecosystem services, and (5) Rights of Nature. These branches share the overarching goal of sustainability, emphasizing complementary aspects of this concept ranging from the institutional (Water integrity) to the social (Water Justice) and the environmental. A sixth branch of water ethics runs counter to the sustainability paradigm, advocating for a normative system of water behavior that can be labeled as "Water Extractivism". This "anti-ethic" fits within our loose definition of water ethics as comprising a set of values and general principles about water which its proponents regard as desirable and in this sense "good". Taken together, these six branches of water ethics constitute an "ecosystem" of normative approaches to water within which the field of "water ethics" proper exists as an island of self-identifying specialists who deliberately employ the terms, *ethic*, *ethics*, and *ethical*. These six branches, plus the main stem of water ethics, are outlined below.

5.1.3 Six Branches of Water Ethics

1. Water integrity. With roots in the anti-corruption movement, the concept of water integrity centers around transparency, accountability, and participation. Transparency refers especially to information about water infrastructure and service contracts as well as water data. Accountability refers to budget processes as well as the maintenance of professional standards of good practice. Participation refers to stakeholder engagement in water planning and policy decisions, and can also refer to direct management participation of water users in operating irrigation systems or urban water supply systems. The Water Integrity Network (https://waterintegritynetwork.net) is the institutional home of water integrity focusing especially on institutional capacity building of operators and decision makers in urban water supply systems (WIN 2016).

2. Water stewardship. Water stewardship has become the catchword for corporate social responsibility within the water sector. The CEO Water Mandate, a UN-affiliated initiative, and others within the business community have adopted the term to describe their sustainable water activities. For example, Business for Water Stewardship (https://businessforwater.org) partners with the National Geographic program *Change the Course* (https://changethecourse.us) and other initiatives to provide, "a portfolio of services that catalyze business engagement and leadership in environmental water stewardship" (Business for Water Stewardship 2018). The Alliance for Water Stewardship (AWS, https://a4ws.org), a partnership of environmental organizations, businesses, research institutes, and others, has developed the Water Stewardship Standard, a detailed set of guidelines certified by trained compliance consultants. The standard is concerned primarily with environmental indicators but also includes some social justice and engagement indicators.

3. Water justice. While social justice has long been a recognized theme of water activism, there has been a more recent application of "water justice' as an overarching perspective on water (Zwarteveen and Boelens 2014; Harris et al. 2017; Sultana 2018; Boelens et al. 2018). What distinguishes water justice as a field is the reinterpretation of recognized moral concerns about water rights—such as intergenerational justice, water rights of Indigenous Peoples, and health impacts from water contamination whether from chemical spills, agrochemical runoff, mine tailings, oil and gas pollution, etc. Water justice refers to the ways in which water is allocated to competing demands of agriculture, industry, cities, etc. and within each of these use sectors, who gets how much water and how safe is that water for people and nature.

4. Ecosystem Services. The looming environmental crisis has prompted the development of new ways to value the natural environment, including water ecosystems. The concept of ecosystem services recognizes the broad range of benefits that society derives from natural ecosystems, and tries to measure the value of nature's services, typically in monetary terms. The approach has led to new appreciation for the economic value of recreation and non-consumptive uses of rivers, including their existence value and the role of protected areas as reserves of biodiversity (CAPNET 2016). While non-economic benefits such as spiritual communing with nature, or the pleasure of viewing the beautiful river, are theoretically included as an ecosystem service, ascribing values to non-marketable benefits is challenging. The result has been an over-emphasis on economic values that can be measured and monetized, and an under-emphasis on subjective benefits that cannot be monetized (Boelens et al. 2014).

5. Rights of Nature. No longer the exclusive domain of philosophers specializing in environmental ethics (e.g., Nash 1989; Boyd 2017), the idea that we should recognize nature's intrinsic rights has entered the constitutions of Ecuador and Bolivia, and it receives serious attention within the United Nations.[4] In addition to inscribing rights of nature into national laws, another approach is to claim legal rights of personhood for rivers (Iorns Magallanes 2019) based on

[4]Following the Rio + 20 meetings in 2012, the United Nations launched a "Harmony with Nature" website featuring examples of national legislation aimed at protecting nature, https://harmonywithnatureun.org/.

the precedent-setting personhood accorded to the Whanganui River in Aotearoa New Zealand.

6. *Extractivism.* This last branch of water ethics refers to the application of moral arguments to justify what can also be viewed as, "the excessive and irresponsible exploitation of natural resources in order to meet the growing 'needs' of our over-consumerist societies" (France-Libertés 2017, p. 6). "*Extractivism* is a mindset and a pattern of resource procurement based on removing as much material as possible for as much profit as possible" (Willow 2019, p. 2). In countries experiencing "regulatory capture" (Dillon et al. 2018) by corporate interests, an ethic of extractivism becomes written into national environmental regulations, including water policies. An illustration is the Trump Administration's rollback of clean water regulations at the behest of industry, and the earlier exclusion of the coal, and oil and gas industries from complying with the Clean Water Act. Justifications range from providing jobs to national security (energy independence) and in the case of sacrifice zones on tribal lands in the American Southwest during the Cold War, for weapons production (Voyles 2015). This "dark side" of water governance makes use of monetized values and normative value principles (ethics) to justify social inequity and ecological harm. Treating the "anti-ethic" as itself a type of ethics might seem preposterous, but if we are to develop a legitimate field of water ethics, we can ill-afford to exclude viewpoints that we disagree with. Better to include the dark side as a type of ethics which is subject to the same ethical assessment as all other types.[5]

The net impact of these approaches—integrity, stewardship, justice, ecosystem services, rights of nature and even water exploitation—is an emerging discourse about how to think about water and how to respond to increasing water stress and climate change. "Integrity" in water governance is about cleaning up the governance process (anti-corruption and transparency), but it also begins to address professional integrity and governance outcomes. "Stewardship" is primarily an environmental concept, though it can also include issues of labor conditions and social justice. "Water justice" is about people in a broad context, including intergenerational environmental justice. Ecosystem services is, of course, environmentally focused, but the implications extend to economics and culture, while the deeper issue of "rights of nature" goes beyond environmental ethics per se to the ethics of respecting Indigenous cultures who see nature as sacred. It is no coincidence that the two countries to adopt "rights of nature" provisions into their constitutions, Ecuador and Bolivia, also have majority Indigenous populations. Conversely, the approach of water extractivism is built around the interests of investors and political opportunists seeking to profit from the impending chaos of climate change.

5.1.4 The Main Stem of Water Ethics

Having considered these six branches of ethics-like schools of thought, we turn now to the main stem of water ethics, the only one which self-identifies with an ethics terminology of ethic, ethics, and ethical. These words contain important nuances of meaning. The word "ethic" refers to a particular set of principles, while "ethics" has two different meanings: (1) As the plural of ethic, it refers to distinct and different sets of principles; and (2) As a singular noun that does not have a plural version, "ethics" refers to the overall field of knowledge about ethical principles. Applying these meanings to water, we have "water ethic" which refers to one coherent set of principles about how water ought to be managed, "water ethics" (plural noun) referring to multiple and often competing sets of principles, and the field of "water ethics" (singular noun) referring to the study of ethical principles related to water.

Ethics introduces the integrative reference of "the good" as a decision-making gold standard. It sounds elusive because it necessarily is. If values are the Christmas tree ornaments, ethics is the tree, the principles underlying the values. Some of these ethical principles are couched in the language of rights: the human right to water; the cultural right to traditional spiritual practices; the natural right of a river to flow, and the right not to be discriminated against on grounds of gender, race or culture. Other ethical principles are derivative principles articulating specific standards for management of water resources, e.g., the principle of management subsidiarity (Dublin Principles 1992) which derives from the ethical value of democratic governance, and the principle of water as a commons, elaborated by Nobel-laureate Elinor Ostrom and others.

5.1.4.1 A Water Ethics Framework

Analyzing or "reflecting" on water values can be facilitated by a framework that focuses our reflection on particular domains or categories, and on the interactions across value categories. This process of ethical reflection helps in sorting out the values and deciding which are most or least important. But ethical reflection aims higher than merely

[5]The ethics of water exploitation is often couched in terms of freedom from national-level environmental regulations in favor of more easily captured local regulatory bodies. For example, the 2016 Platform of the US Republican Party states, "We must never allow federal agencies to seize control of state waters, watersheds, or groundwater. State waters, watersheds, and groundwater must be the purview of the sovereign states….We firmly believe environmental problems are best solved by giving incentives for human ingenuity and the development of new technologies, not through top-down, command-and-control regulations that stifle economic growth and cost thousands of jobs."

establishing value hierarchies; it aims towards action: What values are we expressing through the ways we use water? The water ethics framework presented here is taken from my 2013 book, *Water Ethics: A Values Approach to Solving the Water Crisis* (Groenfeldt 2013)[6] and from the draft Global Water Ethics Charter (Ziegler and Groenfeldt 2017) which is elaborated below. This framework is constructed around five value categories in the context of water:

1. *Environmental values*—Values about the health and welfare of fish, wildlife, rivers, wetlands, aquifers, and the whole water-linked ecosystem;
2. *Economic values*—about not wasting resources and finding least-cost solutions; applying water to its most productive uses; and recognizing economic values embedded in other kinds of values, like ecosystem services of the river and the tourism potential of water recreation.
3. *Social values*—Values about equity and social justice (not shutting off the water service for poor families that have no income; not situating the uranium mine in Indian country just because it's easier to get a permit there) as well as values about social benefits from water: safe water and sanitation; healthy rivers and wetlands; the social benefits of a robust agricultural economy that depends on secure water for irrigation.
4. *Cultural values*—Spiritual values about rivers and springs, whether a special spring like Lourdes or every river in Australia, which are all sacred to Australian First Nations; emotional and aesthetic benefits from walking along a river, kayaking on it, or swimming or fishing in it, and our relationship to water bodies as part of our place-based cultural and personal identities.
5. *Governance values*—Values about who should be involved in decisions about new water investments or policies, and the institutional architecture for making those decisions at multiple levels.

These values are relevant not only to direct water decisions (e.g., how much water should go to irrigation) but also to the "values-chain", the values advanced through the way that the irrigation water is used and the crops produced. What agricultural practices does the irrigation water support? Are the farm workers adequately compensated (social values)? Are pesticides impacting the groundwater (environmental values) or drinking water (social values)? Do the crops grown enhance cultural identity? Nutrition? Environmental services? Do the soil management practices sequester carbon (CO_2 offsets) and capture water? The ethical ripple effects can be far-reaching, extending to consumer health, economic security, and personal and planetary well-being (Molders 2014).

In addition to the five value categories we can distinguish four general principles: (1) Precaution (We should approach this interconnectedness between humans and nature with an attitude of humility and adopt the fundamental principle of precaution to guide our management interventions.), (2) Water as a commons (We all depend on water and have a shared responsibility for its management (Kallhoff 2017), (3) Intergenerational justice (We have a responsibility to all future generations to be good stewards of their water today) and (4) Knowledge and education (We have a moral obligation to generate knowledge about water in all its aspects and attend to the governance of that water knowledge). We can also distinguish between *describing* the ethics already in place (*descriptive* ethics) versus advocating for the ethical principles one finds desirable (*prescriptive* ethics). A second distinction is between *preventative ethics*, which focus on what we should NOT do (Don't pollute!) and *aspirational ethics*, which focus on what we would like to see happen (Restore the river!).

Finally, there is an over-riding "meta ethic" about water governance that borrows from the field of medical ethics, where the practice of ethics related to medical decisions has become the expected and often legally mandated practice. The meta-ethic for water goes something like this: Since water is fundamental to life itself, decisions about how water is managed and governed should be guided by ethics. It is, in effect, unethical to make major decisions about water that do not consider the ethical implications. We have a moral responsibility to treat water decisions with serious attention, and ethics needs to be part of that attention.

5.1.5 Working with Ethics

A key feature of values-based decisions is the notion that the values we hold dear are not necessarily obvious even to ourselves. The first step in working with values is a process of self-discovery, identifying what our values are and making them explicit, and deciding which ones are core/fundamental values and which ones are less important. In the case of a company, or any collective organization (the analogy with water would be the water stakeholders), the emphasis is on harmonizing the values of the diverse employees into a common 'corporate culture' that everyone understands and can accept. The values are typically documented in the form of a code of ethics, which reminds the employees about their responsibility to act according to the corporate values and with personal integrity. Ethical behavior can then be defined as adherence to the company's code of ethics (Craft 2013).

[6]A second edition of this book was published in 2019 (Groenfeldt 2019).

Within the water sector, codes of ethics have become an important tool for promoting 'integrity', a term defined by the Water Integrity Network[7] as having four dimensions: transparency, accountability, participation and 'integrity' (i.e. non-corruption). While the concept of integrity emphasizes core processes, its meaning can also include water management outcomes such as social justice and sustainable water ecosystems (WIN 2016).

Transforming these abstract values into proper ethics requires a process of 'ethical reflection' (Harris 2008). More specific than 'thinking' and more holistic than 'analysis', ethical reflection is the process by which 'the ground or basis for a belief is deliberately sought and its adequacy to support the belief examined' (John Dewey, cited in Harris 2008, p. 385). Ethical reflection can be framed as a form of strategic thinking oriented around outcomes. "[Both] ethical reflection and the strategy process focus peoples' attention on the preparation and justification of future actions by raising the question: What do we want to achieve?" (Behnam and Rasche 2009, p. 80).

Closely related to the notion of ethical reflection is 'moral imagination' (Werhane and Moriarty 2009, pp. 2–3) which introduces an active, creative dimension to the reflection process:

> Moral imagination includes an awareness of the various dimensions embedded in a particular situation – in particular, the moral and ethical ones. It entails the ability to understand one's situation from a number of perspectives. Moral imagination enables managers to recognize a set of options that may not be obvious from within the overarching organizational framework. Moral imagination is the ability to discover and evaluate possibilities within a particular set of circumstances by questioning and expanding one's operative mental framework.

5.2 Approaches to Water Ethics

In this section we consider two types of approaches to establish water ethics standards. One is the formulation of comprehensive normative prescriptions that are considered to be universally applicable, while at the same time acknowledging the possibility of some regional or cultural differences. The emphasis is on what can be considered universally true. The other type of approach focuses on specific value principles such as environmental values or social justice. These narrow systems of value frameworks are also intended to be universally applicable.

[7]https://www.waterintegritynetwork.net.

5.2.1 Comprehensive Prescriptive Frameworks

5.2.1.1 UNESCO's Approach

The 1998–2004 UNESCO-COMEST initiative on "Water and Ethics" identified a number of fundamental ethical principles (Brelet and Selborne 2004, pp. 5–6) which have been incorporated unchanged in subsequent UNESCO statements including the 2011 report on *Water Ethics and Water Resource Management* (Liu et al. 2011) and the 2018 report on *Water Ethics: Ocean, Freshwater, Coastal Areas* (COMEST 2018). These principles are the following (taken from Liu et al. 2011, p. 17):

Human dignity: for there is no life without water and those to whom it is denied are denied life;
Participation: for all individuals, especially the poor, must be involved in water planning and management with gender and poverty issues recognized in fostering this process;
Solidarity: for upstream and downstream interdependence within a watershed continually poses challenges for water management resulting in the need for an integrated water management approach;
Human equality: for all persons ought to be provided with the basic necessities of life on an equitable basis;
Common Good: for water is a common good, and without proper water management human potential and dignity diminishes;
Stewardship: for protection and careful use of water resources is needed for intergenerational and intra-generational equity and promotes the sustainable use of life-enabling ecosystems;
Transparency and universal access to information: for if data is not accessible in a form that can be understood, an opportunity will arise for an interested party to disadvantage others;
Inclusiveness: water management policies must address the interests of all who live in a water catchment area. Minority interests must be protected as well as those of the poor and other disadvantaged sectors. In the past few years the concept of Integrated Water Management (IWRM) has come to the fore as the means to ensure equitable, economically sound and environmentally sustainable management of water resources;
Empowerment: for the requirement to facilitate participation in planning and management means much more than to allow an opportunity for consultation. Best ethical practice will enable stakeholders to influence management."

These principles are derived mostly from the UN Universal Declaration of Human Rights (United Nations 1948) and the proclamation of the 1977 UN Water Conference which "formulated an international consensus on a number of policy and operational measures" including that, "all peoples … have the right to have access to drinking water in quantities and of a quality equal to their basic needs" (Falkenmark 1977). In describing the intent of the UNESCO-COMEST initiative on Water and Ethics, Selborne (2000, p. 3) states that, "The aim is to help lay a foundation of trust, justice and equity in the availability of and access to freshwater resources for the entire community of nations." These ethical principles, in other words, are intended as universally applicable and not subject to reinterpretation by special interests such as political parties or corporate lobbyists.

How then, should we treat the rise of extractivist values promoted by the current political regimes in the United States, Russia, and Brazil, supported by extractivist corporate and investor interests? As noted above, the ethic (or anti-ethic) of "extractivism" has long been applied in the United States to justify particular exceptions to normal practice, such as uranium mining Sacrifice Zones for weapons production during the Cold War era, and environmental exemptions accorded to the coal and oil & gas industries in the name of economic growth. This type of "regulatory capture" whereby military or corporate interests exert influence over water-related regulations has expanded into "policy capture" whereby wholescale national policies are rewritten to meet the interests of corporations and investors, supplanting the traditional functions of governments. Examples of extractavist water policies are the rewriting of the US Clean Water Act to substantially weaken its scope and standards (Bloomberg Editorial Board 2018), and plans of the Bolsonaro regime in Brazil to fast-track hydroelectric dams in the Amazon (Rocha 2019). The moral justification offered in both the US and Brazil cases is presented in terms of a binary choice between economic security versus environmental security. In this sense the ethic of extractivism represents an "anti-ethic", a reaction against the body of ethics that is aligned with principles of environmental sustainability, and cultural and intergenerational justice.

5.2.1.2 Indigenous Water Ethics

The search for a comprehensive set of universal ethical principles about water has not been limited to the UNESCO-COMEST lineage that has descended from the Human Rights discourse. A parallel track has been developed through meetings and statements of Indigenous Peoples organizations and initiatives of Indigenous leaders. The Indigenous Peoples Kyoto Water Declaration is perhaps the best known. The declaration was drafted by the Indigenous participants at the third World Water Forum held in Kyoto in 2003. The Kyoto Declaration was initially communicated to the World Water Forum in a march through the conference center with the indigenous participants speaking the declaration in unison, followed by a press conference. Later the declaration was posted on various websites and is also included in the UNESCO publication, *Water and Indigenous Peoples* (Chibba et al. 2006).

Two sections of the Indigenous Declaration outline a set of universal ethics for water governance (though without using the ethics terminology). The first section, titled, "Relationship to Water" explains why Indigenous Peoples feel a responsibility to protect water ecosystems. Another section is labeled "Right to Water and Self Determination" and describes the rights and responsibilities of Indigenous Peoples to protect their cultural ways of life:

a. Relationship to Water

- We, the Indigenous Peoples from all parts of the world assembled here, reaffirm our relationship to Mother Earth and responsibility to future generations to raise our voices in solidarity to speak for the protection of water. We were placed in a sacred manner on this earth, each in our own sacred and traditional lands and territories to care for all of creation and to care for water.
- We recognize, honor and respect water as sacred and sustains all life. Our traditional knowledge, laws and ways of life teach us to be responsible in caring for this sacred gift that connects all life.
- Our relationship with our lands, territories and water is the fundamental physical cultural and spiritual basis for our existence. This relationship to our Mother Earth requires us to conserve our freshwaters and oceans for the survival of present and future generations. We assert our role as caretakers with rights and responsibilities to defend and ensure the protection, availability and purity of water. We stand united to follow and implement our knowledge and traditional laws and exercise our right of self-determination to preserve water, and to preserve life. …

b. Right to Water and Self Determination

- We Indigenous Peoples have the right to self-determination. By virtue of that right we have the right to freely exercise full authority and control of our natural resources including water. We also refer to our right of permanent sovereignty over our natural resources, including water.
- Self-determination for Indigenous Peoples includes the right to control our institutions, territories, resources, social orders, and cultures without external domination or interference.
- Self-determination includes the practice of our cultural and spiritual relationships with water, and the exercise of

authority to govern, use, manage, regulate, recover, conserve, enhance and renew our water sources, without interference.

- International law recognizes the rights of Indigenous Peoples to:
  - Self-determination
  - Ownership, control and management of our traditional territories, lands and natural resources
  - Exercise our customary law
  - Represent ourselves through our own institutions
  - Require free prior and informed consent to developments on our land
  - Control and share in the benefits of the use of, our traditional knowledge.

5.2.1.3 Global Water Ethics Charter

The idea of formulating a global charter on water ethics was a recommendation from the 6th World Water Forum held in Marseille, France in 2012. The concept emerged from the ad hoc "Working Group on Ethics, Culture and Spiritualities" which organized a session to identify commonly shared value principles across religious, cultural, and philosophical traditions. The group noted that even well-known ethical principles about water, environment, and social justice, whether derived from major religions, Indigenous cultures, or secular philosophy have had little influence on actual water policies. What was needed was the "recognition of spiritual and ethical values and principles and their consideration in decision-making process in the water sector" (World Water Council 2012). By the following year (2013) a core group of three organizations—French Water Academy, UNESCO's Division of Water Sciences, and Water-Culture Institute (based in Santa Fe, New Mexico)—agreed to work together to develop a "Water Ethics Charter‵. Along with this core team, six other organizations and individuals joined the Steering Committee to get the process underway: Alliance for Water Stewardship, Botin Foundation, Club of Rome, Indigenous Environmental Network, Water Youth Network, and an individual expert, Amb. Magdy Hefny from Egypt.

In 2014, some two years after the Marseille Water Forum, the Steering Committee met at UNESCO-Paris to establish the broad framework for a water ethics charter and agree on aims and expectations. The development of a charter document was seen as the leading edge of an integrated set of outreach and awareness-raising activities to promote the application of ethical principles in water policies and decision-making. The process of developing the content of the charter relied on a list of about 80 experts compiled from the personal contacts of the Steering Committee members. These experts were sent a provisional outline of the intended Charter (Draft 1.0) with an invitation to provide feedback about issues the charter should address and any other guidance. Some thirty experts submitted substantive comments which were then compiled into a spread sheet and incorporated into a new version (Draft 2.0) as the first comprehensive draft of the charter. This draft was presented at the 2015 World Water Forum in Daegu, South Korea. Though the intention had been to hold a series of regional consultations to further develop the Charter, funding constraints precluded further progress. Draft 2.0 of the Water Ethics Charter is publicly available on the website of the Water Ethics Network[8] and has served to stimulate scholarly interest, if not yet practical implementation in policies or on-the-ground initiatives. The 2016 meeting of the International Society for Environmental Ethics (ISEE) in Kiel, Germany, devoted a series of sessions to presentations about the Charter, which were compiled into an edited volume, *Global Water Ethics: Towards a Global Ethics Charter* (Ziegler and Groenfeldt 2017). A summary version of the Water Ethics Charter is given below:

Water Ethics Charter (Draft 2.0)

Part 1. Introduction

This Charter establishes the moral and ethical foundations to guide decision-making around the use of water and the protection of water resources and water-reliant ecosystems. The following General Principles should guide decision-making: (1) Precautionary Principle, (2) Water as a commons, and (3) Intergenerational Justice.

Part 2. Environmental Issues

We need an environmental ethic which will safeguard the integrity of water ecosystems in the face of unprecedented human pressures and climate change.

General Concepts: Water ecosystems have inherent rights, and intrinsic value. Operational Principles: (1) maintain or improve the health of natural water ecosystems; (2) no net loss from current conditions.

Part 3. Economic Issues

Water has an inherent economic dimension, but transcends monetary value. General Concepts: Water use should be reasonable and frugal, emphasizing reuse; Existing water stocks should be maintained; private ownership of water must be balanced with accountability to the larger society. Operational Principles: Water for basic human needs should

[8] https://waterethics.org/the-water-ethics-charter/.

be effectively free, whereas water used in economic activities should have a market cost.

Part 4. Social Principles

General Concepts: Water should be explicitly recognized as a commons and central feature of life for individuals and the larger society. Everyone has a right to safe water and a healthy environment.

Operational Principles: Promote universal access to safe water and sanitation; ensure water justice for all and especially future generations.

Part 5. Cultural and Spiritual Principles

Water and water ecosystems provide important cultural and spiritual meaning. General Concepts: Rights of indigenous and traditional peoples to live according to their cultural traditions including economic livelihood strategies and religious ceremonies.

Operational Principles. Water infrastructure should accommodate customary cultural uses as a matter of priority and subject to "free prior and informed consent".

Part 6. Water Governance

General Concepts: Incorporate whole watersheds; reflect the interests of all stakeholders; manage at the lowest practical level; priority to social and environmental responsibilities.

Operational Principles: Transparency, accountability, and stakeholder participation are central to good water governance.

5.2.2 Value-Specific Ethical Prescriptions

Since water is so important to so many sectors of life and economy, a number of normative frameworks have been developed for specific sectors. For example, the OECD undertook a 4-year initiative to develop a set of 12 principles on water governance (OECD 2015), the International Water Association has developed 17 principles for water-wise cities,[9] and 29 charitable organizations involved in Water and Sanitation for Health (WASH) programs in developing countries compiled the WASH Sustainability Charter[10] to promote best practices. Two initiatives which have an explicit values emphasis are the Environmental Flow Standards originally formulated at a 2007 conference in Brisbane, Australia and recently updated, and the Blue Communities Project which invokes the principle of water as a commons to promote public access to safe and affordable water.

5.2.2.1 Environmental Flow Standards

An environmental flow is the natural water regime of a river, wetland, or coastal zone which maintains the ecosystem (Postel and Richter 2003; Poff and Matthews 2013). A minimum environmental flow is the smallest amount of water required at any given time to allow the ecosystem to function (Petts 2009). There are both economic and ethical reasons for maintaining environmental flows. From an economic perspective, "Environmental flows provide critical contributions to both river health and ultimately to economic development, ensuring the continued availability of the many benefits that healthy river and groundwater systems bring to society" (Dyson et al. 2003). From an ethical perspective, rivers have intrinsic rights to exist, and we have an intrinsic responsibility to respect those rights (Boyd 2017).

Since the 1990s, the concept of environmental flows has been gradually incorporated into water laws from Europe to South Africa to Australia. The South African National Water Act, adopted in 1998, established a reserve consisting of an unallocated portion of water that is not subject to competition with other water uses. It refers to both quality and quantity of water and has two segments: the basic human need reserve and the ecological reserve. The former refers to the amount of water needed for drinking, cooking, and personal hygiene, and the latter refers to the amount of water required to protect the aquatic ecosystem.

In Europe, the Water Framework Directive, enacted in 2001, required that European rivers and groundwater attain "good ecological status." The Directive does not require any particular flow levels, but instead defines ecological status in terms of biological communities, water quality, and channel morphology. In order to meet healthy standards, rivers need a certain flow quantity and flow regime. The details are different for each river, hence the practical wisdom in setting outcome indicators of ecological status, rather than stipulating the flow inputs (Acreman and Ferguson 2010). In Australia environmental flow policies were introduced during the 1990s along with new institutional arrangements to hold and manage environmental water allocations, including programs to buy back water entitlements from water users and return the water to the environment (Le Quesne et al. 2010: 47–8).

Normative standards for environmental flow were endorsed by participants at the 2007 Brisbane River Symposium as the Brisbane Declaration. This was the first consensus document on what the term should convey, and marks a turning point for elevating environmental flow to the status

[9] https://www.iwa-network.org/projects/water-wise-cities/#the_17_iwa_principles_for_water-wise_cities.
[10] https://washcharter.wordpress.com.

of a global standard that has become generally accepted (Arthington et al. 2018). A ten-year review of the Declaration at the 2017 Brisbane River Symposium reaffirmed the original principles, and added new statements about the importance of cultural heritage and "local knowledge and customary water management practices [which] can strengthen environmental flow planning, implementation, and sustainable outcomes" (Arthington et al. 2018: 11). Key elements from the 2007 Brisbane Declaration on Environmental Flows include the following[11]:

> *Freshwater ecosystems are the foundation of our social, cultural, and economic well-being.* Healthy freshwater ecosystems – rivers, lakes, floodplains, wetlands, and estuaries – provide clean water, food, fiber, energy and many other benefits that support economies and livelihoods around the world. They are essential to human health and well-being.
>
> *Freshwater ecosystems are seriously impaired and continue to degrade at alarming rates*. Aquatic species are declining more rapidly than terrestrial and marine species. As freshwater ecosystems degrade, human communities lose important social, cultural, and economic benefits; estuaries lose productivity; invasive plants and animals flourish; and the natural resilience of rivers, lakes, wetlands, and estuaries weakens. The severe cumulative impact is global in scope.
>
> *Water flowing to the sea is not wasted.* Fresh water that flows into the ocean nourishes estuaries, which provide abundant food supplies, buffer infrastructure against storms and tidal surges, and dilute and evacuate pollutants.
>
> *Flow alteration imperils freshwater and estuarine ecosystems*. These eco- systems have evolved with, and depend upon, naturally variable flows of high-quality fresh water. Greater attention to environmental flow needs must be exercised when attempting to manage floods; supply water to cities, farms, and industries; generate power; and facilitate navigation, recreation, and drainage.
>
> *Environmental flow management provides the water flows needed to sustain freshwater and estuarine ecosystems in coexistence with agriculture, industry, and cities*. The goal of environmental flow management is to restore and maintain the socially valued benefits of healthy, resilient fresh- water ecosystems through participatory decision making informed by sound science. Ground-water and floodplain management are integral to environmental flow management.
>
> *Climate change intensifies the urgency*. Sound environmental flow management hedges against potentially serious and irreversible damage to freshwater ecosystems from climate change impacts by maintaining and enhancing ecosystem resilience.

The related concept of *cultural flows* was also developed in Australia and refers to "water entitlements that are legally and beneficially owned by Indigenous Nations of a sufficient and adequate quantity and quality, to improve the spiritual, cultural, environmental, social and economic conditions of those Indigenous Nations."[12] Cultural flow can also refer to that portion of an environmental flow which accommodates a particular cultural practice that depends on certain flows, for example, to attract wildlife into the riparian forest, or to induce a certain species of fish to enter a floodplain pool. Adjusting the flow (volume and timing) of regulated rivers can often support locally important cultural practices. The meaning of the term "cultural flows" continues to evolve (Taylor et al. 2016) and can facilitate integration of the diverse cultural values of water (recreation, psychological wellbeing, aesthetic enjoyment, cultural heritage) into the water planning process.

5.2.2.2 Governance ethics: Blue Communities

The Blue Communities Project[13] promotes the ethical principle of water as a commons and a public trust (Blue Communities Project 2016). An alliance between the Council of Canadians and the Canadian Union of Public Employees (CUPE), the Project encourages municipalities, organizations (e.g., universities) and First Nations communities both in Canada and world-wide, to take a pledge about water. The pledge, which is made through one or more formal resolutions or statements by the community's governing body, has three elements:

1. Recognizing water and sanitation as human rights,
2. Banning or phasing out the sale of bottled water in municipal facilities and at municipal events, and
3. Promoting publicly financed, owned, and operated water and wastewater services.

These three conditions are mandatory, but the details of how they are fulfilled can be flexible, in order to be able to adapt to different local circumstances. As of 2018, over 20 cities in Canada, one in the United States (Northampton, Massachusetts) and a number of cities in Europe (including St. Gallen and Bern in Switzerland, Paris in France, Thessaloniki in Greece, and Berlin in Germany) have joined the Blue Communities (Ozbay 2018). In addition to municipalities, the designation of "Blue Community" has also been awarded to several universities, the World Council of Churches, and (so far) one Indigenous community, the Tsal'alhmec First Nation in British Columbia.

The Blue Communities initiative is a continuation of a 20-year campaign against austerity policies and the commercialization of water, centered around the work of Maude Barlow and the Council of Canadians (Barlow and Clarke

[11]The full text is available on the website of the International River Foundation, https://riverfoundation.org.au/wp-content/uploads/2017/02/THE-BRISBANE-DECLARATION.pdf.

[12]This definition is taken from the 2010 Echuca Declaration, which can be found at https://culturalflows.com.au.

[13]https://canadians.org/bluecommunities.

2002; Barlow 2013). They started the Blue Communities initiative "so that municipalities could take a proactive position regarding their responsibility to water services. A Blue Community treats water as a common good to be shared by everyone and as the responsibility of all. Because water is central to life, it must be governed by principles that are based on sustainability and justice in order to preserve water for nature and future generations" (Barlow 2016).

5.3 Applying Water Ethics

How can the normative frameworks for making best ethical use of water be applied in real settings? This is a complicated issue, but it is helpful to bear in mind that tacit normative frameworks embedded in conventional water policies are being implemented routinely. Innovation is the exception and not the rule. The motivation for taking risks in trying out new policies, which is ultimately what this chapter is advocating, stems from the inadequate performance of conventional policies founded upon conventional normative frameworks about how best to govern water. If we don't want to repeat the mistakes of the past, we will need to try something else.

The field of Water Ethics suggests that by reflecting on our values about water as an integral aspect of our agenda setting—a "Look before you leap" type of assessment—we are likely to make better decisions. One central reason for expecting better decisions to emerge from attention to ethics is that careful reflection on our values and on the interaction of those values, will almost inevitably lead us to greater awareness of the likely multiplier effects and potential synergies as well as tradeoffs implicit in alternative choices. By orchestrating the interactive effects of alternative scenarios, we can approximate the work of modelers who want to see into the future what the pros and cons of various decisions are likely to be. Generally speaking, the best solutions will have multifunctional benefit streams. The literature on multifunctionality would suggest that contributing to multiple SDGs is likely to be more impactful than aiming very narrowly at one particular type of outcome (Netherlands Enterprise Agency 2016).

The three cases of applied water ethics discussed in this section share the common feature of contributing a wide range of benefits from the water that is used. The first example, Agroecology, might use water delivered by irrigation canals or wells, or might rely on natural precipitation, but one way or another, water is a necessary input. Farmers practicing agroecology produce not only food, but through soil management they sequester carbon, and through the mix of crops grown together, there is steady demand for local labor throughout the growing season, creating local jobs. There are also cultural benefits from growing traditional foods and reinforcing the sacred connection with the land, as well as community empowerment through the cooperation of local farmers. The second example of applied water ethics is the trend of re-municipalizing city water systems that had been sold to private companies, a common trend in the 1990s. Local citizens become more empowered when they control their water system, albeit indirectly through the municipal government. The third example is that of corporate water stewardship, exemplified most dramatically by the Swedish Textile Water Initiative, and illustrating that private companies can be ethical with respect to water, while still making a profit.

5.3.1 Agroecology: Towards an Ethical Agriculture

Agroecology, an approach based on both ecological and social principles, is finally coming of age as a solution to the multiple challenges of climate change, sustainability, and social justice. Though the approach was formalized in the 1970s (Altieri 1985) as a counterpoint to conventional agriculture, it remained marginalized by vested interests committed to the high-input, industrial mode of growing food. Proponents of agroecology saw themselves as participants in a cultural transformation to bring society and nature back into alignment (Pretty 2002; de Schutter 2011). Today agroecology is in vogue, thanks to a revaluing of its multiple benefits. "The FAO has an agroecology office at its headquarters in Rome, agriculture ministers from around the world are drafting public policy on 'agroecology,' and universities are scrambling to offer agroecology curricula and initiate new research programs" (Rosset and Altieri 2017).

In his keynote address to the International Symposium on Agroecology in April 2018, FAO Director-General José Graziano da Silva noted that agroecology transcends the farm, and provides many economic, social and environmental co-benefits. He was joined in opening the Symposium by French Member of Parliament and former Minister of Agriculture, Stéphane Le Foll,[14] who was instrumental in placing agroecology as the centerpiece of France's national agricultural policy. The significance of the French government promoting agroecology as main-stream policy is the demonstration that it is not a policy for developing countries only but for technologically advanced countries as well.

The aim of national agriculture sectors is not limited only to producing food (though that remains important) but also to contribute more broadly to the UN Sustainable

[14]Agroecology in France: Changing production models to combine economic and environmental performance: https://agriculture.gouv.fr/changing-production-models-combine-economic-and-environmental-performance

Development Goals (SDGs) and the goal of "living well". Agroecology will not necessarily produce more food than intensive industrial styles of farming, but the aggregate benefits of local employment, ecosystem resilience, carbon sequestration, public health (from nutritious foods grown without toxic chemical additives), cultural identity, and greater stakeholder involvement in agricultural decision-making support multiple SDGs (Casey 2016; Bruil et al 2019). Through its Scaling up Agroecology Initiative, FAO is advancing "a vision to bring agroecology to scale and transform food and agricultural systems to achieve the SDGs" (FAO 2018: 1). Complementary initiatives are also being pursued by the International Fund for Agricultural Development (IFAD) and the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IBPES).

5.3.2 Re-municipalization as a Water Ethic

The story of Cochabamba's unhappy experience with water privatization has entered the water governance history books as a clear failure for privatization, and a clear win for the people (e.g., see the account by Barlow and Clarke 2002). The underlying story is the clash of values and ethics. The municipal government of Cochabamba had adopted the World Bank ideological view of privatization as a way to improve water governance by unleashing the power of the private sector. From a business perspective, that might have made sense, but from a social perspective, it was disastrous, causing extreme economic and physical hardship to the poor. The people protested and the foreign company that had taken over control of the city's water (through a legally binding contract with the city government, and financing from the World Bank) was forced to withdraw. The municipal government took back control over the water system; the people had won!

The World Bank's promotion of the private sector in Cochabamba might have stemmed from good intentions for expanding water access for the poor, or it might have reflected the interests of donor countries to send more business to their compatriots (Bakker 2010). There is a fairly strong consensus, however, that the policies favoring private takeovers of large urban water systems were very much overdone by the World Bank and the regional international development banks in the 1990s. Indeed, the pendulum has been swinging away from urban water privatization to urban water re-municipalization (Lobina 2017). Inspired by the example of Cochabamba, the citizens of Berlin voted in 2013 to buy back the city water utility which had been privatized by a previous city administration in the 1990s (Härlin 2017). As the new owners of the city's water utility, the citizens embarked on a community-wide planning initiative to devise a Berlin Water Charter[15] stipulating key value principles that would guide the new era of citizen-led water governance.

The case of Berlin is one of the more dramatic water governance reforms, but it is not unique. The city of Paris took back its water utility in 2010 simply by not renewing the long-standing contract with Veolia and Suez, and creating a new public entity, Eau de Paris (Le Strat 2010). Since then, the global trend to re-municipalization has become unmistakable, though not uniform. The Berlin Water Charter illustrates why public management of urban water supplies is clearly desirable if public sector governance capacity is strong. Public water service provides important opportunities to engage stakeholders and empower them to forge a relationship to the water they depend upon every day. The Berlin Water Charter was formulated through consultations organized by the Berliner Wassertisch (Berlin Water Table), the same group that had led the campaign to remunicipalize the water system. The question they felt needed to be addressed was how would water management under public control be different? What values did they wish to address?

The dominant theme of the Berlin Water Charter is the principle of water as a commons for all people, present and future. This is not a comprehensive framework of water ethics writ large with all values systematically addressed; rather, it highlights key principles which will guide the new public water managers. Here is a summary of the 4-page charter:

1. *General Principles*
   - Access to water is a human right
   - Water must be affordable for all
   - The water utility shall be a public corporation with no privatisation
   - Governance will be transparent with close coordination of stakeholders
2. *Social and Economic Principles*
   - Water charges will be for actual costs, but not for profit
   - Pricing model will take burden away from small consumers
   - No private companies may be integrated into the water utility
   - Drinking water quality must be maintained with no degradation
3. *Environmental Principles*
   - Drinking water sources will be local groundwater and Spree and Havel Rivers

[15] See the website of the "Berlin Water Table" (https://berliner-wassertisch.net/), or download the English text of the Berlin Water Charter at https://berliner-wassertisch.net/assets/Charta/Berlin_Water_Charter2015.pdf.

- Natural environment of drinking water sources will be maintained in good status;
- Organic agriculture is encouraged to reduce water pollution
- Surface waters and water protection areas will be developed in harmony with nature;
- Fracking and oil/gas extraction is banned in and around Berlin.

4. *Legal Principles*
   - This Water Charter is the basis for interpreting existing or new laws or provisions.
   (Source: Berliner Wassertisch 2015)

McDonald (2018: 50) identifies three recurring value positions among advocates for remunicipalization: "Expand democratic control, improve equity, [and] improve environmental sustainability." Privatization advocates, on the other hand, favor values which "improve water service performance and reliability, reduce costs to the state [and] ensure market-friendly practices in water." An ethics perspective contributes to the discussion of public versus private governance of urban water supply and sanitation through clarifying the governance goals. What are the value objectives beyond cost savings? Is there a goal to expand service to poor neighborhoods? Is there a corresponding ethic that water connections will not be turned off for lack of payment? Is there also a social and governance goal of community development and capacity-building through stakeholder engagement in water planning and management?

5.3.3 Corporate Water Ethics

The business sector has embraced the concept of "water stewardship" in developing water strategies that serve two overlapping objectives: (1) contributing towards sustainability goals, and (2) managing water risk (Sym 2017). The most direct and immediate way that companies can manage their water risk is to decrease their demand by lowering their water footprint. A factory's water footprint refers to net water use, after subtracting water that is reused, recycled, or reclaimed during or after the manufacturing process (Hoekstra et al. 2011; Hoekstra 2013, 2015). A smaller water footprint implies higher water productivity (economic water ethic) with less water removed from nature (environmental water ethic). Society is better off because there is more water that can be used for other purposes.

By investing time and resources into finding ways to use less water to produce the same products, and to return good quality water back to the environment, manufacturing industries are acting "responsibly" and ethically. In the case of older factories designed without careful attention to water wastage, financial returns to water conservation investments can be dramatic. An initiative to reduce water use in 35 textile factories (for weaving and dyeing) near Delhi, India, implemented 85 "low- hanging fruit" recommendations based on water audits. The results were staggering: Over a single year, the return on investment was 765%, with an average payback time of 11 days per project (SIWI 2014).

Companies can also engage in water stewardship outside their factory fence by reducing their impact on local water ecosystems, or proactively helping other users (municipalities, farmers or even other companies) to reduce their water impacts. The business motivation, of course, is not only protecting the physical water in the basin, but earning the acceptance (social license) of the neighbors. The operative ethical principle that legitimizes the company's social license is the widely held view of water as a commons (Wagner 2012) regardless of legal ownership.

In addition to practicing water stewardship inside the factory fence, and outside that fence within a shared water basin, companies can also engage in shaping water policies and regulations. Corporate efforts to influence water policies typically focus on seeking exemptions to environmental standards; for example, coal companies in the United States have waged a protracted political battle against oversight by the Environmental Protection Agency, and the efforts of the oil and gas industry to spread disinformation about climate change is notorious (Grasso 2019). In theory, however, for-profit companies could also be lobbying on behalf of sustainability ethics. Water stewardship within the textile industry is addressing all three levels: within the factories, at the river basin level, and at the policy level.

5.3.3.1 Swedish Textile Water Initiative

The Swedish Textile Water Initiative (STWI) is a network of Swedish fashion brands working cooperatively to help their suppliers in India, Bangladesh, China, Turkey, and Ethiopia to adopt water-conserving measures. STWI grew out of the concern of one family-owned company, Indiska, to help its suppliers in India to treat the wastewater resulting from printing and dyeing cotton and silk textiles, which is a major source of water pollution. With technical support from Stockholm International Water institute, the initiative developed into the current network of 29 brands and 277 suppliers. The aim is no longer just improving the water footprint of the textile manufacturers in the supply chains, but transforming water use within the whole fashion industry. "The STWI guidelines are being promoted by brands that believe in acting responsibly and want to do so through suppliers that they have a direct relationship with" (STWI 2014: 8). Though some very large companies (Ikea, H&M) are members, the policy clout of the initiative seems to owe its success to the network itself, more than to the individual companies.

5.3.3.2 Detoxing Fashion

Another initiative focusing on water ethics in the fashion industry is the Greenpeace "Detox" campaign.[16] In a hard-hitting expose of chemical pollutants linked to clothing production of some well-known brands, Greenpeace highlighted the fashion/textile industry as the number two pollution culprit, after the oil industry (Greenpeace 2018). The opening salvo of the campaign was a 2011 report focusing on China, *Dirty Laundry: Unravelling the Corporate Connections to Toxic Water Pollution in China*, which was quickly followed by another report, *Dirty Laundry 2—Hung up to Dry*, painting a broader, global picture of systemic carelessness within the fashion industry (Grappi et al. 2017).

From an ethics perspective, the most important feature of the Fashion Detox campaign was brushing over the issue of legal compliance with national pollution regulations and aiming the message of accountability squarely on the textile companies themselves to clean up their industry. Legal compliance means little when many of the most harmful chemicals are not regulated. Greenpeace compiled its own "Do Not Use" list of chemicals based on recognized authorities such as the Stockholm Convention on Persistent Organic Pollutants[17] and the EU Water Framework Directive list of priority hazardous substances. The Greenpeace strategy of bluster and drama fit the culture of the fashion industry perfectly, and to the credit of some of the major brands that were attacked, the industry listened. Rather than trying to defend their past behaviors, major brands responded with specific plans for complying with much of what Greenpeace was asking for (Grappi et al. 2017). The science was sound, and the marketing intelligence was clear: Consumers were concerned, not only for their own health, but for the health of the planet. Here we see a perfect storm of applied ethics. The disruptive force of the Greenpeace campaign energized the latent ethical principles of both customers and companies.

5.4 Status and Prospects for a Field of Water Ethics

There are two reasons to be optimistic about the prospects for a robust and recognized field of water ethics. One reason is that there is already consensus on a broad set of water values thanks largely to the legacy of Integrated Water Resources Management (IWRM). The "big tent" established by the concept of IWRM, which gave recognition to diverse values among water users, has encouraged broad participation of diverse stakeholders. This diversity is on display at the triennial World Water Forums which attract many thousands of participants. But the cracks in the IWRM paradigm are also evident at these water forums, in the guise of "Alternative Water Forums" organized by the NGO sector to provide an opportunity for grassroots groups to discuss the dark sides of the water sector: Dams that destroy river ecosystems and flood the ancestral territories of Indigenous communities; toxic mine spills that kill the fish that local communities depend upon.

Can water ethics become an antidote to the inequities and injustices of the real water world? There is a fairly strong consensus about the water values we should aspire towards. In this section we consider five key water values that are widely shared among the global water community. These provide a basis for hope, but how can consensus about water values be leveraged into ethical behavior that can counteract the powerful forces of illegal corruption and legal extractivism? How can water ethics be activated and enacted? Strengthening the field of water ethics would provide new opportunities for developing theories and methods and enhance the contribution of water ethics to the challenges of water in the Anthropocene.

5.4.1 The Global Consensus on Water Values

By distilling the values implicit in global and regional water statements made during the three decades since the 1992 Dublin Principles, we can distinguish five key value propositions representing a remarkable cross-cultural consensus: (1) nature needs to be kept alive (ecological function); (2) everyone has a right to water and sanitation (social justice); (3) water should be used responsibly in agriculture and industries (responsible use); (4) stakeholders should be involved in decision-making (participation), and (5) diverse cultural identities and understandings about water should be respected. These five principles constitute a conceptual foundation for envisioning and formalizing a shared water ethic.

1. Environmental values: Keep nature alive. The notion that restoring natural ecological functions is desirable is a central tenet of IWRM which assumes that ecosystem services have value, and healthier ecosystems generally have more of those values than unhealthy ones. Healthy water ecosystems are fundamental to water security and resilience (UNEP 2009), and whether or not we accord nature the right to exist (Boyd 2017) the practical implication could be the same either way: It is in the interest of humans that nature (and especially water ecosystems) be alive and healthy.

2. Social values: The human right to water and sanitation. Since access to drinking water is a matter of life or death,

[16] https://www.greenpeace.org/international/act/detox/.

[17] https://chm.pops.int.

and sanitation is needed to protect the safety of water supplies, the logic behind the UN General Assembly's 2010 vote to accord access of safe water and sanitation the status of a human right seems unassailable. It is up to individual countries, of course, to implement this right. The infamous case of contaminated water supplies for the city of Flint, Michigan, stands as a reminder that, even in developed countries like the United States, the human right to water cannot be taken for granted (Rothstein 2016).

3. Economic values: Responsible use. The intuitive concept of using water carefully was given an economic interpretation in the Dublin Statement (1992) that, "Water has an economic value in all its competing uses and should be recognized as an economic good,". The more recently popularized concept of "One Water" (Kirshen et al. 2018) reminds us that not only water, but also water values, are connected. The violation of social ethics in Flint had a huge economic impact, while the lead that poisoned the tap water also became an environmental problem as the lead contaminated wastewater was released into nature.

4. Governance values: Participatory water governance. The principle "that decisions are taken at the lowest appropriate level, with full public consultation and involvement of users in the planning and implementation of water projects" (Dublin Principles 1992) is a central feature of IWRM. Participation is also central to promoting financial and professional integrity (anti-corruption), transparency and accountability within the water governance system (WIN 2016). And though the interests of Indigenous Peoples and the natural environment were seldom cited in early IWRM discussions of participation, both are generally (but not always) included in contemporary lists of stakeholders. This is an example of the "social learning" taking place within the IWRM approach (Pahl-Wostl et al. 2007). Indigenous Peoples' interests have been energized through the concept of free, prior and informed consent (FPIC) embedded within the 2007 Declaration on the Rights of Indigenous Peoples (United Nations 2008). The participation of Nature can sometimes be accomplished through the concept of legal personhood for rivers such as the Whanganui River in New Zealand (O'Donnell and Talbot-Jones 2018).

5. Respect the diversity of water culture. National governments usually deem rivers as economic resources but Indigenous communities, such as the Standing Rock Sioux Nation in South Dakota (United States) regard their rivers, such as the Missouri, as foundational to their spiritual and cultural identity as a people. The question is not whose ontology will win and whose will lose; that question was answered in the nineteenth century with political and military force, confirmed by dam construction on the Missouri River in the twentieth century, and further re-affirmed in 2017 with the forcibly imposed construction of the DAPL pipeline through the traditional territories of the Standing Rock Sioux Nation (Whyte 2017). The question for water ethics now is how can multiple worldviews about society's rightful relationship with nature—and associated values about water—co-exist in a politically amicable way?

5.4.1.1 Sustainability Through Shared Water Values

The task for the field of water ethics is to develop skills and tools for accommodating value diversity. For Indigenous and traditional peoples whose cultures have co-evolved with rivers, lakes, or desert oases, there are particularly compelling issues of cultural sovereignty at stake. It is challenging for traditional cultures to compete for the loyalties of its young people who are increasingly connected to the globalized system of market capitalism, yet it is that same global market-based system that has brought our planet to the brink of climate destruction. Who is to say that Indigenous communities should make way for the economic forces that are threatening our common future? Or to re-phrase the question with a different premise: What can we learn—from Indigenous cultures, and from our own cultural value traditions of religion, philosophy, humanities, and science—about forging a sustainable relationship with water?

Globally accepted ethical prescriptions about water can be easily ignored (because there is no enforcement), while local water decisions are accountable to locally held cultural principles and norms, which in turn are influenced by local politics and economic incentives. What is the potential for applying principles of water ethics within this messy context of practical, mostly local water decisions? One scenario could be the following: By forging a fresh set of ethical principles, or simply clarifying the ethics already in place but hidden in the background, local decisions about water can be informed by those ethics. This does not mean that the decisions actually taken will be consistent with those ethics, since power, politics, and greed also exert influences that may be counteractive. But going to the trouble of articulating key ethical principles can enhance the likelihood that those ethics will have some influence on decisions and outcomes.

5.4.2 Enabling Conditions

Just as a wood stove needs kindling and a match to activate the larger pieces of wood and create a useful fire, there are two enabling conditions that need to be met in order to catalyze the study of water values into a practical form that can be effectively applied to actual water decisions. The first enabling condition is establishing recognizable categories. It's difficult to see the interplay of cultural values and ethics influencing our relationship with water until we establish the basic categories of "water values" and "water ethics". These categories signal that there is something to be gained in exploring the values connected with water, and the value principles ("ethics") by which the values can be organized into a coherent system. But without a concept of "water values" or "water ethics" – when these exist only as tacit norms that go unrecognized by the policy makers – communication across cultural and ontological boundaries breaks down and polarization ensues.

This is one explanation, or at least a contributing factor, in making sense of the violent clash between the pipeline company and the Army Corps of Engineers on one side and the Standing Rock Sioux Tribe and their Indigenous and non-Indigenous supporters on the other (Whyte 2017). If the Army Corps had internalized an understanding of and appreciation for the water values of the Tribe, and had internalized the ethic of respecting the very different values held by the Indigenous water protectors, perhaps the confrontation would have turned out differently. But without framing the tribal water protectors' values as constituting an ethic that deserves respect, that there is an ethical responsibility for taking a different value system seriously, the message of the water protectors was unable to get through. The words of the water protectors, "Water is life!" could not penetrate the ontological armor of the other side.

The second enabling condition that I believe to be a prerequisite for the useful activation of water values and ethical principles is the establishment of a recognized field of water ethics. The diversity of values and ethical principles need operating space for discussion, analysis, reflection, negotiation, and argument. And how to create that field, that space? It takes a village of Indigenous wisdom-keepers, philosophers, humanists, artists, and others who are experts in values and ethics, but not necessarily in water. And it also takes the input of water experts who are willing to turn their attention to values and ethics. Indeed, the nascent field of water ethics that already exists has been shaped more by water experts who have written about ethics, than by ethicists or humanists who have written about water. The advantage of this skewed ratio is that the field of water ethics is already oriented towards practical application.

5.4.3 Nurturing the Field of Water Ethics

How can the still-emerging field of water ethics develop into a recognizable body of study and become acknowledged as an important and necessary domain of water governance? Simply describing its basic principles and documenting illustrative examples can help to systematize and publicize the field. This is a useful start, but it is clearly not enough. An analogy can be made with the emergence of the field of bioethics in the 1970s. Bioethics was of broad interest to environmental and natural resources management, in addition to medicine and public health. Before 1980 we might well have imagined that departments of bioethics would emerge in liberal arts colleges, rather than medical schools (Thompson 2015). But of course, that did not happen. The field of medicine adopted bioethics with enthusiasm, while the social sciences, humanities and the agricultural sciences as well—largely ignored the ethical dimensions of their various disciplines. Bioethics was embraced by the medical fields as useful and, indeed, essential to a broad range of decisions ranging from treatment protocols to research strategies. Today virtually all medical schools in the US and Europe have dedicated faculty lines in medical bioethics (Thompson 2015: 81), whereas agricultural ethics remains poorly elucidated as a field, and water ethics is almost unheard of.

Why the lack of interest in the ethics of natural resources? In pondering this question with regard to agricultural ethics, Thompson (2015: 82–83) suggests that the broad range and dynamism of the social sciences has taken up the intellectual space where a field of natural resources ethics might otherwise have taken root. Social justice, human rights, and environmental values have been quite thoroughly addressed by the social and economic sciences. But ethics is most definitely needed to sort through the multiple and often conflicting values that people have about the use of water and our relationship to water ecosystems. The "value added" of ethics is in the approach of ethical reflection to assess the goodness of competing values and value principles.

Within the established water profession there is renewed interest in water values to inform sustainable water governance (Garrick et al. 2017). As water sustainability concerns continue to mount the interest in values is likely to increase as well, and there is some reason to anticipate a renewed interest in how ethics can help in sorting through conflicting, overlapping, and sometimes synergistic values (Groenfeldt 2019). The project of building a field of water ethics and the project of defining a new water ethic are very much intertwined. A new water ethic can only take form if there is a field of water ethics to nurture that project, while the field of water ethics cannot be created out of nothing; it needs to grow in response to a demand.

The good news for water ethics is that we are living in the Anthropocene, a high stakes epoch where humanity can ill afford ignoring certain ethical principles, such as precaution and solidarity. Yet as budding water ethicists, we cannot responsibly sit back and wait to be asked for our advice. Part of an ethical response in times of crisis entails stepping up to offer what help we can provide. The field of water ethics will advance most effectively through engagement with the intractable ethical issues of water governance. Just as progressive corporations recognize a dual benefit in promoting basin-level water stewardship (Water risk is reduced while their social license to operate is enhanced), the project of water ethics faces a similar opportunity. By engaging with our water colleagues to help address practical water challenges we can enhance our own intellectual license to operate and advance the field of water ethics.

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David Groenfeldt is Director, Water-Culture Institute, and Adjunct Professor of Anthropology at University of New Mexico. Following his Ph.D. research on irrigation development in India, David worked on water governance with IWMI in Sri Lanka, and with NGOs, consulting firms, the World Bank, and other agencies. In New Mexico he served as director of Santa Fe Watershed Association (2006–2009) and founded Water-Culture Institute (waterculture.org) in 2010 to promote integration of ethics into water policies and practices. He is the author of Water Ethics: A Values Approach to Solving the Water Crisis (2nd Edition, 2019) and co-editor of Global Water Ethics: Towards a Global Ethics Charter (2017).

6 Water Law and Rights

Joyeeta Gupta and Joseph Dellapenna

Abstract

This chapter covers issues of water law and rights in terms of generic issues. Following an introduction to law, it discusses the origins of water law, how water law is organized, various issues related to the quantity of water (including property rights and priority of use), issues related to the quality of water and environmental concerns and integrated water resource management. It then discusses key issues in transboundary water law, before drawing conclusions about the future challenges to water law.

Keywords

Sovereignty • Territorial integrity • Property rights • Water access • Equitable and optimal utilization • Navigation • Boundary issues • Dispute resolution • Legal pluralism • Sustainable development goals

6.1 Water Law and Rights

Water law applies to water usage at all levels, from regulations by the smallest local governments up to state/provincial, national, regional, and international or global laws. Water law consists of the formal and informal institutionalization of norms, principles, instruments, procedures and practices over the centuries. Legal positivists focus only on the formal institutionalization of social practices in laws and regulations adopted by the state. Water governance scholars would argue that it is also necessary to consider the informal rights acquired through the centuries which are sometimes recognized in formal legal documents (Gupta 2013). The latter would argue that especially in the arena of water and land, customary tenure rights are often not written down or formally recognized and allow for expropriation by unscrupulous interpretation of the black letter of the law. We have thus two reasons for expanding our discussion of water law and rights to informal processes—first, that (water) law has historically emerged from custom and customary practices tend to legitimize the law (Dellapenna and Gupta 2009); and second, in the global context, any ignorance of customary rights may lead to conflict at best and expropriation of rights at worst.

Law is primarily concerned with the rules governing society in terms of who has, and what should be the, rights, responsibilities, powers, and privileges, and the principles that determine this allocation (Dellapenna 2009). We will open this chapter with a brief discussion of the concept of law in general and how it connects to customary practices. This will also serve to illustrate the links of regulations from the smallest local governments up to state/provincial, national, regional, and international or global laws. In terms of water, this implies—who has rights to access, use, and pollute water, who has responsibilities with respect to water quality and quantity, who has powers with respect to water, and are there actors with specific privileges to water. In terms of principles—the question is what norms apply to the domestic and international governance of water (Gupta 2013)?

While there are seemingly infinite variations between these different bodies of law, they tend to fit into a fairly limited number of patterns. While some of this is imposed by the nature of the resource itself, other features reflect the spread of laws by various means from place to place and time to time. This chapter, among other matters, will describe the process by which these patterns have been disseminated across the globe.

J. Gupta (✉)
University of Amsterdam, Amsterdam, Netherlands
e-mail: J.Gupta@uva.nl

J. Dellapenna
Peking University School of Transnational Law, Shenzhen, China
e-mail: jwdellapenna@gmail.com

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Table 6.1 Types of water and regulation

Water types	Regulation
Blue surface water	Mostly on ownership/access, allocation, pollution and navigation
Blue groundwater	Significantly less regulation on ownership/access, allocation, recharge and pollution
Grey and black water (waste water and sewage)	Some regulation on discharge and quality especially in the industrialized world
Green water in soil and trees	Hardly regulated
Atmospheric water (water vapour/clouds)	Hardly regulated
Snow/ice	Hardly regulated

Water itself is a complicated issue. It not only flows from one place to another, it changes physical form from solid to vapour. In doing so, water is inherently different from other fixed resources like land and minerals. In particular, water lends itself to reuse—the water you use today is the water I used yesterday, and so on. Furthermore, as water is essential for life, each of the specific forms and flows of water have specific roles in nurturing the physics, chemistry, and biology of the Earth. In most legal systems, the focus has been on surface water, but there is an increasing focus on groundwater. There is much less focus on green and grey water or on maintaining the different ecosystem services of water. Table 6.1 summarizes the regulatory status of the different types of occurrence of water.

Water has historically been framed in the various religions differently (Dellapenna and Gupta 2009). For example, in ancient Hinduism, water could not be owned and people only had usufructuary rights (the right to use) water. Water was seen as a gift of God in Islam and this religion was among the first to formulate a human right to water. Today, the notion of a human right to water and sanitation is increasingly being accepted at different levels of governance (e.g. UNGA 2010; UNHRC 2010). At the same time, as water is scarce, there is a strong push to see it as an economic good (e.g. ICWE 1992). Still others discuss water as a heritage of humankind (e.g. European Union Water Framework Directive 2000).

This chapter focuses on the concept of law (see Sect. 6.2), key issues of water law (see Sect. 6.3), key challenges in transboundary water law (see Sect. 6.3), before concluding with a reflection on the new issues (see Sect. 6.4).

6.2 The Concept of Law

Readers from industrialized societies and developing countries with inherited colonial legal systems are likely to have a firm idea of what the word "law" means, derived from experiencing the legal systems in their societies, a model of how law works when something is described as a law and some claim of right or obligation as legal. The model they are likely to have in mind envisions a legislature acting formally to create a highly determinate rule enforced by the police acting against violations of the "law." As George Jackson put it, "[t]he ultimate expression of law isn't order, it's prison" (Jackson 1972). This notion of law is called "legal positivism" because it focuses attention solely on "positive" law, law that is formally enacted and formally enforced.

The foremost legal proponent of positivism in English law, John Austin, defined law as "the command of a sovereign" to be enforced by a sanction (Austin 1998). By this theory, the practice of law pertains to identifying the commands of a specific sovereign and properly using those commands to achieve a desired result. Most people who live under modern legal systems are probably comfortable with the foregoing description of what law is and how law operates, at least in the setting of their own national legal systems. This model actually does not go very far to explain the phenomenon we call "law" even in a national legal system, and it certainly doesn't explain international law or law in less formal legal systems.

Consider the fairly mundane example of traffic laws. In the United States (or anywhere else in the world for that matter), nearly everyone drives faster than the legal speed limit. There could never be enough police to compel people to drive at or below the legal speed limit. If the government ever attempted to reach this goal, it would fail simply because too many people violate the law. The best that can be achieved is to keep most people driving not very much faster than the official speed limit through selective enforcement targeting those who violate the official speed limit too egregiously (Laws That Are Made to Be Broken 1977). Yet the legally prescribed limit remains "the law"; no one could avoid conviction for speeding on the basis that the law is not effectively enforced or that the designated speed limit is not "the law."

Contrast the situation regarding speed limits with the situation regarding traffic lights. People in the United States and other developed countries (and some developing countries) seldom simply drive through red lights (although in some areas they often cheat a little). If nearly every one were to disregard red lights, the laws proscribing driving through those lights could no more be enforced than the speed limits. The reason for the different behaviors regarding speeding and red lights is self-interest: To drive through a red light is far more dangerous than speeding, and would be suicidal if nearly everyone did so. When only a few violate a rule, a few police are adequate to enforce the rule against the violators. Yet one's emotional response to another's driving through a red light is not simply that the act is dangerous, including to those in the car violating the rule. Most people perceive driving through a red light (or running a stop sign) as anti-social behavior, and are supportive of the law as law. H. L. A. Hart, a leading twentieth-century legal positivist, argued that the decision to obey traffic signals, and the sense of moral outrage against those who do not, is legal and not merely a moral attitude because if one were to ask such a driver why she acted or thought as she did, she would refer to the law to explain her actions and thoughts (Hart 1961). This brief exploration of traffic laws presents us with the problem of the moral authority of law, the "puzzle of legitimacy" (Hart 1961). A brief exploration of this puzzle reveals some truths about the functioning of law in general and international law in particular.

Now consider the subtler situation regarding contracts. Contracts, voluntarily defined and assumed obligations, are an essential feature of modern life; without compliance with contracts, the planning that is a central feature of modern economies would be impossible. Every modern state has well-developed laws of contracts, laws that tend to be highly technical. Yet business people, let alone consumers and others, often know nothing about these technicalities, or, even worse, "know" something about these technicalities that is, in fact, false as far as formal positive law goes. As a result, one well known study of the contracting process in Wisconsin found that between 60 and 75% of the contracts made in the state between wholesalers and retailers were not valid under the state's law of contracts, largely because of errors in the attempt to form a contract (Macaulay 1963). Yet business between wholesalers and retailers in Wisconsin did not suffer. In fact, such "legal" problems are probably typical of most contracts made in most places around the world.

Contracts actually are enforced not so much by formal law as by informal sanctions based on the sense of the relevant community, and enforcement often leads to radically different means and results than would be achieved were the parties to resort to legal processes (Macaulay 1985). Indeed, the decision to resort to litigation is a signal of a far greater problem than mere failure to fulfill a particular promise; it signals one's decision to break off all relations and to severely impede the possibility of entering into future relations with the person whom one sues (Macneil 1978). Legal professionals seem to have considerable difficulty accepting that their formal rules and processes often are beside the point. Still, an occasional decision reflects the truth that law is not in the formal rules but in the intent of the parties which usually means the customs, usages, and practices of a particular trade or industry (see, e.g., *Columbia Nitrogen Corp. v. Royster Co.* 1971).

The rules of contract law can hardly be characterized as "commands of a sovereign" without seriously distorting the actual functioning of the system. The "rule" rather accepts that the parties themselves form a community and within that community create law for themselves. This rule, while seldom explicit in the common law (law mostly applicable to the UK and former colonies of the UK, including the US), is the central tenet of the law of contracts in the civil law (applicable in continental Europe) tradition: "Legally formed agreements have the force of law for the parties" (*Code Civil* § 1134 1804). And in the (U.S.) Uniform Commercial Code, one encounters such "rules" as that if the parties to a sale fail to set the price for the goods sold, the price is a "reasonable price" (UCC § 2-305 1990), or that if the parties to a sale fail to indicate when delivery is due, it is due at a "reasonable time" (UCC § 2-309(1) 1990), and so on. Such rules indicate that the true basis of contracts and commercial law is the social sense of legitimacy granted to or withheld from particular voluntary conduct. For domestic contract disputes, the relevant society is not the nation, the state, or the province, but the more narrowly defined subset of participants in a particular portion of the economy or perhaps even only the parties to the agreement.

The Austinian paradigm that so many now think of as the "natural way" to think about law is a wholly inadequate notion of what law is and how law operates. The point was perhaps best captured by Professor A. L. Goodhart: "It is because a rule is regarded as obligatory that a measure of coercion may be attached to it; it is not obligatory because there is coercion" (Goodhart 1953). Even modern positivists have conceded as much when they embrace a normative explanation of positive law that does not depend on an identifiable "sovereign" or the presence or absence of a "command" or a "sanction." Hans Kelsen developed a widely influential positivist theory where legitimacy derives from a "*grundnorm*" (a "basic norm" or "basic law") that in turn just is, or at least is derived from social notions that are not explicable in strictly legal terms (Kelsen 1992). H. L. A. Hart sought to explain the origins and functions of law through a "habit of obedience" as the source of law and legitimacy, rather than coercion (Hart 1961). These theories, particularly Hart's "habit of obedience," seem inadequate to capture the sense of legitimacy that underlies law, yet they are closer to the reality of what makes law "law" than the notion of command or sanction that are popularly thought of as constituting law.

"Law" then refers to an organic mechanism whereby certain claims of right are elevated to the status of socially established norms and other claims of right are denied standing; it is, in a phrase, a means for society to make sense of things (Geertz 1983). At least in law-oriented societies, when such normative judgments are accepted as law, few will violate the norms and those who do will pay a higher price than someone who violates a mere social or moral convention: The price might well be exposure to official coercion, but it might also entail other social means of enforcement such as censure or even ostracism.

This leaves a question: What is the function of formal law, "law on the books"? Informal law functions successfully when each person in a particular community knows the others in the community and what they are doing, each depends on the others for a wide range of social supports, and each realizes that overreaching too far or too often will cost them the social supports that he or she needs to survive or to thrive. As a society becomes larger and social interaction becomes less personal, the complex web of mutual reciprocities that ensures compliance with purely customary norms breaks down. Formal law, particularly written formal law with specialized processes to make and enforce law, arises as a response to that breakdown. Formal law provides a means to achieve adequate certainty and predictability of right and obligation to people in the society. This was as true of Hammurabi's Babylon or the Rome of the *Decemviri* as it was of medieval Islam or modern Europe. A good example is the process whereby during the last 20 years, under the impact of the creation of the European Union with its "single market" and the resulting competition from English, Dutch, and American law firms, the French method of dealing with hostile corporate takeovers through informal arrangements among a few leading men has broken down to be replaced, both nationally and internationally, by a highly formal set of legal rules and institutions that mirror the similar institutions that were created 90 years earlier in the United States and about 10 years earlier in the United Kingdom (Trubek et al. 1994). Opportunities to create certainty and at least the appearance of determinate outcomes knowable in advance multiplied enormously with the invention of the printing press (Dellapenna 2000). Printing made possible not only the mass distribution of "law" in a way not before possible, it also married formal law to the centralized state for it made centralized control possible, but only if legal actors (lawyers, jurists, and lay people who pay attention to formal law) were required to follow the letter of the law. From this possibility arose the characteristic form of modern law—nationally unified legal systems that claimed a monopoly over legal questions. From such institutions, intended to enable autocratic rulers to rule *by* law, emerged the important modern notion of the rule *of* law (the *Rechtstaat*) (Franck 1992).

We are not denigrating the formal processes of law. Certainty and predictability are important values, particularly for those who seek to make firm plans (contracts, as it were) for the future. Formal law also serves the valuable social end of ensuring that the state itself abides by the law created by the state and by society. Yet societies change, sometimes faster than the state would like. These changes affect, directly and immediately, the informal law that underlies much if not all formal law. The problem confronting lawyers and judges is to mediate the resulting tension between the need for stability and certainty in the law with the need for flexibility and change to accommodate new social realities (Cardozo 1921). If there is too little flexibility and change, the formal law loses touch with social realities. Using contracts or other mechanisms, many, perhaps most, people will develop alternative means for recognizing and enforcing obligations. On the other hand, too much flexibility and change make planning and legal control impossible.

As this brief analysis suggests, the law in every country is "path-dependent," a result of what has gone before as well as what is sought for the future. At the extreme, even in contemporary societies, formal law may play little or no real role in structuring social relations or resolving disputes (Dellapenna 1997). In each society, one must learn who the lawyers and judges are, to whom they are connected, and what their role in the state and the economy is. A judiciary or other dispute resolution process functions effectively only when it is embedded in structures of social, political, and economic power. Yet that embedding might serve only to entrench existing power structures to the disadvantage of innovators or the poorly connected.

With the forgoing concept of law in mind, one can see that a society (of people, of communities, or of states) is never without law, but that law can take a myriad of forms and express highly varied content. We must be leery of overstressing formal legal structures for water except when they actually reflect how water is managed and disputes over water are resolved. In many ways our discussion of law here mirrors the ongoing discussion on governance, where governance scholars argue that there is a shift from centralized, top-down, hierarchical approaches to more diffuse systems of rule-making in society. The shift from top-down towards diffused systems of governance is also found in water governance (Gupta 2013; Gupta and Pahl-Wostl 2013). We can now approach the evolution of water law and understand how pervasive and varied it is even while searching out patterns of consistency across societies (Dellapenna and

Gupta 2009). If we find such patterns, it is the consistency and not the variations that demands explanation.

6.3 Key Issues in Water Law

6.3.1 Introduction

Today, water law as found around the world is a patchwork of local customs and regulations, national legislation, regional agreements, and global treaties, together creating a global legal governance framework for water. This framework results from complex historical evolutionary processes (Dellapenna and Gupta 2009; Dellapenna et al. 2015). Water law, as we have defined it, has a long history pre-dating the ancient civilizations. In fact, given how broadly we have defined water law, there probably never was a society without water law of some sort. Furthermore, one can trace formal water laws back to the earliest human civilizations found in major river basins: the Yellow River, the Indus River, the Nile River, and the Euphrates and Tigris Rivers. So central was the need to regulate water consumption in these river basins—basins in which exotic rivers flowed across dry, even desert, areas—that Karl von Wittfogel would later conclude that this need drove the emergence of basin-wide (or near basin-wide) empires in each region (Wittfogel 1981).

Across different civilizations, some common issues have emerged over time. These include issues regarding who has access to water and how does this access come about, how issues related to the quantity of water can be regulated, how issues related to the quality of water can be regulated, how navigation issues are dealt with, what the policies with respect to boundaries are, and how disputes are resolved.

Regardless of whether one accepts Wittfogel's claims, we have evidence of the earliest laws relating to water from each region. The most developed record of these laws is found in Mesopotamia where vast amounts of records of contracts and legal cases have been excavated by archeologists. Several codes of laws inscribed on steles have also been recovered, the best known of which is the *Code of Hammurabi* (1738 BCE 1910). These laws reveal a process of communal management, although the actual provisions of the various codes were limited to liability for flooding a neighbour's fields (Kornfeld et al. 2009). The ancient Hindu *Arthashastra* (*ca.* 300 BCE) (Kauṭalya translated by Rangarajan 1992) are similarly limited, providing that the water belonged to the king but authorizing private uses on payment of a tax so long as the private actor properly maintained the infrastructure with severe penalties for causing injury to another water use or water user (Cullet and Gupta 2009). The *Laws of Manu* (*ca.* 200 BCE) are to similar effect (Cullet et al. 2009; Doniger and Smith 1991). The *Law of Moses* (*ca.* 1000 BCE) was gradually elaborated in the rabbinical tradition, but remained focused on a few simple rules of rights to use water and the duty to protect its purity (Laster et al. 2009).

These and later water law systems reflect the *cultural origins* of law. Water law developed in a highly contextual manner reflecting the history, geography, and political systems of the countries concerned. As a result, today there are almost 200 different national water law systems, each with country and region specific characteristics. At the same time, these water law systems exhibit certain recurring patterns. Some of these are purely cultural, reflecting the predominant forms of social structures of the time. Foremost among these in ancient times is that the laws generally are presented as having been divinely revealed. Other features reflect the nature of the resource and patterns of use. Thus the right to use water is variously granted to owners of riparian land (land contiguous to the water source) or because of temporal priority in putting the water to use (Scott and Coustalin 1995). The riparian approach generally required a sharing of the water, while the priority approach often did not. Often there would be some mixing of the two principles, and sometimes preferences were given to particular types of use (*e.g.,* irrigation vs. municipal uses). And from the beginning, the laws addressed questions of pollution as well as the allocation to particular uses. Perhaps because these laws tended to be most developed in arid or semi-arid regions, they emphasized allocation rather than pollution (Dellapenna 2009; Teclaff 1985).

6.3.2 How Water Law Systems Spread Across the Planet

As already noted, the nature of the water resource and the nature of the uses of the resource to some extent provide a measure of unity to patterns of water law. Still, there is continuing debate about what sort of water law is best, leaving aside the possibility of mixing elements of the fundamentally different approaches of riparianism and temporal or other sorts of priority (Dellapenna 2008a; Trelease 1974). In addition to these possibilities, the purely social, or perhaps one should say jurisprudential, features of water law systems create the possibility of receiving, voluntarily or otherwise, the water law from another state or nation. Several processes served to spread principles of water law from their place of origin to different parts of the world. These include: (1) the spread of civilizations or cultures (Kornfeld et al. 2009); (2) the spread of religion, important when laws are seen as a result of divine revelation (Laster et al. 2009; Naff et al. 2009); (3) the impact of conquest and colonization, including the spread and decline of Communism (Cullet and Gupta 2009; McKay and Marsden 2009; Gupta and Zaag 2008; Leite Farias 2009; Kidd 2009;

Nilsson et al. 2009; Kotov 2009); (4) the widespread codification of legal principles in the nineteenth century (Watson 1993); (5) the rise of engineering and of epistemic communities (Biswas and Tortajada 2009); (6) the rapidly spreading influence of environmentalism (Zellmer 2009); and (7) the second wave of globalization (Gupta 2003), with elements often marketed by aid agencies and development banks (Dellapenna 2008a). These various influences overlap and often continue to co-exist within a single society.

The result today is a complex set of national water law regimes composed of overlapping and contradictory elements derived from one or more of the above processes. In many nations, there remains residual indigenous laws in conflict with water laws imposed by colonial regimes or imported from "more advanced" systems, all subsumed in attempts at water law reform deriving from international legal standards or the prevalent thinking of epistemic communities (Cullet and Gupta 2009; Leite Farias 2009; Kidd 2009; Nilsson and Nyanchaga 2009; Gupta et al. 2014a; Zaag 2009). As a result, in many nations plural systems of water law compete for application (Cullet and Gupta 2009; Nilsson and Nyanchaga 2009; Gupta and Leendertse 2005). As these sources indicate, it is not unusual to find some communities of water users still applying indigenous law to manage their water resources even when that law lacks formal legal recognition, while other communities apply the formal law left from a colonial regime, and yet other communities seek to apply markets or otherwise to embrace whatever legal thinking appears most modern. The resulting pluralism can be seen as positive in recognizing interests that cannot be aggregated in universalist approaches (Krisch 2006) or as negative in the fragmentation of interests and policies that leads to a breakdown in legal approaches. Recent efforts to integrate different regulations into one comprehensive water law sometimes succeed for better (Laster et al. 2009) or worse (Kotov 2009). In other cases, they flounder on the resistance of those who are committed to earlier regimes (Cullet and Gupta 2009; Leite Farias et al. 2009; Nilsson and Nyanchaga 2009). It would also perhaps not be out of place to mention here that recent 'land grabbing' either by the private sector or even by the public sector (in order to reserve land for protected areas or for biofuel/plantation production) (Gupta et al. 2013), has also led to loss of customary access to land and water for local people.

6.3.3 The Organization of Water Law

National water law is generally organized in one major water law while often there are a series of other laws that directly or indirectly cover water. This makes it a very difficult issue to actually study. Typically water law is spread through the following laws (see Table 6.2).

Water law is either organized as centralized in unitary governments such as the Netherlands or power is shared with provincial governments in federal states such as the US, India, and Germany. In the former, the central state has the authority to govern water. In the latter, the Constitution generally specifies whether the centre or the state has authority over water. The national state generally has authority over international water issues, and over inter-provincial issues; while the provinces have authority over the water within the state. This is, for example, the situation in India; however, where there is water shortage, this leads to conflict between two or more provinces. In India, despite the role of the Central Government in governing inter-state water, disputes between states on water issues have become very problematic in recent years (e.g. Cauvery river between Karnataka and Tamil Nadu). There have been discussions about sharing such water, but these have become heated very fast as farmers see their livelihood at risk as a consequence of such sharing.

Sometimes the authority over water shifts across levels. Thus, in both Australia and the US states came together to create a federal government but reserved authority over water to the states. In both nations, the authority over water has shifted gradually to the central level both because the scope of the problems was seen more and more as national and because the federal government has access to greater resources for funding solutions to the problems. Problems posed by the constitutional structure have been overcome in part by reinterpreting the constitutional documents but also by providing financial incentives to the states to comply with federal plans (Costanza et al. 1997; Craig 2010; Pilz 2010).

Beyond the formal distribution of authority over water, river basins may also have authority over water. In such situations, river basin organizations decide how water within the basin is to be managed (Huitema and Meijerink 2014). Furthermore, issues of water service provision is decided at the municipal level. However, the relationship between the river level and the city level is a very troubled one (Brandeler et al. 2018). There has been debate through history as to what is the most appropriate level to govern water. The principle of subsidiarity shifts water responsibilities to the lowest possible level; however, at these levels, there is no incentive to share water with other levels or areas where water is scarce. At the same time, the nature of global trade in water or goods that embody water and the global nature of the hydrological cycle subject to the impacts of global climate disruption have led some to argue in favour of governing at the global level (Vörösmarty et al. 2015). The issue of how one determines at what level water should be governed becomes thus a critical challenge.

Table 6.2 Water law is generally found in different laws

Law	Generally covers
Customary Law	Ownership and access; and rules regarding sharing
Water Law	The water authorities, plans, and sanctions on water
Agricultural Law	Irrigation for agriculture
Energy Law	Access to hydropower
Constitutional Law	Human rights; division of responsibility between levels of the state
Land Law	Land ownership and use
Easements/tort	Who can use water, pollute water and related sanctions
Contract Law	Public private partnerships
Environmental law	Water standards and pollution standards

6.3.4 Quantity Issues

6.3.4.1 Introduction

Issues related to water are generally in relation to quantity (who owns how much?; how is water to be shared?; what are the priorities in water sharing?; how does one deal with floods and droughts?), quality (what is the quality of water—is it suitable for the different uses of water?, is it capable of supporting other life forms), and climate change (how does climate change influence water and vice versa?) (WWAP 2009; Cambridge University Press 2014; Zhuo et al. 2016).

6.3.4.2 Property Rights

Today the almost 200 national legal regimes define the right to use water in terms of the relationship of the use to the water source (Gupta and Dellapenna 2009). As with ancient water laws, the relationship might be based on the location of the use (a riparian connection linking land ownership with water), the timing of the use (a temporal or seasonal priority system), or the nature of the use (preferences for the most socially important uses, also referred to as ‘priority of use’). Through history a number of concepts on water ownership and access have emerged (see Table 6.3).

Rights to use water are often characterized as property rights, which allow a somewhat different typology of water rights. They might be a system of: (1) common property (where the resource is shared freely among those with lawful access to it, without collective decision making); (2) private property (where defined water rights are allocated to particular users who have considerable control over the water allocated to their use); or (3) community or public property (where water is shared among users but is managed jointly by those entitled to share in the resource) (Schlager and Ostrom 1992; Dellapenna 2010). Each of these types of property must recognize to some extent at least the public nature of water as a natural resource, and therefore even in the most thoroughly privatized water property regime there will be regulations in order to enforce the property or water right regime, in order to protect the resource from pollution, and (recently, at least) to promote or preclude markets (Klijn et al. 2009).

Property rights in water can be rights of access to use water (usufructuary rights), the right of exclusion (to exclude others from access), the right to manage water, and the right of alienation (to be able to sell the water) (Schlager and Ostrom 1992).

Sometimes these rights are absolute in terms of fixed volumetric units per unit of time as in Chile. Sometimes these rights are relative to the total share (such as in the Subak system of irrigation in Bali and hill irrigation in Nepal) or relative to each other’s rights (as in California).

In recent decades, markets based on a private property regime for water resources have been promoted as the best way to manage the resource (Griffin 2006). This has generated considerable controversy about the utility of markets (Dellapenna 2000; Klijn et al. 2009; Dellapenna 2008b). Private property regimes for water have also led to the development of the concept of tradeable water rights, where those who have more allocations than they need can sell to those who have less allocations than they need—thereby promoting a so-called efficient system. However, such property rights systems have led to hoarding during drought and can be problematic in practice.

6.3.4.3 Priority of Use and the Human Right to Water

Emerging recognition of a human right to water has been pressed as a counter to the push for markets (UNGA 2010; Obani and Gupta 2015; Gupta et al. 2010). Such a human right to water and sanitation has and can be adopted in national laws by states and can imply that individuals (or their representatives—often Non-Governmental Organizations) whose rights are violated can seek a remedy in court. Many countries in the world are now engaged in implementing the human right to water and sanitation and the

Table 6.3 Concepts of water ownership and access

Concept	Explanation
Absolute ownership	When the owner has complete control over the water not withstanding changing circumstances
Riparian use	When water ownership is linked to land ownership (e.g. in Common Law and some other countries)
Correlative rights	When the rights of one water user are linked to that of others. In times of shortage, everyone uses less (e.g. California)
Proportional water rights	When water rights, often in customary systems (e.g. in Nepal, Bali, Sri Lanka), are a portion of the total available water
Reasonable use	When access is subject to the water being used reasonably
Prior appropriation	When those who use the water first get rights to the water
Permits	When access to water is subject to a permit to use the water
Public trust	When the state controls the water for the public good
Priority of use	Certain uses of water have higher priority over other uses; countries may make a list of such priorities
Tradeable water rights	Water rights in terms of fixed quantities per unit of time that can be traded among water users

literature discusses the key challenges in doing so (Obani and Gupta 2016). The adoption of a human right to water and sanitation in a country can also imply that this use of water is prioritized over other uses. Ancient Islamic law prescribed that drinking water was to be prioritised over water for animals and agriculture. Today, many countries still make priorities regarding which sectors should have access to water in the event of water shortage. For example, the Water Law of Taiwan (1983) prioritized domestic and public water supply, followed by agriculture, hydropower, industrial, navigation, and finally other uses. The Water Act of Zimbabwe (1998) prioritizes water for domestic uses, then animal life, then for making bricks for the private use of the owner or lessee of the land, and then for dip tanks, and finally for commercial uses.

6.3.4.4 Irrigation Law

Since well before the time of Hammurabi, there have been efforts to irrigate crops. Since the industrial revolution, there has been an emphasis on increasingly using irrigation facilities to channel water to agricultural fields. In most countries, irrigation law was a separate area of water law, although this is being increasingly merged in national contexts. Irrigation law was encouraged to address issues of low productivity, control the lack of predictable rainfall, socio-economic challenges, lack of traditional irrigation facilities, and increasingly may take environmental degradation into account.

Thailand's water law (1942) stated that "irrigation" means any undertaking carried out by the Royal Irrigation Department to procure water or to retain, store, reserve, control, supply, drain, or allocate water for agriculture, energy, public utilities, or industry and includes the prevention of damage caused by water as well as navigation within the Irrigation Area." Such laws defined different types of waterways—those that supplied, drained, conserved, or retained water for irrigation purposes and those that were also used for navigation.

Such laws allocate a series of responsibilities (e.g. who gets water when and for which uses; against which tariff and who collects it; who maintains and repairs the water bodies when, where and at whose cost; whose land can be taken (expropriated), when and under what circumstances and against what sort of compensation for constructing such waterways; who controls the process; and who makes decisions regarding future developments. Such responsibilities are shared between ministers, director generals, irrigation engineers and local people including village chiefs and councilors. There would also be a system of penalties for disobeying the law.

Some of the challenges arising from the law is the way in which (a) land is appropriated for conducting such facilities; (b) the transfer of control over water from the farmers to the person/authority in-charge of such facilities and hence the transfer of power; and (c) the difficulties in paying commercial rates especially for the small-holder farmers who then get increasingly marginalized.

6.3.4.5 Drought and Floods

Increasingly, many countries in the world are developing legislation to also deal with situations of drought and floods. Sometimes this is integrated in a single legal instrument and sometimes legislation is spread through different instruments. Following the adoption of the UN Convention to

Combat Desertification, many states have developed national instruments to address the challenge of droughts. This often involves the appointment of an agency to coordinate policy on this issue and may include provisions on soil conservation, cattle grazing, grass burning, and spatial planning.

Floods are also a major challenge in many parts of the world. Most countries have been unable to structurally address this. The Netherlands is an example of a country that has successfully used legislative and technological approaches to manage the risk of floods. They combine safety standards with specified ‘room for the river’ to expand when floods occur so that damage is contained, adaptive planning, and flood defence works (Gupta et al. 2014b). The 23 Water Boards have the authority to levy a tax on residents that ensures that there are sufficient finances to cover the costs of addressing floods.

6.3.5 Water Quality, Human Health and Environmental Concerns

Water quality is critical for human health and the health of ecosystems. The law and policy of water service provision to households at the municipal level has to continuously deal with a range of issues—ensuring that there is enough water of adequate quality and quantity, that there is a good quality infrastructure for such service provision to all households and units of production, that there are rules for waste water recovery and treatment before disposal or reuse (as in the case of Singapore), and rules of cost recovery. The key challenge facing many developing countries is the difficulties in accessing water of sufficient quality and quantity, providing drinking water services especially to rural and peri-urban informal settlements, and cost-recovery given the large percentage of people in these countries who live below the poverty line. This raises all kinds of challenges in terms of inclusive service provision (see e.g. Schwartz et al. 2018).

A range of principles, tools and instruments have been adopted by different countries to try and minimize the impact of pollution on water and to protect the ecological quality of water. Table 6.4 provides a list of some of these principles, tools, and instruments, and a brief explanation of each of these.

Many states have implemented laws to protect wetlands. This has been encouraged by the RAMSAR Convention on Wetlands (UN 1987). Establishing such wetlands helps to ensure that wetland biodiversity is protected.

In addition to the above, economic instruments are also used to shape behaviour. Pollutants are taxed, subsidies are used to encourage environment friendly behaviour, soft loans may be provided to stimulate the purchase of environment friendly technologies, emission permits may be traded, and there may be deposit-refund schemes to help reduce pollution. In recent years, payment for ecosystem services has also become popular—more so in the literature than in countries. The idea behind these payments is that those who benefit from good quality water should pay for these services to provide funds to help cope with the pollution of the water (Bouma and Beukering 2015). The problem with billing for ecosystem services is the high degree of uncertainty on what the value received is and how to allocate responsibility to pay for the services among the numerous persons who receive the benefit (Brown et al. 2007). Corporate social responsibility requires companies to use resources including water in a responsible manner.

6.3.6 Integrated Water Resource Law

Increasingly since the 1990s, the water policy world is moving towards the concept of integrated water resource management. This requires an integration between the supply and demand side of water, between the qualitative, quantitative, and other aspects of water governance (Gupta 2013; Gupta and Zaag 2008; Hooper 2006; Holden 2013). While many scholars are very much in favour of an integrated approach, others argue that such an integrated approach is far from politically and socially possible—as the water system is not a modelling environment in which water use can be optimized. Furthermore, such a comprehensive approach is possible when one assumes that there are no owners of water or people with legal access rights so the state can redistribute water between different uses and users based on either nationally determined priorities or through the market where the economic price of water determines who gets water.

A new approach to water is the ‘nexus’ approach. Increasingly, the integrated water resource management approach is giving way to the ‘nexus’ approach which is seen as more manageable because, instead of putting water at the centre of all discussions, it tries to focus on the trade-offs and synergies between different sectoral goals such as food, energy, and water; or water, climate change, and energy (e.g. Weitz et al. 2014).

6.4 Key Issues in Transboundary Water Law

6.4.1 Introduction

In a very real sense, the creation of regional water law systems is as old as the earliest recorded bodies of formal water law. The hydraulic empires that so impressed Wittfogel (1981) can be considered as regional water law systems. These supranational systems generally imposed

Table 6.4 Legal principles, tools and instruments regarding water quality

Principles, tools and instruments	Explanation
Prevention principle	States can take action to prevent harm
Precautionary principle	States can take action to prevent harm even if the cause-effect relationship is unclear, if the possible harm is irreversible
Polluter pays principle	The polluting party should internalize the costs of pollution in her management plan
Spatial planning	When water bodies in different areas are allocated different uses and standards
Strategic environmental assessment	When policy programmes are subject to the approval a strategic environmental assessment before being approved
Environmental impact assessment	When projects are subject to the approval of an environmental impact assessment which specifies what the environmental and water consequences of a specific project are
Pollution permits	Permits are issued to ensure that those polluting into water bodies do not go beyond a specific amount
Performance standards	Standards may specify how much water can be used in specific products or processes
New source performance standards	Sometimes the standards only apply to the performance of new sources
Water quality related standards	These standards may specify what the quality of specific water bodies should be for specific uses (e.g. bathing, recreation, specific species of fish)
Best available technology	Industries should use the best available technologies to reduce harm; sometimes this is qualified by the term "not entailing excessive costs"
Bans	Bans on polluting water, or using water for specific purposes
Design standards	Standards that may be prescribed on the design of specific products
Behavioural standards	Standards that relate to how people should behave with respect to water
Information standards	Standards can be applied to labels and packaging of products
Liability	Those polluting water bodies may be held liable in a court of law
Protected areas	The designation of Protected Areas to protect water bodies or wetlands

imperial rules on certain limited questions of water management while deferring to local customs or laws for the day-to-day management of water resources. Such hybrid, regional regimes were created and recreated down through centuries unless, as sometimes happened, the imperial system became strong enough to displace any vestiges of indigenous law (Kotov 2009).

These regimes have aimed to prevent transboundary water conflicts by addressing key transboundary issues. Such conflicts were traditionally in relation to the sharing of water, but also in relation to water quality issues. Such disputes have been recorded in all parts of the world in a database on transboundary disputes (TFFD n.d.). A key element of such transboundary disputes is the notion of sovereignty.

6.4.2 Sovereignty

The idea of sovereignty dates back to the origin of discussions on the nation state. In its extreme form, it is a claim that states can do as they choose within their jurisdiction. In relation to water, this has been developed extensively into a different concept of sovereignty, one that recognizes that no nation can be isolated in how it behaves, particularly in relation to water—an inherently shared resource. The result is a long history of international water agreements. International water agreements can be traced back at least 800 years. A true international water law developed only in the last two centuries with changes in technology imposing a need to develop workable agreements for managing the shared resources. Water is too important, and all nations are too vulnerable, to allow complete disregard of the interests of neighbours.

International law in general provides the institutional framework and rules for treaty making, interpretation, and dispute resolution, for countries to work together peacefully (Shaw 2008). International water law empowers international actors by legitimating their claims, but it also limits the claims they are allowed to make (Dellapenna 2008b).

International water law as a global phenomenon is found in customary international water law.

Customary international law develops through a process in which States make a claim and other States put forth counterclaims until they reach an agreement (Danilenko 1993). Identifying customary law is an informal and challenging process. For the customary international law of water resources, one traces its evolution largely through increasingly common treaties that began in the late eighteenth century with a focus on freeing up navigation, then turned into various forms of allocation treaties with the spread of the industrial revolution in the nineteenth century, and began moving towards cooperative or joint management regimes in the twentieth and twenty-first centuries (Dellapenna 1994).

Customary international water law as we find it now is based on principles that in some respects resemble the common principles that underlie national water laws, but take on different colourations in order to apply to an incompletely organized community of states (Mirumachi 2015). Customary international law today includes three principles. First, the principle of limited territorial sovereignty over national waters that limits the rights of states and requires them to consider the needs of other riparians (Dellapenna 2001). This principle emerged through a dialectic process where the claim of absolute territorial sovereignty (absolute control over national waters) competed with claims for the absolute integrity of state territory (absolute rights over waters flowing into a state from elsewhere, i.e., that waters flowing along or across national boundaries cannot be altered in terms of quantity and quality from what would naturally have occurred). Today, limited sovereignty is expressed in terms of the principle of equitable utilisation (ILA 1966, 2004; UNGA 1997), i.e., the need to share international waters according to principles of equity (fairness). The second principle is the no-harm principle that emerges from the Roman law maxim, *sic utero tuo ut alineium non laedes*—"Do not use your property so as to injure the property of another" (Dellapenna 2008b). The third principle is the obligation to settle disputes peacefully. Some states also claim historic rights, i.e., the right to use the quantity of water they have been using (Brunnee and Toope 2002). Such disputes arise especially between countries at different levels of development—e.g., Egypt and Ethiopia (Sanchez and Gupta 2011; Dellapenna 1996).

The codification of the customary international law took a major step forward with the International Law Association's approval of the Helsinki Rules on the uses of International Rivers (ILA 1966). The UN General Assembly asked the International Law Commission to bring greater certainty to this body of law by preparing a codification of international water law based in large part on the Helsinki Rules. The result was the UN Watercourses Convention (see Sect. 6.4.5), approved by a vote of 103-3 on May 21, 1997 (UNGA 1997). In 2014, it reached the required minimum of 35 ratifications needed to enter into force for ratifying states. This document, although not yet ratified by the majority of countries world-wide is nevertheless seen as an authoritative, if conservative, reflection of existing customary water law (Gabçikovo-Nagymaros Project Case (Hungary/Slovakia) 1997). This convention adopts the principles of limited sovereignty (equitable utilisation), no harm, and peaceful resolution of disputes, with great emphasis on procedures states are to follow. It recognizes the right of all riparian states to engage in discussions around a shared watercourse to deal with existing situations where actions or agreements by or between some riparians have repercussions on others (c.f. Salman and Uprety 2002).

The process of drafting and ratifying the Convention, however, highlighted the potential contradiction between the principles embedded in it—primarily the contradiction between the obligation to avoid harm to another state in a strong sense versus the obligation to share the resource equitably. How is a state to avoid all harm if the state is to exploit its share of the common resource? The Convention's answer is to give primacy to the principle of equitable utilization. (Compare Articles 5 and 7.) The Convention, aiming to serve as a global comprehensive approach to water governance, is more of a limited framework and although it includes environmental values and some of the modern ideas of water governance, it was arguably out-of-date when it was adopted as it scarcely referred to legal developments in the environmental, human rights, and investment arenas, but nevertheless it has influenced regional law in Southern Africa, South Asia, and Europe (Zaag 2009; Farrajota et al. 2009; McCaffrey 2007). Although the Convention entered into force in 2015, only 36 countries (mostly downstream states) have ratified it (Gupta 2016).

Increasingly regional agreements have emerged as additional sources of law for participating states as well as resources for inferring a developing customary international law. A major regional and increasingly globally relevant source of water law is the 1992 UN Economic Commission for Europe Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE 1992). This treaty covers transboundary surface waters and groundwater. It obliges parties to prevent, control, and reduce transboundary impacts, and to use such waters "with the aim of ecologically sound and rational water management, conservation of water resources, and environmental protection". It also embraces the principle of equitable utilization, but the emphasis is on environmental protection—one aspect of the "no harm" side of the equation in general customary international water law. Its 1999 Protocol (UNECE 1999) focuses on health aspects with respect to water and includes a range of environmental and water related principles. Since the

Convention is now open to universal participation, it is now competing with the UN Watercourses Convention in leading global water governance.

There are hundreds of other bilateral and multilateral international water agreements (TFFD n.d.). These agreements increasingly show the development of administrative law where legislative and judicial functions are giving way to administrative rule making on a day-to-day basis by river basin commissions being set up for the purpose (Farrajota 2009). International adjudication of water disputes is another rich and old area with cases relating to water transfers between France and Spain (1957) and the no-harm principle in the Trail Smelter Arbitration of 1941, along with several others (Castillo-Laborde 2009).

The most recent effort to pull all of this together in a comprehensive codification is the Berlin Rules on Water Resources, approved by the International Law Association in 2004 to replace the Helsinki Rules (ILA 2004). This non-binding document integrates the latest insights from environmental, humanitarian, human rights, and resource law. These comprehensive rules cover all national and international fresh waters and related resources (the aquatic environment) and thereby penetrate within national jurisdictions. It includes the principles of public participation, the obligation to use best efforts to achieve both conjunctive and integrated management of waters, and the duties to achieve sustainability and the minimization of environmental harm. It identifies the rights and duties of states and persons, the need for environmental impact assessments, and covers extreme situations including accidents, floods, and droughts. The Berlin Rules are grounded in existing law but also reflect the direction in which global water law is heading. Groundwater traditionally has been neglected by national and international water law. The Berlin Rules (ILA 2004) provides the first attempt at a comprehensive codification of the customary international law of groundwater. The UN Law Commission subsequently adopted draft articles on transboundary aquifers that was noted but not approved by the UN General Assembly (UNGA 2008; UNESCO 2009).

6.4.2.1 The Evolution of Sovereignty in Water Law

Let us now turn to examine how the concept of sovereignty has evolved in water law (Dellapenna et al. 2015). It became important as the idea of the nation state came into prominence particularly with the Treaty of Westphalia in 1648 and the works of scholars such as Machiavelli, Luther, and Hobbes. This notion influenced both national water law systems and transboundary water law from the seventeenth century onwards. Colonized countries lost their sovereignty and also their right to control their own waters to their colonizers. After World War II, the concept remained a corner stone of modern states and has been used by states to claim "permanent sovereignty" over their natural resources (UNGA 1803). Through the centuries after 1648, the increasing emphasis on sovereignty led to confrontation of claims of absolute territorial sovereignty with claims to the absolute integrity of state territory. The environmental movement strengthened the emerging tenet in law that states should not cause harm to others, although the application of this principle remains contested.

One way to conceive of the rise of supranationalism within the EU or via river basin organizations is that sovereignty is partly sacrificed for the greater good of all the parties concerned. Another way to conceive of the rise of supranationalism is that states are choosing to realize their sovereignty by expressing it through cooperative supranational institutions. The second wave of globalization has led to neo-liberal dominance, which challenged concepts of sovereignty further by marginalizing the role of the state. Ironically, markets needed stronger regulation of international contracts and this led to a spate of bilateral and multilateral agreements on trade and investments (e.g., Cossy et al. 2005; WTO 1994). The neo-liberal approach and enhanced private sector participation in water management led to legal challenges and inspired a reaction in the form of the human rights approach that tries to pierce the veil of sovereignty to protect the customary and modern access rights of the most vulnerable in society (Gupta et al. 2010; UNGA 2008). As we move into the future, water may be framed more and more in terms of its 'global public good' characteristics, its ecosystem services, and its links to energy, food, and climate (Kaul et al. 1999). The latter has led to the replacement of the integrated water resource management jargon with 'nexus' jargon (Gupta et al. 2013)—but under either form of jargon it is important to understand the relationships between different issue areas. As the subject matter of water reaches the global scale in administrative and spatial terms, it will challenge the notions of sovereignty as we know it, and law will have to rediscover itself in an effort to cope with it. Some might see legal systems—local, national, supranational, and global—as impediments to the ability to cope adequately with the water needs of the coming century, but our history of water law shows that the legal system is able, if slowly, to rise up to the challenge of change. Increasingly as issues of water governance become very technical, technocratic solutions may be proposed and may lead to growing formal and informal administrative law and governance in the water field. Such administrative law may result from the adoption of norms with a strong technocratic input (optimizing water management) which might be adopted by various water management bodies as a result of international development cooperation processes but without a formal international legal consensus on it.

Rivers often form the natural boundary between states. Traditionally there are two boundary rules—if the river's physical form changes gradually, so does the boundary of the related states. If the river's form changes overnight, the boundary does not change–it does not follow the river. Boundaries can be successive, contiguous, or based on the median or thalweg lines. Successive boundaries are when rivers flow from one country to another. Contiguous boundaries have one country on one river bank and the other on the other river bank. The median line is the formal line equidistant from both sides which determines the political boundary between contiguous states most of the time. The thalweg (the centre of the main navigation channel) is deemed to be the boundary along navigable waters in order to ensure that all contiguous states have navigational access to the watercourse (Flushman 2002).

6.4.3 Regional and Supranational Water Laws

The demise of most empires in the second-half of the twentieth century did not mean the end of supranational systems. Instead, the twentieth century saw states voluntarily creating regional water laws. Today, the European Union is the leading example of regional water law (UNECE 1992; Aubin and Varone 2004). The establishment of the European Economic Community (the predecessor of the European Union) in 1957 led to the coordination of water law within the region. Water law has been seen more as a sub-set of environmental law within the EEC/EC/EU context as there was no formal mandate for water governance. It was thus included in the six Environmental Action Programmes adopted since 1973. In the first phase (1973–1988), water policy and law focused on water quality issues and standards (e.g., Directives on: Drinking Water; Bathing Water; and the Quality of Fresh Waters Needing Protection or Improvement in Order to Support Fish Life). Following the formal mandate to legislate brought about by the 1987 Single European Act, in the second phase (1988–1995), the focus shifted to emission standards (manure disposal) and water treatment (e.g., Directives on: Cadmium; Hexachlorocyclohexane; Nitrates; Integrated Pollution Prevention and Control; and Urban Waste Water). In the third phase, the European Union created a comprehensive policy through its Water Framework Directive 2000. This directive, which applies to all EU member states, has an eco-centric logic, aims at good status for all water bodies and at management at the river basin scale, and includes a wide variety of instruments (Aubin and Varone 2004). The EU has complemented this strategy with a Marine Strategy Framework Directive in 2008.

Another type of regional system is the growing number of river basin organizations and boundary water commissions. Although such river basin organizations rarely have strong supranational law making functions, they are increasingly part of the growing system of international administrative law that some scholars argue is the cutting edge of new law-making internationally (Kingsbury et al. 2005; Krisch and Kingsbury 2006).

6.4.4 The Global Level Agreements

At global level, there are four agreements of direct relevance to water law. The RAMSAR Wetlands Agreement (UN 1971) is a legally binding agreement between 169 countries to conserve about 2293 wetlands of international importance, covering a land area of 225 million hectares worldwide. This is an international agreement but regulates areas that could fall only within national jurisdiction. Because of this, Ramsar's implementation, unfortunately, leaves much to be desired (Gardner et al. 2009).

In 1992 the UN Economic Commission for Europe countries adopted the Water Convention (UNECE 1992) formally known as the Convention on the Protection and Use of Transboundary Watercourses and International Lakes. It has since been opened up for global participation. It is currently in force but has less than 40 parties. The Convention addresses "blue water" (surface and ground water) and requires states to prevent or reduce transboundary impacts through a range of instruments (e.g. principles, standards, limits, monitoring). It calls for ecologically sound and rational water management that also aims to conserve the use of water. It mentions principles such as reasonable and equitable use, the precautionary approach, and the need for the polluter to pay. In 1999, the UNECE countries adopted a follow-up Protocol on Water and Health (UNECE 1999) which pays significantly more importance to issues of health, including access to good quality water and sanitation services.

In 1997, the UN member states adopted the UN Convention on the Law of the Non-Navigational Uses of International Watercourses (UNGA 1997). This drew heavily on the work of the International Law Commission and was inspired by the work of the International Law Association's Helsinki Rules of 1966 (ILA 1966). The Convention has recently entered into force and has 36 Parties. The Convention addresses the governance of transboundary watercourses but limits it to those that flow into a common terminus. Its key element is its focus on a number of criteria of equitable and reasonable sharing of the waters between different countries, its recognition that no use of water should have priority over other uses, and its requirement that states should not cause harm to others (McCaffrey 2007).

In 2010, both the UN General Assembly and the UN Human Rights Commission adopted Resolutions on the Human Rights to Water and Sanitation (UNGA 2010; UNHRC 2010), where the UNHRC's Resolution is a much more developed description of the right. These two resolutions make explicit what has been somewhat implicit in previous Conventions—such as the rights of women (UNGA 1979) and children (African Charter 1999) to water and implicit in other declarations on economic, social, and cultural rights (UNGA 1966). Although two Declarations recognize the right to water and sanitation services, they are not yet legally binding. There is debate among scholars as to whether this has evolved to an extent that it can be referred to as global customary law.

In addition to the above, there are discussions ongoing within the UN system on groundwater and the scholarly community has produced another code called the Berlin Rules (ILA 2004; Conti and Gupta 2016). These Rules cover all surface and ground waters, both that within national jurisdiction and those between states. It provides more attention to ecological aspects as well as the role of public participation in decision making.

6.4.5 Other Relevant Agreements

Water law is also influenced by environmental treaties, as well as treaties dealing with trade and investment. Among the environmental treaties, the biodiversity treaty (CBD 1992) requires the protection of biodiversity and this has implications for how water is divided between human use and the "use" by nature. The Climate Change Treaty (UNFCCC 1992) aims at mitigating and adapting to, the impacts of climate disruption which will mostly affect water through rising temperatures leading to melting glaciers, rising sea levels, greater evaporation, changing hydrological patterns, and increasing risks of extreme weather events (IPCC 2014). The need to climate proof water agreements is becoming very urgent (Cooley and Gleick 2011).

Water is also increasingly being traded either in bottled water and drinks, or in other products that have been made through the use of water. Such trade and investment is regulated by trade law, investment law, and contract law. For example, investment law tends to protect the interests of the investor as opposed to the issues related to water. It tends to require equal treatment for nationals and foreigners and the ability of foreign investors to transfer their money out of the country, as well as compensation where a resource is expropriated or there is damage to the investor. The combination of existing treaties on investment and trade in the area of water shows that once the private sector is allowed to invest in water, countries cannot show preference to domestic investors—and this means that if foreign investors come in, their confidential contracts with the state may endow them with water resources that are difficult to expropriate subsequently.

Finally, in 2015, the United Nations General Assembly adopted the Sustainable Development Goals which calls on all countries to protect the ecological context as well as the social goals simultaneously and requires that the Goals should be met in relation to other Goals (Gupta and Nilsson 2017; Gupta and Vegelin 2016). One of these Goals focuses on water related issues and aims to ensure the availability and sustainable management of water and sanitation for all. It has six targets that focus on universal and equitable access to safe and affordable drinking water and sanitation services, reducing pollution, enhancing water use efficiency, implementing integrated water resource management, promoting transboundary cooperation, and protecting water-related ecosystems. These targets have an impact on the achievement of many of the other 16 Goals listed in the document.

6.4.6 Dispute Resolution

Disputes happen all the time. The Watercourses Convention prescribes a set of procedures regarding how disputes should be resolved (UNGA 1997). It suggests that when states are in conflict with each other, sometimes such conflicts are with respect to facts (TFFD n.d.). It recommends the establishment of an international fact finding commission to determine the facts. Once this is done, possibly conflicts can be resolved either through negotiation and mediation. If these fail, dispute resolution is possible through arbitration or the International Court of Justice.

Table 6.5 summarizes and explains the different modes of dispute resolution.

6.5 (New) Issues in Water Law

Water law today has to grapple with a number of new issues. First, legal pluralism. Legal pluralists ranging from anthropologists through legal geographers to lawyers argue that legal pluralism is critical to protecting the rights of local people and ensuring that top-down legal processes do not marginalize people. Legal pluralism is a theory that looks at how increasingly there are multiple sets of rules applicable within the same jurisdiction.

We have argued earlier that law originated from customary approaches. In that sense law and custom should be coherent at local to national level. At the same time, international water law also built on transboundary water customs and also should be fairly coherent. However, the movement of water law world-wide through the spread of religion, conquest, the spread of ideologies (e.g. communism, globalization), and now the spread of science has led to a situation where laws at the international level precede

Table 6.5 Modes of addressing disputes

Modes	Explanation
Fact finding	Establishment of a neutral fact finding commission to determine the facts at dispute
Negotiation	A process between parties to reach a consensus
Mediation	A process facilitated by a third party to enable the disputing parties reach a consensus
Arbitration	Where the parties set up an arbitration court with judges from each of the countries in dispute and an additional impartial judge; the court is expected to adjudicate based on relevant national and international law depending on the parties concerned
International Court of Justice	Where the parties agree to go to the International Court of Justice in Hague and let their dispute be adjudicated based on the evolving state of international law

the domestic level, and where legal instruments adopted at the national level precede a proper domestic debate regarding its relevance and usefulness. As a consequence, the fresh water sphere is riddled with cases of legal pluralism at the international and national levels, especially in the context of the developing world. At the international level, there are many examples of legal pluralism within water law. Take the case of the human right to water. The legally binding UN Watercourses Convention specifically states that no use of water has priority over other uses, while the non-legally binding UN General Assembly Resolution and UN Human Rights Council Resolution on the Human Right to Water and Sanitation clearly recognizes such a right (UNGA 1997, 2010).

Legal pluralism is problematic when it implies that there are major contradictions in the water law. Addressing such contradictions becomes vital. But this will inevitably imply considerable negotiation between relevant stakeholders.

Second, water has many ecosystem services (see Table 6.6). However, most water laws have focused on provisioning and to some extent the cultural services; the supporting and regulating services have scarcely been the subject of regulation and in the future this may need to become the case. Furthermore, given that there is extensive biodiversity destruction, the need to reserve water for biodiversity to flourish becomes increasingly important. Some courts have started to recognize the river as a 'living entity' in order to protect it (Salim v. State of Uttarakhand 2017). The Madhya Pradesh state government in India has declared River Narmada as a 'living entity' (Ghatwai 2017).

Third, in the context of the Anthropocene Era, we have to face the limits at the global scale of fresh water availability and the limits to which we can pollute it or develop infrastructure on it—as this impacts on the life in fresh water bodies (Crutzen 2006). This is leading to intense competition to access and control water either through returning to the concept of sovereignty, or through using contracts to access water, directly or indirectly, elsewhere (Gupta 2018). The recognition of such global limits to water implies that governance actors may try to access water elsewhere through international contractual transactions often under private international law (also referred to as 'water grabbing' Franco et al. 2013; Mehta et al. 2012). This can take many forms—the use of subsidiaries to purchase land with attendant water rights, the use of public-private partnerships where the private party gets access to the water rights, or the outright purchase of water rights. This can be done under national law, or international contract law, or the bilateral investment treaties. Understanding the relationship between private international law and water will need to become a critical element of water law in the future.

Furthermore, water shortage may lead states to use their hegemonic power to refuse to share their water claiming sovereign rights to the water (Zeitoun and Allan 2008). There are plenty of examples of states who are avoiding sharing water with other countries. This is reflected in the large number of upstream countries who have not ratified the UN Watercourses Convention or the UNECE Water Convention (Gupta 2016). As water challenges become more and more problematic, there is a good chance that countries will return to a situation of 'my country first'. President Trump announced in Davos in 2018 that not only does he feel that for him it is 'America first', but he would find it logical if all countries looked at their own interest first. This does not bode well for water cooperation. With the development of technology to access green (water in plants and soil) and atmospheric (water in the air) water, the water grabbing efforts are spilling into this area. This is a new frontier for water governance. All this implies that water justice issues from local to global level may become even more intense in coming years (Boelens et al. 2018).

In order to deal with such kinds of problems, the Sustainable Development Goals (SDGs) were adopted in 2015 and aim to try and create some rules regarding how countries should deal with water. This policy document has 17 Goals and 169 Targets; one Goal is focused on water and tries to

Table 6.6 The many ecosystem services of water flows to humans and to other living creatures

Services	Examples
Supporting	Water transports nutrients enriching the soil; some forms of water (ice and snow) store water; it can cause erosion or control erosion; it enables photosynthesis
Regulating	Water and water flows play a part in regulating the water cycle and the climate; water flows enable the water to become purified and recharge aquifers; can spread disease unless properly managed; some kinds of water (snow) have an albedo effect
Provisioning	Drinking water, water for food, fodder, energy, water for transport; habitat for humans, birds, and insects, supports land—too much extraction can lead to subsidence
Cultural	Inspires art, religion, knowledge, enables recreational activities; some forms of water (ice) preserve life from the past or records of how life was before

Source Derived from Hayat and Gupta (2016)

present the key elements of water governance for the twenty-first century (Gupta and Nilsson 2017; Gupta and Vegelin 2016).

Fourth, we are also reaching the boundaries of what can be achieved by simply governing water. Water is closely related to land, energy, and food and this inevitably means that adopting an integrated water resource management approach may not be enough (Gupta and Zaag 2008; Hooper 2006; Holden 2013). Increasingly the literature is talking about using the 'nexus' approach and developing law for the nexus will be the next step. The SDGs also require this because they argue that the Goals need to be achieved in an interrelated and interlinked manner.

Fifth, the traditional boundaries of local, regional, national, transboundary, supranational, and global law are possibly out of date. The drivers or causes of water use and abuse may be local (e.g. local water pollution), but they may be also global (e.g. trade in water directly and indirectly—through trade in virtual water). The impacts of water use and abuse can be local (e.g. people falling sick from drinking poor quality water) or global (impacts on global salmon stocks). All this means that it becomes increasingly important to look at the different levels of water law simultaneously. Climate disruption and water is an example par excellence of where the multi-level nature of water and climate come together (IPCC 2014). Global climate law scarcely takes global water law into account (Conti and Gupta 2016), and transboundary water agreements have scarcely started to ensure that they are climate proofed.

Sixth, with the rise in the number of global disasters that even if caused by the forces of nature are increasingly exacerbated by human activity, disaster policy is being developed at the global through to national level. Most of these disasters involve water—floods, droughts, and extreme weather events. Water law has taken a fairly incremental approach, and has not so far mainstreamed a disaster management approach within its framework. This is another area where we expect a lot of developments in the future.

Finally, water governance will force us to revisit our notions of 'development' (Gupta et al. 2015). Water will limit our potential for development if it is not governed properly. But 'development' itself will need to account for the carrying capacity of water. Inevitably, water governance will require us to understand how to analyse our GDP and whether wealth and income indicators need to be modified to take into account resource limits.

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Joyeeta Gupta is professor of environment and development in the Global South at the University of Amsterdam and IHE-Delft Institute for Water Education in the Netherlands. She has been a lead author with the Intergovernmental Panel on Climate Change and the Millennium Ecosystem Assessment and has just completed her role as Co-Chair (2017–2019) of UNEP's Global Environment Outlook-6 published by Cambridge University Press. She is presently the co-chair of the Earth Commission (2019–2021).

Joseph Dellapenna has taught environmental and international law for 50 years, in the United States and at Asian and European universities. He is a lead author of *Waters and Water Rights* (LexisNexis 2018), the leading treatise on water law in the United States. He wrote the chapters on riparianism, groundwater, and international law. He served as rapporteur in the drafting of the *Berlin Rules on Water Resources* by the International Law Association in 2004 to replace the *Helsinki Rules on the Uses of the Waters of International Rivers*. He also serves as director of the Model Code Project of the American Society of Civil Engineers.

Water Discourses

7

Léna Salamé, Daene C. McKinney, Jerome Delli Priscoli, Toshio Koike, Jack Moss, Mara Tignino, Owen McIntyre, Hussam Hussein, Mahsa Motlagh, Aaron T. Wolf, Lynette de Silva, Natasha Carmi, Danilo Türk, and François Münger

Abstract

The water epistemic community discusses water matters and directly or indirectly advises policy and decision makers in ways that reflect its beliefs on one hand, and its agreements and disagreements, on the other hand. It discusses water in ways that reflect the variety of scientific and indigenous backgrounds of its members, the richness of their different expertise, their cultural and social beliefs, practices and aspirations, as well as their ethical, spiritual and religious values. These discourses cover issues as complex as the value of water and the nuances between water security, sustainability and integrated water resources management. They deliberate over statements as sensitive as claims insisting that wars will be fought over water. They examine the impacts of phenomena such as climate change over water and how humans should adapt to it; and the list is as long and vast, as the number of complex issues intertwined with the governance of water. Is water an instrument of peace, or rather the source of (inevitable) conflict? Are water infrastructures good or bad? What are the limits of international law in the management of transboundary water resources? How should one refer to and assist, a person who has been displaced because of water related hazards? This chapter shares with the reader a

L. Salamé (✉)
Paris, France
e-mail: lenasalame@gmail.com

D. C. McKinney
Department of Civil, Architectural and Environmental Engineering, University of Texas, Austin, TX 78712, USA

J. Delli Priscoli
GWP TEC, IWR USACE (ret.), Arlington, VA 22201, USA
e-mail: jdpriscoli@gmail.com

T. Koike
International Centre for Water Hazard and Risk Management (ICHARM), Public Works Research Institute (PWRI), 1-6, Minamihara, Tsukuba, 305-8516, Japan
e-mail: koike@icharm.org

J. Moss
Former Director, AquaFed – the International Federation of Private Water Operators, 75004 Paris, France
e-mail: info@aquafed.org

M. Tignino
Faculty of Law and Institute for Environmental Sciences/Geneva Water Hub, University of Geneva, Geneva, Switzerland
e-mail: Mara.Tignino@unige.ch

O. McIntyre
University College Cork, College Road, Cork, T12 K8AF, UK
e-mail: o.mcintyre@ucc.ie

H. Hussein
Department of Politics and International Relations (DPIR), University of Oxford, Manor Road, Oxford, OX1 3UQ, UK
e-mail: hh.hussam.hussein@gmail.com

M. Motlagh
Bonn Alliance for Sustainability Research/Innovation Campus, Bonn, Germany
e-mail: mahsa.motlagh@gmail.com

A. T. Wolf
College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA
e-mail: wolfa@geo.oregonstate.edu

L. de Silva
Program in Water Conflict Management and Transformation, Oregon State University, Corvallis, OR 97331, USA
e-mail: desilval@geo.oregonstate.edu

N. Carmi · F. Münger
Geneva Water Hub, Organisation Météorologique Mondiale (OMM), Geneva, Switzerland
e-mail: ncarmi@genevawaterhub.org

F. Münger
e-mail: fmuenger@genevawaterhub.org

D. Türk
Former President of the Republic of Slovenia, Ljubljana, Slovenia
e-mail: danilo.turk@up-rs.si

Geneva Water Hub, Organisation Météorologique Mondiale (OMM), Geneva, Switzerland

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non-exhaustive selection of such discourses. It sheds the light on a number of expressions, buzz words and polemics that have been overused—sometimes—with a relative indifference of their subtleties.

Keywords

Water discourses • Political will • Capacity building • Knowledge development • Water governance • Risks • Dialogues • Policies • Uncertainties • Water resources sustainability • Sustainable water resources management • Integrated water resources management • Water security • Hydro-economic modeling • Sustainability indices • Climate change • Water security • Adaptation strategies • Water pricing • Market discourse • Costs • Revenue • Value of water • Complexity • Trade-off • Political dilemma • Usages of water • Policy objectives • Policy instruments • Price • Taxes • Market principles • Affordability • Stakeholders • Valuing water • Environmental refugees • Migrants • Push factors • Pull factors • International water law • Transboundary aquifers • Fragmentation • Sovereignty • Distributive equity • Malthusian rationale • Neo malthusian • Water wars • Water conflicts • Water cooperation • Hydropolitics • Conflict transformation • Faith-based traditions • Spiritual practices • Transformative practices • Water conflict management • Water cooperation • Water diplomacy • Water-related disaster • Flood • Sediment disaster • Vulnerability • Self-help • Mutual-support • Public-support

Abbreviations

ASCE	American Society of Civil Engineers
BATNA	Best Alternative to a Negotiated Agreement
CEO	Chief Executive Officer
COP21	Conference of the Parties 21st session
Covid-19	Coronavirus Infectious Disease 2019
DRR	Disaster Risk Reduction
EIA	Environmental Impact Assessment
ETHZ	Swiss Federal Institute of Technology Zurich
GCM	Globe Circulation Models
GDP	Growth Development Product
GHLP-WP	Global High Level Panel on Water and Peace
GOWP	Global Observatory on Water and Peace
GWH	Geneva Water Hub
HydroSOS	Global Hydrological Status and Outlook System
IDPs	Internally displaced persons
ICJ	International Court of Justice
IHL	International Humanitarian Law
ILC	International Law Commission
INDCs	Intended Nationally Determined Contributions
IOM	International Organisation for Migration
IWRM	Integrated Water Resources Management
MENA	Middle East and North Africa region
MLIT	Ministry of Land, Infrastructure, Transport and Tourism of Japan
MOOC	Massive Open Online Course
NATO	North Atlantic Treaty Organization
NCA	National Climate Assessment
NGO	Non-Governmental Organisation
ODA	Overseas development assistance
OECD	Organization for Economic Cooperation and Development
SDC	Swiss Agency for Development and Cooperation
SDGs	Sustainable Development Goals
UN	United Nations
UNECE Water Convention	Convention on the Protection and Use of Transboundary Watercourses and International Lakes
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	UN Framework Convention on Climate Change
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
UNIGE	University of Geneva
UN IPCC	United Nations International Panel for Climate Change
UNSC	United Nations Security Council
UN-Water	United Nations Water
UNWC/UN Water Convention	United Nations Convention on the Non-Navigational Uses of Transboundary Watercourses
UPWCD	Universities Partnership for Water Cooperation and Diplomacy
USAID	United States Agency for International Development
USCCSP	US Climate Change Sciences Program
U.S. ICA	U.S. Intelligence Community Assessment (ICA)
WASH	Water sanitation and hygiene
WMO	World Water Data Initiative
WWC	World Water Council

7.1 Introduction—Political Will = (Trust + X^2) * Perseverance

The most common excuse we hear for not achieving good water governance, efficient transboundary cooperation, sustainable development or any other cherished objective in this field, is the lack of political will. Decision makers, analysts, scientist, activists, are all fond of saying that we have all the technology we need to address the water crisis—all we lack is political will. Everything is in place except that one "little" element. What is political will? How do you build it? And how can we influence it in the right direction?

A decade ago Hammergren characterized political will as "the slipperiest concept in the policy lexicon," calling it "the sine qua non of policy success which is never defined except by its absence." (Hammergren 1998).

In the literature 4 main elements of political will have surfaced.

1. A sufficient set of decision makers
2. With a common understanding of a particular problem on the formal agenda
3. Is committed to supporting
4. A commonly perceived, potentially effective policy solution (Post et al. 2010).

To kick off this process, one obviously needs to establish trust among concerned players (i.e. decision makers at any level, whoever they are and whatever the issue at stake is). Trust is necessary to mobilize the right set of players who would then be willing to work together. Without it, decision makers would not even come around the same table, let alone make decisions together.

One also clearly needs to ensure perseverance and long term commitment. Water governance processes are long and difficult. They are complex, they impact a humongous set of stakeholders, they have to survive, and be revived, throughout governmental changes and upheavals.

This covers the first and third conditions stipulated above and it already sounds like the hardest things to achieve; and yet, this is not even close to be enough for the accomplishment of the political will, which is in turn necessary to achieve good water governance.

The second and fourth conditions are still missing along with an essential ingredient: the binder of all 4 elements. This binder is "knowledge and capacity". It is the X in the subtitle formula and *it has to be squared* to indicate its primordial importance. Without it the process ultimately and inevitably falls apart. It is indeed not enough to have a sufficient set of decision makers who trust each other. They have to get "interested" in the issues at hand. They have to "understand it" (condition No. 2). And only if, and when, they do, can they develop effective and mutually accepted solutions (condition No. 4), which they then have to explain clearly and convincingly to their constituency and obtain its approval.

Only knowledge and well developed capacities can foster these two conditions. The epistemic "water community" is the one who makes such knowledge and capacity available to policy and decision makers. With all its efforts the community facilitates their understanding of issues at stake, gets them interested in those, and finally informs the development of their solutions. With this support from the epistemic community all 4 elements constituting political will become available and can be firmly bound together in the hope to achieve effective water governance.

The equation used as a subtitle of this section is of course a suggestive, rather than a rigorous mathematical one. It could initiate alone a full-fledged contradictory discourse as to whether it represents or not the structure of political will in an accurate manner. However, this debatable nature reflects the actual slippery characteristics of political will who is supported and informed by the prevailing water discourses.

The term "water discourses" stands for different intellectual frames within which water, its manifold attributes, utility as well as associated stresses and threats are viewed, narrated, discussed and evaluated. Their ultimate goal is to formulate principles and recommend solutions to policy and decision-makers.

Water discourses reflect values, concerns, and compassion. They are logical constructs, but not always necessarily technically or scientifically robust. At the same time, they reflect the plurality and multiplicity of opinions on a given topic. Their proliferation indicates their inherent and sometimes limited focus while it mirrors and feeds the character seldom objective or rationale of human decisions. Thus instead of one "Water Discourse" we have quite a number of them, partially conflicting but frequently also supplementary to each other.

The water epistemic community indeed discusses water matters and directly or indirectly advises policy and decision makers in ways that reflect its beliefs on one hand, and its agreements and disagreements, on the other hand. It discusses water in ways that reflect the variety of scientific and indigenous backgrounds of its members, the richness of their different expertise, their cultural and social beliefs, practices and aspirations, as well as their ethical, spiritual and religious values.

These discourses tackle countless numbers of questions that interest policy and decision makers. It informs them and hence impact the governance of water resources and related institutions. These discourses weigh the pros and cons of affirmations which can spark political and media antagonisms at national and international scales. They discuss added values and shortcomings of their own respective perception and observations. They debate and question practice on the ground.

Their exchanges and the product of their continuous debates enrich the scientific basis upon which political will may be mobilized. Sometimes, their discourses are literally taken over and continued in political arenas where they morph into yet another dimension of argumentation and polemics. They end-up, being reflected in the reality on the ground. Once a discourse's outcomes advance to constitute the underlying paradigms and foundations of legally enshrined or customary governance practices, they impact our lives and daily routines of interactions with water.

These discourses are thus key elements in the constitution of a "common understanding of a particular problem" (second condition above) and the "rapprochement" towards a "commonly perceived, potentially effective policy solution" (fourth condition). They also contribute in building the knowledge and capacities of decision and policy makers and directing them in their actions.

They cover issues as complex as the value of water and the nuances between water security, sustainability and integrated water resources management. They deliberate over statements as sensitive as claims insisting that wars will be fought over water. They examine the impacts of phenomena such as climate change over water and how humans should adapt to it; and the list is as long and vast, as the number of complex issues intertwined with the governance of water.

Is water an instrument of peace, or rather the source of (inevitable) conflict? Are water infrastructures good or bad? What are the limits of international law in the management of transboundary water resources? How should one refer to and assist, a person who has been displaced because of water related hazards?

This chapter shares with the reader a non-exhaustive selection of such discourses. It sheds the light on a number of expressions, buzz words and polemics that have been overused—sometimes—with a relative indifference of their subtleties.

Section 7.2 starts with a discussion of the long evolution of a well-known discourse, from sustainable water resources management, to integrated water resources management and, more recently, water security. Section 7.3 addresses the question of adapting to climate change impacts and how the water community and the climate change community might communicate to the benefit of informing and harnessing political will. Section 7.4 follows with an illustration through the case of Japan. It shows how increasingly vulnerable but well informed societies can use intensified hazards as a chance to adapt and achieve drastic social change. Section 7.5 explains how achieving a sustainable balance between costs, revenues and value appreciation can be challenging for policy and decision makers. Section 7.6 tackles a legal discourse that has occupied the minds of people, politicians and decision makers a lot in the past decade: the question of environmental migration, their rights, the legal protection they can aspire to. It is followed by another Sect. 7.7 on a legal discourse spelling-out issues related to the fragmentation of international water law, discrepancies between various legal texts and how they might serve or harm political will and decision making in transboundary contexts. The chapter goes on with another famous (or infamous) debate—in Sect. 7.8—around the idea of water wars and how they might influence the minds of key actors and then in turn the reality on the ground. Section 7.9 discusses approaches of conflict management in situations of risks and uncertainties. Section 7.10 brings spiritual and faith-based traditions to the table as solutions applicable to water diplomacy at various levels and scales. These tools bring ethical and moral water-considerations into the otherwise tough political processes. The chapter finishes on a high with Sect. 7.11, arguing how water can be used as an instrument for peace, informing, debating and ultimately mobilising political will behind a set of arguments and solutions.

7.2 The Sustainability Discourse

7.2.1 Introduction: Sustainable Water Resources Management, IWRM and Water Security

7.2.1.1 Sustainable Water Resources Management

Sustainable development was introduced broadly by the Bruntland Commission (WCED 1987) as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." This declaration recognized the priority of the essential needs of the poor and the limitations imposed by technology and social organization on the environment's ability to meet present and future needs. However, the description is very optimistic, but vague with details left for later and lacking specificity for implementation (Bartlett 2006: 22; Benton 1994: 129). This was a somewhat narrow path from which to begin the discourse on sustainable water management. From there, the discourse has proceeded to various definitions of sustainable development of water resources, integrated water resources management, and more recently water security. All of these have more or less been based on what has become known as the "triple bottom line" of balancing economic, social and environmental development to achieve sustainable pathways.

Recognizing that there is no clear, commonly accepted definition of sustainability, we can consider the debate over how it might best be done. The sustainable development of water resources was defined by a joint UNESCO/ASCE committee as "*Sustainable water resource systems are those designed and managed to contribute fully to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity*" (Loucks and Gladwell 1999). This was a recognition of the failure of previous "meet the requirements" approach to water resources management and allocation, where water use strategies accommodated projected population growth and economic development with minimal consideration of ecological carrying capacity or water resource availability (Loucks and Gladwell 1999). The sustainability approach also recognized the notions of no long-term decrease of future generation welfare as a result of water resource systems and consideration of risk, resiliency and vulnerability (Loucks 1997). Although the original concept of sustainable water resources management is still valid, water management policies that promote sustainable water resources systems are difficult to identify because of growing environmental, water scarcity and climate change considerations.

7.2.1.2 Integrated Water Resource Management

Integrated Water Resource Management (IWRM) became an over-riding paradigm for discussing, legitimizing, and implementing policies of water resources management, subsuming the notion of sustainability (Orlove and Caton 2010). IWRM has been defined as "*a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*" (Global Water Partnership 2000). IWRM is an empirical concept built upon on-the-ground experience of practitioners (UNESCO 2009). IWRM sets out to reconcile competing uses for water, with legitimacy attained through public participation, and with coordination and technical competence assured through specialized basin entities or agencies where they exist (IWRM 2015). New issues of water management continue to emerge, particularly climate change mitigation and adaptation, ecosystem degradation and the water-energy-food security nexus (Hissen et al. 2017). The Agenda 2030 Sustainable Development Goals (17 SDGs with 169 associated targets) have embraced water resources through SDG-6 (Ensure availability and sustainable management of water and sanitation for all), and Target 6.5, in particular, indicates that IWRM must be implemented at all levels by 2030 (United Nations General Assembly 2015). IWRM is generally envisioned to have 4 main components: (1) an enabling environment of policies, laws, plans and strategies; (2) political, social, economic and administrative institutions; (3) management instruments, or tools and activities that enable decision makers and users to make rational and informed choices; and (4) financing for water resources development and management (United Nations Statistics Division 2018).

7.2.1.3 Water Security

Over the past decade or so, the global discourse on sustainable water resources management has been used to shape the IWRM concept (Kramer and Pahl-Wostl 2014). However, water security has recently supplanted the concepts of sustainable water management and IWRM in the policy discourse (Staddon and James 2014; Gupta et al. 2016). Much of this has been prompted by predictions of a global water crisis and its effect on different facets of livelihoods and economies (Fischhendler and Katz 2013). Water security has been defined as "*the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water related risks to people, environments and economies*" Grey and Sadoff (2007). Sadoff and Grey's definition of Water Security and others (Grey et al. 2013; Hall and Borgomeo 2013) highlight the importance of risk management in the consideration of water security. More recently, the United Nations has expanded Grey and Sadoff's definition to explicitly capture interactions with wider social, economic, political, and environmental systems as "*the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against waterborne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*" (UN-Water 2013b). The World Bank has viewed water security as "*a state in which water is effectively and sustainably managed, both to leverage its productive potential and to mitigate its destructive potential*" (World Bank 2017). Water security seeks to balance human and environmental water needs while safe-guarding essential ecosystem services and biodiversity (Bakker 2012). It incorporates and extends key aspects of IWRM and includes a return to the conceptual focus on risk, resilience and vulnerability, bringing the importance of risk management into the discourse.

7.2.2 Sustainability–How Do We Implement It?

Many guidelines for implementing sustainable water resources management have been published (United Nations Conference on Environment and Development 1992; Serageldin 1995; Loucks and Gladwell 1999; Loucks 2000). No doubt these guidelines have provided some assistance and guidance to those who are involved in planning and decision making in specific regions. However, they are very broad and must be translated into operational concepts that can be applied to the planning and management of water resources systems in specific basins. The connection between the technical water planning problems (hydrology and environmental aspects) and the socioeconomic conditions of society must be considered. To achieve sustainability, a region's environmental management and socioeconomic development goals must be considered in terms of sustainability criteria or goals. Who will define these goals? Who will be responsible for ensuring that reasonable strategies are developed to achieve these goals? Who will be responsible for monitoring the long-term success or failure of these attempts?

One method that has been used to assist in the analysis and design of sustainable water resource systems is *hydro-economic modeling*. Short-term and long-term objectives based on sustainability criteria, e.g., in terms of risk minimization in water supply, environmental conservation, equity in water allocation, and economic efficiency in water infrastructure development, can be incorporated into hydro-economic modeling frameworks so that system performance can be evaluated and controlled in light of system sustainability (Cai 1999; Harou et al. 2009).

7.2.2.1 Hydro-Economic Modeling

Management of water resources requires an interdisciplinary approach, integrating natural and social sciences (McKinney et al. 1999). Important economic concepts that need to be considered in the sustainable management of water resources include transaction costs, agricultural productivity effects of allocation mechanisms, inter-sectoral water allocations, environmental impacts of allocations, and property rights in water for different allocation mechanisms. Hydro-economic models are best equipped to assess water management and policy issues in a river basin setting (Cai et al. 2002). It is at the basin level that hydrologic and economic relationships can be integrated into a comprehensive modeling framework and, as a result, policy instruments, which are designed to make more sustainable use of water resources, are likely to be developed and applied at this level.

7.2.3 Sustainability–How Do We Measure Achievement?

A water resources sustainability index that makes it possible to evaluate and compare alternative management policies for water resources systems. The sustainability index (SI) summarizes the performance of alternative policies from the perspective of water users and the environment; it is also a measure of a system's adaptive capacity to reduce its vulnerability. SI is an integration of performance criteria that capture the essential and desired sustainable characteristics of the basin. The index facilitates comparison of policies when there are trade-offs among performance criteria. The extent to which water management policies are sustainable can be determined using the SI. Sustainability can be measured by individual, group of individuals, geographic region, or sector (Sandoval-Solis et al. 2011).

7.3 Water Resources Investments and Adaptation to Climate Change

Since the dawn of human civilizations, societies made water investments to deal with the exigencies of nature. Today, most reasons world leaders and the climate change community, cite as to why we should be concerned with climate changes, deal with impacts of water events such as sea level rise, floods, drought, tsunamis and more.

What messages on adapting to climate change impacts might the water community bring to the climate change community? This section offers eight reflections to try and respond to this question.

7.3.1 Relationship Between Climate Change and Water Resources Management

There is a close relationship between climate and water resources management because the changes in temperature, precipitation and snowmelt observed now and projected for the future can cause changes in seasonal and spatial distribution of water, causing floods and droughts (USACE 2011).

Nevertheless, the data on climate changes and water, precipitation and stream flow are still vague. For example, the charts in Figs. 7.1, 7.2 and 7.3 show that:

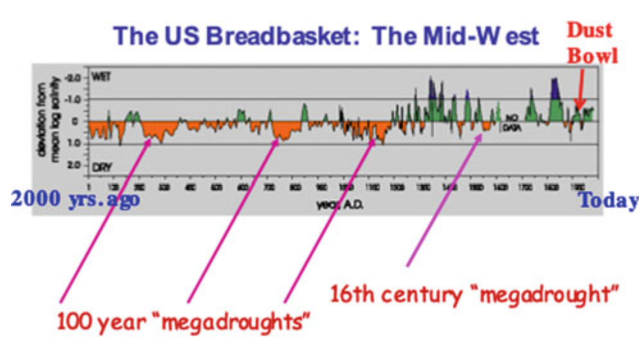

Fig. 7.1 2000-year climate history of central US. *Source* HRS Centre for Hydrometeorology and remote sensing, Overpeck, University of California, Irvine, 2004

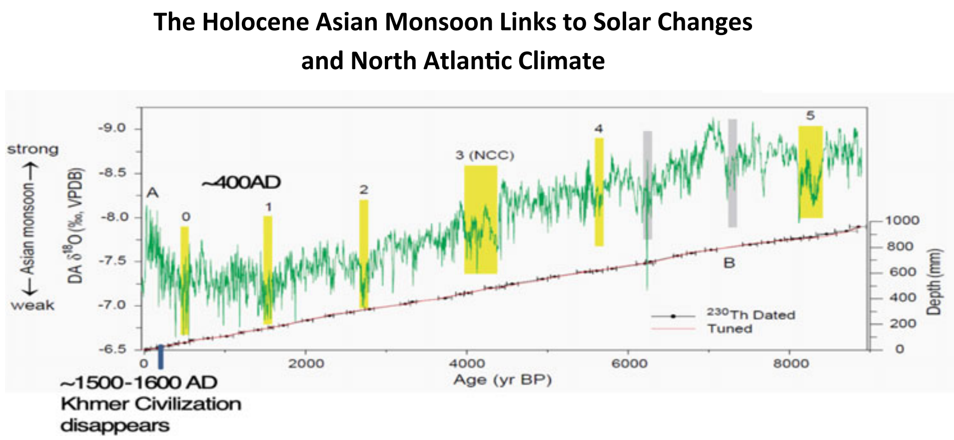

Fig. 7.2 The Holocene Asian Monsoon links to solar changes and North Atlantic climate. *Source* Wang et al. (2006) also presented by E. Stakhiv, USACE IWR, Johns Hopkins SAIS, Lecture, in "International Water Issues", December 14, 2016

- In North America droughts have pronounced multi-year to multi-decadal variability, but there is no convincing evidence for long-term trends toward more or fewer events.
- The Holocene Asian Monsoon is linked historically to solar changes and the North Atlantic climate over thousands of years.
- The decadal variability in Mekong rainfall pattern exists over thousands of years.

Climate variability and the key water related events stemming from such changes have always been with us. However, regional trends in extreme events are not always captured by current Globe Circulation Models (GCM) and it is difficult to assess the significance of these discrepancies and distinguish between model deficiencies and natural variability.

This leads some hydrologists to conclude that factoring in resiliency in water resources systems design and planning is still the safest approach.[1]

Historical exploration of climate variability clearly shows how closely linked the professional water community needs to be to the climate change community.

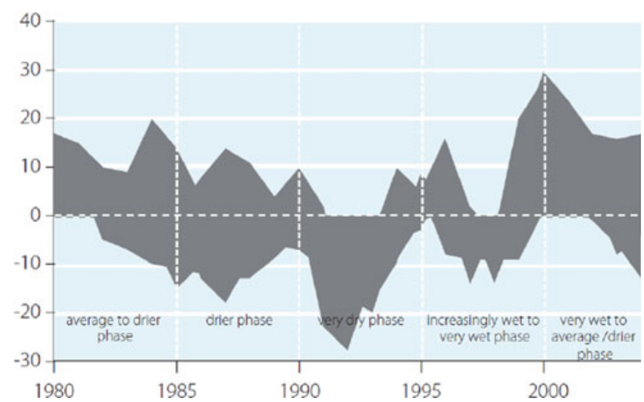

Fig. 7.3 Decadal variability in Mekong rainfall (percentage of the range in annual rainfall values compared to the long-term term historical mean). *Source* Mekong River Commission 2010, also presented by E. Stakhiv, USACE IWR, Johns Hopkins SAIS, Lecture, in "International Water Issues", December 14, 2016

7.3.2 Water Security is Crucial to Achieving Adaptation to Climate Change

Water security is crucial to achieving significant human adaption to impacts of climate changes and offers important new "soft power' to decision makers.

Water security is increasingly prevalent in the world debates. The World Water Council (WWC) has used Water Security to frame its agenda which is contained in, "A Pact for Water Security" published in 2013 (WWC 2013). The U. S. Intelligence Community Assessment (ICA 2012) noted:

> During the next 10 years, many countries […] will experience water problems—shortages, poor water quality, or floods—that will risk instability and state failure, increase regional tensions […] Between now and 2040, fresh water availability will not keep up with demand absent more effective management of water resources. Water problems will hinder the ability of key countries to produce food and generate energy, posing a risk to global food markets and hobbling economic growth.

Our English dictionaries defines security as, "freedom from danger, from fear or anxiety, from want or deprivation." (Webster's 1985). This definition closely parallels the history of humanity's management of water, of becoming engineers to assure we have good water, in the right quantity at the proper time and place, to predict floods, impound water for droughts, use water to help us generate wealth and avoid deprivation. Indeed, thousands of years ago Yu the Great became the first unifier of China in large degree due to his flood control measures (Fig. 7.4).

To the degree that humans enhanced their personal sense of security and reduced internal fears from the fatalisms of

[1]Lecture by Sorooshian (2010).

Fig. 7.4 Yu the Great. *Source* https://www.travelchinaguide.com/intro/history/prehistoric/great_yu.htm

droughts and floods, they became more sedentary and less migratory, they began to create, they invented languages, they freed up time to invest, and they started to mold their homes. Security defined as freedom from fear, anxiety, want and deprivation was enhanced.

All rich civilizations have invested social capital in actions to help achieve the sense of managing such uncertainties as a precursor to growth and prosperity. When such efforts deteriorated so too did societies. The same is true today.

This puts projections of variabilities and ways to deal with them in the historical purview of water resources management. Thus water actions, behavioral management and hard infrastructure, are really prime societal means to adapt to, and manage, the uncertainties of change, and are the keys to social resiliency; and thus keys to achieving what we might call the small "s" of security and show in Fig. 7.5. To the degree they achieve stability they contribute to the larger sense of security through reduced sense of vulnerability and contribute to the large "S" of social system stability and security.

Unless societies do something to attenuate the impact of flood and drought they have little chance to develop. Indeed, we see people in such societies become fatalistic. They accept and actually come to expect the fate of being wiped out and starting again every several years. Fear and security, the small "s," is pervasive and carried in memory generationally.

In Southern Africa, 61% of the area, 77% of the people and 93%[2] of the water are in shared basins; meaning that international river basins form an important element of the Southern African Regional Security Complex.

In Fig. 7.6 Turton and Warner map how countries in Southern Africa are both adaptively and water secure. We see many countries that are water secure but adaptively not secure thus pointing again to the role of water infrastructure investment in reaching social stability.[3]

Further Fig. 7.7 shows a relationship between water infrastructure investment and democracies in Africa. Both reveal a political economy of water investments as platforms for growth and achieving the small "s" security.

Water security is achieved through balancing the productive use with managing vulnerabilities to its destructive power; to balancing access to it with living with acceptable levels of risks from unpredicted event (Grey and Sadoff 2007).

The Asian Development Bank notes the close correlation between achieving national water security and governance (Fig. 7.8).

USAID studies have begun to show (Fig. 7.9) that most states that are highly fragile or at high risk for instability are also vulnerable to climate related threats. However, the converse is not true. Once again this shows the importance of the linkages of adaptation investments to stability.

War and large scale violence are what we might call the big "S". They are the traditional concerns of the security community. Investments in the small "s" of water security become critical to enhancing the big "S" or avoiding large scale social violence and instability and governance.

The security communities worldwide could well look at strategically important areas of the world and ask how they might use the soft power of water investment and ask: "How might investments in water actions achieve the small "s" and thus help achieve big "S"—security."

7.3.3 Fears of Climate Change Impacts Prevents Anticipation and Adaptation

We are raising fears and anxieties over impacts of projected changes in climate while inadvertently denying means to cope with these impacts.

The major reasons repeatedly used in talking points of international officials, for why we should deal with climate change are potential water related events and their projected social impacts. They primarily are social impacts of: frequency and intensity of droughts and floods; sea level rise; water access and scarcity; water quality and health problems; increased frequency of torrential rain; intensification of typhoons/hurricanes, and; others. Fortunately, the world is placing increased focus to adaptation. Too dominant a focus on mitigation with little on adaptation can mean we could

[2]Turton A. R., personal communication, September 2010.

[3]Personal communication with Antony Turton, September 2010.

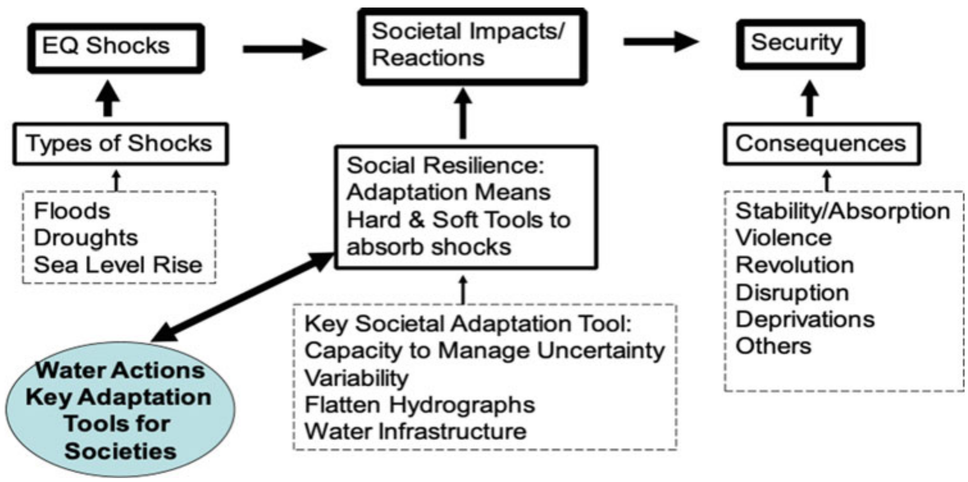

Fig. 7.5 Environment/water actions are adaptation tools and keys to societal security/stability. *Source* Delli Priscoli (2009)

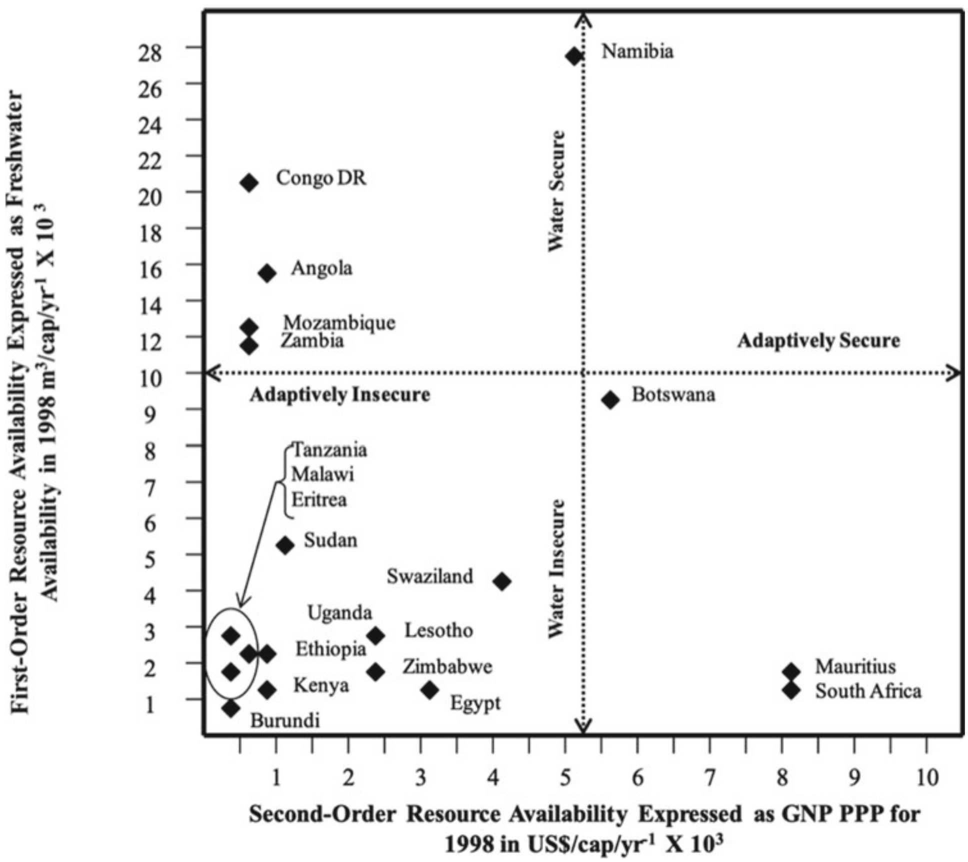

Fig. 7.6 Adaptive security matrix. *Source* Turton and Warner (2002)

inadvertently deny people adaptive means to cope with these projected high impact events. This raises important ethical and public policy issues.

Information from GCMs do not offer adequate reliability in precipitation and run off. And such is necessary to gauge potential social impacts. Regional trends in extreme events are not always captured by current models and it is difficult to distinguish between climate model deficiencies and natural variability (USCCSP 2008). Never the less, the climate models leave water managers to contend with 23 GCMs generating numerous scenarios (Delli Priscoli and Stakhiv 2015). This is juxtaposed to over 100 years of peer reviewed analytical approaches to risk and uncertainty of extreme events in the hydrological community.

If the academic and political communities are going to offer reasonable social impact assessments of projected climate changes, we must encourage more cooperation between climate modelers and hydrologic modelers. We need better

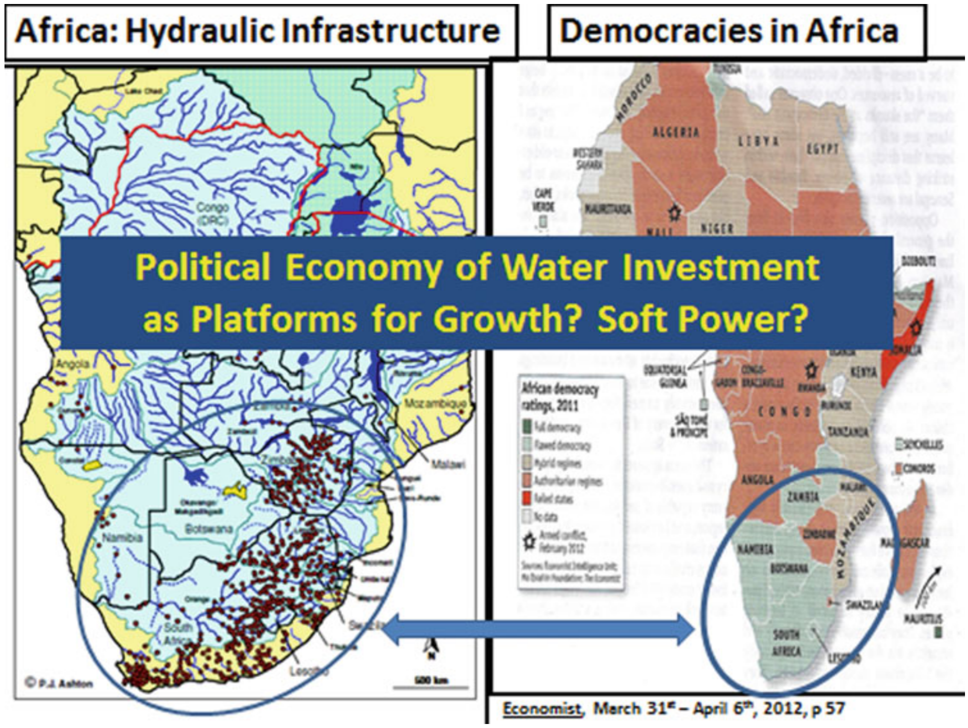

Fig. 7.7 Hydraulic infrastructures and democracies in Africa. *Source* The Economist, March 31–April 6, 2012, page 57

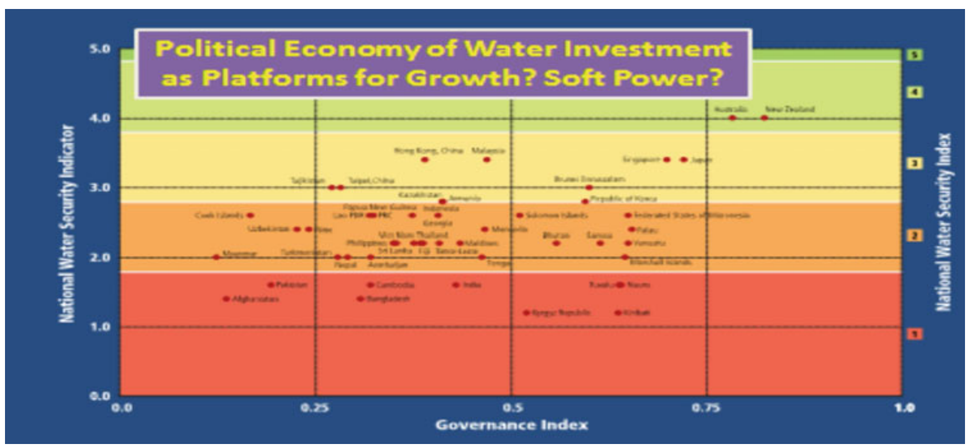

Fig. 7.8 National water security and governance. *Source* Asian Development Bank (2013)

understanding of adapting to what? To do this we also need to close the gap between how engineers versus scientist use technical information especially on characterizing risks.

Closing this gap is necessary if we are to relate to the general public. It is the first step in learning about potential social impacts of changing climate. It is necessary if we are to formulate macro-economic benefits/costs of water infrastructure investment so as to provide baseline for public debates on national trade–offs. It is essential to our financing institutions capacity to do socio-economic vulnerability assessments for water infrastructure investments? It is essential to insurance industries capacities to produce realistic actuarial rates.

7.3.4 Managing Variability and Risk Reduces Poverty and Creates Wealth

Managing variability and risk, in water resources especially, is necessary to reduce poverty; break the fatalistic determinisms pervading intergenerational memories, and; to create wealth by building platforms for growth.

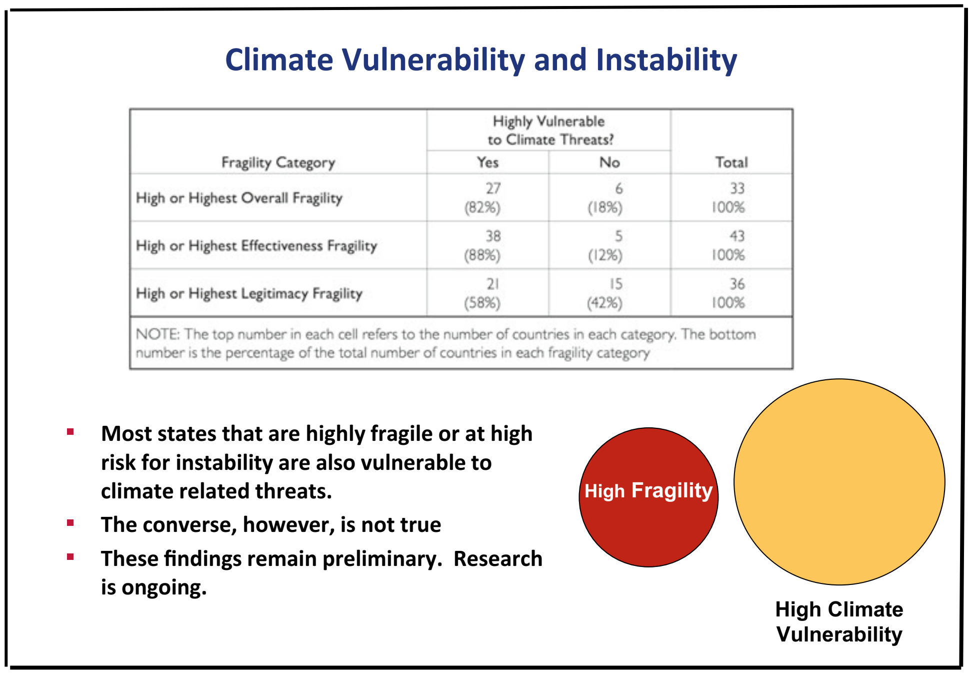

Fig. 7.9 Climate vulnerability and instability. *Source* Moran et al. (2018) used in J. Delli Priscoli's lecture "Defining Water Security and Transforming Water Conflicts," Harvard Kennedy School of Government

To understand social impacts, we must understand that the change in climate is not from some stable sense of nature or climate we experience today to dire unknown future perturbations. Nature is always changing; climate is always changing; social systems are always changing. To assess social impacts of climate change we need to relate that projected climate events and changes to our human activities: in other words, how are two ever changing dynamic systems likely to relate.

When looking at thousands of years of human and climate interactions on the Nile, paleontologist and archeologists note that the only constant is change, thus questioning the validity of making climate change the prime dependent variable! But for social impacts it is the shorter decadal changes that are crucial. Failures to help humans react to such decadal changes can result in terrible social events; some have even noted cannibalism. Historically, the major macro social means to help humans to adapt in the shorter term have been water investments (Delli Priscoli and Hassan 1998).

In 2007 Grey and Sadoff referred to World Bank data describing Zimbabwe, Ethiopia, Kenya and Mozambique and the variance of their GDPs depending on rainfall. In fact, the variations in GDP due to the inability of dealing with variations in rainfall (the peaks and lows of the hydrograph, floods and droughts) might account for almost 25–30% of variations in GDP. The International Water Management Institute (IWMI), in 2009, notes that Ethiopia's limited ability to cope with droughts and floods are estimated to cost the economy one-third of its growth potential (Grey and Sadoff 2007). If such assessments are close to reality that could negate effectiveness of much development aid in its hitherto administered form.

It seems that water infrastructure investment brings damages as a percentage of GDP to roughly 5% levels in the rich world as opposed to around the 25–30% often estimated in the poorer world. Means to flatten the hydrograph must be taken to avoid accelerating the discrepancies between the poor and rich. Much of the prescriptions of the rich to the poor, behavioral and individual regulation are not what those same rich used to gain wealth.

Figure 7.10 shows a relationship between the Human Development Index and Damages as % of GDP. It also shows a movement of the transition countries toward the upper left.

Figures 7.11 and 7.12 paint similar pictures for post war Japan and modern China. They capture some of the interactions between the two dynamic systems; nature and humans. As the index—damages as percentage of GDP—lowers it also is an indicator of increased resiliency; resiliency to allow the social systems to continue functioning even under the stress of large scale hazard events.

We might then ponder: do rich countries have high resiliency because they are rich or did they become rich because they invested in resiliency measures?

7.3.5 Communication Around Risks Impacts Policies and Governance

How risk is communicated and managed will impact the health of our political cultures; and governance structures.

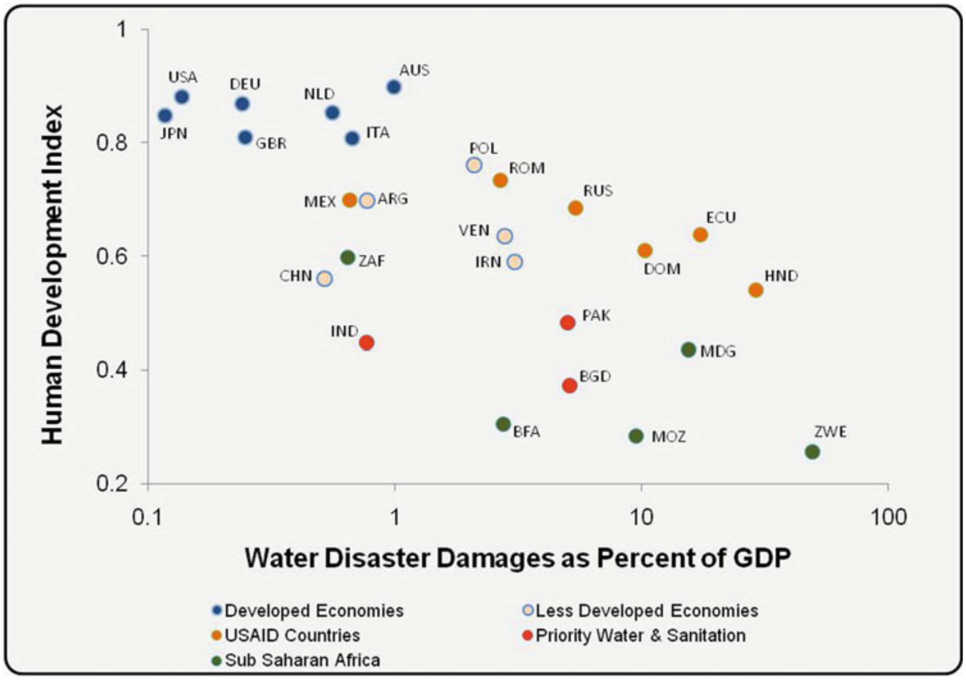

Fig. 7.10 Human development and water disaster damages as percent of GDP. *Source* Mendoza (2010)

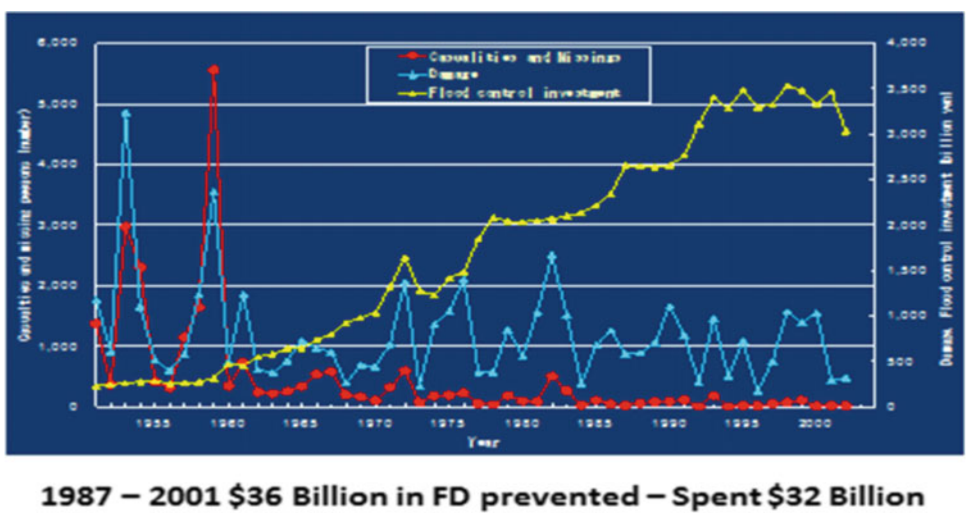

Fig. 7.11 Flood damage and flood control investment in Japan. *Source* MLIT (Ministry of Land, Infrastructure, Transport and Tourism, Japan) (1987)

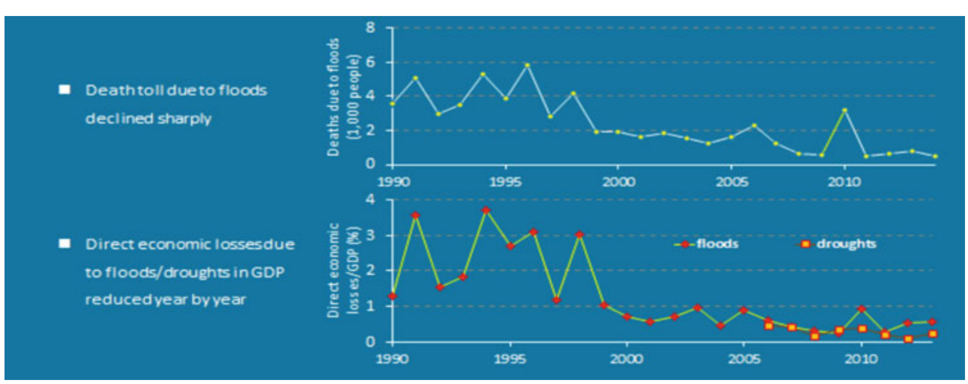

Fig. 7.12 Strengthening of flood control and disaster mitigation strategy. *Source* Water in China, Ministry of Water Resources China, Strengthening of Flood Control and Disaster Mitigation Capacity, in 2015 also presented to World Water Council BOG Nanjing, 2015

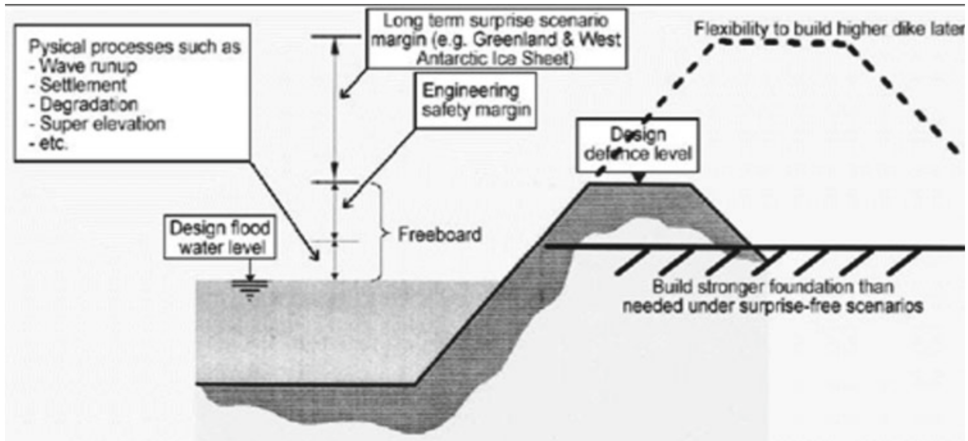

Fig. 7.13 Climate uncertainty leads to engineering uncertainty. *Source* Dessai and van der Sluijs (2007)

The water climate dialog makes us aware that somehow we need to collectively better describe risks and uncertainties with those publics we seek to serve—we may be adding confusion to confusion with different uses of data, definitions of uncertainty and risk; stemming from our separate communities. If we do not improve, we all risk having our publics react by rejecting what they perceive as dueling experts and dueling visions of science and engineering and ultimately depreciating the credibility of science; something none of us want.

The emerging paradigms of Disaster Risk Reduction (DRR) place the onus of understanding the complexities of risk reduction options on the public and local officials. In order for the new paradigm to succeed, we need to dramatically improve risk communication policies and procedures for DRR. Some argue that the 100-year flood should be termed the 1% or high risk flood, and the 500-year event becomes the 0.2% or extreme risk flood. Some believe, however, that the movement to a risk-based water resources planning and decision making framework and away from designing to pre-determined engineering design standards may result in more structures being built in flood hazard zones, increasing exposure and susceptibility to flooding. The water resources management options and the context of water and risk are dealt in more detail in Chaps. 18 and 22 respectively.

What happens if the populace decides to accept a 'tolerable degree' of risk that is greater than engineering design standards, based on their calculation of a risk-cost optimum?

In a democratic society, the key is to link risk with responsible behavior; to encourage the active choice and acknowledgement of flood risks, versus a passive reliance on institutional actions or solely on a professional paternalism—be that an ecological or engineering paternalism. However, the public must somehow be fully aware of both the risks and consequences.

Defining 'tolerable risk' and 'residual risk' no longer remains a scientific or technical exercise, as it quickly moves into the realm of political choices, with aspects of equity, social justice, joined with a myriad of other aspects of ethics and morality. More details of the ethical aspects of water resources management are available in Chap. 5. With climate change and adaptation, that becomes exceedingly more difficult because of increased uncertainties that complicate rational decision making and engineering adaptive measures (Fig. 7.13).

There is no 100% safety; there will be residual risk. Systems can perform as designed while events still overwhelm them—this is hard to communicate. Therefore, people must actively choose/accept levels of risk versus passive be told what to accept. Communities need to be involved in risk management of where they live.

7.3.6 Behavioral Regulations Are Insufficient as Adaptive Strategies

Behavioral regulations and individual life style changes are insufficient adaptive strategies for most of the world. Adaptive water resources strategies will require various forms of infrastructure and storage.

Recently, the CEO of a prominent environmental NGO publicly stated,

> If we do not do anything about climate change the people of Bangladesh will continue to be flooded … and … we can no longer engineer our way out of the crisis of climate change…[4]

Is such a statement accurate? What does it say to policy makers? What does this say about how we dialog between the water community and climate change community which is introducing more uncertainty? What is the best strategy for

[4]"The Great Mississippi River: Restoring Balance Symposium," Symposium VIII of the Religion, Science and the Environment Symposia, under the auspices of His All Holiness Ecumenical Patriarch Bartholomew, 18th–25th October 2009, New Orleans.

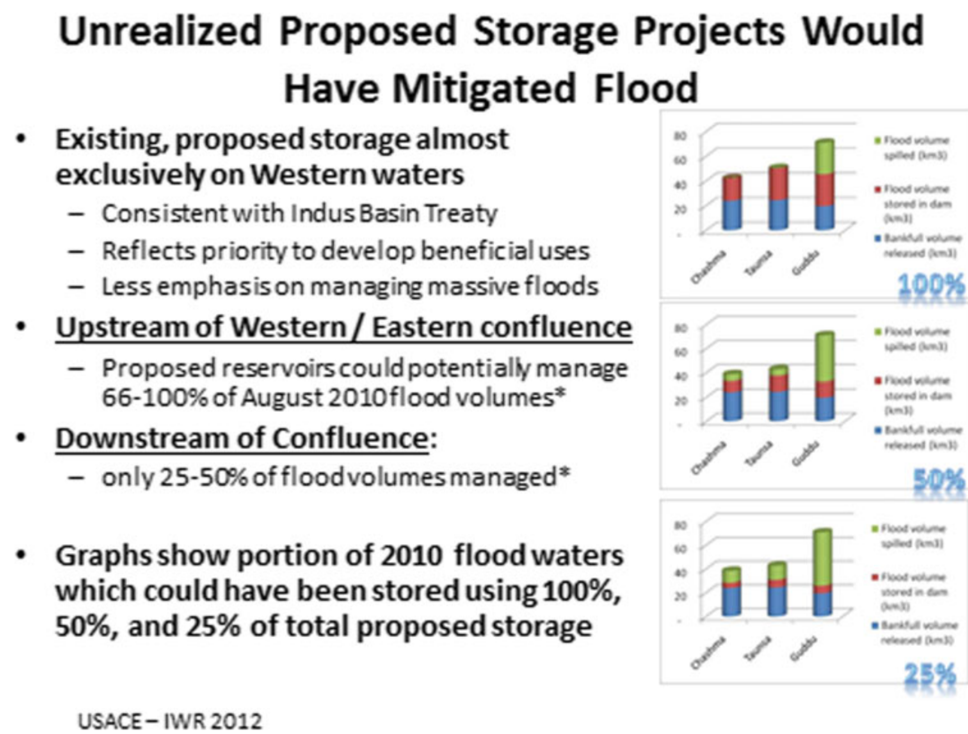

Fig. 7.14 Unrealized proposed storage projects. *Source* U.S. Army Corps of Engineers, Institute for Water Resources, Joint Post Pakistan Flood Study, Ft. Belvoir, va. 2012

dealing climate uncertainty and water resources: hard structures or soft behavioral changes?

The answers are not obvious. Some answer by saying the "soft path," or behavioral management is the best approach and even the most democratic. Early UN IPCC reports and many others spoke of water demand and institutional adaptation as primary components for increasing system flexibility to meet uncertainties of climate change. However, several mainstream professional water associations in the world were not so sure and emphasized changing operating rules and looking at hard infrastructure.

Primary reliance on demand management can be dangerous; especially where there is little water availability. Water demand management is dealt with in Sect. 18.6. What are the social/political impacts when our primary means to adapt is to order people to behave; this is unlikely to produce more democracy. In fact, one can argue that the investment in water infrastructure provides more social resiliency as it buys time and space for people to continue living and coping with and recouping from, water related disasters. And it is increasing social resiliency that is critical to prepare for social impacts of uncertain future events.

For example, in the late summer of 2011 the Mississippi River reached some of the highest recorded levels in US history. This was managed through the Mississippi River and Tributaries (MR&T) project which was constructed over the last 70 years (USACE, MVD 2012; Post 2011 Report).

The 2011 event was close to the size of the historic 1927 event. By contrast in the 2011 event over 4.0 million people were protected. The MR&T realized $478.3 billion in flood damages prevented which means that it had a large positive return on public investment. A similar story can be seen in the performance of the three Gorges Dam in the Yangtze floods of 2011.

Tragically the non-attention to water infrastructure investment resulted in significant losses in the Indus floods of that period. One fifth of the country was covered. Ten million people were left homeless and more than 21 million people were affected. The White House noted that every dimension of our Relationship—politics, economics and Security—shifted as a result of this historic disaster.[5] The Washington Post reported that "instead of forging unity, the Disaster seems to have deepened age-old fissures. The four provinces are engaged in cut throat battles for shares of flood aid money and people fleeing from the flood stream to the city Karachi (The Washington Post 2010).

Pakistani/U.S. post flood studies showed that proposed reservoirs could potentially have managed 66–100% of August 2010 flood volumes. Figure 7.14 shows portions of 2010 flood waters which could have been stored using 100, 50 and 25% of total proposed storage.

While some have seen the Indus flood as an indicator of climate change most hydrologists see it as a less then extreme 50-year event. What happened? Over the years socio-economic activities increased with little attention given to adaptive investments to help manage large events. If

[5]U.S. White House, coordinator for Afghanistan and Pakistan, August 23, 2010.

this situation is repeated worldwide; one may ask, what will happen if larger scale extreme events occur?

In October 2012, people up and down the Eastern Coast of the United States suffered enormously from Super storm Sandy induced storm surges that flooded major urban areas and severely damaged hundreds of kilometers of shoreline. One hundred seventeen people in the U.S. were killed and 650,000 homes were damaged or destroyed. Damage estimates for New Jersey—New York area alone exceeded $60 billion. Political arguments of who will pay and how much should be rebuilt continue.

Sandy alerted the U.S. to the growing challenges of climate variability and urban design. Figure 7.20 was developed by National Geographic and depicts how Manhattan would look with an additional 1.5 m or so of sea level rise, plus the 4-m-high storm surge from Sandy.

The third National Climate Assessment (NCA) for the U. S., May 2014, noted:

> The nation's economy, security, and culture all depend on the resiliency of urban infrastructure systems. How will New York City and other coastal cities prepare for this type of inundation (US Global Change Research Programme 2014)?

Post Sandy assessments revealed that along the Atlantic coast, there was significantly less damage and social disruption from hurricane Sandy, around those areas with existing hurricane shore protection projects. While this shows the importance of infrastructure investment it also brings to light the difficult questions of how to choose what to protect and how to fund protections and how to integrate structural and non-structural measures (Delli Priscolli and Stakhiv 2015). Figure 7.15 illustrates the new paradigm for flood risk management.

Storage, multi-purpose reservoirs and non-structural methods, must be at the center of societies' climate change adaptations to deal with the projected impacts of climate change. This is one of the most tangible and pressing points of water—climate change dialog; one that is at the heart of dealing with social impacts of changing climate.

So what is the best strategy for water when dealing with uncertainty of the types projected in climate change? The answer has huge implications for type and health of political cultures.

7.3.7 The Focus on Adaptation Can Improve Dialogs Between the Rich and Poor

The World Water Council (WWC) initiated dialogs on water climate change and adaptation revealed virtual opposite views of what the rich countries prioritize versus what the poor countries prioritize for water adaption measures (Fig. 7.16). The developed countries are more likely to think of environment and security in terms of global environmental changes and developing countries are more concerned with the human security implications of local and regional problems.

Using prescriptions for structuring water, based on the experiences of one socio-economic stage for another stage, is dangerous and likely to provoke resentments or even violence. Thus the rich—poor dialog over water is an important part of achieving security. The climate—water dialog offers enormous opportunity to restructure this rich—poor dialog in such directions.

Investment in water infrastructure (hard and soft) is a primary means both to achieving social ends of reducing poverty and to managing climate uncertainties for acceptable social stability, resiliency and security. This should be a powerful message to pursue in the water-climate change dialog as it moves to means for adaptation.

7.3.8 We Know Climate Change Impacts and How to Approach Them

Despite the uncertainties we have basic ideas of where most important social impacts will occur and on how to approach them.

Coastal areas will be most vulnerable on all scenarios due to sea level rises, ground subsidence and storm surges. At the same time, mega cities, mostly near the sea, continue to grow (US Global Change Research Programme 2014). This raises many questions: What should be done? What levels of protection should we seek? How will we pay? Can we realistically talk of relocating cities?

We are learning much of eco-system service of estuaries and wetlands such as dissipating storm surge impacts and

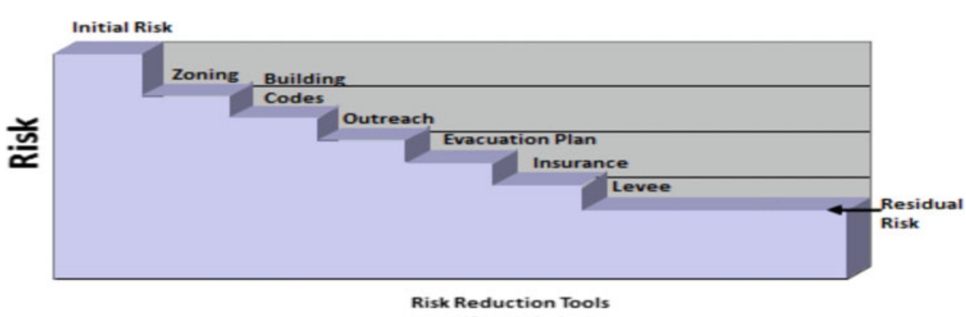

Fig. 7.15 Flood risk management: the new paradigm. *Source* U.S. Army Corps of Engineers, Head Quarters Civil Works, Briefing, Washington, D. C. 2012

Political Dialogue: Ministers DC's-LDC's-TC'S

	Best Practises	No regret	Climate proofing
Developed countries	+	+	+
Countries in Transition	+	+/-	-
ODA	+	-/+	-

Fig. 7.16 Political dialogue ministers DC's-LDC's-TC's. *Source* Joint IWA—World Water Council workshop, Delft IHE, August 2008

more. There is broad consensus, regardless of climate change projections, that we must increase efforts to re-nourish and restore their functions. To build flexibility we need also to think of beneficial uses of flood zones to reduce vulnerability and to increase resiliency of ecosystems; these increase resiliencies.

Regardless of the extent of changes, we need early better warning systems; the social component of this is critical. We need to increase the people centered flood warning as dissemination and communication critical.

Existing social inequities are likely to be accentuated under most change scenarios. Since absolute safety is not possible, we must find ways to minimize effects when and if project design values are exceeded. Communicating risk is difficult already but even more difficult regarding residual risk. More Community participation in disaster preparation needs to be undertaken in what we know are vulnerable areas and population.

7.3.9 Conclusion

UN-Water notes, "Adaptation to climate change is mainly about better water management."[6] Water investments must be key parts of any adaptation strategies or mechanisms negotiated around climate variability. A survey by French Water Partnership (Cran and Durand 2015) reports that 92% of Intended Nationally Determined Contributions (INDCs), part of the Paris COP21 agreements, submitted to the UN by 129 countries include water. The survey notes that water is the first priority noted for adaptation.

The rhetoric "more floods and more droughts" is not sufficient: more then what? Where? It is misleading. Humans have a rich history of their interactions with climate: we need to better mine this collective experience and rely on our history in our policy proclamations.

Events in nature have always impacted and forced behavioral changes from humans. However, as humans' capacity to reflect and understand has grown so too has the capacity for humans to think ahead and act to mitigate or adapt to anticipate changes; to actively interact with their destinies. Humans discovered they did not just migrate as climates changed; they become sedentary and developed means to adapt to changes. Theses interactions have grown ever more complex; so much so that it is hard to separate the human from nature—they really are one.

The heart of this paradigm is that more than preserving or restoring we are actually jointly designing our ecology—our home—with nature.

7.4 Flood Management Policy Evolution Against Intensified Hazards and Vulnerability of Society—A Case in Japan

7.4.1 Heavy Rainfall Events and Risk Reduction Measures in Japan

In recent years, extreme water-related disasters have occurred one after the other in Japan: Izu-Oshima heavy rain disaster in 2013, Hiroshima sediment disaster in 2014, Kanto and Tohoku heavy rain disaster in 2015, Hokkaido and Tohoku heavy rain disaster in 2016, Northern Kyushu heavy rain disaster in 2017, and Western Japan heavy rain disaster in 2018. These disasters open up a long list of complex issues such as the number of victims, the diversity of damage types, and problems related to evacuation and flood control structures.

After the sediment disasters in Izu-Oshima and Hiroshima, the Sediment Disaster Prevention Act was amended in November 2014. It then mandated the prompt public announcement of the basic investigations' results on, sediment disaster risk as well as, the enhancement of warning and evacuation systems for better sediment disaster management. In January 2015, the national government proposed a new disaster-related policy, "The way of disaster prevention and mitigation corresponding to a new stage". It places the highest priority on the protection of human lives and the prevention of devastating social and economic damage. In May 2015, the Flood Risk Management Act was revised. The revision requires that underground malls implement measures for safe evacuation and inundation prevention. It also requires that measures for the protection

[6] https://sustainabledevelopment.un.org/content/documents/UNWclimatechange_EN.pdf.

of lives be implemented, assuming floodwaters, landside waters, and storm surges of largest scales based on scientifically applicable methods. In July 2018, the government also published a calculation method as per the new requirements of the Flood Risk Management Act, to define the "largest expected hazards".

Despite these national efforts, problems still arose when the Kanto and Tohoku heavy rain disaster occurred two months later, in September 2015. Many people were very late to evacuate from floods caused by overflows and levee breaches. They were stranded in houses and other places surrounded by floodwaters. As a result, about 1,300 people were rescued by helicopter and nearly 3,000 by ground forces. Post-disaster investigations found that the evacuation order was not issued—in some areas—before the levee breaches. In response to lessons learned from this disaster, the Social Infrastructure Development Council submitted another report to the national government in December 2015 (Council for Social Infrastructure Development 2015). The report aims at rebuilding a risk-conscious well-prepared society against water-related disasters. It proposes the basic planning concept for the reduction of damage during large-scale flooding, including measures to, save people from being stranded, ensure wide-area evacuation, and prepare structures and facilities for better risk management.

The national government later decided to apply the report's proposals to rivers managed by prefectures in addition to those managed by the State. In August 2016 however, the Hokkaido-Tohoku heavy rain disaster occurred and caused severe damage to areas along prefecture-managed rivers. Residents of an elderly home were killed, and the local economy was devastated as a consequence of the disaster. In response, another report was submitted, addressing the basic concept for rebuilding a risk-conscious and well-prepared society against water-related disasters in small- and middle-sized rivers (Council for Social Infrastructure Development 2017). The report encourages more cooperation between the State and prefectures in order to totally avoid flood victims and aim at fewer socio-economic losses as a consequence of flooding of small- and middle-sized rivers.

Based on these two reports, the Flood Risk Management Act was amended in May 2016. The revision legalizes the creation of a council for damage reduction during large-scale flooding by State and prefectural rivers. It recommends that a council should be organized based on geographical considerations and administrative boundaries. The revised act also requires that managers of facilities whose users need help to evacuate in case of emergency, prepare an evacuation plan and conduct evacuation drills. In addition, the State government is now allowed to practice the authority originally belonging to prefectures, if necessary, in the case of post-disaster reconstruction projects and dam redevelopment projects. To accelerate the effect of the revisions, the MLIT also announced in June 2016, an urgent action plan for rebuilding a risk-conscious and well-prepared society against water-related disasters.

The Northern Kyushu heavy rain disaster occurred merely two weeks after this announcement by the MLIT. At that time, a band-shaped precipitation system formed over the Seburi Mountains on the border between Fukuoka and Saga Prefectures. As much as 169 mm hourly rainfall poured on Asakura City, Fukuoka Prefecture, slightly short of 187 mm—the highest hourly rainfall recorded during the Nagasaki heavy rain in 1982. The rainfall reached 778 mm after nine hours, which made it among the most extreme rainfall events since meteorological observation started in Japan. Asakura City, who experienced the 2012 Northern Kyushu heavy rain disaster, had prepared for heavy rainfall and associated hazards. It created disaster prevention maps to assist citizens in taking independent action in cases of emergencies designated evacuation sites in each community, and conducted evacuation drills. On the day of the disaster as well, the city issued evacuation preparation information, evacuation advisories, and evacuation orders at appropriate timings. Despite all these measures, the City found itself faced with the sad reality of 35 citizens either killed or missing.

Record heavy rainfall hit Hiroshima, Okayama and Ehime Prefectures of Western Japan in July 2018, leaving around 250 people either dead or missing. A single heavy rain event fatally made over 200 victims for the first time since 1982. Severe damage was also caused to economic and other activities. The Cabinet Office of Japan estimated that the infrastructural damage added up to between 0.9 to 1.7 trillion Yen (approximately 10 to 20 billion US Dollars), which is an order of magnitude larger than the amount caused by other recent flood disasters.

The disaster resulted from continued heavy rainfall during 24 to 72 h, over almost all parts of western Japan. The record intense convergence of water vapor indeed lasted for several days over the region due to the characteristic meandering pattern of the jet stream. Experts pointed out another factor that contributed to the extreme phenomenon: continuous supplies of water vapor into the atmosphere due to higher sea surface temperatures around Japan at that time.

Increased floodwaters induced by the heavy rainfall devastated many parts of western Japan in different forms of hazards such as inundation due to levee breaches and overflows, debris flows, mudflows, and urban inundation. Hiroshima, Okayama and Ehime Prefectures, where many observation stations recorded 24 to 72-h rainfall of over the 100-year return period, experienced particularly severe damage. In some places, the backwater phenomenon occurred at the confluence of the main and tributary streams; in other places, multiple factors were found to have contributed to unprecedented disasters, in which sediment transported from hills and mountains deposited in rivers, reducing their cross-sectional area and eventually causing floodwaters to overflow. Moreover, with eight dams in the three Prefectures filled up to the flood control capacity, the dam operators were forced to start the operation prepared to cope with extreme floodwaters and prevent dam failure. This was another aspect of this heavy rain disaster deserving attention. This disaster was as if all types of recent disasters had occurred simultaneously all across western Japan.

After carefully analyzing the characteristics and issues related to the disaster and devising a basic policy for effective disaster management, the Social Infrastructure Development Council submitted a report to the MLIT on December 13 (River Council for Social Infrastructure Development 2018), suggesting a series of actions that should be implemented immediately. The report proposes organizing a system to promote self-help and mutual support in case of disaster towards building communities where each member can take appropriate evacuation action independently. To this end, it suggests calling for more cooperation from the private sector such as the mass media and communication companies, increasing the quality and quantity of information on disasters, risks and evacuation, as well as improving tools and methods for informing the public better. The report also provides advice on social infrastructure planning to prepare for multi-hazard and hazards exceeding the design capacity of structures and offers proposals to accelerate post-disaster recovery and reconstruction, and raise public awareness of disaster risks. Overall, it stresses the importance of a “multi-layered” effort, in which actions planned from different perspectives are taken for well-defined purposes.

7.4.2 Increasingly Intensified Water-Related Disasters

Water-related disasters continue to be more destructive. As the climate continues to change, the frequency and pattern of heavy rainfall changes, and in turn, it affects the pattern of river-related disasters, which are used to create disaster types never seen before. Furthermore, as Japan’s population is decreasing and aging rapidly, the society as a whole is losing awareness towards risks.

7.4.2.1 Changing Natural Hazards

The Automated Meteorological Data Acquisition System (AMeDAS), a regional meteorological observation system operated by the Japan Meteorological Agency, started its operation in 1974, collecting hourly rainfall data from about 1,300 stations across the country. According to the data collected by AMeDAS, unprecedented heavy rainfall occurs more frequently throughout the country. The finding is from an analysis in which the total observation years of 44 were divided into three periods, then the yearly number of stations that recorded the highest 24-h rainfall in history was counted, and an average number of such stations was calculated for each period. As shown in Fig. 7.17, the average was around 20 stations per year in the first two periods while it was more than 50 in the last period. In July 2018 with a heavy rain event, a new record was registered at only 14 stations for hourly rainfall, but 125 stations were registered for 48-h rainfall, and 123 stations for 72-h rainfall, which shows that about 10% of the stations in Japan observed the highest long-term rainfall in the history of the country.

As the pattern (e.g., intensity and frequency) of heavy rain has changed, the patterns of sediment- and water-related disasters have started changing. In Northern Kyushu during the heavy rain disaster of 2017, slope failures and debris flows occurred in many parts of the Sefuri Mountains, which are mainly covered with granodiorite and schist rocks. Decomposed granite soil, produced from granodiorite rocks and weathered deep inside of the mountain, played a critical role in this disaster. This type of soil, locally called “*Oni-masa* (evil decomposed granite),” was transported from the mountains to the rivers through slope failures and then in debris flows. After temporarily depositing in and around the river courses, the soil was again transported downstream in floodwaters and filled the narrow,

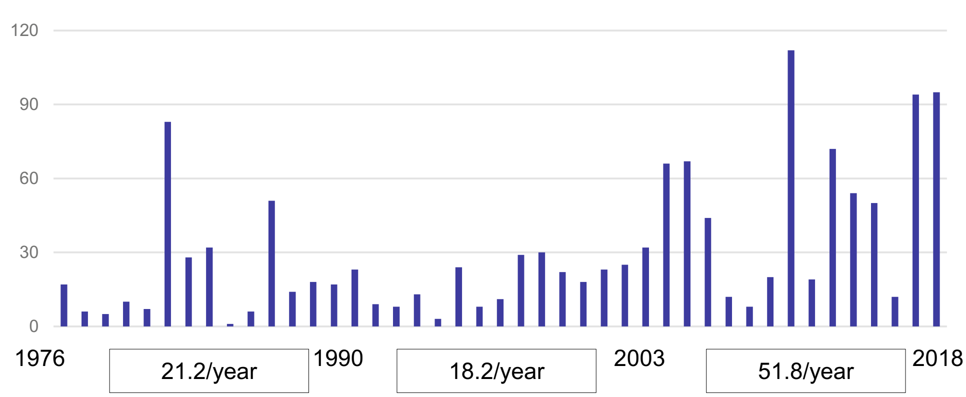

Fig. 7.17 Yearly number of AMeDAS stations that recorded the highest 24-h rainfall in history

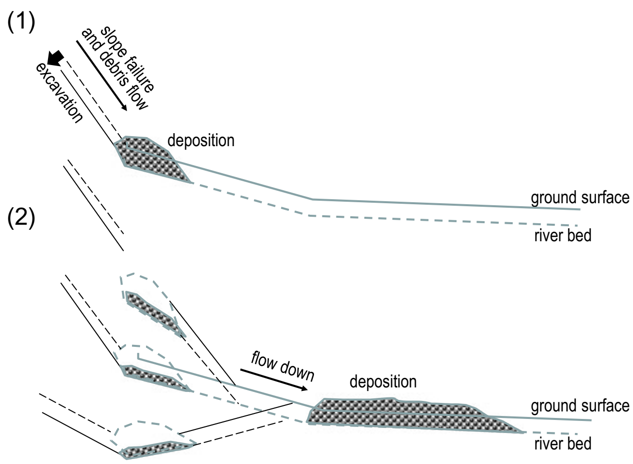

Fig. 7.18 Two step processes of the flooding caused by a combination of sediment and floodwaters. (1) Forming deposition by slope failures and debris flows. (2) Transportation of the deposited sediment downstream in floodwaters, filling the narrow, gently-sloped river courses running, and spreading floods, sediment and driftwoods over the valley plains

gently-sloped river courses running through the small plains in the valley bottoms (Harada and Egashira 2018). As a result, the flood flow was blocked from running in the river courses and spread over the valley plains, and completely changed the idyllic landscape of the area. Figure 7.18 illustrates the processes schematically. In fact, a similar disaster occurred in the Pekerebetsu River of Hokkaido when the Hokkaido and Tohoku regions were hit hard by heavy rain in 2016. This type of disaster became widely recognized by the public as "flooding caused by a combination of sediment and floodwaters" when it also occurred in July 2018 in many parts of Hiroshima Prefecture.

Given the same total rainfall, the flood peak is larger when the rainfall duration is shorter and the intensity is greater. Conventionally, short, strong rainfall patterns derived from historical events have been used to define the design flood peak discharge for planning river channels and dam reservoirs. In some recent cases, however, the rainfall has become longer, and total rainfall has become larger as reported in the July 2018 heavy rain event. A larger rainfall leads to a larger discharge for a longer period even if the flood peak discharge does not reach the design level. Consequently, dams use up the flood control capacity. In addition, if one considers the case of rivers merging at a confluence, typically, the flood runoff starts first in tributaries and then moves to the main stream. However, when the discharge in tributaries is still large because of longer heavy rainfall while the flooding is reaching its peak in the main stream, the backwater phenomenon occurs at the confluence. It has been commonly known that a levee breach on one side saves the other, but this conventional wisdom may not necessarily be the case in all cases. Once the backwater phenomenon starts, the water level remains high for a long period even if a levee breaches on one side of the river. Then, the levees weaken as more water permeates into the levee bodies, and eventually the levees breach on both sides of the river. During the July 2018 heavy rain, the area around the Oda River, a tributary of the Takahashi River in Okayama Prefecture, suffered severe damage when this phenomenon occurred concurrently with other factors. Figure 7.19 shows the complicated processes of the series of bank breaches schematically (River Council for Social Infrastructure Development 2018).

7.4.2.2 Increasingly Vulnerable Society

During the Hokkaido and Tohoku heavy rain disaster in 2016, nine residents lost their lives at an elderly home in Iwaizumi Town of Iwate Prefecture. The Northern Kyushu heavy rain disaster in 2017 claimed 40 deaths, 80% of which were 60-year old or beyond. In the July 2018 heavy rain disaster, about 56% of the victims were 65 or older. However, in Mabi Town of Kurashiki City, Okayama Prefecture, where the inundation depth reached around five meters, the number for the same age group shot up to nearly 90% (Ohara and Nagumo 2018). In Japan, demographically speaking, the ratio of the working-age people, aged between 15 to 64 per one aged 65 and over, was 3.9 in 2000, and 2.3 in 2015, and it is estimated to be 1.4 in 2065. A downward trend in this ratio indicates that a smaller percentage of people will be able to help themselves and help others evacuate and take other necessary actions in case of disaster and that a larger percentage of people will need help from others.

The Kanto and Tohoku heavy rain disaster in 2015 highlighted different problems in disaster management: evacuation information was issued too late, and few residents evacuated in time. Another lesson was learned from the July 2018 heavy rain disaster, which fatally affected the areas around the Takahashi and Oda Rivers. The municipal offices in charge of the areas had published a sediment and flood hazard map for 100- and 150-year heavy rain events. The inundation depth during the disaster virtually matched the depth illustrated in the hazard map. Moreover, a questionnaire survey later found that many residents in the areas had known about the map before the disaster. However, the survey also revealed that only a quarter of the residents had understood how to utilize the map (Council for Social Infrastructure Development 2018). These results indicate that providing the population with risk information is not enough as the population does not necessarily understand its real purpose.

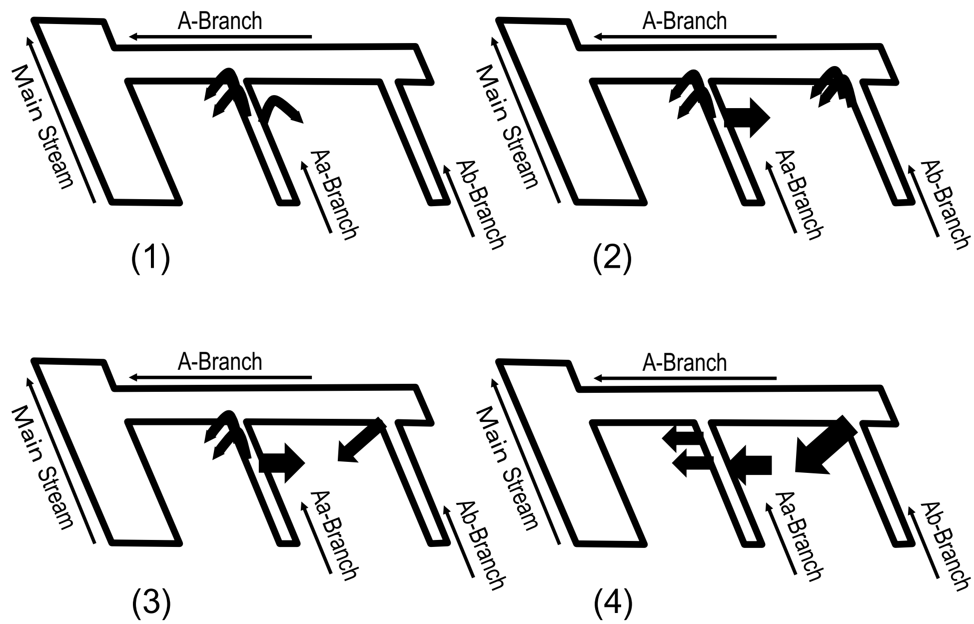

Fig. 7.19 Processes of the series of bank breaches. (1) overflow at both banks of Aa-Branch, (2) bank breach at the right bank of the Aa-Branch and overflow at the confluence of A-Branch and Ab-Branch, (3) bank breach at the confluence of A-Branch and Ab-Branch, increase of the inundation depth and change of the flood direction at the right bank of the Aa-Branch, (4) bank breaches at the left bank of the Aa-Branch

7.4.3 Towards River Planning and Management that Can Adapt to Social and Environmental Changes

What needs to be done to cope with increasingly intensified water-related disasters? The key is to build a new flood control system by visualizing changes in risk, which arise as natural hazards change in pattern and intensity and society becomes more vulnerable. A new system should also be built by utilizing the evidence-based combination of various structural measures with non-structural risk-reduction approaches.

7.4.3.1 Coping with Changing Natural Hazards

The Flood Risk Management Act was partially revised in 2015, and the expected largest natural hazards (river and urban floods) were determined in July 2015 as the criterion for implementing measures that can minimize disasters' damage to lives, property, society and economy even in case of flooding or other events due to hazards whose intensity exceeds the capacity of structures. At that time, it was generally considered as too early to use climate change simulation results to define the hazards. They were thus defined based on rainfall data from past observations. With Japan divided into 15 zones, the highest average rainfall intensity was calculated for each zone in relation to its area and rainfall duration, based on past observational data. After defining the relationship between the area of a zone and the rainfall intensity at each hour of the rainfall duration by using the highest average rainfall intensity, the relationship is applied to a river basin in the same zone. This approach is designed on the assumption that the heavy rain that occurred in a given zone will recur anywhere in the same zone.

In recent years, a present-climate reproduction experiment (1951–2011) and a future climate prediction experiment (2051–2110) were conducted using high-resolution global atmospheric models and high-resolution regional atmospheric models. The former experiment calculated 100 members using different initial values by adding small perturbations to sea ice and sea surface temperature, while the latter experiment calculated 90 members by adding perturbations to the pattern of sea surface temperature predicted in the future. A present-climate non-global warming experiment (1951–2011) was also conducted by fixing the greenhouse gas concentration at the pre-Industrial Revolution level and using the sea surface temperature without the trend components and corresponding sea ice as the boundary conditions. By dynamically downscaling data obtained from these simulations, more advanced products were developed, for they can help reflect the effects of topography and cumulus convection in simulation (Hoshino and Yamada 2018). These types of products make it possible to compare the occurrence of heavy rainfall, which is considered as very basic of probability density function, under the present and future climate conditions while considering the uncertainty. Such products also make it possible to assess the greenhouse effect in the present climate and, understand the impact of climate change quantitatively.

7.4.3.2 Coping with Increasingly Vulnerable Society

In order to protect oneself from unprecedented hazards, one needs to strengthen imagination about what may happen next and be able to react to signs of coming hazards and take appropriate actions automatically. For individuals to achieve and exercise this capacity, science and technology should not only provide them with accurate forecasting information but also, with the necessary support to increase their understanding of the given information. It should also offer them opportunities to plan sequences of necessary actions to practice in normal times, and take on their own when necessary.

Science and technology should also be interactive by always keeping a dialogue open with the general public, answer questions and explain scientific findings in an easy-to-understand manner. To strengthen self-help, mutual-support and public-support in the whole disaster risk reduction processes, including preparedness, evacuation, response and recovery, such interactions are also key to increase public trust in science and technology as illustrated in Fig. 7.20. All this requires an actor to facilitate dialogues among the public, local and national governments, and the science and technology community. This landscape indicates that universities, citizen's groups, and private think tanks are expected to play such vital role as facilitators.

The power of individuals becomes the power of a community when people gather and unite as one group. Similarly, the power of a community contributes to strengthening the power of a region and then the power of a nation. The disaster management office of the government enhances its action by cooperating with other offices in charge of urban development, traffic control, and environmental protection to promote the transformation or creation of a society to build a new society that is resilient, dynamic and sustainable. To that end, government offices should share data and information, coordinate disaster-related policies with other policies from different fields. Fields such as those expected to lead the next generation, towards smart cities, innovative mobility services, and green infrastructure. Efficient coordination would ideally go through the data platform initiative aiming at integrating real and virtual spaces, and implant quality social infrastructure. A crisis created by increasingly intensified hazards and increasingly vulnerable societies should be taken as a chance to make a drastic social change. Now is the time that science and technology and society collaborate in an interdisciplinary and transdisciplinary way, and, through this collaboration, sensible decisions be made and then executed with persistence.

7.5 The Water Pricing and Market Discourse

7.5.1 Introduction

We use water because it is valuable - but we lose it because it is free.

(Adapted from Pavan Sukhdev).

In the global political discourse, water is an orphan: mostly neglected and undernourished. This may seem strange because, water is one of the fundamental elements or resources that underpins, or undermines, all three dimensions of sustainability—social, environmental and economic. The sad truth though is that water has a very low profile in international political priority setting, while in many

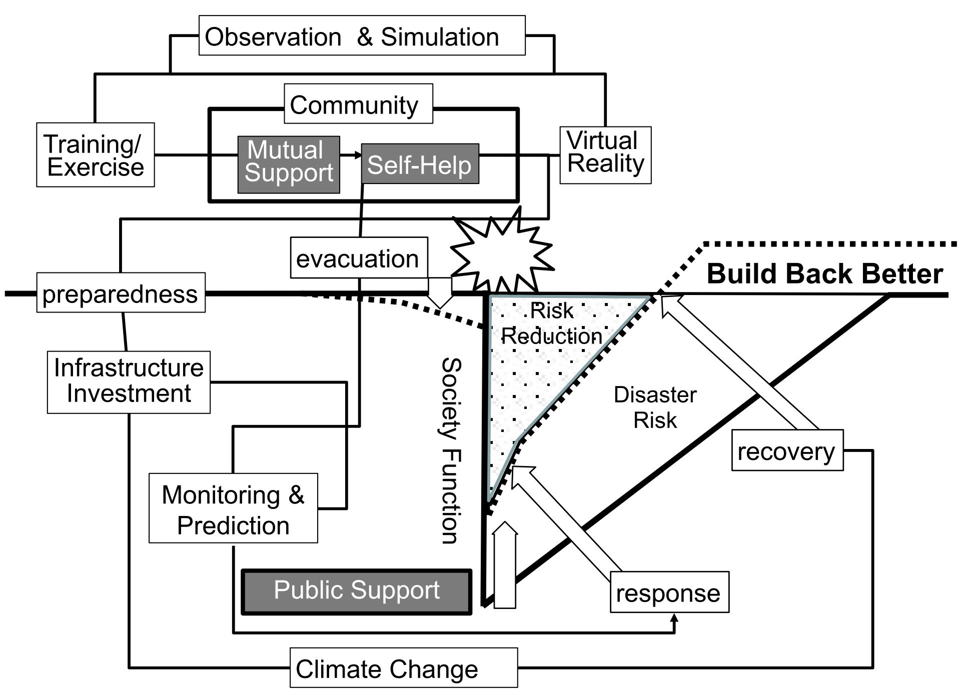

Fig. 7.20 Contributions by science and technology to public-support, mutual-support and self-help for reducing water-related disaster risk in the overall disaster management processes including preparedness, evacuation, response and recovery

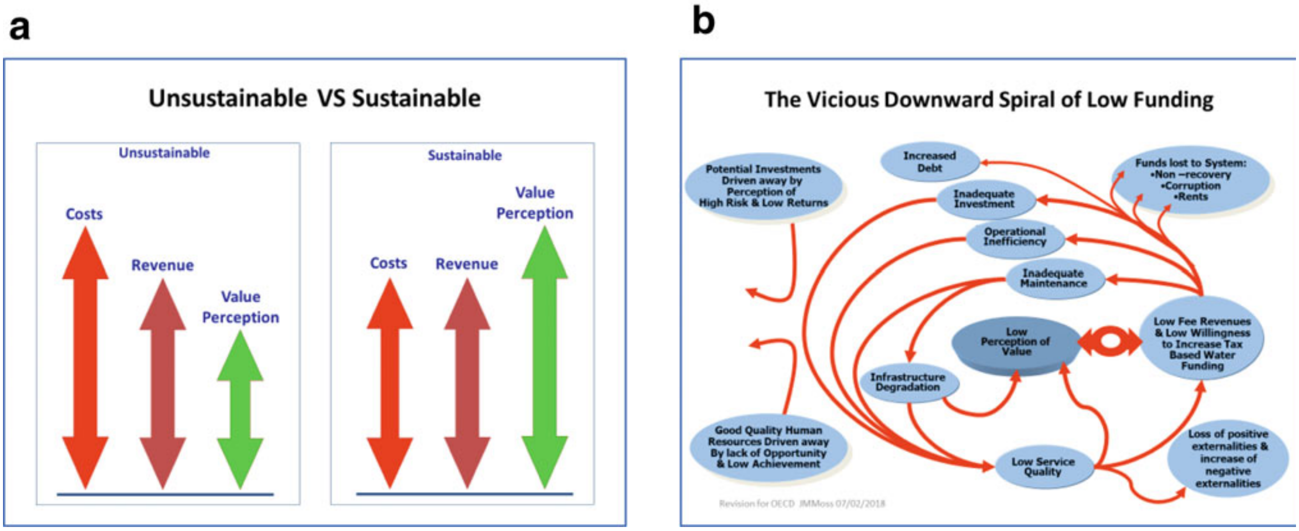

Fig. 7.21 **a**, **b** Unsustainable water economics need reversing to escape the vicious downward spiral of low funding and failing services

countries the economics of water are based on premises that are unsustainable. The relationships between costs, revenues and value of water are the wrong way round (Fig. 7.21a). The result is that almost all levels of water management are under-resourced, trapped in a 'vicious downward spiral' (Fig. 7.21b) and as a result the sector is virtually, if not actually, bankrupt. This is reflected in the poor state, or even complete lack, of water management systems, infrastructure and services in many locations.

It is possible that the UN 2030 Agenda for Sustainable Development[7] might change this situation. However, not much will happen unless a realistic approach to water economics and finance is adopted across all dimensions of water management.

This politico-economic challenge is now widely recognized, but meeting it effectively over the long term proves to be elusive. Some people advocate pricing and others markets. On their own neither of these work because of the unique roles that water plays and the governance that water decision making requires. Both these approaches have real weaknesses and ignore the real complexity behind the problem, so debating them in isolation does no more than maintain an arena for ideological conflicts. At best, these resolve nothing, and at worst they prevent progress on making tangible improvements where they are needed.

The billions of people who suffer from underperforming services or lack access altogether, the water resources that are degrading, and the ecosystems that are decimated by pollution or over-extraction, all deserve better attention. The urgency to deliver solutions is growing faster than the commitment to finding and implementing the courses of action needed.[8] This means that it is becoming increasingly difficult to overcome the growing burdens of financial, social and environmental debt.

There are no miracle solutions and there never will be. The best option outcomes will come from actions based on a deeper understanding of the multi-faceted complexity of water in a sustainable context. This requires both realistic approaches to water economics, and political decisions that take account of them.

This section will attempt to highlight the linked political and economic challenges and suggest some ways to progress beyond simplistic concepts and ideologies.

7.5.2 Need for Precision and Clarity to Unravel Complexity

It is essential to escape from broad generalisations and unravel the complexity by being very clear on a multitude of different aspects of the water challenges. All too often, water is treated as a homogeneous entity, as if it is the same thing everywhere, fulfilling the same functions for all users and uses. This leads to it being nothing, being managed nowhere and those who should take responsibility for it not doing so. To escape from this trap some precise, context specific, questions need to be answered.

[7]United Nations General Assembly Resolution A/RES/70/1. Transforming our world: the 2030 Agenda for Sustainable Development—21 October 2015.

[8]UN-Water SDG 6 Synthesis Report—2018 Forthcoming.

7.5.2.1 What Water?

Water is powerful. It can be constructive either as a substance or through the services it provides and equally it can be destructive through droughts, floods and as a vector of disease. As it flows through the water cycle and value chain, water takes on different natures and fulfils different roles. Water is required to satisfy many different needs of different users and uses in different times and places. It has critical interactions with other natural, human and economic resources.

This means that before any meaningful decisions are taken, trade-offs decided and economic policy instruments mobilised, it is essential to define the water or waters that are being considered. It is important to be clear on what water, of what quantity and quality, where, and when, is under consideration for the decisions needed in each given situation. It is also necessary to identify how many different demands on the available water there are and how these interact or interfere with each other.

Important in making such a case by case analysis is the need to identify when water is playing a role or function as a 'substance', a 'good', a 'commodity' or a 'service'.

A great deal of the ideological discourse that impairs progress in water management is based on a deliberate over-simplification of these distinctions. This viewpoint treats all water as a 'global common' and thus excludes all other roles and, in consequence, the necessity of managing the diversity of situations that arise in reality. While it is broadly true that at global level, the water, be it in the sea, the atmosphere, or occurring naturally on or under land, can be considered a 'common', this does not hold up when faced with practical reality. Even 'naturally occurring' water requires management and protection to be sustainable and to avoid 'tragedy of the commons'[9] situations. This incurs real effort and real costs, which have to be met by someone, somewhere, sometime.

Economists identify many different types of commodities, goods and services. These include, common goods, public goods, private goods, common pool resources, club goods, normal goods, rival goods, and excludable goods. At some point in the water cycle and viewed from the point of view of an individual use or user of water, almost all of these can be applied in a specific case.

Moreover, water, especially in the wastewater part of the water cycle can also be a nuisance or 'bad' that conveys social, environmental and economic harm. It seems that 'bads' can take as many forms as 'goods', thus affecting both individuals and the community.

To add another layer to the complexity, these 'goods' or 'bads' and the systems needed to deliver or overcome them for users and uses, generally take the form of natural monopolies. This means that free markets are not able to help determine prices or the value of either water or the services it provides or of the damage it can do.[10]

7.5.3 Individual Versus Collective Positions

A single user can have multiple relationships with water, thus viewing it as complying to different definitions with different values within a short space of time. The collective view of the community as a whole might be quite different from the individual's point of view.

This might mean that in certain limited circumstances setting a price or resorting to a market to determine what should be paid could work, while in most cases, such principles are not applicable.

In very limited circumstances an individual user can potentially arrive at a sustainable decision on how to compensate whom for the water or water use that person is enjoying or the harm that use is causing to others. However, that not only means the person needs to be able to determine the costs and benefits, but also needs to know clearly to whom, and how, to pay the balance in a way that provides sustainable compensation for them.

In the more usual situations, the information needed and the competing interests are too complex for this to succeed. This means that to be able to reach decisions on how to recover the costs of benefits (or dis-benefits) of water other processes need to be employed.

7.5.4 The Role of Politics and the Political Dilemma

The need to find acceptable shared understanding, decide priorities equitably and arbitrate between competing interests can only be met through appropriate political process by means of a stable system of water governance.[11] This means that strong political leadership is essential and this imposes a real responsibility on those political decision makers. Even though in today's climate, when people are increasingly disenchanted with politics and less willing to accept the decisions or dictates of politicians, it remains difficult to see how these issues can be resolved other than through a political process.

In this context '**p**olitical' (small 'p') is the process of making decisions that apply to members of a group or community in order to organise and control the distribution of resources, opportunities, risks and benefits within that

[9]Elinor Ostrom—Governing the Commons—The evolution of institutions for collective action—Cambridge University Press—1990.

[10]Ostrom – op cit.

[11]OECD Water Governance Initiative.

community and between its members. At the same time, it also organises the interrelationships between that group and other communities and states. This is not the same as '**P**olitical' (big 'P') in the sense of power politics, but of course the two politics are closely related.

The challenge is to find the best long-term fit between the positions taken by different individuals or sub-groups that may reflect divergent or competing interests or be based on different scales of space or time. Making trade-offs of this kind is essentially a political (small 'p') task.

It has been said that inherent to the idea of "economy" are trade-offs—more of this for less of that, recognising that the number of absolute win–win policies, anywhere, ever, is near nil.[12]

The challenge for the decision makers in formulating policy, determining cost recovery levels and determining trade-offs in the field of water governance are considerable. The decisions required are full of uncertainties, involve many (all) stakeholders, are unlikely to please everybody and rarely show quick results. In short everything that plays badly in the short horizons of power Politics (big 'P').

To make matters worse, not only are the policy challenges numerous and complex, but the policy instruments to solve them are very limited in number. Laws and regulations are difficult and costly to devise and enforce. Pricing instruments are limited to tariffs, taxes and subsidies.[13]

In politics at all levels, there are pressures and temptations to take short-term expedients with soft palliative effects when long-term decisions that face hard realities are needed. This is often particularly strong in the politics of water-related decision making. It is compounded by the emotional connotations that water carries. The difficulties of understanding the complexities of water issues and their interaction with social and economic activities and environmental forces, when added to these, are probably the root cause of the common "unsustainable downward spiral" in the economics and performance of many water institutions. They are the prime reason why water pricing, as a financial or policy instrument, is rarely effective in ensuring that adequate funds are available for water resource management and other water services.

So, what can policy makers do to improve the situation? How can their advisors and water experts help them? What roles can water users and other stakeholders play?

[12]Janan Ganesh—Financial Times November 21 2017.
[13]Managing Water for All: An OECD Perspective on Pricing and Financing, OECD 2009.

7.5.5 Some Suggestions for a Way Forward

The simple answer is "a great deal" and yes, everybody can play a part. Indeed, they must do urgently before it is too late.

While it is beyond the scope of this section and the competence of its author to provide all the answers, the following are some suggestions. These build on the analysis outlined above.

7.5.5.1 Publicise and Prioritise the Importance of Water Issues

At all levels, from the global to the very local, there is a need to do more to help everybody to understand the urgency and impact of a multitude of water issues and the way these affect different stakeholders, users and uses. All those who know about these issues have a responsibility to spread the word in accurate and precise ways.

7.5.5.2 Identify and Segregate the Different Conditions, Roles and Usages of Water

In order to arrive at good policies and processes, the complexities outlined above need to be analysed and unravelled. One of the ways to avoid confusion and conflicting interests is to have the many different issues identified and described as clearly as possible. This can be done by identifying the different 'value drivers' and 'value perspectives'.[14]

7.5.5.3 Break These Down into Their Component Parts

In this way different problems that need to be solved in different ways are not mixed together in an impenetrable tangle. Once identified it is easier to determine the kind of policies and policy instruments that can be used to allocate the costs and benefits, design cost recovery systems and set up the regulations and incentives that will enable them to function.

7.5.5.4 Develop a Collective Valuing of Water Approach

The steps 2 and 3 above will be made more effective if a collective valuing water approach is taken.[15, 16] Considerable work has been done in recent years to develop approaches to determining the full value of water and the

[14]J. Moss, G. Wolff, G. Gladden and E. Guttierez: Valuing water for better governance, CEO Panel 2003.
[15]High Level Panel on Water: The Bellagio Principles on Valuing Water, 2017.
[16]Australian Water Partnership: Valuing Water: A Framing Paper for the High-Level Panel on Water, 2016.

benefits it provides in ways that enable the perspectives of all users and uses and all externalities to be taken into account.[17,18]

This approach also gives a better chance for agreement to be reached on the roles that water is playing for different interest groups, in a practical and pragmatic way, that can help to avoid or overcome ideological positions that often impede progress. It enables the different value perspectives and value drivers to be identified.

Having involved stakeholders in separating out all the component uses of water in a way that achieves consensus, it is then necessary to determine the economic characteristics of water in each of these roles. The aim should be to be as clear as possible on whether, in that identified role, the water is a 'good' or 'bad', 'public' or 'private', 'excludable' and so forth.

7.5.5.5 Use the Above to Define Clear Policy Objectives

With the clarity and agreement provided by these steps, it should be much easier for the appropriate decision makers to determine clear policy objectives. A policy objective in this sense is the precursor step to setting a policy. It is a definition of what outcome the policy is aiming to achieve. It requires clear statement of the problem to be solved and way it is planned to be overcome. Setting clear, well defined policy objectives is important to enable appropriate policies to be developed that work for each specific challenge. It is also a way to improve the chances that the ensuing policy is aligned with other interests and reducing the risk of unintended consequences.

7.5.5.6 Match These Policy Objectives with Corresponding Policies Supported by Appropriate Policy Instruments

Once the policy objectives are clear, an actual policy can be formulated and with it the policy instruments needed to make it work. In the context of devising cost recovery, this is where things become even more challenging, because there are only three kinds of economic policy instruments available, **T**ariffs or prices, **T**axes and subsidies, or fiscal **T**ransfers (the 3Ts).[19]

If one accepts the Tinbergen rule that any one policy can only be supported by a single policy instrument, this does not give a great deal of scope for resolving multi-faceted problems. This is one of the reasons for breaking the challenges down into the smallest discrete and well-defined component parts that are practical. In this way, in theory at least, the three basic policy instrument tools can be available and adapted in detail to several objectives in parallel, thus multiplying the number of precise instruments available for the best effect.

As indicated above, one of the difficulties in this field is the very limited range of economic policy instruments that can be used in comparison with the number of policy objectives that need to be satisfied. This is illustrated in the diagram below Fig. 7.22, which indicates in the column on the left an extensive list of potential policy objectives. These can only be funded in the long-term by the three kinds of policy instruments (the 3Ts), of which only tariffs and taxes are truly sustainable.

The revenue streams that can provide this funding are shown on the right of the diagram. These are slightly more numerous and can be broken down further to increase the range of options available.

The water allocations for abstraction rights that can be issued to enable water market to function are included within the category T1 as 'other user charges'.

7.5.5.7 Measure and Monitor All Decisions and Outcomes with Appropriate Metrics

Good data enables good management and good management generates good data. The converse is equally true and is a factor that contributes to the vicious downward spiral. This means the process of setting and implementing water policy is not complete without designing appropriate and well-focussed performance indicators that can be measured and monitored effectively. This implementation process should enable all parties to see and review how well the policy is working and to adjust it in a timely way if needed. The design of key performance indicators and the measuring, monitoring and review process is important because if not done well these can lead to misleading or erroneous conclusions. Nevertheless, the search for perfection can lead to paralysis so to progress imperfectly is better than not to progress at all.

7.5.5.8 Use Prices Where Possible

Price is arguably the most effective and transparent policy instrument and theoretically can be used to send effective signals to users. However, there needs to be a simple and obvious link between the price charged and the benefit enjoyed that is comprehensible for users so that it impacts their behaviour. Ideally the purchase of the product or

[17]World Business Council for Sustainable Development (WBCSD): Business Guide to Water Valuation: 2013.
[18]Dustin E. Garrick, Jim W. Hall, Andrew Dobson, Richard Damania, R. Quentin Grafton, Robert Hope, Cameron Hepburn, Rosalind Bark, Frederick Boltz, Lucia De Stefano, Erin O'Donnell, Nathanial Matthews, Alex Money: Valuing water for sustainable development; 2017.
[19]Managing Water for All: An OECD Perspective on Pricing and Financing, OECD 2009.

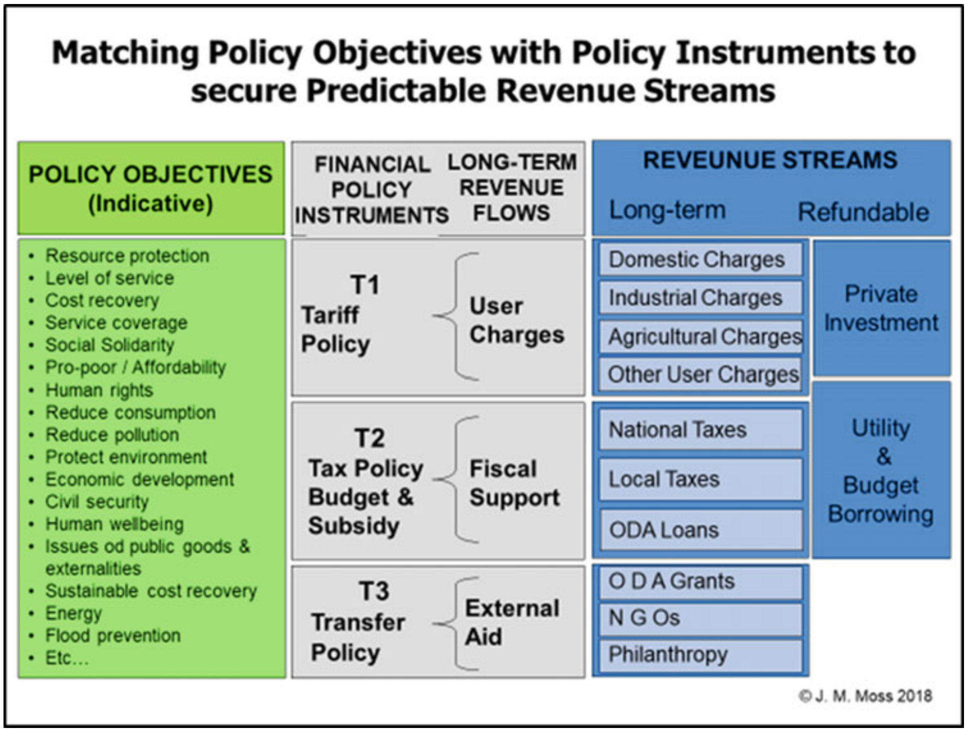

Fig. 7.22 Matching policy objectives with policy instruments to secure predictable revenue streams

service should be measurable and its use variable at the user's discretion.

A volume-based water use tariff can be effective to send messages to users about water conservation for economic or environmental protection. It is less effective for sending signals about wastewater and pollution issues. Volume-based charges or tariffs can be used for domestic, commercial, industrial and irrigation consumption and can also be applied to water abstraction and wastewater discharge.

A fixed or standing charge is very logical to cover the invariable costs of availability of the basic infrastructure that are incurred whether or not the service is used. For example, the costs of a dam for irrigation do not disappear in a rainy year when irrigation is not needed. Similarly, the size and part of the operating costs of public water supply systems is often determined by the constraints of fire or flood protection. This represents another fixed cost and the benefits are only appreciated if a fire or flood occurs. The invisible effect on insurance premiums is missed. Factors of this kind mean that such charges tend to be unpopular and be seen as a tax. Deciding whether to use a volume related or a fix charge can involve some difficult trade-offs.

Isolating and explaining each price element is possible in many cases, but requires considerable and regular explanation and runs the danger of creating a complex presentation of items in the billing process.

These constraints underline the necessity of breaking policy objectives down into discrete and recognizable components and then deciding if each of these prices are workable. It has to be recognized that using prices, whilst preferable, is not always possible.

7.5.5.9 Use Taxes When Needed

Having exhausted the possibilities of pricing, the other basic option is to resort to a system of taxes. Taxes can be raised at different geographical scales, by different organizations, for different purposes and with different effects. As a general rule, the closer in both geography and organization they are to the use or user of water the easier it is to make them understandable, transparent and to use them to send messages to users.

Many of the costs mentioned above can be covered as a local tax if the appropriate authority has the mandate to do so. In this case, it is advisable to have accounting safeguards that ensure that the taxes are adequate (in combination with tariffs if these are used) to ensure that the revenue stream is dedicated to the water system in question and is predictable, reliable and sufficient over the long term.

Significant costs arise in water management at a scale and by organizations that extend beyond the immediate local context. Usually, there is little choice but to cover these costs from regional or nationally raised taxes. Examples include basin and aquifer resource management, environmental protection or restoration, flood control, navigation, hydroelectricity, etc.

When a tax is raised at anything above the local service level, it becomes increasingly difficult to show that it has a clear link with the policy objective it is aimed to finance. This means that taxes or charges raised at these levels are much less likely to be able to send messages to users and other stakeholders. It also means that unless strict budgetary control and administrative procedures are in place, and these are protected from political interference, the revenues that were identified to fulfil a specific policy objective may not arrive in a predictable way, where and when intended.

The transfer of tax revenues from the collecting to the spending authority will normally take the form of subsidies or fiscal support. In most cases, this makes them more appropriate to paying for large irregular capital expenses than for routine operation and maintenance.

Tariffs (prices) and taxes of the kind outlined above both raise money for the systems or services from the people who ultimately benefit from those services. This means that, so long as they are set at adequate levels, they are sustainable over the long term.

The third 'T' of the trio, is transfers in the form of overseas development assistance (ODA). This is a way of using tax revenue from taxpayers who do not benefit, or at least only very indirectly, from the services. They cannot be relied on permanently and therefore, while being very useful to initiate and accelerate development, are unlikely to lead to sustainable long-term outcomes.

7.5.5.10 Consider Market Principles Carefully

Market principles can work in limited circumstances, but they only really work in carefully prepared and regulated conditions.

There are few examples of 'free markets' being used to set prices and recover costs of water delivery. The most common is where tanker services are used for water supply. Competition between tanker operators and consumer demand for water has some influence on the prices charged. However, these 'markets' are rarely transparent and unbiased and raise a large number of negative issues for the community as a whole. There are even fewer examples where policies and regulations to overcome these issues have been put in place.

There are some examples where specific policies and their attendant regulations have been used to mobilize 'controlled' markets. The most common are those that are used in water deficient regions to optimize the use of scarce resources for agriculture. These are not really markets for water, but markets for abstraction rights or allocations of water. However, they do permit 'water trading' that in principle ensures that the available water is used for the most beneficial outcomes.[20]

The few examples that do exist show that markets can work when they are deliberately facilitated, regulations are clear and data is accurate, timely and available. This requires clear and consistent policy making and subsequent administration of regulations.

7.5.5.11 Devise and Enforce Regulations that Support Allocation Decisions, Prices, Taxes, Markets and Subsidies Systems in Line with the Policy Objectives

Responsible political decision making to arrive at sustainable water management requires well-designed and well-implemented rules and regulations. These are needed to ensure that the trade-offs that are essential to preserve an equitable balance between different interests are made and carried out fairly. They are needed to keep all the parties (including the decision makers) "honest" and to enable the powerful, the weak and the voiceless (nature) to coexist.

It is easy to think of regulations being constraining, and whilst this is often the outcome when seen from an individual stakeholder's position, viewed collectively, regulations should be conceived as enabling—permitting the maximum benefit for the greatest number of interests. Rules and regulations form another family of policy instruments that can be an adjunct to the 3Ts and greatly enhance their effectiveness.

Clear rules and regulations are required at every stage, from policy formation to implementation, and at all scales from the supranational hydrological unit through to the local level. This presents a significant challenge of coordination and consistency.

In practice, regulations also need to be reviewed regularly to ensure that they are being applied as intended and are the achieving the outcomes required. If they are not, this can be because the original policy objective was misconceived, that the situation they were designed for has evolved, or that the regulations have not been applied properly.

The success of regulations, and indeed the whole governance system they underpin, depends on some key factors. These include regulatory independence from all parties, the skills and means available within the regulatory body, the respect and level of compliance by the regulated, the transparency of the process and the quality of the data and information used. Particular threats to good regulation come from political interference, under resourcing and "regulatory capture".

7.5.5.12 Manage Exceptions with Care

In almost any policy outcome, some kind of exception is likely to occur. When they do, great care is needed to ensure that the solution adopted does not undermine the whole

[20] Murray Darling Basin Authority: https://www.mdba.gov.au/managing-water/water-markets-and-trade (Accessed 6/2/2018).

policy. Short-term expedients or ill-conceived palliatives can undermine the long-term policy objective.

A common pitfall in water governance and economics is the exception of 'affordability'. There certainly are farmers who would find it difficult to pay the costs of irrigation or water pollution prevention measures. There are also people who do not have enough income to pay domestic water and wastewater charges. National interest, social solidarity, equity, human rights compliance—there are many reasons why some people should be given support. There are also a number of ways that can be used to provide help so long as these are dealing with exceptions and not the general rule. If they do become the general rule, this probably means that there is a failure in the policy objective, policy formulation, policy instrument and policy implementation chain that requires review and adjustment.

The common pitfall is the one that, seeing that some people are unable to pay charges above a certain level, a charge is set that is lower than the real costs. Unless the shortfall this creates is compensated for by some other policy instruments, this leads to the downward spiral of service degradation. This can sometimes become the problem of 'lack of willingness to charge' on the part of the policymaker rather than a 'lack of ability to pay' on the part of the users.

There is an extensive body of literature[21] and practical experience on appropriate and effective methods of providing assistance to those who find themselves in genuine difficulties with payment. Describing these is beyond the scope of this section. To be effective the beneficiaries need to be targeted and the instruments used require careful application. They usually depend on special charges, specific payment regimes, or some form of subsidy. While the use of such approaches is clearly necessary in specific cases, they almost always come with both economic and social costs. They can be costly to administer, give rise to stigmatization of the people they target and sometimes deliver unintended benefits to users who do not need them. For these reasons, it is important to pay attention to the perversity of subsidies and social support systems, but recognize that these may be necessary to overcome genuine problems of affordability and the need to prioritize the human rights to water and sanitation.

7.5.6 Identifying All the Costs

The viability of any water system depends on the association of all the costs incurred with all the revenues collected. The cost recovery system has to be set in advance and in accordance with the service and performance levels that are targeted. Actual costs result from the investments made, the efficiency of operation and the flow of revenue to the service to cover them. Cost and price are therefore interdependent. Each has an impact on the other.

Establishing all the costs (including 'direct' and 'indirect'), both in advance at the estimation stage and controlling them as outcomes can prove to be very difficult.

Direct costs are categorized in various groups, capital investment (infrastructure), operating expenses (e.g. labour, energy) maintenance and renewal, and financing. The time cycles of each these can vary substantially. For example, capital investment costs are often very large, but occur infrequently, while labour costs have to be paid on a recurring basis and immediately. The effects of time and uncertainty lead to the difficulties with identifying, assessing, allocating and pricing risk.

Indirect costs are even more challenging. These include items such as resource cost, externalities (both positive and negative) and opportunity costs.

Designing a cost discovery system has to take account of these differences. An aggregate has to be made to include and cover all of the costs completely. However, the estimates of costs, benefits and risks are often made by a range of different parties, who have different inherent assumptions and objectives. Similarly, the control and allocation of costs can be interpreted differently by different interests in the value chain.

Here again, good governance in the form of administrative procedures, reporting, audits, monitoring and regulation, all of which should have a strong emphasis on transparency, is essential.

7.5.7 Involving Stakeholders in Making Trade-Offs

Identifying the range of interests of different uses and users, understanding their relative importance and deciding how to accommodate them is a central problem. It is a problem that has to be faced even when setting prices or stimulating market forces as means of creating revenue streams to cover costs. It becomes even more critical when allocation and trade-off decisions have to be made politically, which is often the case.

The water allocations or trade-offs that have to be made are often looked upon as simple binary arrangements. This is usually too simplistic. The issues are multi-faceted and involve several interested parties who have different objec-

[21]The social dimensions of tariffs for water supply and sanitation services—OECD 2018.

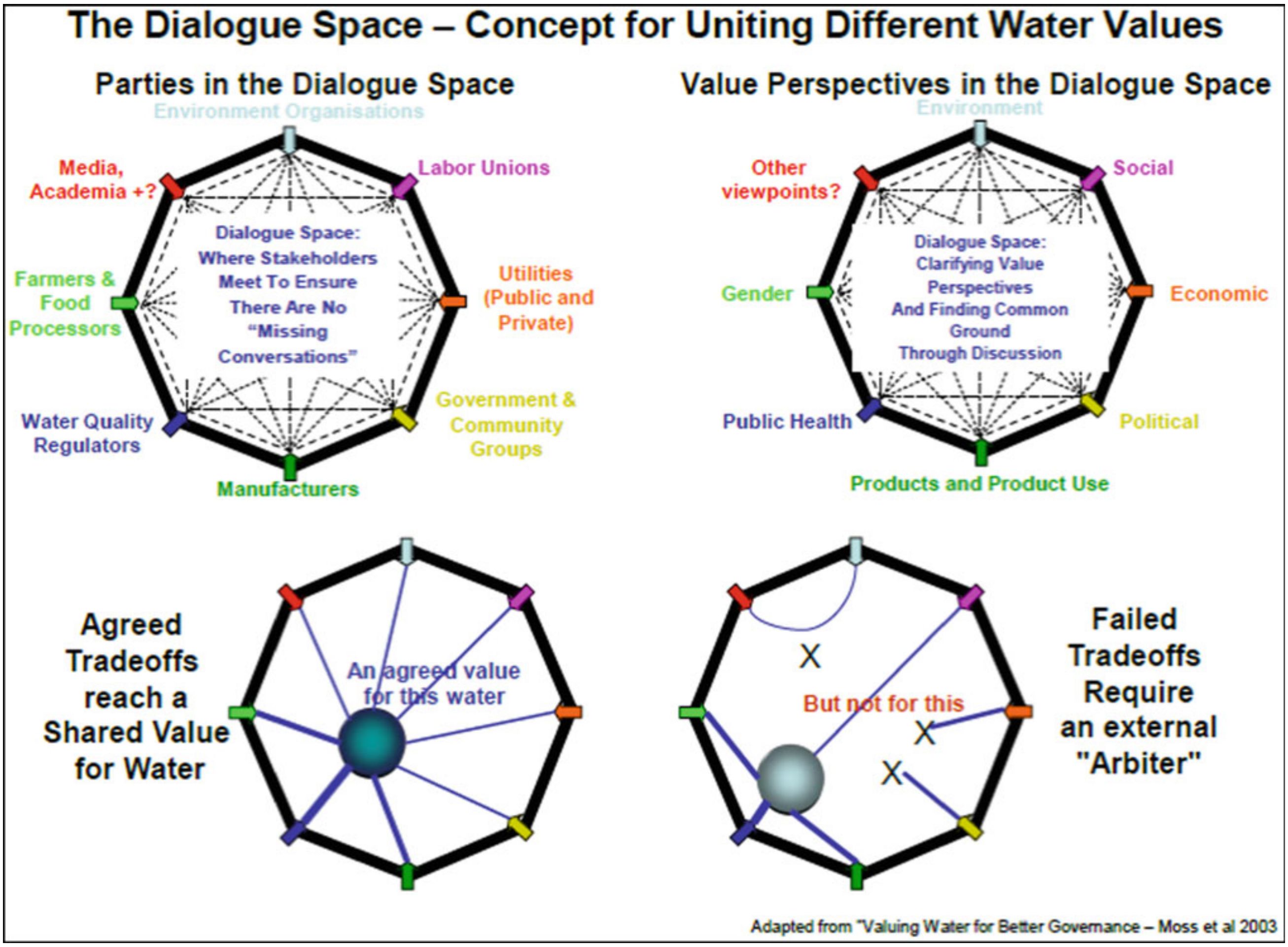

Fig. 7.23 Using the 'Dialogue Space' to agree multi-variant trade-offs

tives. These positions can be identified using a 'dialogue space'[22] approach based on 'value perspectives'[23] and 'value drivers'[24] that enables multiple stakeholders to converge on shared understanding and multi-variant trade-offs (Fig. 7.23).

It is becoming more and more common to hear this kind of stakeholder engagement approach being advocated. It is an approach that has considerable merit but is also quite complicated to achieve and to maintain. It can be hard to assemble all the stakeholders who should be represented, especially the weak and voiceless ones. This can be difficult even at a modest local scale and generally becomes progressively more difficult as the scale increases. It is important that the representatives of different stakeholder groups truly speak for that group. It is important to establish the legitimacy of the convening party and the neutrality of the conduct of the consultations. The process needs to be conducted in a way that gives all participants confidence and ensures that some 'voices' do not dominate and thus distort the outcome. There is always a danger that certain groups that actually want to distort the outcomes can achieve their ends by 'consultation capture' or boycotting the process.

The final outcome, whether a complete consensus or not, needs to be a set of decisions that inform policy objectives. These outcomes need to be endorsed by the politically responsible decision making, who must be involved in the process. Even if a complete consensus is not reached, the decision maker, who is probably forced to make decisions and direct the policy chain anyway, will be better informed. This should assist in setting prices, stimulating markets, and defining regulations and subsidies.

7.5.8 Conclusion

Setting the revenue levels needed to cover the costs of any water service that preserves or enhances the value of the substance water, or that the water service, delivers to

[22] J. Moss et al. (op cit).
[23] Ibid.
[24] Ibid.

stakeholders presents a significant series of challenges. The instruments available to meet these challenges are very limited which means that the problem needs to be broken into as many component parts as practicable. It will never be easy to achieve satisfactory outcomes as conditions and pressures inevitably involve in the time interval between decision and outcome can be very long.

This section has argued for a series of pragmatic and practical steps, built around the concepts of 'valuing water' and discrete steps in the policy making process, which can help communities and their leaders to arrive at solutions, at the different scales involved, that can ensure that viable and sustainable water supplies and services can be provided.

To be effective, prices or taxes should not be set in an arbitrary manner. The use of markets or market forces have only very limited potential but can be considered as a way to enhance water use or operational efficiency.

7.6 Environmental Migration, Rights of Refugees and Impact on Water Conflicts

Environmental degradation, and in particular water scarcity, may play a role in influencing a person's decision to migrate. In 2017, according to UN statistics, the number of international migrants reached 244 million and 763 million internal migrants.[25] The Global Water Institute estimated that around 700 million people in 43 countries suffer from water scarcity.[26] Moreover, two-thirds of the global population live in areas that experience water scarcity for at least one month a year.[27]

Making assessments and predictions about environmental migration is a complex undertaking. Because migration involves numerous variables, it is often impossible to isolate environmental factors as the sole drivers of the decision/necessity to move. As it was noted "the decision to migrate is often made because of a variety of "push" and "pull" factors. Rarely is the decision to migrate made due to a single reason".[28] This recognition does not mean to deny that the degradation of the environment may be one of the drivers of displacement.

Migration can occur due to a combination of various environmental factors, which are more numerous and more intense today. Droughts, desertification and water scarcity are likely to increase because of climate change. Soil degradation graduality diminishes the productivity of land, affects livelihood, and thus compels people to move to other areas once their land becomes uninhabitable. Moreover, changing precipitation patterns creates pressures on the availability of water supplies. Sea level rise will extend areas of salinisation of groundwater and estuaries, resulting in a decrease in fresh water availability for humans and ecosystems in coastal areas. Already, environmental migration in Asia has been directly linked to glaciers melts.[29] Most of the largest rivers in this region, including the Ganges and Bhramaputra, which provide water to around 500 million people, survive on meltwater from glaciers in Himalaya. Lower-lying populations could be affected by reduced water flows as glacial meltwater is indispensable for these populations to maintain supplies during dry seasons.

As these examples illustrate, water insecurity may be among the causes of migration.

Literature has mostly focused on climate change induced migration and displacement due to disasters.[30] Water issues have mostly been considered in relation to land degradation, desertification and extreme weather events such as floods, hurricanes and typhoons.[31] First, this section examines the lack of an agreed terminology for the category of persons having, or not, crossed international borders due to environment degradation. The use of the term 'environmental

[25] E. Mach: Water and Migration: How Far Would You Go for Water? In: A. de la Rochefoucauld, C. M. Marenghi, Water and Human Rights. a Catholic Perspective on the Human to Water (Caritas in Veritate Foundation Working Papers, 2017), p. 80.

[26] Global Water Institute. Future Water (In)Security: Facts, Figures, and Predictions (2013).

[27] M. Mekonnen, A. Hoekstra: Four Billion People Facing Severe Water Scarcity. Science Advances. 2(2) (2016). Available at: https://advances.sciencemag.org/content/2/2/e1500323/tab-pdf (accessed 20 April 2018).

[28] F. Renaud, J. J. Bogardi, O. Dun, K. Warner, Control, Adapt or Flee. How to Face Environmental Migration? InterSections, No. 5, United Nations University, Institute for Environment and Human Security, pp. 9–10 (2007).

[29] Office of the United Nations High Commissioner for Human Rights, Climate Change and the Human Rights to Water and Sanitation, Position Paper (2009). Available at: https://www.ohchr.org/Documents/Issues/Water/Climate_Change_Right_Water_Sanitation.pdf (accessed 20 April 2018).

[30] See: M. Morel, N. de Moor: Migrations climatiques: quel rôle pour le droit international? Cultures et Conflits (88) (2012) pp. 61–84. Aavilable at: https://journals.openedition.org/conflits/18580#quotation (accessed 20 April 2018). Projet de Convention relative au statut international des déplacés environnementaux, Revue européenne de droit de l'environnement, Centre international de droit comparé de l'environmment (4) (2008), pp. 452–505. A. Epiney: « Refugiés écologiques» et droit international in C. Tomuschat, E. Lagrange, S. Oeter (eds.), The Right to Life, Leiden/Boston (2010) pp. 371–401. H. Zeghbib: Les réfugiés environnementaux. Une catégorie juridique en devenir. Hommes et migrations (1300) (2012), pp.132–142. C. Cournil: Les 'réfugiés environnementaux': enjeux et questionnements autour d'une catégorie émergence. Migrations Société (128) (2010/2), pp. 69–79. R. Zetter: Protecting People Displaced by Climate Change: Some Conceptual Challenges', in J. McAdam (ed.), Climate Change and Displacement, Multidisciplinary Perspectives, (Oxford/Portland 2010), pp. 131–150. R. Cohen and M. Bradley: Disasters and Displacement: Gaps in Protection. International Humanitarian Legal Studies (Vol. I 2010), pp. 63–78.

[31] See for example: R. Cohen and M. Bradley (2010).

refugees' has been criticized by scholars[32] because of the risks of confusion with the legal definition of refugee under the 1951 Geneva Convention relating to the Status of Refugees. According to this Convention, refugees are defined as any person having a 'well-founded fear of being persecuted for reasons of race, religion, nationality, membership of a particular social group or political opinion'.[33] Moving beyond this lack of agreed terminology, the second part of this section will underline that international law protects the rights of persons displaced as a result of environmental degradation. Emblematic examples are the 2009 African Union's Convention for the Protection and Assistance of Internally Displaced Persons in Africa (Kampala Convention) and the 2010 Agenda for the Protection of Cross-Displaced Persons in the Context of Disasters and Climate Change (Nansen Initiative).[34] In light of these and other instruments, the section argues that human rights law, international refugee law and international humanitarian law provide solid legal frameworks to protect the rights of environmental migrants. A final part puts environmental displacement in the context of water conflicts. It is argued that water can be both a trigger and a victim of conflicts. More specifically, through the case study of water scarcity, it is explained how environmental disasters can trigger or enhance armed conflicts, which themselves may intensify environmental problems and, thus, aggravate the causes of displacement.

7.6.1 The Disagreement Over the Term 'Environmental Refugees'

In the absence of a clear terminology for those having crossed borders for environmental reasons, misleading terms have been used early on. In 1985, El—Hinnawi, proposed to call 'environmental refugees' 'people who have been forced to leave their traditional habitat, temporarily or permanently, because of a marked environmental disruption (natural and/or triggered by people) that jeopardized their existence and/or seriously affected the quality of their life'.[35]

In 1993, Myers defined 'environmental refugees' as:

> people who can no longer gain a secure livelihood in their erstwhile homelands because of drought, soil erosion, desertification, and other environmental problems. In their desperation, they feel they have no alternative but to seek sanctuary elsewhere, however hazardous the attempt. Not all of them have fled their countries; many are internally displaced. But all have abandoned their homelands on a semi-permanent if not permanent basis, having little hope of a foreseeable return.[36]

Despite these definitional attempts, the United Nations High Commissioner for Refugees insisted that the term 'environmental refugees' may be confused with the status of refugee established by the 1951 Geneva Convention. Such confusion should be avoided,[37] as using the term 'refugee' would risk to undermine the regime of protection granted by the 1951 Convention. In this regard, the Chaiperson's Summary of the 2011 Nansen Conference of 2011 noted that: "the terms 'climate refugees' and 'environmental refugee' should be avoided, as they are legally inaccurate and misleading". The Conference however also recognized that there is "a need to clarify the terminology for displacement related to climate change and other natural hazards".[38]

Considering the risk of confusion, international instruments have increasingly used the category of 'migrants' to define the phenomenon of flows of persons in a country or across the borders resulting from environmental factors. According to the International Organisation for Migration (IOM):

> Migration refers to the movement of a person or a group of persons, either across an international border, or within a State. It is a population movement, encompassing any kind of movement of people, whatever its length, composition and causes; it includes migration of refugees, displaced persons, economic migrants, and persons moving for other purposes, including family reunification.[39]

The use of the term migration can be explained as revealing the increasing recognition of the need to better understand migrations flows, especially related to the impacts of climate change. For example, the 2010 Cancun Agreements adopted under the umbrella of the UN

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[32] See especially: R. Zetter (2010). R. Cohen and M. Bradley (2010).
[33] Article 1A (2).
[34] Convention for the Protection and Assistance of Internally Displaced Persons in Africa, 23 October 2009. Available at: https://au.int/sites/default/files/treaties/7796-treaty-0039_-_kampala_convention_african_union_convention_for_the_protection_and_assistance_of_internally_displaced_persons_in_africa_e.pdf (accessed 20 April 2018). Nansen Initiative: Agenda for the Protection of Cross-Border Displaced Persons in the Context of Disasters and Climate Change (Nansen Initiative, Geneva, 2015). Available at: https://nanseninitiative.org/wp-content/uploads/2015/02/PROTECTION-AGENDA-VOLUME-1.pdf (accessed 20 April 2018).
[35] E. El-Hinnawi: Environmental Refugees (United Nations Environment Programme, Nairobi, 1985), p. 4.
[36] N. Myers: Environmental Refugees in a Globally Warmed World. BioScience, 43(11), 752, pp. 752–761, (1993).
[37] UNHCR, 'Climate change, natural disasters and human displacement: A UNHCR perspective', 23 October 2009, 3. S. Castles: Environmental Change and Forced Migration: Making Senses of the Debate, Working Paper No. 70, New Issues in Refugee Research (Refugees Studies Centre, University of Oxford, 2002), p. 5.
[38] Chaiperson's Summary, Nansen Conference on Climate Change and Displacement in the 21st Century, Oslo, 6–7 June 2011, para. 21. Available at: https://pnc.iucnp.org/wp/wp-content/uploads/2011/06/Chairpersons-Summary-Nansen-Conference-on-Climate-Change-and-Displacement.pdf (accessed 20 April 2018).
[39] Glossary on Migration by the International Organization for Migration, 2011.

Framework Convention on Climate Change (UNFCCC), affirmed that States should take "[m]easures to enhance understanding, coordination and cooperation with regard to climate change induced displacement, migration and planned relocation, where appropriate, at the national, regional and international levels".[40] Moreover, following the Doha Conference in 2012, an Advisory Group on Climate Change and Human Mobility was established to make recommendations to UNFCCC Parties on the need to include migration and displacement in the COP 21 in Paris. The Doha decision encouraged "further work to advance the understanding of and expertise on loss and damage, which includes […] enhancing the understanding of […] how impacts of climate change are affecting patterns of migration, displacement and human mobility".[41] More recently, migrants' rights have been formally recognized in the 2015 Paris Agreement.[42]

The term of 'environmental refugee' is not included in international instruments and should be avoided as it does not correspond to the definition given by the 1951 Geneva Convention. It is also misleading because of the confusion between a refugee who is a person outside their country of nationality or residence and internally displacement persons (IDPs) who remain in their own country. The term 'environmental migrants' would suitably cover both IDPs and cross-border displacement.[43]

The terminological disagreement does not preclude the analysis of how existing legal frameworks capture the phenomenon. It should be noted, however, that linguistic choices will ultimately have an impact on what legal frameworks apply, and how, to the people who have to cross borders for environmental reasons. Leaving this question aside for now, the following developments move beyond the conceptual disagreement to focus on the protection of the rights of persons displaced as a result of environmental degradation, by existing international legal frameworks.

[40]The Cancun Agreements: Outcome of the Work of the Ad Hoc Working Group on Long-Term Cooperative Action under the Convention, Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010, FCCC/CP/2010/7/Add.1, Decision 1/CP.16, para. 14(f).

[41]Decision 3/CP.18, para. 7(a) (vi).

[42]Paris Agreement, 12 December 2015, preamble. Available at: https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf (accessed 20 April 2018).

[43]F. Renaud, J. J. Bogardi, O. Dun, K. Warner (2007). F. G. Renaud, O. Dun, K. Warner, J. J. Bogardi: A Decision Framework for Environmentally Induced Migration, International Migration, 49 (S1), e5–e29 (2011).

7.6.2 International Legal Frameworks

Climate change, water scarcity, land degradation or flooding have already caused cross-border displacement and migratory movements. As the limitation of water uses and disaster-related movements are likely to become more diverse and new patterns will emerge, the question arises as to whether and how current international law addresses this pattern. There are several provisions relevant to the issue but they are scattered throughout three main areas of international law: international humanitarian law, human rights law and international refugee law.

First, international human rights law is a body of law applicable both in times of peace and armed conflicts. Some instruments of human rights law such as the International Covenant on Civil and Political Rights point out that State parties may take measures derogating from their obligations under the Covenant to the extent and so long as they are necessary 'in time of public emergency which threatens the life of the nation',[44] a condition that may exist for instance in situations of sudden-onset disasters or violent conflict over diminishing water resources. Everyone is protected by human rights law by virtue of being a human being and, as such, persons on the territory of a foreign State and stateless persons are also protected under human rights law. The principle of *non-refoulement* prohibits that a country receiving asylum seekers return them to a country in which they would likely be in danger of persecution based on 'race, religion, nationality membership of a particular social group or political opinion'.[45] At the 2011 Nansen Conference, the importance of human rights principles, and in particular the principle of *non-refoulement*, was highlighted as a possible protection framework for those displaced across borders but not falling under the refugee protection regime.[46]

Human rights protection, while important, has however a limited protection system. In particular, it does not regulate admission into a foreign State and provides no clear answer on what status should be conferred to those persons during their stay abroad. Article 14 of the Universal Declaration of Human Rights establishes the right to seek and enjoy asylum, but not to receive it, as this remains a sovereign decision of the State. In contrast, Article 18 of the EU Charter of Fundamental Rights guarantees the right to asylum but limits it to cases of persecution as defined by the 1951 Refugee Convention.

In addition to general human rights provisions, there are a number of specific treaties relevant for persons moving or

[44]Article 4.1. International Covenant on Civil and Political Rights, 1966.

[45]Article 33 of the 1951 Convention relating to the Status of Refugees, 1951.

[46]Chaiperson's Summary, Nansen Conference on Climate Change and Displacement in the 21st Century, Oslo, 6–7 June 2011, para 22.

displaced to another country. Particularly important is the International Convention on the Protection of the Rights of All Migrant Workers and Their Families, as it is a basis for the protection of individuals who have crossed borders in the context of climate change. However, it only applies if the individual concerned is a 'migrant worker', i.e. a 'person who is to be engaged, is engaged or has been engaged in a remunerated activity in a state of which he or she is not a national' and his or her family members.[47] In addition to this restriction, it should be underlined that the number of States that have become party to this Convention is limited.[48]

Second, moving to the next corpus of norms, international refugee law applies to persons who have been compelled to flee across borders. As such, it provides a specific status and ensuing status rights exclusively for non-national of a state and stateless persons. 'Refugee' is defined in the 1951 Convention on the Status of Refugees and its 1967 Protocols as a person who 'owing to well-founded fear of being persecuted for reasons of race, religion, nationality, membership of a particular social group or political opinion, is outside the country of his nationality and is unable or, owing to such fear, is unwilling to avail himself of the protection of that countries'.[49] The list of criteria given by the Convention is strictly political. Environmental, social or economic considerations are excluded. Environmental reasons have not been included among the reasons of persecutions. As detailed as this provision may be, it fails from addressing the case of individuals who owe to well-founded fear of being subject to natural disasters, or unwillingly had to take refuge abroad because a natural disaster actually occurred.

At the regional level, the Arab Convention on Regulating Status of Refugees in Arab Countries of 1994 contains a broader definition of the word "refugee". This broader notion is particularly interesting as it encompasses people who unwillingly took refuge abroad 'because of the occurrence of natural disasters or grave events resulting in major disruption of public order in the whole country or any part thereof'.[50] Overall, however, the degree to which refugee law helps address normative gaps in relation to displaced people by environmental degradation remains very limited because of its very object, which is itself constrained to people who had to leave the territory of their state of origin, or who are stateless.

The Convention on the Status of Stateless Persons of 28 September 1954 may become important in the case of loss of territory and the end of statehood. International law traditionally sets the three criteria of (i) population, (ii) effective state authority and iii) state territory as the three constitutive elements of statehood. This Convention could be of relevance in the context of the disappearance of islands States due to the rising seas and erosion. According to the Convention, the state of domicile or residence should offer a set of status rights to stateless persons and facilitate their naturalization as much as possible.[51]

The inherent limitations of refugee law and of the norms on the status of stateless persons make them ill-suited for dealing with the case of environmental migrants. Indeed, the majority of those displaced by environmental degradation, is not crossing borders but is likely to become internally displaced. Persons displaced within the territory of states due to climate-related events are IDPs. According to the 1998 United Nations Guiding Principles on Internal Displacement (hereinafter Guiding Principles), IDPs are 'persons who have been forced or obliged to flee or to leave their homes or places of habitual residence, in particular as a result or in order to avoid the effects of […] natural or human-made disaster, and who did not cross an internationally recognised State border'.[52] Even though the Guiding Principes do not explicitly include climate change or water scarcity as a cause of internal displacement, they list the cases of internal displacement in a non-exhaustive manner. The majority of those displaced by impacts of climate change or water scarcity do not cross border but they are likely to become internally displaced. The 2011 document of the Nansen Initiative, explicitly recognises natural and man-made disasters as possible causes of displacement, irrespective of whether or not they relate to changing climate patterns.[53]

Beyond international human rights law and international refugee law, norms and principles of international humanitarian law (IHL) can also be used to prevent the environmental situation from deteriorating before individuals are forced to move. For example, in the context of the protection of objects indispensable to the life of civilian populations such as water installations, Article 54 of the First Protocol Additional to the Geneva Conventions of 12 August 1949, and relating to the Protection of Victims of International Armed Conflicts makes reference to the fact that attacks against these objects may move away the population from an area of conflict. In this regard, the Protocol is clear that forced displacement of population because of the destruction of objects indispensable to their survival is prohibited under IHL. By establishing such prohibition, one of the goals of the 1977 Additional Protocol is to prevent the emergence of such

[47]Article 2.1. International Convention on the Protection of the Rights of All Migrant Workers and Members of their Families, 1990.
[48]51 State parties as of 25 April 2018.
[49]Article 1(A) (2) of the Convention on the Status of Refugees.
[50]Article 1 of the Arab Convention on Regulating Status of Refugees in Arab Countries.
[51]Article 32.
[52]Report of the Representative of the Secretary general, Mr. Francis M. Deng, submitted pursuant to Commission Resolution 1997/3, Addendum Guiding Principles on Internal Displacement, 1998, para. 2.
[53]The Nansen Conference: Climate Change and Displacement in the 21st Century, Oslo, 5–7 June 2011, Chaperson's Summary, para. 19.

undesirable behaviours and, thus, prevent the destruction of objects that would lead to the displacement of populations.

The applicability of these legal frameworks to the case of displaced individuals facing environmental disasters, if imperfect, must be acknowledged and activated. The following developments aim to emphasize this necessity by showing how water scarcity, displacement and armed conflicts are intertwined.

7.6.3 Displacement, Water Scarcity and Armed Conflicts

Without establishing a unique causal phenomenon, it is considered that environmental deterioration may cause displacement; that water scarcity is likely to trigger or, at least, enhance conflicts; that displacement can also intensify conflicts, which themselves may exacerbate environmental deterioration.[54] The origins of a significant number of migrants' movements are found in the linkages between climate change, water scarcity, poor governance and conflict. While environmental deterioration may cause displacement, it should be recalled that environmental degradation acts together with other factors such as economic, demographic or political ones.[55]

Like other environmental factors of migration, water scarcity can lead to temporary and permanent movements depending on the duration and severity of water stress as well as the coping capacity of populations. Most people moving because of water insecurity try to reach water resources closest to home, traveling the shortest distance possible. Migration related to water tends to be internal or regional, considering that those who do not have the means to access water locally will seldom have the means to move beyond their region. Often, the decision to migrate in the context of water scarcity is the result of environmental factors (e.g. rainfall variability, drought, desertification, salinization), combined with human factors (e.g. unsustainable land and water management).[56]

Inequality in the distribution of water resources and risks of shortage are contributing causes of tension and conflict between States. Let us take the situation of Syria prior to the beginning of the civil war in 2011.[57] When droughts are prolonged as a result of climate change, farmers may be forced to migrate to urban centres. This is especially true in situations where proper water governance and efficient irrigation systems are absent or weak. Likewise, the Darfur conflict, characterized by rivalry between local communities and tribes for access to arable land and water resources, is a prime example of such a relationship between water scarcity, migration and conflict.[58]

Not only can water be a cause of displacement, this resource may also be targeted during armed conflicts. There are significant examples—from the 2006 Lebanon war and the 2011 intervention by the North Atlantic Treaty Organization ('NATO') in Libya to the conflict in Syria—where the destruction of water supplies, sanitation systems and electrical facilities caused serious disruption and deprived the population of water supplies.[59] These cases illustrate that water may be used as a military strategy and it may be a 'victim' of wars.[60]

Given the possible impacts of armed conflicts on water, the provision of access to water, sanitation and hygiene (WASH) to refugees and displaced people is one of the highest priorities of UNHCR. Because of the cross-cutting and pervasive nature of access to water and sanitation services, the UNHCR put this issue at the heart of 1992 Water Manual for Refugee Situations and the 2008 Guidance for UNHCR Field Operations on Water and Sanitation Services. The field operations carried out by UNHCR and other humanitarian organisations such as the International Committee of the Red Cross contribute to the protection of the human right to water. This right must be respected both in times of peace and war. The principles and rules dealing with the protection of refugees and IDPs could reduce the risk of tensions due to the pressure over water and sanitation on the local environment. Similarly, international refugee law provides the protection of the rights of displaced population and local communities in their access to sources of water.

7.6.4 Conclusion

The existing international legal frameworks protect the rights of migrants but the norms are scattered throughout three main areas of international law: international humanitarian law, human rights law and international refugee law.

[54] T. Hagmann: Confronting the Concept of Environmentally Induced Conflict. Peace, Conflict and Development 6 6, 1–22 (2005).

[55] G. Hugo: Environmental Concerns and International Migration. International Migration Review, 30 1, pp. 105–131 (1996). F. Renaud, J. J. Bogardi, O. Dun, K. Warner (2007).

[56] J. J. Bogardi, F. Renaud, F.: Migration Dynamics Generated by Environmental problems, Proceedings 2nd International Symposium "Desertification and Migrations", Almeria, Spain, 25–27 October 2006.

[57] P. H. Gleick: Water, drought, climate change, and conflict in Syria. Weather, Climate and Society, 6, pp. 331–338 (2014).

[58] United Nations Environment Programme (UNEP): Sudan: Post-Conflict Environmental Assessment. Synthesis Report (UNEP, Nairobi, 2007).

[59] M. Tignino: Water During and After Armed Conflicts. What Protection in International Law? Brill Research Perspectives in International Water Law (1.4) (2016).

[60] Salamé, L., Swatuk, L., and van der Zaag, P., (2009) 'Developing Capacity for Conflict Resolution Applied to Water Issues', Chapter 6 in Blokland, M. W., Alaerts, G. J., Kaspersma, J. M., & Hare, M. (Eds.) Capacity Development for Improved Water Management, Taylor and Francis, London.

More can be done to strengthen the relationship between water and migration policies. First, migration should be integrated in legal frameworks on water. For example, by recognizing the need of pastoralists to move in times of droughts and environmental stress or, as has been done by some African states, by developing transhumance agreements that permit movements along traditional routes across international borders. Pastoralists in Africa often rely on traditional informal arrangements that facilitate cross-border movements to have access to water resources. Second, the water needs of migrants may be included implicitly in the interpretation and application of international instruments such as the UN Convention on the Law of the Non-Navigational Uses of International Watercourses. For example, a watercourse or an aquifer State should take into account 'the social and economic needs of the watercourse States concerned" and "the population dependent on the watercourse in each watercourse State' in determining the equitable and reasonable uses of a shared water resource. In light of this principle, a watercourse or an aquifer State should take into consideration migrants' needs when they determine the equitable use of transboundary water resources.

If more can be done, it is because migration in water policies is not explicitly arranged under current laws and treaties. In that context, a better understanding of the links between water and migration can be obtained from looking at more traditional types of migration in response to water stress. Pastoral livelihoods are a prime example of a livelihood that uses migration as a key element in a rural livelihood strategy. As an internal and cross-border issue, migration poses challenges to the traditional governance systems, as it needs to be addressed at all levels, local, national and international.

International law may strengthen the inclusion of migrants' rights in water management. The governance of fresh water is attracting increasing attention at the international level. The centrality of water resources governance to the international community's agenda is attested by the Sustainable Development Goals (SDGs). Moreover, in June 2015, the Organization for Economic Cooperation and Development (OECD) adopted the Principles on Water Governance. These instruments point out the centrality of principles on equitable sharing of water resources and the need to ensure their protection for future generations.

Because of the increasing number of conflicts and associated (forced) migration and due to the fact that migration is seen as one of the drivers of sustainable development (benefits of migration have been recognized by the Sustainable Development Goals (SDGs), especially under target 10.7), there is a window of opportunity in the current international arena for discussing and moving forward with migration policies, and integrating migration in water governance and vice versa.

7.7 Sovereignty, Fragmentation and the Limitations of International Water Law: The International Law Commission Draft Articles on Transboundary Aquifers

7.7.1 Introduction

Through the adoption in 2008 of Draft Articles on the Law of Transboundary Aquifers,[61] the International Law Commission (ILC) belatedly recognised the vital importance of groundwater resources in satisfying urgent human needs, as well as the distinct geophysical characteristics and unique vulnerability of such resources. After decades of neglect of international groundwaters by the international community, preparation of the Draft Articles offered the Commission an opportunity to contribute to the elaboration of a comprehensive and coherent body of international rules covering the utilisation, protection and management of all shared transboundary water resources. However, rather than promoting further convergence in this field around principles and approaches now firmly established in international water law, the Draft Articles as adopted create additional uncertainty and confusion. They would appear to take a regressive approach to the management of shared groundwater resources, which is less concerned with cooperative management than with facilitating the unilateral use of such resources by the aquifer States. The Draft Articles emphasise the territorial sovereignty of aquifer States in a manner that undermines the commitment to engage in equitable and reasonable utilisation of shared water resources on the basis of a distributive conception of equity.

This departure from the legal approach long established in respect of international watercourses would appear to be due in large part to a failure on the part of the Commission to fully consider the scope of existing generally relevant instruments, or to fully understand the distributive nature of the conception of equity residing at the very heart of international water resources law and informing every aspect thereof. The values underlying the traditional approach are based upon a recognition of the unique and total dependence of humans upon water, not alone in terms of immediate human survival, but also in terms of their economic, social, environmental and cultural human development.

[61]UN Doc. A/RES/63/124 (2009). See *Report of the International Law Commission on the Work of Its Sixtieth Session*, UN GAOR, 62nd Sess., Suppl. No. 10, UN Doc. A/63/10 (2008).

7.7.2 Fragmentation in International Law

The phenomenon of fragmentation in international law has long been recognised by expert commentators,[62] and has even been the subject of an in-depth study by the ILC in 2006, which concluded that 'fragmentation does create the danger of conflicting and incompatible rules, principles, rule-systems and institutional practices.'[63] It is understood to be a particular problem in the field of international environmental and natural resources law, which has seen significant treaty proliferation, as illustrated by the hundreds of multilateral environmental agreements (MEAs) adopted since the early 1970s. This has led to the creation of an extensive complex of cooperative inter-State institutions, some of which are rule-making in nature, as well as a broad range of rules on pollution abatement and remediation, on biodiversity conservation, and on related inter-State information-sharing and permitting procedures.[64] Koskenniemi traces fragmentation in international law to the practice, which is particularly prevalent in international environmental law, of delegating international legal standard-setting to take place 'within the framework of multilateral treaty law-making processes'.[65] Such "treaty congestion"[66] was always likely to create regime overlaps, regulatory lacunae and legal inconsistencies, especially when one considers the complex interactions between the rules of international environmental law and other fields of international law, such as international human rights law, international natural resources law or international economic (trade and investment) law.[67] One leading commentator has noted, for example, that.

> [t]he fragmentation of international environmental law arising from the creation of multiple regimes and institutions with similar or conflated regulatory mandates is extant, and has undoubtedly given rise to the risk of duplication, divergence, and even conflict between environmental standards and obligations.[68]

7.7.3 Fragmentation in International Water Resources Law

Unfortunately, it appears that the risk of legal fragmentation giving rise to such confusion, and even to conflicting normative requirements, also arises in the field of international water resources law.[69] While the international rules applying to international "watercourses", which are normally understood to include rivers and lakes which cross or form the territorial boundaries of States, as well as groundwater bodies hydrologically connected thereto,[70] is quite extensively developed and thoroughly codified, the law applying to transboundary aquifers is more nascent due to a dearth of international practice. There are barely a handful of instruments dedicated to the cooperative management of shared international groundwaters,[71] compared with over 400 agreements relating to transboundary surface waters.[72] To make matters worse, for a variety of historical reasons river basin agreements tend to completely ignore or only nominally address the issue of groundwater resources.[73]

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[62]See, for example, M. Koskenniemi and P. Leino, 'Fragmentation of International Law? Postmodern Anxieties', (2002) 15 *Leiden Journal of International Law* 553–579.

[63]United Nations General Assembly, *Fragmentation of International Law: Difficulties Arising from the Diversification and Expansion of International Law (Report of the Study Group of the International Law Commission)*, UN Doc A/CN.4/L.682 (13 April 2006), at para. 14.

[64]See, for example, T. Stephens, 'Multiple International Courts and the "Fragmentation" of International Environmental Law', (2007) 25 *Australian Yearbook of International Law* 227; J. Ellis, 'Sustainable Development and Fragmentation in International Society', in D. French (ed.), *Global Justice and Sustainable Development: Legal Aspects of Sustainable Development* (Martinus Nijhoff, Dordrecht, 2010) 57–73.

[65]See F. M. Platjouw, *Environmental Law and the Ecosystem Approach: Maintaining ecological integrity through consistency in law* (Routledge, 2016), 99–120, at 106, citing M. Koskenniemi, 'International Legislation Today: Limits & Possibilities' (2005) 23 *Wisconsin International Law Journal* 61.

[66]'"Treaty congestion" is a term of art used to describe the problems of actual substantive treaty conflict, treaty obligation and objective conflicts, and procedural conflicts which arise as a result of the proliferation of international treaties in the past three decades.' See B. L. Hicks, 'Treaty Congestion in International Environmental Law: The Need for Greater International Coordination', (1999) 32/5 University of Richmond Law Review 1643–1674, at 1646. See further, D. Anton, '"Treaty Congestion" in Contemporary International Environmental Law', in S. Alam, et al.(eds.), *Routledge Handbook of International Environmental Law* (2012).

[67]See, for example, O. McIntyre, 'Substantive Rules of International Water Law', in A. Rieu-Clarke, A. Allen and S. Hendry (eds.), *Routledge Handbook of Water Law and Policy* (Routledge, London, 2017), 234–246, at 235.

[68]K. Scott, 'International Environmental Governance: Managing Fragmentation through Institutional Connection', (2011) 12 *Melbourne Journal of International Law* 1, at 4. See further, Platjouw, *supra*, n. 5, at 105.

[69]See further, O. McIntyre, 'International Water Resources Law and the International Law Commission Draft Articles on Transboundary Aquifers: A Missed Opportunity for Cross-fertilisation?', (2011) 13 *International Community Law Review* 1–18.

[70]Article 2(a) of the 1997 UN Convention on the Law of the Non-Navigational Uses of International Watercourses (New York, 21 May 1997), (1997) 36 *ILM* 22, in force 17 August 2014, defines a "watercourse" as.'a system of surface waters *and groundwaters* constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus' (emphasis added).

[71]See further, McIntyre, *supra*, n. 9, at 4–5.

[72]See, K. Mechlem, 'Moving ahead in protecting Freshwater Resources: The International Law Commission's Draft Articles on Transboundary Aquifers', (2009) 22 *Leiden Journal of International Law* 801–821, at 803.

[73]Mechlem, *ibid.*, at 804.

Nevertheless, when charged with codifying the international law applying to transboundary aquifers, the International Law Commission (ILC) appears, almost inexplicably, to have studiously ignored key elements of the established legal framework,[74] including even its own earlier work on international watercourses.[75] Despite the undoubted customary status of many of the requirements set out in the 1997 UN Watercourses Convention (UNWC),[76] the ILC's 2008 Draft Articles on the Law of Transboundary Aquifers make no reference to this or any other seminal instrument or codification[77] in the area international water resources law. Though there had been previous attempts to codify the field of international groundwater law[78] and to provide guidance on national measures,[79] these were not widely endorsed or followed by States. While the 2008 Draft Articles follow a similar format to the UNWC, they are in a number of significant respects radically different and arguably less progressive.

7.7.4 The Challenge of Scope and Definition

Problems immediately arise regarding the respective scope of application of the 2008 Draft Articles and the UNWC, as the latter purports to apply to groundwaters physically linked to shared transboundary surface waters.[80] This position has been clear since the adoption of the 1994 ILC Draft Articles on the Non-Navigational Uses of International Watercourses,[81] which formed the basis of the 1997 Convention. In conjunction with the adoption of the 1994 Draft Articles, the ILC also adopted a Resolution on Confined Groundwaters,[82] which made a clear distinction between groundwater 'related to an international watercourse', to which the 1994 Draft Articles and thus the UNWC apply, and 'confined transboundary groundwater', to which the Resolution would apply. In any case, the Resolution would commend States to be guided where appropriate by the principles set out in the 1994 Draft Articles, which were in effect the result of an exercise in codifying the rules of international water law over a period of more than 20 years. It is quite clear, however, that the ILC was not at this time focused upon groundwater and these arrangements did leave clear lacunae in coverage. For example, it appears that neither the UNWC nor the 1994 Resolution would apply to aquifers that are recharged solely from precipitation or that discharge either into the sea or into another aquifer. Such 'orphaned' resources included important groundwaters, such as the Rus Aquifer shared by Saudi Arabia and Qatar and the Mountain Aquifer underlying Israel and the West Bank.[83]

Therefore, in the 1990s the Commission had been concerned to ensure consistency and coherence in the rules of international law applying to both surface waters and groundwaters, whilst recognising that unique regulatory challenges might occasionally arise in the case of shared groundwater resources due to their particular hydro-geological characteristics. Also, by addressing the problem of 'regulating transboundary groundwater',[84] which appears sufficiently broad to include both 'related' and 'confined' groundwater, the ILC Resolution also appears to have tacitly acknowledged that it may not always prove easy to divide groundwater resources into these two mutually exclusive categories. The International Law Association had likewise sought to promote such coherence in adopting the 2004 Berlin Rules, Article 42 of which provides that the rules generally applicable to 'internationally shared waters' should apply to an aquifer that is either connected to international surface waters or that is unconnected to such surface waters but is intersected by the boundaries of two or more States.[85]

The 2008 ILC Draft Articles, on the other hand, define an "aquifer" as 'a permeable water-bearing geological formation underlain by a less permeable layer and the water

[74]Exemplified by the 1997 UN Watercourses Convention, *supra*, n. 10, then the only globally applicable international treaty instrument in the field of international water resources law. However, since opening up to global accession, the 1992 UNECE Water Convention constitutes another globally applicable framework convention relating to shared international freshwater resources, Convention on the Protection and Use of Transboundary Watercourses and International Lakes, 17 March 1992, 1936 UNTS 269.

[75]ILC 1994 Draft Articles on the Law of the Non-Navigational Uses of International Watercourses, ILC, *Report of the International Law Commission on the Work of its Forty-Sixth Session*, II(2) *Yearbook of the International Law Commission* (1994).

[76]See, for example, the Commission's own endorsement of the customary status of the principle of equitable and reasonable utilisation as formulated in Articles 5 and 6 of the UNWC, *ibid.*

[77]A notable example of such an instrument would be the International Law Association's seminally important 1966 Helsinki Rules on the Uses of the Waters of International Rivers, International Law Association, *Report of the Fifty-Second Conference of the International Law Association* (ILA, Helsinki, 1966).

[78]International Law Association 1986 Seoul Rules on International Groundwaters, ILA, *Report of the Sixty-Second Conference of the International Law Association* (Seoul, 1986). See also, Chapter VIII on 'Groundwater' of the ILA 2004 Berlin Rules on Water Resources, ILA, *Report of the Seventy-First Conference of the International Law Association* (Berlin, 2004).

[79]UNECE 1989 Charter on Groundwater Management, UN Doc. E/ECE/1197ECE/ENVWA/12.

[80]See the definition of "watercourse" set out in UNWC Article 2(a), *supra*, n. 10.

[81]*Supra*, n. 15.

[82]*Yearbook of the International Law Commission,* 1994, vol. II (Part Two), at 135.

[83]See Mechlem, *supra*, n. 12, at 805–806.

[84]Resolution on Confined Groundwaters, *supra*, n. 22, para. 1.

[85]*Supra*, n. 18.

contained in the saturated zone of the formation',[86] which would appear to include both confined groundwaters and those connected to surface waters. The inclusion of "recharging aquifers",[87] "recharge zones"[88] and "discharge zones"[89] within the regime proposed under the Draft Articles very strongly suggests that aquifers connected to surface waters are included. While the ILC's Commentary to the 2008 Draft Articles acknowledges the danger of overlap with the general rules of international water law and highlights the need for clear priority in the case of conflict, the Commission failed to clarify the matter by declining to include in the final text the originally proposed Draft Article 20 on the relationship between the Draft Articles and other conventions and international agreements.[90]

Therefore, the 2008 Draft Articles give rise to systemic uncertainty regarding which set of rules ought to apply to transboundary groundwaters physically connected to a system of surface waters, quite apart from any scientific or legal uncertainty that might persist as to the nature, extent or adequacy of any hydrological connection between groundwaters and surface waters. Such uncertainty regarding the scope of application of the respective water resources regimes produces a number of unhelpful anomalies. For example, as they only apply to a "transboundary aquifer" or "transboundary aquifer system",[91] it would appear that the 2008 Draft Articles do not apply to an aquifer that is situated entirely within the territory of one State but contributes to the flow of an international watercourse. One would expect that such water resources would be included within the concept of an "international watercourse",[92] to which the UNWC or the general rules of international water law would apply. Commentators have noted the irony, in the light of the emphasis on the sovereignty of aquifer States under Draft Article 3, of exempting such "sovereign resources" from the *lex specialis* rules of the Draft Articles[93] and thereby ensuring that they remain subject to the more general international rules.[94]

It is beyond question that, during several decades of codification and elaboration of international water law, first of the ILC's 1994 Draft Articles and later of the UNWC, the drafters involved did not focus sufficiently, if at all, on the unique regulatory challenges posed by shared international groundwater resources. It is all the more regrettable, therefore, that the ILC's 2008 Draft Articles exacerbate the resulting legal uncertainty and confusion that have inevitably impeded inter-State cooperation regarding these vitally important resources.[95] Moreover, the 2008 Draft Articles mark a retreat from the integrative approach adopted under the ILA's 2004 Berlin Rules, which include an Article 6 on 'Integrated Management' and, more specifically, an Article 5 on 'Conjunctive Management' which provides that 'States shall use their best efforts to manage surface waters, groundwater and other pertinent waters in a unified and comprehensive manner'.[96] The Commentary to Article 5 explains that this provision expresses 'a duty on the part of States to participate in a system of conjunctive management' and notes broad international support for such a duty.[97]

7.7.5 The Spectre of Sovereignty

The key difference introduced by the 2008 ILC Draft Articles, and the one which can be linked to several of the other departures from the established paradigms of international water law, is the inclusion of an express reference to the sovereignty of aquifer States over the aquifer in a manner implying that this is the key guiding principle of the instrument. Draft Article 3 includes a strident articulation of territorial sovereignty, which is unusual in international water law. It is also worth noting that it precedes the provisions setting out the key legal principles traditionally governing this area,[98] thereby implying that such principles are subject to strict consideration of the requirements of sovereignty, whatever these may be. Draft Article 3 provides that

> Each aquifer State has sovereignty over the portion of a transboundary aquifer or aquifer system located within its territory. It shall exercise its sovereignty in accordance with international law, and the present draft articles.

Whilst it is self-evident that each aquifer State enjoys sovereignty over its respective portion of the geological formation within which shared groundwater is held, just as a watercourse State enjoys sovereign control over the portion

[86] Draft Article 2(a).
[87] Draft Articles 2(f) and 12.
[88] Draft Articles 2(g) and 11.
[89] Draft Articles 2(h), 6, 10 and 11.
[90] *Report of the International Law Commission on the Work of Its Sixtieth Session, supra*, n. 1, at 15–17. The proposed Draft Article 20 would have accorded clear priority to the provisions of the 2008 Draft Articles (or any resulting convention) over the provisions of the 1997 UNWC in the case of any conflict.
[91] Draft Articles 1 and 2.
[92] UNWC Article 2.
[93] Mechlem, *supra*, n. 12, at 809.
[94] C.G. Lathrop, 'Finding the Right Fit: One Design Element in the International Groundwater Resource Regime', (2009) 19 *Duke Journal of Comparative and International Law* 413–431, at 422–423.
[95] See further, S.C. McCaffrey, 'The International Law Commission Adopts Draft Articles on Transboundary Aquifers', (2009) 103 *American Journal of International Law* 272–293, at 274.
[96] *Supra*, 18.
[97] *Ibid.*, at 13.
[98] Draft Articles 4 and 5 set out the principle of equitable and reasonable utilization, usually regarded as the overarching and cardinal rule of international water law, while Draft Article 6 sets out the closely related obligation not to cause significant transboundary harm.

of the riverbed of an international watercourse falling within its territory, aquifer States would not normally be understood as enjoying exclusive sovereign rights over the transient water resources contained therein. However, read in conjunction with the Draft Articles' inclusion within the definitional scope of an "aquifer" of both the 'permeable water-bearing geological formation' and the 'water contained in the saturated zone of the formation',[99] Draft Article 3 clearly amounts to an attempt to exert national sovereign control over the shared water resources per se. While a geological element might certainly be subject to a form of territorial sovereign control analogous to property,[100] it would be more usual to regard the migratory natural resource as subject to a sovereign right to utilise, which would be limited by an obligation to consider the corresponding sovereign rights of other aquifer States.[101] These would be identified through the process of equitable balancing of related needs and benefits inherent to the principle of equitable and reasonable utilisation.

Of course, the Commission could have avoided this difficulty by providing separate definitions for an "aquifer", focusing on the geological formation, and for "groundwater" contained therein, along with parallel legal regimes for the sovereign control and protection of the functioning of the former, and for the utilisation and shared management of the latter. It is not at all clear why the ILC departed from this established practice,[102] whilst even expressly referring in its Commentary to the definition of an "aquifer" provided under the EU Water Framework Directive, which only includes the 'geological strata' and not the water contained therein.[103]

In contrast, the drafters of the 1997 UNWC, which at various stages included the ILC itself and the Sixth Committee of the UN General Assembly, had not found it necessary to reiterate the sovereignty of watercourse States over those portions of their national territory associated with an international watercourse. As regards any question of watercourse States enjoying sovereignty over the shared international watercourse, or the water resources contained therein, the UNWC takes a markedly different approach, providing instead that

> Watercourse States shall cooperate on the basis of sovereign equality, territorial integrity, mutual benefit and good faith in order to attain optimal utilization and adequate protection of an international watercourse.[104]

This provision epitomises the key difference in tone between the UNWC and the 2008 Draft Articles and demonstrates how the latter instrument lacks the nuance and subtlety inherent to international water law, requiring as it does a delicate consideration and balancing of the diverse interests of States located in different positions on a watercourse and/or characterised by different levels of dependence upon its waters. The 2008 Draft Articles' clear emphasis upon aquifer States' sovereignty over shared groundwater resources, with its implicit stress upon the narrow and short-term self-interest of aquifer States, appears to represent something of a retreat from the needs-based, distributive equity that is central to the principle of equitable and reasonable utilisation, and is thus so characteristic of the UNWC.[105] In fact, it appears inconsistent with the entire historical and conceptual development of this cardinal principle of international water law which, at its most basic level can be understood as a means of limiting, on the basis of the sovereign equality of States, the flawed application of absolute theories of territorial sovereignty in the particular and unique context of shared freshwater resources.[106] It

[99]2008 ILC Draft Articles, Article 2(a).

[100]The Commentary to the 2008 Draft Articles, *supra*, n. 1, at 39, notes the quite radical view expressed by certain States, and seemingly supported by the ILC, that.'water resources *belong* to the States in which they are located and are subject to the exclusive sovereignty of those States' (emphasis added).

[101]See, for example, the 1978 judgment of the Swiss Federal Court in *Argau v. Zurich*, quoted by S. C. McCaffrey, *The Law of International Watercourses* (2nd ed.) (OUP, Oxford, 2007), at 390, which suggests that, as regards the use of shared water resources, it is necessary, on the basis of the sovereign equality of States, for the normal exercise of sovereignty to be severely curtailed. See further, McIntyre, *supra*, n. 9, at 12.

[102]See, for example, Article 3 of the ILA's 2004 Berlin Rules, *supra*, n. 18, which defines "aquifer" and "groundwater" separately. See also, the Ixtapa Draft Agreement Relating to the Use of Transboundary Groundwaters, Article 1, (1985) 25 *Natural Resources Journal* 715; the Bellagio Draft Agreement Concerning the Use of Transboundary Groundwaters, Article 1, (1989) 29 *Natural Resources Journal* 663.

[103]Directive 2000/60/EC, (OJ L 327, 22 December 2000), Article 2 (11).

[104]UNWC, Article 8(1).

[105]On the 'distributive' nature of equitable apportionment of quantum and uses of shared international water resources under international law, see O. McIntyre, 'Utilization of shared international freshwater resources—the meaning and role of "equity" in international water law', (2013) 38/2 *Water International* 112–129. See further, L. F. E. Goldie, 'Equity and the international management of transboundary resources', in A. E. Utton and L. Teclaff (eds.), *Transboundary Resources Law* (Westview Press, London 1987); J. Lautze and M. Giordano, 'Equity in transboundary water law: Valuable paradigm or merely semantics?, (2006) 17 *Colorado Journal of International Environmental Law and Policy* 89–122; V. Lowe, 'The role of equity in international law', (1992) 12 *Australian Yearbook of International Law* 54.

[106]See further, O. McIntyre, *Environmental Protection of International Watercourses under International Law* (Ashgate, Farnham, 2007), who explains at 76–78 that the principle of equitable and reasonable utilisation is based on the doctrine of "limited territorial sovereignty".

certainly runs counter to the spirit and intent of the related "community of interest" approach in international water resources law,[107] which has been endorsed consistently by the International Court of Justice (ICJ) in both the Gabčíkovo-Nagymaros[108] and Pulp Mills[109] cases, and can only be understood as a diminution of individual State sovereignty over shared water resources as 'it expresses more accurately the normative consequences of the physical fact that a watercourse system is, after all, a unity'.[110]

Concerns regarding the downgrading of the principle of equitable and reasonable utilisation, and the distributive equity values inherent thereto, are compounded by the particular formulation of the '[o]bligation not to cause significant harm' set out in Draft Article 6, which declines to include any reference to the payment of compensation in the event that the most equitable and reasonable accommodation of riparian States' interests nevertheless involves harmful use of the shared waters. Therefore, in contrast to the position under the UNWC,[111] it is not implicit under the 2008 Draft Articles that the principle of equitable and reasonable utilisation enjoys priority over the duty to prevent significant transboundary harm in the case of transboundary aquifers. This again conveys the impression that the Draft Articles are less concerned with distributive equity than with robust unilateral use rights based on territorial sovereignty, which, as with the analogous property rights to which the ILC's 2008 Commentary alludes,[112] would only be restricted to the extent strictly necessary under the *sic utere tuo* principle.[113]

The potentially regressive influence of the emphasis on sovereignty employed in the 2008 Draft Articles upon established patterns of equitable inter-State cooperation over shared water resources has been aptly illustrated by the 2010 Guarani Aquifer Agreement,[114] which cites the Draft Articles in its Preamble. The Agreement defines the "Guarani Aquifer System" as a 'transboundary water resource', thereby focusing on the water resources element rather than the geological formation, but reiterates that '[e]ach Party exercises sovereign territorial control over their respective portions'[115] after identifying the four aquifer States as 'the sole owners of this resource'.[116] This unhelpful language is strongly reminiscent of that employed in the 2008 Draft Articles and the associated ILC Commentary, and would appear to confirm the fears of one leading commentator in respect of Article 3 of the Draft Article, who observes that 'the first sentence of Article 3 lets the genie of sovereignty out of the bottle, and the second sentence cannot put it back in'.[117]

This apparent retreat from distributive equity as the overarching paradigm, in favour of a more assertive territorial sovereignty, is borne out elsewhere in the text of the 2008 Draft Articles. For example, the Draft Articles appear to place considerable emphasis upon natural, geophysical characteristics as a factor in determining an equitable and reasonable allocation of shared groundwater resources. Draft Article 5(1)(d) stresses 'contribution to the formation and recharge of the aquifer', which the Commentary explains 'means the comparative size of the aquifer in each aquifer State and the comparative importance of the recharge process in each State where the recharge zone is located'.[118] Whilst geophysical factors are listed first amongst those identified as relevant to equitable and reasonable utilisation

[107] See further, J. Gjørtz Howden, *The Community of Interest Approach in International Water Law: A Legal Framework for Common Management of International Watercourses* (University of Bergen, 2019).

[108] *Case Concerning the Gabčíkovo-Nagymaros Project (Hungary/Slovakia)*, (1997) ICJ Reports 7, para. 85, where the Court quoted from a seminal statement on the community of interest principle by the Permanent Court of International Justice in the *Territorial Jurisdiction of the International Commission of the River Oder* case, Judgment No. 16 (10 September 1929), PCIJ Series A, No. 23, at 5–46.

[109] *Case Concerning Pulp Mills on the River Uruguay (Argentina v. Uruguay)*, (ICJ Judgment, 20 April 2010), para. 281.

[110] McCaffrey, *supra*, n. 41, at 165, who further explains that.'[w]hereas the doctrine of limited territorial sovereignty merely connotes unilateral restraint, the concept of a community of interest evokes shared governance, joint action' (original emphasis).See further, McIntyre, *supra*, n. 46, at 28–40.

[111] In clarifying the relationship between the principle of equitable and reasonable utilisation and the duty to prevent significant transboundary harm, the ILC's 1994 Commentary to the Draft Articles on the Non-Navigational Uses of International Watercourses, supra, n. 15, states, at 236, that.'the State whose use causes the harm shall … consult with the State suffering such harm over … the extent to which such use is equitable and reasonable taking into account the factors listed in Article 6'.

[112] See *supra*, n. 40.

[113] It is instructive that Lathrop notes, *supra*, n. 34, at 423, in relation to internal groundwater resources, i.e. those located wholly within the territory of a single State, that.'Such sovereign resources, being fully excludable, are private goods. Their "ownership" structure most closely resembles private property: a single rights-holder … that is subject only to the omni-present rule of property ownership *sic utere tuo ut alienum non laedas*'.

[114] Guarani Aquifer Agreement (Argentina, Brazil, Paraguay, Uruguay), (San Juan, 2 August 2010).

[115] Article 2 (emphasis added). Though Article 3 does seek to qualify such unilateral sovereign control by providing that.'The Parties exercise in their respective territories the sovereign right to promote the management, monitoring, and sustainable utilization of the Guarani Aquifer System water resources, and shall use such resources on the basis of reasonable and sustainable use criteria, respecting the obligation of not causing significant harm to the other Parties or the environment.'.

[116] Article 1 (emphasis added).

[117] McCaffrey, *supra*, n. 35, at 291.

[118] *Supra*, n. 1, at 45.

under the UNWC,[119] any impression of the de jure or de facto priority of such factors has been emphatically dispelled by the very minor significance normally attributed in the practice of general international water resources law to such factors as the extent of a shared watercourse or drainage basin within the territory of a riparian State or its contribution to the river's flow.[120] In practice, priority has tended to be given to factors concerned with human and economic need and dependence, thereby stressing the distinctly distributive character of the equity involved. The 2008 Draft Articles actively stress those geophysical factors peculiar to transboundary aquifers, which suggests a less distributive approach more in keeping with the precepts of State sovereignty over, and property in, the groundwater resources concerned.

Similarly, the 2008 Draft Articles suggest something of a retreat from the intense procedural and institutional cooperation required to achieve the community of interest approach necessary to give meaning to the rather vague and flexible principle of equitable and reasonable utilisation and the distributive equity inherent thereto. Though Draft Article 15 on '[p]lanned activities' links any EIA to the procedures of inter-State notification, consultation, negotiation and independent fact-finding, as subsequently recognised by the ICJ in the Pulp Mills case,[121] and though Draft Article 7(2) clearly provides that 'aquifer States should establish joint mechanisms of cooperation', the Draft Articles provide considerably less detail about, and place less emphasis upon, procedural obligations than is the case with Articles 11–19 of the UNWC. This omission seems rather at odds with the Court's findings on the centrally important role of procedural rules for the general duty of cooperation and the key substantive obligations of international water law[122]—including equitable and reasonable utilisation, prevention of significant transboundary harm, and environmental protection—set out once again in the Draft Articles.[123] It suggests a recognition on the part of the Commission of the potential role of detailed legal requirements for inter-State procedural engagement in placing practical limits upon aquifer States' sovereign freedom of action.[124]

7.7.6 Conclusion

Even though the ILC's 2008 Draft Articles on Transboundary Aquifers are now highly unlikely to give rise to a generally applicable multilateral convention in this field, it is nevertheless unfortunate that the international community has been deprived of a long-overdue opportunity to clarify and rationalise the international rules applying to international groundwater resources in a manner that is coherent with the established rules applying to international watercourses. As a dedicated instrument specifically designed to address the particular challenges associated with the legal management of such resources, the Draft Articles undoubtedly provide helpful guidance concerning their cooperative utilisation and protection. However, with their emphasis upon the sovereign rights of aquifer States, the Draft Articles also represent a retreat from the established paradigm of distributive equity—a paradigm based on values likely to prove essential to ensuring effective inter-State cooperation regarding this essential resource as we enter an era in which the global freshwater crisis has come to be recognised as 'the new environmental crisis of the twenty-first century'.[125] In this context it is disappointing that the Commission failed to seize the opportunity to craft a legal framework for ensuring the conjunctive, and therefore optimal, management of shared international surface and groundwater resources.

7.8 The Discourse on Water Wars

7.8.1 Neo-Malthusian Rationale

The discourse on water wars is embedded in a Malthusian rationale, which focuses on the deterministic relation between physical water scarcity and conflicts, seeing a deterministic link between scarcity and increased population in explaining how water wars will be inevitable. Malthus mistakenly argued over two centuries ago that food production would not be enough to meet the needs of the growing population, and this would result in famine and deaths. Neo-Malthusians inform the discourse on water

[119]Article 6 of the UNWC on '[f]actors relevant to equitable and reasonable utilization' lists first, in Article 6(a),'Geographic, hydrographic, hydrological, climatic, ecological and other factors of a natural character'.

[120]See A. Tanzi and M. Arcari, *The United Nations Convention on the Law of International Watercourses: A Framework for Sharing* (Kluwer Law International, The Hague, 2001), at 124; X. Fuentes, 'The Criteria for the Equitable Utilization of International Rivers', (1996) 67 *British Yearbook of International Law* 337–412, at 398–407; McIntyre, *supra*, n. 46, at 179–183.

[121]*Supra*, n. 49.

[122]*Pulp Mills, ibid.* See further, Owen McIntyre, 'The Proceduralisation and Growing Maturity of International Water Law', (2010) 22 *Journal of Environmental Law* 475–497, at 488–491.

[123]Draft Articles 4–6 and 10–12.

[124]See further, O. McIntyre, 'Sovereignty and the Procedural Rules of International Water Law' in T. Tvedt, O. McIntyre and T. Kassa Woldetsadik (eds.), *Sovereignty and the Development of International Water Law* (I. B. Tauris, London, 2015) 321–340.

[125]See E. Brown Weiss, *International Water Law for a Water-Scarce World* (Martinus Nijhoff, The Hague, 2013), at 1.

wars, and include new threats such as climate change. The assumptions behind scarcity are that natural resources are finite, limited, and scarce, emphasising environmental limits and absolute scarcity (Gleick et al. 2009). This neo-Malthusian approach emphasises the linear relationship between hydrological systems, climate patterns, population growth, and pollution on the available water resources, which are finite and limited (Linton 2010). The book *Limits to Growth* published in 1972 underlines the absolute scarcity and the environmental limits to growth, as the earth has physical limited resources to support the needs of human society (Meadows et al. 1972). If the thresholds are breached, this would result in the collapse of the world system (Meadows et al. 1972). The book highlights the necessity to limit needs and consumption patterns, and this is particularly important in today's society, which is driven by abundance that leads to never-ending needs and desires. Recent developments within this stream of literature are the concepts of anthropocene and of planetary boundaries, which are based on the belief that the growing population and the human activities are putting a further pressure on the Earth System, and this could cause irreversible changes to the climate and to the environment, ultimately resulting in catastrophic events (Rockström et al. 2009).

7.8.2 The Construction of the Discourse on Water Wars

Some scholars identified water scarcity as the main driver of water wars in semi-arid regions like the Middle East, suggesting the possibility for water wars in the Middle East (Lowi 1995; Gleick 1993). For these scholars, what is special about water, is that water is not only scarce, but also vital, a matter of national security, and demand is outstripping supply, making competition for the shared water resources leading, towards armed conflicts. Remans (1995) emphasised that the Middle East, South America, and South Asia are "well-known examples" of water wars, while Homer-Dixon (1994: 19)—studying the case of Jordan—concludes that "the renewable resources most likely to stimulate interstate resource war is river water", and Butts (1997: 72) notes that "history is replete with examples of violent conflicts over water", especially in the Middle East. Boutrous Boutros-Gali, former UN Secretary General, said that "the next war in the Middle East will be over water, not politics" (in Butts 1997: 65). Late King Hussein of Jordan identified water as the only issue that might lead Jordan to war with Israel. Water was symbolically described as the "blue gold", for which countries will be fighting for in the twenty-first century. The image of "blue gold" was first used by Barlow and Clarke (2002), but in the context of water privatisation and commodification. In the 1990s, mass media have extensively emphasised this idea of water wars, with titles such as "the water bomb", "water wars and peace", "Africa's potential water wars" (Sid Ahmed 1999; Adam 2000; Smith 1999).

7.8.3 Academics Supporting the Discourse

In 1984, Naff and Matson (1984: 181) started the academic discourse on water wars arguing: "water runs both on and under the surface of politics in the Middle East". Homer-Dixon had a central role in developing this discourse in academia, analysing several shared river basins looking for links between scarcity of water resources and armed conflicts. He concluded that "the renewable resource most likely to stimulate interstate resource war is river water" (Homer-Dixon 1994: 19). For him, "environmental scarcities are already contributing to violent conflicts in many parts of the world. These conflicts are probably the early signs of an upsurge of violence in the coming decades that will be induced or aggravated by scarcity" (Homer-Dixon 1994: 6). For Homer-Dixon, developing countries will not be able to adapt to the social effects of environmental degradation, consequently becoming more vulnerable to conflicts and wars over scarce water resources. In fact, scarcities of resources will lead to social unrest that can result in violent civil and inter-state conflicts. The development of this literature in academia led Amery (2001: 51) to refer to it as "the well-established and thoroughly documented positive link between resource scarcity and violent conflict". At the end of the past century, many others have also contributed to the academic research reinforcing the discourse on water wars, and linking scarcity of water resources with wars and armed conflicts. For Westing (1986: 9), "competition for limited [water resources…] leads to severe political tensions and even to war". For Trolldalen (1992: 61), "competition for both quality and quantity of shared water at a local level often leads to international water conflicts". Water scarcity as leading to water wars was picked up and developed also by the scholars and practitioners working on strategic studies (Sherk 1999), as Samson and Charrier (1997: 6), who suggested that "growing conflict for increasingly scarce water resources looms ahead". In the 1990s, this discourse on water wars was captured also by several administrations and governments, who believed that water scarcity represented a potential threat for their national security. As reported by Floyd (2010: 75–76), Homer-Dixon has briefed in several occasions the US State Department on the threat of potential water wars. Measures taken by the US administration included the creation in 1993 of the new governmental position of Deputy Under Secretary for Environmental Security in the Defence Department. For Ohlsson and Turton (1999) the relevant question became quantitative: what is the threshold of water scarcity? This question pushed engineers and hydro-geologists, pioneered by Falkenmark, to research the idea of water stress threshold and indicators of water scarcity (Falkenmark et al. 1989).

7.8.4 Limits of the Water Wars Discourse

The discourse on water wars was viewed as an unfounded hyperbole by several academics, as the empirical evidence linking water scarcity and armed inter-state conflicts was not straightforward (Allan 2002; Alam 2002). Homer-Dixon has recognised that he overstated the deterministic approach adopted for his analysis of hydropolitics (Homer-Dixon 1999: 139). He (1999: 139) admitted that the story is more complicated than it appears:

> In reality, wars over river water between upstream and downstream neighbours are likely only in a narrow set of circumstances: the downstream country must be highly dependent on the water for its national well-being; the upstream country must be threatening to restrict substantially the river's flow; there must be a history of antagonism between the two countries; and, most importantly, the downstream country must believe it is militarily stronger than the upstream country. Downstream countries often fear that their upstream neighbours will use water as a means of leverage. This situation is particularly dangerous if the downstream country also believes it has the military power to rectify the situation.

Nevertheless, it has to be noted that even when he changes his mind and tries to correct his statement, his explanation is still narrow-minded. In fact, he apparently had a case like the Nile's in mind and it is very well known that the geographic, political, socio-economic and hydrological setting of the Nile (or similar basins) are not the same around the world. Delli Priscoli (1998) underlined that the discourse on water wars has been conducting towards misleading conclusions with extensive speculation rather than sharp analysis. In particular, Allan (2002) developed the concept of virtual water, meaning the water necessary to produce any good or service, such as food. For Allan, importing one kilo of cereal meant importing the corresponding amount of water used to produce it. For him, food security does not necessarily mean food self-sufficiency. In this way, Allan (2002) explained through the concept of virtual water trade why there have not been water wars in the Middle East—as in this region over 60% of water is used for irrigation.

Water conflicts scholars from the International Peace Research Institute have also showed that the discourse on water wars has not solid empirical evidence (Toset et al. 2000). The discourse on water wars has also been criticised for overlooking whether other variables could be the real causes of conflicts where there is water scarcity. For instance, Smith (1994) argues that in the Senegal River conflict, ethnic and class reasons were more important than natural resources as drivers of the conflict. For Levy (1995: 45), general poverty rather than water scarcity is the main driver of conflict in the cases considered by Homer-Dixon, who focused only on developing countries. Moreover, Brown and Mcleman (2009) suggest a correlation between underdevelopment, lack of democracy, and conflict rather than with water or natural resources scarcity. Gleick (1994) has also questioned the fact that conflicts over water are a new phenomenon. Some scholars have argued that water scarcity can be an opportunity for water peace rather than wars (Salehyan 2008; Reuveny 2007; Nordås and Gleditsch 2007).

This claim is further supported by the work of the Oregon State University, led by Wolf, who analysed transboundary water interactions in the past 50 years, finding no instances of water wars, and showing that there have been more cases of cooperation (Wolf 1998). In other words, Wolf (1998) proved that the number of cases of water conflicts over shared water resources is minimal compared to the instances of transboundary cooperation. However, Wolf's idea of a continuum of cooperation or conflict has been criticised by the recent critical hydropolitics literature, developed by the London Water Research Group. This critical hydropolitics literature has focused on cooperation and conflict over shared water resources and Zeitoun and Mirumachi (2008) critically examine the role of treaties, which are often seen as a positive example of cooperation. They argue that cooperation is not always good, as treaties can codify an existing asymmetrical status quo, and treaties can also become the subject of the conflict. Zeitoun and Mirumachi (2008) developed the Transboundary Water Interaction Nexus (TWINS) matrix to analyse the nature of conflict and cooperation between riparian states over shared water (Zeitoun and Mirumachi 2008). In this way, they go beyond the idea of a continuum of conflict or cooperation, emphasising the co-existence of conflict and cooperation. They also show the nuances of conflict and cooperation, as there are different degrees of cooperation and of conflict, and not only armed conflicts.

7.8.5 Critics to the Assumption of Water Scarcity

The discourse on water wars has been criticised also for its assumption of water scarcity. In fact, the literature that looks at the politics of scarcity challenges the neo-Malthusian understanding of scarcity and its assumptions, seeing the problem in the way that scarcity is conceptualised. This literature focuses on issues of access to natural resources, emphasising power asymmetries, and access to water. For this literature, the mainstream discourse of water scarcity is used to justify certain projects and interventions, like dams and mega-projects, silencing discussions about alternative solutions. These solutions are often engineering or market-oriented solutions, which overlook the socio-economic problems within water scarcity, often proving tragic results for the urban poor communities. This is shown by Shiva in the case of India (Shiva 2002) and Perreault in the case of Bolivia (Perreault 2006). Scholars within this critical body of literature have shown how the discourse of water scarcity is deployed to support the political agendas of the states. Swyngedouw (1999) and Bakker (2002) analysed the case of Spain, showing how the state deployed this discourse to justify huge infrastructural projects; Alatout (2008) showed how it was used to justify the huge infrastructural projects and legitimise the building of Israel; Edwards (2013) shows the deployment of the discourse of water scarcity by powerful actors to support market-oriented reforms, Hussein (2016, 2017a) shows how the discourse of water scarcity is constructed in Jordan to drive towards supply side solutions, legitimising in particular the construction of the Disi water conveyance (completed in 2013) and the on-going Red Sea Dead Sea Canal project (Hussein 2017b, 2018).

For this critical approach the issue is in the inequitable institutional and governance arrangements. As emphasised by Mehta (2010: Chap. 1), the key issue is not about the availability of a resource, but rather about who has access in an adequate quantity to it, which is the outcome of political processes and decisions of inclusion and exclusion, which could be linked to the price of water, to the lack of infrastructures, or to social exclusion. The attention should be on who primarily benefits by the sanctioned solutions and improved efficiency. It should also be on who is marginalised from these solutions. It is argued that the increased benefits will be privatised and go to those in the powerful class, while the poor will be further marginalised, if judicious re-distributive mechanisms are not adopted (Allouche et al. 2015: 616). Solutions should therefore be on dismantling the institutional barriers that cause discrimination and inequalities. Clear examples of structural inequality and distribution in the water sector come from: the West Bank, where it has been argued that water scarcity is an issue of structural discrimination against Palestinians and privileged access to water to illegal Israeli settlements; in apartheid South Africa, where inequalities based on discriminatory policies were extensive also in the water sector (Movik 2012); and in India, where access to certain wells is denied to so called lower caste women (Singh 2006). Nevertheless, in the scarcity discourse, efficiency arguments prevail on equity arguments, and neo-Malthusians arguments are enriched by the scarcity concept. For Mehta, it is necessary to consider who is consuming what and for whom are the limits. Scarcity is for Mehta "a crisis of unequal power relations" for the control of water resources (Mehta 2005: 4). Mehta argues: "this naturalization of scarcity […] largely benefits powerful actors. Thus, water 'crises' must also be seen as the crisis of skewed access to and control over a finite resource" (Mehta 2005: ix). Mahayni emphasises that the hegemonic scarcity discourse neutralises factors like inequitable access to natural resources, which need to be addressed to solve the scarcity issue (Mahayni in: Harris et al. 2015). Mehta explores the meanings and experiences of scarcities, as the hegemonic framing tends to present scarcity as a singularised problem, overlooking the diversities within it. This results in the hegemonic framing overlooking regional differences within the same country, or cyclical variations over time. Also Lankford shows the necessity of moving beyond the volumetric in order to solve the issue of water scarcity, underlining the need for water distribution among its users and of water equity (Lankford in Mehta 2010: 195–196). As shown, this critique undermines the main assumption of the discourse on water wars: water scarcity. This literature shows the necessity to investigate issues of access and equity rather than simply of quantity and of balance between supply and demand. It also showed that at the sub-sovereignty level (social) power relations matter most and not the water war scenarios. In fact the water and violence discourse should be carried out along these different scales showing that two farmers who may have to share a well which is the only source of water may kill each other but the same simplistic reaction is gradually vanishing as we move towards larger scales where options and trade-offs and bargaining space "automatically" grows.

7.9 Decision Making Under Risk and Uncertainty: Approaches from Dispute to Cooperation in Transboundary Basins

7.9.1 Introduction

Water systems crossing national boundaries make riparian states of any shared basin connected in a complex network of environmental, political, economic, and security interdependencies. Meanwhile, water insecurity is emerging, in various forms, as a massive challenge for the global community. Transboundary basins where each riparian state has its own agenda filled with ambition, preferences, challenges, and threats, thus need "smarter" governance (Rogers et al. 2010). National boundaries make water issues political, and so the sensitivity and complexities of transboundary water management multiply (Moller 2005).

As water availability decreases due to population growth, together with the trend in water demand, tension and competition over secure access to this limited resource, will increase (UN Water 2013a). Maintaining stress-free relations between states is crucial to ensure water availability for human, economic, and environmental necessities. Although many international water agreements have been signed throughout history, the way countries manage emerging pressures around water in order to avoid further conflicts, is often not clear. The complexity of governance arrangements mirrors the complexity of interactions among population growth, economic and political aspirations, geographic factors, and uncertain climatic conditions for transboundary cooperation over shared waters. Given its size and scale, the challenge calls for a practical, case-specific, and dynamic governing framework. Such a framework would bring together actors from across a range of sectors and allows them to work pro-actively and address these interrelated issues (Josef and Kipping 2006). For doing so, we need to understand how power is exercised in the governance of waters, how decisions are taken and implemented, who the stakeholders are, and what incentives they face in a transboundary context (Harris and Booth 2013).

Water is crucial for security. It has become an essential element not only in the fight against poverty but also in the context of peace and political stability (see Sect. 7.3). While there is a potential for dispute, transboundary basins provide significant opportunities for international cooperation leading to economic growth, sustainable development, and security (Sadoff and Grey 2002). Contemporary transboundary water management is a process of sharing water among different allocation arrangements, distributing benefits assigned to such allocations, and consistently resolving conflicts among involved stakeholders. While cross-border cooperation is linked to many other political factors and international relations considerations, experience evidenced that a resource as treasured as water can be a catalyst for cooperation rather than conflict when it is shared (Dinar 2007; Wolf 2007). Transboundary water-related challenges force governments and other stakeholders towards closer collaboration to safeguard the availability of adequate water, and ensure that appropriate measures are taken in the interest of water security (Islam and Susskind 2013). Water security discourse is dealt with in detail in Chap. 8.

Across the world, hundreds of agreements have been signed in the course of history, and even hundreds of institutions have been set up to manage water equitably and sustainably. Globally, 153 countries share rivers, lakes, and aquifers, and 592 transboundary aquifers have been identified by UNESCO's International Hydrological Programme to date, which is home to more than 40% of the world's population. However, only fewer than half of the world's transboundary basins are subject to any kind of formal agreement outlining how the resources are to be shared and managed cooperatively (Granit 2010). Although the number of transboundary water disputes in the last 70 years was not significant, much work is necessary in order to reach peaceful and functioning agreements. Since 1948, 37 conflictive incidents of acute intensity over water occurred, 295 international water agreements were signed, including the UNECE Water Convention and 116 river basin organizations that were established reflecting different levels of transboundary cooperation through institutionalized cooperative practices (Schmeier and Gerlak 2014).

In bringing together diverging interests of riparian states, one creates a space of mutual economic interdependence, which can enhance interest in collaborative management through legitimate agreements. Transboundary river agreements also act as capacity building measures to boost social and economic cohesion in a region and, by extension, peace, and security in the long-term (IWA 2015). Nevertheless, such agreements must be flexible in nature. They should capture future uncertainties with foresight while resolving contemporary water-related issues. For example, even though the Indus water treaty is a successful cooperative transboundary water management agreement between India and Pakistan, it does not provide for environmental changes. As such, current climate change events may put the past successful institutions at risk (Zawahri 2008). Such agreements must be revisable and flexible in order to evolve and to adapt to external spurs, whether these are variations in the ecosystem, climate, or socio-economics or population growth. Reaching an agreement on how to share transboundary water resources requires concerned stakeholders to identify mutual benefits and costs, as well as potential areas where their interests converge and then, develop mechanisms to secure them over time (Motlagh et al. 2017).

7.9.2 Moving from Conflict Towards Cooperation

A move from single-purpose to the multi-purpose planning of a river basin is necessary to capture the full range of potential benefits such as hydropower, irrigation, industries, navigation, fisheries, etc. Phillips et al. (2006) indicated that joint development of shared water resources could provide additional benefits to all riparian countries by enhancing economies of scale, increasing planning horizons, bringing efficiency, reducing costs, and attracting the investments required for water resource management.

In any water system, cooperation is formed as stakeholders aim to develop and sustain a good relation towards reaching a satisfactory output (Mostert 2003). Stakeholders cooperate when the perceived net benefits of cooperation are more significant than that of individual actions, and when the distribution of the expected benefits seem reasonable (Phillips et al. 2006). The higher the perceived and potential gains are, the better is the chance of success for mechanisms to promote cooperation in water management. A secure water future is likely to stem from some level of cooperation in transboundary management. Results may materialize in the shape of information sharing alone, or along with coordinated arrangements in the form of partial collaboration. Furthermore, in better cases, it can even result in joint actions (such as joint infrastructure development). In all cases, an apt joint institutional mechanism should be in place (Sadoff et al. 2015).

UNDP (2006) stated that the prevention of water conflicts could not be achieved without adequate cooperation in managing those waters through robust and equitable structures and institutions for collaboration at national and international levels. This cooperation should not be seen as a goal per se, but rather as an essential instrument to meet the objectives of each riparian country, improve water governance and, attain noticeable progress towards regional security and sustainable development (Leb 2015). Through collaboration, riparian states can collectively develop a better understanding of water governance challenges associated with climate change. They can then work together towards sustained wellbeing in the long-term and how it may be enriched in practice (Madani and Hipel 2011).

A fundamental shift in the way we manage our transboundary waters is urgently needed to avoid any form of conflict. One of the primary objectives of transboundary water management is the identification of potential cooperation areas. This can happen through the establishment of common platforms allowing for the development of frameworks, which in turn help decision makers understand and mitigate the risk of conflicts. Conflict prevention and resolution are highly political processes in which politicians make decisions on resource use. On the other hand, political structures in riparian countries, as well as hegemony and power asymmetries among them, affect related arrangements significantly (Chikozho 2015). According to Earle et al. (2010), political borders divide transboundary basins; politicians make decisions on transboundary water resources, and political structures in each riparian country shape the status of transboundary water management in a unique way. In other words, the management of transboundary waters is heavily influenced by 'hydro-politics,' and this must be considered when aiming at achieving cooperation with the ratification of agreements at basin level by all riparian states (Kim and Glaumann 2012).

Literature analysis suggests that transboundary river basins are characterized by profound economic and political asymmetries among their riparian countries; these asymmetries shape the nature of cooperative arrangements as well as some of the constraints that may emerge. Zeitoun and Mirumachi (2008), propose an analytical method helping transboundary water initiatives respond to power asymmetry. They note that the most dominant riparian is often able to direct the outcome of any interaction with neighboring states towards its own benefit and gains. There are two possibilities to counter such situations: either find ways to strengthen the weaker actors or level the playing field for cooperation through facilitation and considerable incentives.

The co-existence of conflict and cooperation is key in addressing challenges raised by differing interests of a multitude of stakeholders who happen to be users of a common pool resource such as shared waters. Adding political factors to cooperation processes makes the terrain for basin-wide negotiations more complex as it adds different perceptions and expectations of decision makers to negotiation processes (van Laerhoven and Andersson 2013). A set of power relations among riparian actors shapes transboundary water management, which in turn may impact coexisting conflict and cooperation over the same waters. Often cooperation is measured against the existence of river basin organizations, the willingness of states to take part in joint actions, or against the presence of multilateral agreements that reflect political power and embed national interests (Ravnborg et al. 2012). When power asymmetry becomes challenging for cooperative actions, one way to influence would be to conceptualize and derive positive-sum outcomes, promoting "win–win" options to the satisfaction of all parties. Assuming that conflict is the lack of cooperation, quantitative studies helpfully led us away from the threat of 'water wars' suggested by environmentally determinist approaches (Fröhlich 2012).

Even though transboundary water issues are complex, it has been proven that water disputes can be mediated through diplomatic mechanisms, equitable benefit-sharing strategies, as well as the development of human and institutional capacities. These can indeed support regional cooperative strategies and allow for the prevention of adverse effects of unilateral measures (Sechi and Zucca 2015). This section focuses on water diplomacy as a capacity building mechanism for transboundary cooperation. In Sect. 10.5 the role of economic instruments to enhance transboundary water cooperation is discussed.

The effectiveness and sustainability of cooperative arrangements are more important than the number of agreements concluded between states in a basin or the presence or absence of a basin management organization. In general, when agreements which address the systematic complexity of the hydrological conditions, and provide a platform for a dynamic negotiation process are in place, the cooperation is likely to be successful in the long-term (De Stefano et al. 2012). Through the cooperative development of water resources, current tensions between riparian countries can be reconciled through political will and bring economic, environmental, and social benefits to all states. With the proper perspective, transboundary water resources can, therefore, become a source of regional cooperation, peace, and security.

7.9.3 Establishment of Transboundary Cooperation

Cooperation comes in various forms, ranging from the initial level of communication to joint action and investment (Sadoff and Grey 2002). Similarly, there are different types and levels of incremental benefits, such as economic, environmental, social, or political ones. Practical cooperation can range from relatively easy data sharing and hazard warning protocols to fully integrated approaches to developing and co-managing basin-wide transboundary waters. The continuum of cooperation can be conceived from unilateral and independent action towards coordination and collaboration to joint investment and management of development projects (De Man 2016).

Cooperative actions are often discouraged by inaccurate information and lack of transparency, but this could be changed with more credible information sharing and trust-building techniques (Wouters 2013). A reliable database of water availability, allocation, and consumption, which includes meteorological, hydrological, and socio-economic data, is a fundamental tool for informed decision making. According to Zeitoun and Mirumachi (2008), cooperation and regional agreements over water must satisfy several initial conditions. For instance, due to the impending influence of sovereignty on treaty formation and cooperation in general, cooperative arrangements need to be "rational" for concerned individuals as decision makers. The idea of individual rationality presumes that countries decide independently whether to participate in a transboundary cooperation and negotiation process; their ultimate aim being to maximize their individual benefits in any possible manner. The direct and indirect spectrum of benefits of cooperative actions indeed often affects the level and quality of cooperation.

Comprehending the hydrological processes and synergies of a river in its upstream–downstream linkages is the basis for problem-solving in the basin. It serves as an appropriate input for effective and efficient planning of cooperative management strategies at the international level (Eynon 2016). Therefore, investigating and understanding upstream–downstream linkages of hydrological, social, and environmental processes, facilitate river modeling and data sharing among riparian states. Satisfactory incentive-compatible options can then be jointly found (Harrison 2006). Technically and economically focused analysis of linkage identification can, however, not fully match real-world complexities due to the overarching political issues and frameworks. Different tradeoffs between benefits, on the one hand, and subjective values such as ethics and fairness, on the other hand, are difficult to associate (Yang and Wi 2018). Nexus research in a transboundary context helps reveal the resource and economic wins or losses for a riparian state, resulting from unilateral acts of another riparian state. In the case of dams, for example, assessing the impact of different operation modes based on the interest of the operating country gives insights into which choice is most beneficial for the neighbors' national interest in terms of resources security, and hence economic benefits.

7.9.4 Water Diplomacy Framework

Diplomacy is a tool frequently used within the consensus-building framework globally. It can be understood as a process of individuals coming together to build mutual understanding and trust across their differences, and generate constructive outcomes through dialogue (De Man 2016). Those outcomes include building or strengthening mutual trust, quality communication, and understanding across differences, expanding participation around relevant issues, jointly analyzing a problem or context, and developing a cooperative agenda for action (Motlagh et al. 2017). Addressing transboundary water conflicts is a core purpose in water diplomacy, rooted in international relations. Water diplomacy methods are therefore expected to play an increasingly important role in preventing, mitigating, and resolving the growing number of water-related conflicts and, create room for more extensive cooperation.

Water diplomacy applies the principle of diplomacy, where agreements are negotiated to advance common agendas among actors. However, it is marked by several significant shifts, both in the substantive content of what is negotiated and who is involved as well as in practice or means of conduct (Zandvoort et al. 2018). Water diplomacy is not understood as the adoption of an agreement only. It incorporates all phases of the negotiation, along with the implementation of related policies, decisions, and programs. Beyond 'water-centric' thinking, key sectors, actors, and institutions across the water, energy, food, and environment domains can be identified, their synergies exploited, and tradeoffs evaluated to achieve overall environmental sustainability goals (Kibaroglu and Guersoy 2015).

Islam and Susskind (2013) defined water diplomacy, which also refers to as hydro-diplomacy, as all methods of interaction between non-state and state actors and the involvement of at least one international governmental organization to practice communication aimed at avoiding hostility. The Water Diplomacy Framework developed by Islam and Susskind in 2013 is an interesting one among many other similar frameworks. It suggests the implementation of a negotiated approach to managing complex water-related problems. It builds on the concept of using mutual gains and negotiated approaches in transboundary disputes. It also recommends, overcoming the historical zero-sum orientation in favor of the pursuit of innovative resolution of water issues at the basin scale. Water diplomacy approaches may use technical methodologies and assessments as entry points. It is, however, equally important to engage politically with the highest levels of government representatives from the beginning of the process. To secure political "buy-in", they have to be fully aware of the process from the start (Alaerts 2015).

According to the traditional understanding of diplomacy, international relations are focused on the states as their main actors. Transboundary cooperation is then primarily applied to government-to-government collaboration. This mode of arrangements among officials and state actors is considered as formal diplomacy. It takes place over a formal process of negotiation (Barua 2018); and cooperation is determined by the political attitudes of riparian basin states. On the other hand, informal diplomacy is referred to, as commencing dialogue among non-state, non-official actors, to build relations, resolve conflict, and build trust, based on agreed agenda and responsibilities.

However, the concept of formal and informal diplomacy has been transforming during recent decades. The multi-track water diplomacy framework has emerged. It stages various stakeholders within the water governance framework to ensure basin-wide water security at multiple scales. This framework is an effective mechanism to support the identification, communication, and resolution of water-related problems across sectors and administrative boundaries, at different levels of governance and decision making processes (Huntjens et al. 2017). When the multi-track diplomacy framework is applied to the water diplomacy notion, many actions, and initiatives—beyond river basin politics and transboundary water agreements—become relevant.

Effective water diplomacy methods need to be flexible enough to respond to different political landscapes and climate changes at global, basin-wide, and national scales. Water-related diplomatic procedures take place in an informal context with non-state actors or sometimes with official actors in informal positions. Water diplomacy tracks and tools such as various dialogue mechanisms and communication techniques, joint fact-finding missions, joint scientific, value-creating method, and mutual gain tactics need to be more accessible to experts, practitioners, and foreign policy actors and stakeholders to work together more effectively (Susskind 2017). Islam and Susskind's water diplomacy framework recommends that a neutral facilitator is hired to conduct a stakeholder assessment. Agreeing to share a resource requires the mediator to be involved in the identification of bilateral as well as mutual costs and benefits, while devising the instruments of securing the benefits and minimizing the costs. In this study, we focus on three main analytical tools of water diplomacy.

7.9.4.1 Multi-stakeholder Participation

Transboundary water management in many countries is characterized by overlapping and competing responsibilities among government bodies at the national and international levels. Disputes often arise when management decisions are formulated without sufficient participation by local communities and water users at all scales, failing to take into account social rights and practices (Susskind 2017). Political willingness for cooperation is essential, and institutions and stakeholders on each side of the border should exchange data and information and develop joint plans for water resource management. After initiating communication and interaction platforms for identified and relevant stakeholders, the objective of the diplomatic approach is to promote the necessity to increase engagement into the negotiation process towards win–win outcomes. Stakeholders of a shared waterbody can belong to one of these groups: governments (national, provincial, municipal), businesses, academia, NGOs (national and international), communities (farmers, urban residents, and locals) (van Rees and Reed 2015).

Stakeholder-centred vision and learning focus on adaptive management of water resources are significant factors to improved management and allocation of water resources (Song et al. 2016). Through tactics introduced by the Water Diplomacy Framework, stakeholders are encouraged to move beyond their initial positions regarding interests, values, and practice and to come up with innovative ways of compensations and value creations. They are encouraged to find common interests and accommodate the needs of all involved parties (Islam and Susskind 2013). Stakeholders' involvement is an on-going, long-term effort that adapts to the conditions, needs, and dynamics of the cooperation process. The notion that stakeholders should be given the voice in the management of their water resources is one of the motives for cooperation, and the key is to ensure that all stakeholders see the benefit of their involvement and know their voices are heard.

The context includes the geo- and biophysical, hydrological and socio-economic factors which shape the interests, discourses and institutions (drivers) determining stakeholders' behavior, and the relationship between them in terms of power asymmetries and politics. The inclusiveness of their participation is also influenced by the tools available to them, such as access and participation in decision making on transboundary water and nature governance, technical capacities, and skills. Interactions between actors, then, lead to specific decisions related to transboundary water governance, which in turn have an impact on water allocation, water pollution, and environmental sustainability.

A number of factors can enable better nexus governance. These are for example the acknowledgment of shared understandings between different stakeholder groups based on their level of interaction and relation, the setting of flexible policy boundaries, the enhancement of knowledge-based dialogues, and the introduction of capacity building plans such as joint training, human skill-building strategies, and institutional capacity development practices.

7.9.4.2 Value Creation in Negotiations

In the negotiation over transboundary waters, value creation to increase mutual gains from cooperation may happen in numerous ways based on the characteristics of each transboundary basin. In general, involved stakeholders look for opportunities to achieve an agreement that is mutually advantageous for all. It requires negotiators to think of tradeoffs in which each gets their most fundamental interest met, in exchange for helping the other sides to achieve their topmost priority (Susskind 2017). At the beginning of a mutual gains negotiation, stakeholders must be reminded that it is in their common interest to engage in the creation of additional values to be added to already existing ones, before determining who gets what and how much. The more value is generated, the higher the chances are that all stakeholders will exceed their BATNA[126] and thus find a mutually beneficial and satisfactory outcome.

Cooperation among stakeholders emerges as a voluntary arrangement to engage in a mutually beneficial exchange instead of competition over a shared resource. The likelihood of cooperation is greater where resources are adequate, and the benefit of cooperation expanded beyond unilateral actions. Zero-sum thinking emerges when people think of water as a fixed and limited resource (Vetter 2016). The value creation technique focuses on positive-sum, or mutual gain approaches during interest-based transboundary negotiations, by challenging old-fashioned thinking about exclusively resource-focused water management. There are three assumptions: (1) water is a flexible, not a fixed resource, (2) science, policy, and politics combine to create water networks, (3) water networks are complex. They need to be treated as open-ended and unpredictable rather than closed and predictable systems. These three fundamental assumptions embedded in the Water Diplomacy Framework have significant consequences on the way water disputes solutions are addressed (Islam and Susskind 2013).

One of the underlying principles of the Water Diplomacy Framework is that water is a flexible resource in availability, and riparian states need to use this insight to expand the probability of conflict resolution. It helps riparian countries shift their focus away from allocating fixed quantities of water, towards the "water flexibility" concept. It gears their thinking way from the competitive perception of shared waters, towards the advantages of allocating the benefits of cooperative water resources management (Islam and Susskind 2013). Through a mutual gains approach, countries can brainstorm options to expand the supply and accessibility of water through conservation, wastewater recycling, technological advances such as desalination, and by imagining new agricultural or industrial processes to use water more efficiently. They thereby free up more water for other purposes. Based on such assumptions, diplomats often focus on what share of the existing water will be given to whom, while the way how benefits will be shared derives from cooperative development actions (Huntjens et al. 2015).

7.9.4.3 Joint Fact-Finding

According to the Water Diplomacy Framework, the root of many complex water-related challenges lies at the intersection of multiple causal forces in observational signatures with often conflicting perceptions and values related to decision making. The issue is about determining who decides, who gets water, how and how much? In such conditions and with such concerns, neither numbers nor narratives will resolve the dilemma to reach a satisfactory solution. One way to address complex water problems is to reframe them as a joint decision making activity starting from the problem's identification, through innovation, and implementation. Shared gains opportunities can then generate politically legitimate strategies and projects, based on science with stakeholders' active participation. In other words, rather than merely sending information back and forth, the Water Diplomacy Framework would encourage riparian states to collaboratively, through information collection and research, assess benefits, values, and shared interests, conduct feasibility studies and, develop a basis to address their outcomes and expected results (Islam and Susskind 2013).

Joint fact-finding is a collaborative process allowing for strategy-setting given resolving disputes and addressing cooperation obstacles by jointly gathering and analyzing scientific or technical data. Such fact-finding strategy can be delegated to a group of experts, policymakers, and stakeholders form each riparian state, often managed by a professional facilitator, to depoliticize the situation and discourage states from censoring information on national security-related issues (Warner 2007). Such transparency in

[126]BATNA in negotiation theory refers to the Best Alternative to a Negotiated Agreement or the most advantageous alternative course of action a party can take if negotiations fail and an agreement cannot be reached.

data collection and distribution can contribute to trust-building and create an environment for cooperative negotiation. It requires the states to work together, generate opportunities, and to develop alternative responses to each current and future problems (Motlagh et al. 2017).

By promoting joint fact-finding in the negotiation process, it is possible to generate a deeper understanding of relevant issues by all decision makers. The end goal of joint fact-finding is not to establish 'the truth,' but arrive at an agreed-upon understanding that is both scientifically sound and publicly credible, which allows stakeholders to engage further in collaborative problem-solving.

This process gives decision makers a basis to identify cooperation opportunities by reducing uncertainties around them, allowing them to understand promising incentives and making cooperation politically more attractive than unilateral action (Islam and Susskind 2013).

Practical approaches such as water diplomacy techniques, IWRM framework, issue linkages, side-payments, and benefit sharing dialogue tools—both at sectoral and transboundary levels—are all needed to tackle complex transboundary water management issues. However, in order to have better leverages in solving problems cooperatively, international water law brings together the legal and quasi-legal instruments of transboundary water agreements. In other words, water diplomacy tools, techniques, and dialogues have to combine with water law to protect riparians' rights and deal with water cooperation complexities. Transboundary water cooperation policy processes indeed happen with different levels of reliability and will. They thus offer different opportunities for the inclusion of negotiations results and decision making in a diplomatic environment alone.

Even though the law is not essential for cooperation, a legal framework can create a more predictable and stable environment, which in turn can reduce any potential for conflict (UNEP 2002). When no formal transboundary water cooperation policy process is in place, informal dialogues may be regarded as early-stage transboundary water cooperation. At the other end of the scale, a transboundary water cooperation policy process may be characterized by a well-established formal framework that includes legal agreements, institutional structures, and joint action programs. It is important to understand international water law in its functionality to facilitate a culture of communication amongst riparian states, provide them with a common language, constitute a starting point for their negotiations, adoption, and further expansion of innovative problem resolution for transboundary water resources management.

Learning from success stories and comparing applied approaches may help to link all instruments and initiatives coherently and then, articulating common methods and principles, which can be later modified and applied to the uniqueness of each basin. The analysis of successful river basin cooperation experience shows that in all regimes, shared infrastructures such as dams, are a primary driver of cooperation among countries. Equitable and reasonable distribution of costs and benefits amongst riparian states plays a significant role in the development of cooperation (Arjoon et al. 2016). Joint actions provide both economic and non-economic benefits that can be extracted in different time frames from short to long term. The involvement of local stakeholders and different types of relevant organizations, at an early stage of the development of transboundary negotiations, may also contribute to preventing water conflicts (Huntjens et al. 2015). Conclusively, it is apparent that different socio-economic contexts need to find their unique set of indicators, interests, and befitting processes to achieve cooperative transboundary water management through diplomatic mechanisms. The integration of science, policy, and practice in multi-track water diplomacy processes can contribute to enhanced transboundary water cooperation precisely in conflict-prone basins.

7.9.5 Concluding Remarks

Sustainable water resources management is one of the foremost global challenges; however, despite the complexity of the challenge, water can become a subject for cooperation and can be transformed from a source of potential conflict into an instrument of peace. Once a cooperative interest exists, the only problem, which remains to be solved, is the allocation of associated joint costs and benefits of cooperation within the framework of international law. Socio-economic approaches that accompany institutional set-ups, under diplomacy shelters, are some of the most effective approaches, which can be used in negotiation processes for achieving basin-wide, sustainable, and functional agreements (Hefny 2011). All mentioned tools and approaches are individually useful, and investing in them often extends to better policies and decision making. As helpful as they could independently be, their effectiveness would undoubtedly increase if they were well combined, in accordance with the law, and while taking into account parties' interests, internationally coordinated engagement is also required to build robust and political involvement by foreign policy communities and governments (Tawfik 2015).

Achieving an agreement around the use of challenging and strategic resources such as water requires a long, intensive, and engaging negotiation process. It has to address the identification of mutual benefits and interests of decision makers. It has to conceive instruments to secure enough benefits and share them equitably in a transparent manner. The main challenge remains, however, to establish how transboundary water management can be sustainable and inclusive while guaranteeing that benefits derived from it, are equitably shared among all stakeholders. Negotiated water solutions—as a result of transformational change in water management—should constitute enabling elements for sustainable and climate-resilient development of concerned states.

Hence, there is a need for innovative, context-specific new tools and approaches to help negotiators and decision makers understand and overcome uncertainties in a transparent manner. For instance, the language barrier among stakeholders can lead to frustration and a lack of motivation for collaborative actions. Coming up with a mutual language to describe and communicate around water issues, can increase trust and transparency among actors, help their interactions and dialogue, and enhance their capacities. Such a mutual language can also support the science-policy dialogue between academics and practitioners. It can make the application of science and evidence in policy development more accessible, and decision making processes better informed.

Before the ratification of new agreements, basin states should make sure that it accommodates significant flexibility measures, and can adapt to future anthropological and natural changes. Furthermore, keeping states engaged and guaranteeing the long-term sustainability of a cooperative agreement requires the investigation of additional gain options. The agreement has to create economic, social, and environmental benefits for all. Any process of water law development will be preceded by a phase during which international partners can express their interests and establish a platform to identify challenges, opportunities, bottlenecks and, formulate the necessary policies, strategies, and approaches to address them (Murthy 2015).

Without adequate cooperative approaches to foster collaboration in transboundary water management, we face unilateral appropriation of water resources, which often leads to tensions among riparian countries and can accumulate over time (Dinar 2008). However, even with the finest of intents, it may prove increasingly challenging to develop the most appropriate policies, laws, and management arrangements for transboundary settlements, during prolonged water-related uncertainties or, when there are tensions between national priorities and transboundary considerations (De Man 2016).

Successful transboundary cooperation cases demonstrate that since cooperation is mostly conditional, as long as a set of *sine qua nones* are available and, particular ranges of incentives are ensured, it does progress. Practice also shows that basin-wide efficiency requires regional cooperation. Moreover, real-life cases teach that cooperative decision making can be made possible in a transparent environment if it is sustained with a variety of compensation options, institutional frameworks, and incentive-compatible considerations.

7.10 Transformative Practices for Water Diplomacy

7.10.1 Introduction

Water conflicts arise, and are expected to increase, because water is often managed for multiple uses and competing demands. In addition, water crosses political borders. Globally, approximately 600 aquifers are shared across an international border (IGRAC 2017); as are about 310 river basins, encompassing 40% of the world's population and close to 50% of the land surface of the earth (McCracken and Wolf, forthcoming). Here, we define a conflict as the perception that one or more parties is being prevented from taking a particular action (such as building a large dam) and that an activity (e.g., economic sanctions, threats of military violence) can be utilized to overcome the difficulty (Frey 1993; Delli Priscoli and Wolf 2009). Such perceptions heighten regional tensions and threaten economic, social and geopolitical stability.

Legal mechanisms and frameworks for mitigating water conflicts among states have their place in the management process. This approach to water diplomacy relies on statutes, regulations, precedence and guidelines; it is a traditional system, often involving courts. However, the legal approach to water and environmental law provides the added challenge of needing to incorporate the complexities of governance and societal, economic, ecosystem and scientific issues and concerns (Steinway and Botts 2011).

Another approach is alternative dispute resolution (ADR) which generally requires fewer resources of finances and time. ADR utilizes arbitration, negotiation and/or mediation to mitigate conflict through settlement. Through an informal court process, an arbitrator provides binding arbitration to arrive at a solution, while parties retain the right to trial through nonbinding arbitration. With negotiation, parties or third party actors work towards reaching an agreement. Mediation provides additional flexibility. A neutral party, a mediator or facilitator, helps guide the process to optimize effective and open exchange, while allowing the parties to play an active role in the process (de Silva et al. 2018). However, ADR generally tends to be content-based (Lederach 2003).

Conflict transformation, which might be regarded as a subset of ADR, focuses on relationships, seeking healthier interactions among individuals, among parties, and between humans and the environment. This approach promotes longer-term constructive change, extending beyond remedy of a single dispute (Lederach 2003). Conflict transformation taps into physiological, emotional, intellectual and spiritual

Table 7.1 The universality of the four worlds. From course material of an annual Oregon State University course entitled "Water Conflict Management and Transformation," offered by the authors

Rothman, Jay. ARIA (1989, 1997)	Adversarial (antagonistic)	Reflective (resonance)	Integrative (invention)	Action
Water Resources (Wolf 1999)	Rights	Needs	Interests	Equity
Water Visual (Wolf et al. 2010)	Basin w/borders	Basin w/out borders	Enhanced benefits	Equitable distribution of benefits
Maslow's (1954) Hierarchy of needs	Physiologic	Safety	Belongingness and love	Self-actualization
Levels of holiness (Sinai, Temple, prayer service)	Physical	Emotional	Mental	Spiritual
Jewish/Catholic Textual Analysis	*P'shat*: literal	*D'rash*: allegorical	*Remez*: tropological	*Sod*: analogic
Kabbalistic worlds (Kemenetz pp.16–17)	*Assiyah* (actualization) It is perfect (h)	*Yetzirah* (formation) You are loved (v)	*Beriyah* (creation) All is clear (h)	*Atzilut* (emanation) I am holy (Y)
Elements and Archangels	West, Rafael, earth	South, Michael, water	East, Gavriel, wind	North, Uriel, fire
Buddhism: Four Sights/Noble Truths/Four Jhannas	Sick/*Dukkha* (suffering)/physical joy	Aged/*Tanha* (desire)/rapture	Dead/*Nirvana* (a-suffering/equanimity	Holy/eightfold path/lucidity
Sufi Muslim Moral Stuctures	*Sharia:* Quranic law	*Tarikah:* inner emotional practice	*Hakika:* direct understanding of truth	*Marifah:* deep attunement to the Divine
Hindu AUM and Vishnu's totems	A—from abdomen/mace—physical strength	U—from chest/lotus flower—glory of existence	M—from throat and above/discus—mind chakra	*Turiya*—silence/conch—primeval sound of creation

necessities, often associated with Maslow's hierarchy of needs (Maslow 1954). Faith-based traditions also perceive the world as built on a scaffolding of physiological, emotional, mental and spiritual experience, a framework often referred to as the four worlds (Wolf 2017). Outlined in Table 7.1 is the universal construct of the four worlds from a selection of faith based traditions and social frameworks.

7.10.2 Spiritual and Faith-Based Traditions

The notion of the four worlds extends back thousands of years, to faith based traditions such as Jewish, Buddhist, Muslim and indigenous people of the Americas (Wolf 2017). These practices provide universal constructs and tools to navigate contentious situations and mitigate disputes. Here we provide a glimpse of how traditions associate with the four worlds.

To give the Jewish perspective, Wolf (2017; Table 7.1) recounts Moses' experiences on Mount Sinai, presenting the "four worlds through four levels of holiness" (p. 38). After spiritual endeavor, the Children of Israel are described as gathering at the base of Mount Sinai, where Moses builds an altar and gives offerings on behalf of the nation. Wolf (2017) states that "this experience of physical construction and sacrifice with the entire nation represents the first level—that of physical holiness" (p. 38). Moses climbs the mountain with the elders, Aaron and his sons, where they experience the presence of God as they eat and drink, in gratitude and bliss. This emotional exhilaration is considered as the second "world." Summoned by God to the summit of the mountain, Moses receives the Ten Commandments and is ordered to teach these edicts. This occurrence is regarded as the third level of knowing: awareness or intellect. The fourth level is experienced at the apex of the mountain, which Wolf (2017) describes as, "the thickness of the cloud itself (*'av ha'anan*), the Divine presence" (p. 39).

From the Buddhist tradition, we learn that Siddhartha, leaves the confines of the palace for the first time, and as he travels through the city of Kapilavast, he witnesses four sights:

> …he saw: an aged man, who represented physical decay, or *annika*, impermanence; a sick person, who experienced *dukha*, suffering; a corpse, suggesting the powerful idea of *annata*, that the link between being and non-being is a tenuous one; and finally an ascetic, a holy man who devoted himself to a spiritual understanding of the roots of suffering (Mills 1999; Rahula 2007; both in Wolf 2017, p. 39).

Wolf (2017) clarifies how the four worlds are experienced through Islam:

> In Islam, the bounded, physical expression of the path to holiness is most commonly manifested through *Sharia*, the law as derived from the Quran. To the physical path of *Sharia*, the Sufis, mystics of the Muslim world, add three, each building on those before: *Tarikah*, the inner practice, expressed with deep emotion through love for each other and for God; *Hakika*, or truth – the direct understanding of the divine presence; and *Marifah*, the deep attunement with God, as intuited through "the eye of the heart" (Smith 1991, in Wolf 2017 p. 43).

In the tradition of many indigenous people of the Americas, the medicine wheel holds spiritual significance. It is in alignment and harmony with the four levels. Furthermore, the Laika Earthkeepers, ancestors of the Inca, had animal symbols that correspond to energy points of the body (chakras): The physical, emotional, intellectual, and spiritual experiences correspond to the serpent, jaguar, hummingbird, and eagle, respectively (Wolf 2017).

The four worlds correlate with the four stages of water conflict management, allowing for a subtle melding of spiritual practices with hydro-diplomacy. In doing so, Maslow's hierarchy of needs (Maslow 1954) are aligned with Rothman's model of the four stages of negotiation (Table 7.1). Rothman initially described his stages as ARI—Adversarial, Reflexive, and Integrative (Rothman 1989). When ARI became ARIA, adding Action, Rothman's terminology (1997) also evolved to Antagonism, Resonance, Invention, and Action. We retain the former terms, feeling they are more descriptive for our purposes. These common water claims (listed in Table 7.2) stem from an assessment of 145 treaty deliberations described in Wolf (1999). Rothman (1995) also uses the terms rights, interests, and needs, in that order, arguing that "needs" are motivation for "interests," rather than the other way around as we use it here. For our purposes, our order feels more intuitive, especially for natural resources. These sets of collaborative skills (listed in Table 7.2) draw from Kaufman (2002), who ties each set of dynamics specifically to Rothman's ARIA model in great detail, based on his extensive work conducting "Innovative Problem Solving Workshops" for "partners in conflict" around the world (Wolf 2010). Simply put, the universality of the four worlds is associated with the four stages of water conflict transformation. Notice for example, that the first row of Table 7.1, corresponds to the first column in Table 7.2. In this way, the lessons that spiritual practices can provide can be linked to water diplomacy application. We begin, by exploring a hydro-conceptual framework, and follow with water diplomacy demonstrations through a spiritual lens.

7.10.3 The Four Stages of Water Conflict Management

The collaborative skills used in the stages of water conflict management (see Table 7.2) provide tools to manage and transform national and international water conflicts. This framework of the four stages is one of several instruments to manage conflict, but is by no means a template; this framework builds on extensive international case studies and the experience of water practitioners, coupled with spiritual practices. The stages follow the Rothman's ARIA model, described earlier.

Stage 1 of the four stages of water conflict management is adversarial, in which the communication style among stakeholders (nations) tends to be argumentative and

Table 7.2 Four stages of water conflict transformation. These negotiation stages build primarily on the work of Jay Rothman (Rothman 1989, 1995, 1997), Kaufman (2002) and Wolf (1999). This table is modified from Fig. 6.1, in Jerome Delli Priscoli and Aaron T. Wolf. Managing and Transforming Water Conflicts. Cambridge University Press, New York, New York, 2009, 354 pp. [© Jerome Delli Priscoli and Aaron T. Wolf 2009; Reprinted with permission]

Negotiation stage	Common water claims	Collaborative skills	Geographic scope
Adversarial	Rights	Trust building	Nations
Reflexive	Needs	Skills building	Watersheds
Integrative	Benefits	Consensus building	"Benefit-sheds"
Action	Equity	Capacity building	Region

combative in nature, with actors believing they know the "wants" of the opposing party. Emphasis is on past interactions. There is little to no trust, nor interest in listening to others regarding the matters of concern. Great efforts are placed on one's own claim to a right to water, through priority, sovereignty or other contextual and geographic framing. Regarding possible remedies, parties may only be aware of win/lose outcomes, and applying legal mechanisms. At this stage, trust-building is essential. It is critical in this stage to place emphasis on practices that promote being fully present, listening without judgement and making actors more cognizant of their own communication style as an avenue to deeper understanding (Cosens et al. 2012).

Stage 2 of water conflict management is reflective. During this phase, the parties display more willingness to listen and an increased ability to learn about the underlying reasons and perspective of the other actors. Focus during this engagement is content-based, with the goal of the resolution process being mitigation of the conflict and movement toward an agreement that addresses the immediate concern of the parties. This phase emphasizes bringing about more awareness of needs and interests rather than rights. Improving listening skills can be essential to building trust and negotiating an advantageous outcome that benefits both sides. This win–win approach comes through parties having the courage to listen to the needs, motivations, and fears of each other. Through this process parties learn to communicate more effectively, and paraphrase and validate what a party member has heard. They learn to voice each other's concerns, opening the way to brainstorming possible workable options. Rich and creative thinking can spark constructive possibilities, increasing the likelihood of everyone benefiting. Metaphorically it is as though a veil has been lifted; emphasis is placed less on rights, sovereignty and political demarcations, and more on what's needed for the river system and the watershed (Delli Priscoli and Wolf 2009).

Stage 3 of water conflict management is integrative, in which parties come to an increased sense of awareness of being an integral part of a system in which stakeholders' concerns are melded with the interests, needs and values of other community actors. This phase allows for a shared and collaborative perspective that gives rise to more comprehensive economic and social benefits. These benefits may extend beyond sharing water to, for example, environmental conservation, agricultural production and even trade (Sadoff and Grey 2002). These benefits may extend to the region, conceptually envisioned without political boundaries, and beyond the confines of the river system. The result should enhance the socioeconomic well-being of a people, which might eventually manifest as increased life expectancy, personal income, and literacy rates (Delli Priscoli and Wolf 2009).

The final stage focuses on implementing actions and ensuring that benefits are equitably distributed among actors, across a country and a basin. In this stage, the needs of each actor or region are incorporated into the solution through agreements. To accomplish this, institutional constraints or political boundaries that might have been removed conceptually, to spawn creative thinking are reinstated. They are replaced to ensure fair distribution of economic, social, and environmental gains among nations and actors. Assessing benefits within political demarcations may require creative solutions or a shift in resources to bring about more equitable basin-country distributed benefits. Innovative water arrangements should be broad, going well beyond water issues, a basin or country boundary (Sadoff and Grey 2002). The allocation of benefits and costs, termed benefit-sharing, can foster robust relationships among actors, providing effective and resilient mechanisms and institutions when implemented appropriately. This allocation can also result in joint actions that include collective participation, cooperative ownership, integrated assessment and design and shared investment (Sadoff and Grey 2002).

Movement through these four stages is not necessarily linear. Consider how the four worlds can exist simultaneously, and how they may not necessarily occur sequentially. Rain provides one example. In the physical realm, in a drought prone region, harvested rain can help maintain vital human body functions. It may also be emotionally gratifying to quench one's thirst. One can certainly intellectualize examination of rain patterns and the quantity of water collected; and spiritually, drinking water can consecrate our entire being. Likewise, a watercourse can serve as a regional-scale example: In the physical realm, the watercourse might represent a community's primary drinking water source; at the emotional level, the watercourse may provide aesthetic value and beauty to a people; intellectually, organizations can calculate the instream ecological flow; and spiritually, the watercourse might be utilized for river baptism or, like the Ganges River, be considered sacred.

Fusing spiritual practices at the appropriate negotiation stage requires creativity and resourcefulness to craft activities for water ministers, professionals and stakeholders for water diplomacy.

7.10.4 Examples Melding Spiritual Practices with Water Engagement

Spiritual practices from faith-based traditions have intangible gifts to offer. They provide guidance and teachings in kindness, compassion and mercy, and pathways to clemency and healing that can be applied to hydro-diplomacy. Provided below are faith-based approaches such as meditation, the application of talking sticks, the use of narrative tools (stories), and love as a spiritual practice.

Meditation is part of many hallowed traditions. It is associated with psychological, emotional, physical, intellectual and spiritual gains. It facilitates feelings of connectivity, including to the universe, Earth systems, life force, and animate and inanimate objects. In this open mode, the meditator's stress is reduced, which can produce a ripple effect, bringing a calmness to others in the same space and encouraging others to be more receptive to listening and hearing differing perspectives. Quieting the mind in this way can bring a sense of clarity to complex challenges, spurring creativity in decision making. So, incorporating meditation and moments of silence, when appropriate (at the start of a meeting and after a meeting break), can bring water delegates to a state of awareness, to be fully present (Tolle 2002). Similar benefits can be gained through the use of a labyrinth for spiritual practices and walking meditations, while providing participants and water practitioners with a direct connection to nature and "contemplative movement" (Barbezat and Bush 2014). Forms of meditation can be introduced at any stage in water conflict transformation, though meditation in motion may be invaluable during the integrative and action stages, when innovation and insights are needed.

The talking stick is an integral part of spiritual and cultural ceremonies performed by indigenous people of North America. It is an object passed around indicating who "has the floor". The talking stick is a sacred symbol of authority and power. When utilized within talking circles during council meetings, there are specific rules for communicating. One rule invites whoever holds the stick to speak without interruption, while others listen without scrutiny, honoring the sanctity of the spoken word (Avant 2017). In this respectful way, each member is permitted to speak and also listen, in turn. Similar approaches can be utilized or modified for facilitating water conflicts, but may be particularly useful in the adversarial and reflective negotiation stages of water conflict management (Table 7.2).

Written and oral storytelling traditions are essential to our communication. Sacred texts, such as the Bible or Vedas, convey stories of the creation of the world and teach us how to act. Stories have the unique ability to activate the language components of the brain, and stimulate the listener to experience the same sensation the speaker is expressing, making it a shared experience (Chen et al. 2017). In this way, we are drawn to listen more acutely, accessing empathy and humanity (LeBaron 2002). This form of social encounter, when appropriate, can provide stakeholders and actors with the opportunity to tell their own water story (one-on-one or in a group setting), providing context that might uncover other aspects of a person's life experience in a non-threatening way. This approach can be especially instrumental in building trust, during the adversarial stage of a negotiation (Table 7.2).

Love as a sacred practice is central in all faith-based traditions. Love for oneself, community and all manifestations within the universe are all regarded as forms of God. Chittick (1983) and Tolle (2002) say that thinking otherwise is to increase the pain (physical and emotional) for ourselves. This concept of "otherness" separates us from our most noble calling. It is only through conscious vigilance (staying fully present) that "oneness" prevails (Chittick 1983; Tolle 2002). For water diplomats to walk this spiritual path of love, consideration during negotiations must be given to the whole, and the fundamental goodness of all.

These examples illustrate how combining the four stages of water conflict transformation and spiritual practices can be used to balance national water interests and water for the regional good, or balancing human needs and ecological conservation while keeping actors and diplomats grounded in ethical and moral hydro-considerations. Integrating the four stages of water conflict transformation and faith-based traditions can expand our perception of water claims and broaden proprietary rights from independent holdings to joint ownership to an amalgamation, in which separateness no longer exists. These stages might be regarded as different ways of being and engaging with other actors. These differences reflect different levels of awareness. Just as a change in the state of matter requires a transfer of energy into or out of a system, likewise, a change in engagement with actors requires new input of information and/or increased energy. This new input facilitates transformation, transcendence or a shift.

7.10.5 Conclusion

Competing demands on water are expected to increase. In addition, about 310 river basins are shared by two or more nations impacting more than one-third of the world's population.

While the legal system and alternative dispute resolution provide mechanisms to mitigate conflicts, they often do not address all the nuances that water presents, and primarily do not extend beyond remedy of a single dispute. Conflict transformation offers longer-term constructive change, more flexibility, and is relationship-centric. The four stages of conflict management (adversarial, reflective, integrative and action) are linked to the physiological, emotional, intellectual and spiritual necessities; a four worlds framework.

This concept is fundamental to faith-based traditions, providing guidance and teachings in kindness, compassion and mercy and offering practices such as mediation. As such, the four stages of water conflict management framework combined with spiritual practices might be a practical tool for water practitioners (Wolf 2017; p. 46). After all, changes in worldview or negotiation stage are a natural part of the human evolutionary process. Individual and collective growth; increased awareness; and physical, emotional, intellectual and spiritual shifts in energy are within the range of the human experience and potential.

Despite these assertions, establishing international water arrangements such as water treaties among contentious states or states and international organizations can take decades: 10 years for the Indus, 30 years for the Ganges, 40 years in the case of the Jordan (Delli Priscoli and Wolf 2009). During those time spans, both ecosystem and human health suffered from poor water and environmental management.

However, if any of us can move toward structures that result in more constructive outcomes, then it is within the capacity of the rest of us (Angelou 2010). Practicing water conflict transformation infused with spirituality can set in motion a more ethical and reverential approach to water. This approach can guide our visionary future of embracing sustainable development goals: water security for all; socioeconomic prosperity and government stability; and equity beyond gender, race, class, sex and age. We can then expect to inhabit a planet with healthier ecosystems; sustainable agriculture, fisheries, and clean energy industries; and efficient and effective water management.

7.11 The Discourse on Water and Peace "A Matter of Survival"

7.11.1 Background

Water is life. It is a fundamental condition of human survival and dignity, and is the basis for the resilience of societies and the natural environment. Unlike other natural resources, water has no substitute: the only substitute for water is water.

Water is scarce: about two billion people still lack access to safe drinking water. Most of them live in fragile, often violent regions of the world where water is a matter of life and death. The growing imbalance in global water supply and demand leads to tensions and conflicts, and could potentially evolve into a widespread threat to international peace and security. Water deprivation is increasingly seen as a fundamentally political and security problem, and no longer simply as a problem of human development and environmental sustainability.

Many transboundary water basins are located in areas marked by interstate tensions and, in some places, armed conflicts, both among, and within states. Although water, historically, has rarely been the direct cause of armed conflicts, the future may not resemble the past since the world's population continues to grow. Water shortages and tensions over water quality can spiral into armed conflict and war. In recent years, water has been increasingly used as a weapon of war by non-state actors, such as in Darfur, Somalia, Iraq and Syria.

Water issues are a global development problem and need to be approached in a comprehensive manner. Over the past century, different and complimentary discourses have been developed in relation to water; some of which have been discussed and elaborated on in previous sections of this chapter. This final section elaborates on the water-peace discourse. It relates to global initiatives offering windows of opportunity for a promising future, using water as a vehicle of peace, particularly within the transboundary water context.

7.11.2 Preventive Diplomacy and Water Cooperation

In modern diplomacy, the role of preventive diplomacy in mitigating and/or limiting the escalation of disputes between the parties, has been recognized by global and state-actors (UN 2011 p. 2). The tendency is to take preventive measures and use different vehicles of peace including that of natural resources to foster cooperation and eliminate potential contributors to conflict (Carmi et al. 2019).

Preventive diplomacy has many forms and should be understood broadly. It includes but is not limited to diplomatic efforts of states to prevent an imminent armed conflict. It involves political engagements of governments, technical expertise, international financial institutions, business ventures as well as a variety of civil society based initiatives. It includes long term efforts to strengthen water cooperation as well as emergency humanitarian assistance in cases of natural disasters.

In 2017, the Security Council held a briefing on Preventive Diplomacy and Transboundary Waters, emphasizing the role of water diplomacy and cooperation in conflict prevention (Whatsinblue 2017). Mr. Guterres identified water scarcity as a "growing concern" among the complex contemporary challenges to international peace and security, and called for strengthening of preventive activity (UNSC 2017). Since then, the UN Security Council held other meetings specifically devoted to the issues of water—related to both, protection of water in armed conflicts and to preventive diplomacy relating to water (Whatsinblue 2018).

This illustrates the growing awareness of the need to strengthen preventive diplomacy in all of its dimensions and water is an integral part of this effort. Some of the relevant forms are well known and historically tested. Transboundary water cooperation has been established in many post conflict situations and has helped preventing recurrence of armed conflicts. Other forms are new or still at the evolutionary stage. The increased awareness of water-related consequences of climate change and consideration of measures to be developed have focused attention on situations such that of the Lake Chad and in the Sahel where curbing the ongoing armed conflict represents an urgent priority. An array of activities focusing on the Aral Sea and water issues in Central Asia belong to the examples of preventive diplomacy which requires long term engagement and careful building of cooperative mechanisms for the future. In the Middle East water cooperation is an increasingly important issue for future peace.

The historic experience of water cooperation has to be understood against the background of the broad needs of preventive diplomacy of our era. In Europe every major peace agreement since the Peace of Westphalia of 1648 included—or was followed by water cooperation arrangements. They were initially related to navigation on international rivers. Subsequently they included a number of aspects of water management and environmental protection. A recent example is the Sava River Treaty, signed in 2002. That treaty bound together several countries of the former Yugoslavia, some of whom were involved in bitter armed conflicts of the 1990s. The constructive potential of transboundary water cooperation is historically proven.

7.11.3 The Development of the Water-Peace Discourse Between Cooperation and Conflict

Competition for limited freshwater resources is alarmingly increasing due to various factors, including a drastic increase in water demand for food, security, and energy consumption, coupled with pollution, and inefficient uses of resources. Climate change increases the erratic frequency of water availability. This increases the tensions and competitions among the various users of freshwater resources.

In the past years, there have been increasing warnings about the possibility that water conflicts and water shortage coupled with poverty and societal instability, could weaken intra-state cohesion and fuel inter-state conflicts. At local level, we see the emergence of increasing intersectorial conflicts. The majority of disputes are complex, multifactorial, but are often expressed as water issues. On the other hand, water is also a tool for cooperation, and is the subject of agreements, and joint commissions, often at the basin or regional levels, as documented in the literature.

The water-peace discourse exists between the two poles of conflict and cooperation, and is built around two key objectives:

- preventing water-related conflicts and
- leveraging water as an instrument of peace.

The discourse is meant to strengthen the linkage between the existing Sustainable Development Goals SDG6 and SDG16. The water-peace discourse has been developed through the interactive dynamics and leadership of the following three main initiatives:

7.11.3.1 The Blue Peace Initiative

The Blue Peace initiative was launched by Switzerland in 2010, based on the premise that water cooperation among borders, sectors and generations can foster peace, stability and sustainable development, by turning competition over limited freshwater resources into collaboration (Blue Peace website).

This initiative has developed within the past decade into a growing global movement which "aims to develop a culture of peace and preserve precious freshwater resources, while achieving equitable and sustainable use of water across boundaries, sectors and generations."

The "Blue Peace Movement" is expanding globally and taking roots. Through a number of events, the "Movement" is addressing water problems of our era, jointly with the broadest representations of civil society, youth, artists, business and academic communities. Such collaborative efforts constitute a stepping stone towards the realization of SDG6 and SDG16.

In 2019, and in a collaborative effort between the Economist Intelligence Unit (EIU) and the Swiss Agency for Development, the Blue Peace Index was developed as "an objective, quantifiable tool to assess countries" and basins degree of transboundary sustainable and equitable cooperation (https://bluepeaceindex.eiu.com/#/).

On February 18, 2020, a conference was held to celebrate the Blue Peace Decade. The conference emphasized the need for intensified action in the field of international water cooperation, notwithstanding the obstacles that impede progress at this stage. The key among these obstacles is the waning commitment to multilateral cooperation generally, and multilateral water cooperation specifically. Therefore, the forthcoming World Water Forum, originally planned for 2021 in Dakar-Senegal before Covid-0.19 pandemic, will carry a particular significance to water cooperation and peace. Some of the aspects that were hitherto underdeveloped, such as the transboundary aquifer cooperation have to be put more centrally now.

7.11.3.2 The Geneva Water Hub

Water can become a theme for collaboration and an instrument of peace. It is with this positive vision that the Geneva Water Hub was established, with the support of the Swiss Agency for Development and Cooperation (SDC), and the University of Geneva (UNIGE) in 2014.

The Geneva Water Hub aims at developing the hydropolitics agenda to help prevent water-related conflicts at intersectoral and transboundary levels at an early stage, and to promote water as an instrument of peace and cooperation, through its three main functions of advocacy, Think Tank, and research and education (Geneva Water Hub website).

In 2015, Switzerland, GWH and the Strategic Foresight Group (SFG) were instrumental in the mobilization of countries to support the creation of the Global High-Level Panel on Water and Peace, described below, for which GWH is the Secretariat—The GWH is now recognized as a global center of the University of Geneva, specialized in hydropolitics.

The GWH defines water diplomacy as "a strategic tool for reconciling conflicting interests including and beyond water, based on the increasing global recognition of the water-peace nexus/pardigm. We view water diplomacy as one form of preventive diplomacy that adopts a multidisciplinary approach and innovative tools, that uses water as a vehicle for peace and a bridge that connects the development and peace agendas. Peace, according to us, is not the absence of armed conflict but rather the prevalence of sustainable development based on the premises that sustainable peace, sustainable development and humanitarian response, are the three edges of a triangle, with water at its center. The convergence of these three agendas is at the heart of the dynamics of the International Geneva.

The GWH continues to look at effectively bringing together partners committed to promoting the water and peace agendas, and it is gaining traction.

7.11.3.3 The Global High Level Panel on Water and Peace (GHLP-WP)

Upon the request of the SDC, a consultation was conducted with governments and experts from across world, which revealed that although water was recognized internationally as a development and human rights issue, yet its implications for peace and security were inadequately addressed. There was a clear need for a global platform that would look into the issue of water in the context of maintenance of peace and security, from a technical to a political level. This led to the launching of the GHLP-WP, on 15 November 2015 at an inter-ministerial gathering presided over by Switzerland, and including the 15 co-convening countries who expressed interest in its mandate.

The GHLP-WP, chaired by Dr. Danilo Türk, one of the co-authors of this section, was mandated to develop a set of recommendations aimed at strengthening the global architecture to prevent and resolve water-related conflicts, that were outlined, 2 years later, in the report "A Matter of Survival" (GHLP-WP 2017). In all of the different chapters of the report, cooperation is a central pillar.

Although the mandate of the GHLP-WP ended in 2017 in terms of the provision of recommendations, yet the Panel continues to enrich the reflection globally on the water-peace discourse, and some of the panelists are actively involved in pushing the agenda forward, each within his area of expertise. In Fall 2019, the Panel met informally during the Budapest Water Summit in October, as it continues to play a main role in the development of the water-peace discourse, and the bridging of the development, humanitarian and peace agendas.

For the first time it is history, the United Nations Security Council, convened a first thematic Open debate, under the presidency of Senegal, on 22nd November 2016, on linkages between water, peace and security. Senegal is one of the co-convening countries of the GHLP-WP and its nominated panelist acted as its vice-chair. This special session was attended by 70 member states in a positive and forward looking atmosphere, and a strong recognition of the role of water in preventive diplomacy, as well as an important enabler to peace and security (United Nations 2016a, b).

In the years that followed, several other thematic sessions on water were held at the UNSC, under the leadership of other countries, also keen on the water-peace discourse. Accordingly, recent armed conflicts and other situations on the agenda of the Security Council have been characterized by water—related issues and the UNSC addressed them in its resolutions and presidential statements.

In its work, the GHLP-WP recognized that new mechanisms of water diplomacy will have to address, inter alia, the issue of the "fragmented landscape" of water related international institutions. In the UN system alone there are 32 entities dealing with water and cooperating within the loosely organized coordination mechanism, the "UN Water".

The role of UN-Water is essential and both the GHLP-WP, and GWH value the contribution it made as an observer to the Panel, and a partner in the discussions on water and peace.

7.11.4 Elements of the Water-Peace Discourse

Since 2017, the Geneva Water Hub, has been following up on the key recommendations of the Panel, and overseeing the implementation of some of them. The report "A Matter of Survival" has received global attention, and to date has been translated into 4 languages. The progress in the implementation of the Panel's recommendations is detailed in the report "Determined Steps" in March 2019, and in the report "Intensified Action" published in June 2020 (Geneva Water Hub 2019a, b, 2020c).

These recommendations call for the development of tools, and the use of the following elements to achieve the main two objectives of the water-peace discourse, and include institutional, legal, financial and political instruments.

7.11.4.1 The Global Observatory on Water and Peace

Many existing organizations and mechanisms are contributing significantly to water cooperation to the extent possible at the current level of international cooperation. However, an important feature of discussions relating to international water cooperation is the limited capacity of international actors to act collectively and effectively at the political and diplomatic levels and the search for a global home of hydro-diplomacy. Accordingly, the Panel report called for the establishment of the Global Observatory on Water and Peace (GOWP), as a global network, to facilitate assistance to interested stakeholders in using water as an instrument of cooperation, in avoiding tension and conflicts, and to promote peace. The GOWP adopts the knowledge management approach, and discreet facilitation rather than the traditional dispute settlement, peacemaking or peace building approaches.

The GOWP is a network of nodes of different natures which possess analysis and strategic foresight capability on water and peace in their "specific context"; this reflection is carried out in a creative dynamic exchange and contributes to creating a discreet "global space" (Safe Space) to progress on the key themes for their regional context, of a generic scope, or of global scope. The GOWP is both in line with the work of the GHLP-WP and is one of its recommendations. There are two main types of nodes: (i) regional nodes (ii) societal nodes.

The current mode of operation of GOWP is flexible and open for further partnerships, given that the GOWP is an inclusive network that ensures linking partners working on water cooperation to fill in the critical gaps of the global water architecture. It was officially launched during the 5th Arab Water Week at Dead Sea in March 2019, under the Patronage of His Royal Highness Prince El Hassan Bin Talal, member of the GHLP-WP. It is expected that the network will further expand to include various kinds of actors committed to the water and peace agenda. The December 2019 edition of the Water Diplomat, included a Water Talk about the Global Observatory on Water and Peace, to further communicate and explain its mandate, and its mode of operation. The Water Diplomat is a free monthly global news and intelligence resource platform accessible online and through a newsletter, launched jointly by the GWH and OOSKA news, with the goal of promoting access to political stakes of water management that are making news around the world (Water Diplomat Talks, December 2019). In addition, there is a series of short videos on the website of the Geneva Water Hub that explain and update the progress in the work of the Global Observatory on Water and Peace (Geneva Water Hub 2020a, b).

The first regional partner of the GOWP in the West African region, the Pôle Eau Dakar (PED) was established by the Senegalese Ministry of Hydraulics and Sanitation. It was officially launched during the Kick–off meeting of the Forum of Dakar on June 19, 2019 in Dakar. Its mission is to "to promote concerted development of skills and practices at local and regional levels to promote integrated management of water resources based on strengthening hydro-diplomacy and peace" (Brochure PED- Initiative Pole Eau de Dakar: Processus de Creation).

In March 2019, the Permanent Council of the Organization of American States (OAS) expressed its interest to contribute to the GOWP node for the Latin American States. The development of regional partnerships in the Middle East and North Africa (MENA) as well as Central Asia are underway. The development of GOWP nodes is closely related to specific interests and challenges that differ from one region to another.

The societal nodes of the GOWP include among others the youth, the media, women water diplomats, and the Group of Friends on Water and Peace in the International Geneva. These partners contribute to the reflection and advancement of the water-peace discourse from their own perspectives.

The GOWP has developed the additional capacity to convene "what is called a Safe Space": a discreet process bringing together identified stakeholders to address a given sensitive "water and peace discourse" issue. Safe space meetings allow discussions, inter alia, on innovative finance, transboundary cooperation and water security in a confidential manner Water diplomacy is here understood as encompassing all these aspects and the concept of "Safe Space" discussions is a vital part of it. A "Safe Space" Fund is being set up to support the launching of promising "Safe Space" processes, or to accelerate an existing process.

7.11.4.2 The Geneva List of Principles on the Protection of Water Infrastructures During and After Armed Conflicts

Water is rarely—if ever—the sole reason for armed conflict. Other factors—economic injustice, political competition and ethnic hostility lead to outbreaks of violence. Increasingly, however, these factors are linked to the disputes over possession of vital resources, including water. It is therefore important that policies aiming at prevention of armed conflict include water issues and water diplomacy into a comprehensive prevention strategy.

In many ongoing armed conflicts, water has been used as a weapon of war. Water infrastructures have often become targets of armed attack. All this has had an extremely negative effect on civilian populations and produced grave violations of international humanitarian law. In addition, water stress and water-related disasters are among the main consequences of global warming and have severe humanitarian consequences. They often cause population movements and tensions resulting in violent conflict and threats to international peace and security.

Following the recommendations of the Global High Level Panel on Water and Peace, the Geneva Water Hub's Platform for International Water Law at the University of Geneva, in collaboration with other academic partners, international and non-governmental organizations, prepared the "Geneva List of Principles on the Protection of Water Infrastructure" (in short the Geneva List) during and after armed conflicts. This document provides the first ever systematic compendium of all existing principles and rules regarding water in armed conflicts, such as international humanitarian law, the human rights to water and sanitation, international water law and international environmental law. The compendium covers water, and water related infrastructures, during armed conflicts and post conflicts and contributes to the agenda for the protection of civilian populations. In addition, it contributed to identify gaps in the legal protection of water related infrastructures such as the electrical infrastructures.

This legal document is destined to States and non-state actors (Tignino and Irmakkesen, forthcoming). In the process of peace building, after an armed conflict ends, care for water infrastructure, water management and international water cooperation becomes a condition for the normalization. Water represents a vital lynchpin between post conflict reconstruction and the long term development strategy. The UN Security Council is expected to develop a policy framework for protecting water resources and installations in armed conflicts and in other situations on the agenda of the Council.

In March 2019, the Geneva List of Principles on the Protection of Water Infrastructure was launched in Washington DC, at a working meeting at the World Bank and, subsequently, at the International Peace Institute (IPI) in New York (Geneva Water Hub 2019a, b). These discussions helped to fine-tune the document and develop close cooperation with UNICEF, which in turn is also leading on the publishing of a series titled "Water under Fire" (UNICEF 2019a, b). These publications aim to improve the protection of civilians, in particular children, who are most affected by the violations of international norms protecting water infrastructure and water resources in armed conflicts.

In addition, the Geneva List of Principles should be used as a training material for military personnel, both within national systems and, in the international operations. Discussions are ongoing with the Sanremo Institute of International Humanitarian Law and, collaboration is underway with the Geneva Academy of International Humanitarian Law and Human Rights as well as the Geneva Centre for Security Policy (GCSP). In addition, the Geneva Water Hub who is a founding member of the Environmental Peacebuilding Association hosted by the Environmental Law Institute in Washington DC, is actively engaged in its Interest Group on Water. Through this endeavour, it will work on reinforcing the role of water in post-conflict situations and peacebuilding activities.

The next steps in terms of the Geneva List will be the monitoring and compliance, and this entails a close cooperation of the Geneva Water Hub and humanitarian organizations and UN bodies.

7.11.4.3 The Blue Peace Financing Initiative

In line with the Panel's recommendation, the SDC, the United Nations Capital Development Fund (UNCDF) and the GWH, together with transboundary basin organizations, countries, municipalities and other partners from the public and private sectors, have developed the Blue Peace Financing Initiative.

The aim of the Blue Peace Financing Initiative is to encourage transboundary and multisectoral water cooperation by facilitating access to financial capital for multisectoral and joint investment plans. It suggests that water is the perfect entry point to develop new opportunities for impact investments contributing to all SDGs. From the investors' perspective, multisectoral investment plans offer very interesting risk reduction properties. Indeed, the likelihood of political, social or economic conflicts driven by diverging interests can be reduced if all interested parties are involved in the negotiation of an agreement based on the reality of water availability. As of today, the Blue Peace Financing Initiative is working at two different levels:

1. at the regional level, with transboundary water organizations; and
2. at the sub-national level, with municipalities or local authorities in both developed and developing countries.

A long-term objective of the Blue Peace Financing Initiative is to also develop a Blue Peace Standard, which will serve as a guideline for any actor on how to approach water as an entry point for cross-sectoral, transboundary and inter-generational cooperation, leading to the sustainable use and management of water in the quality and quantity needed and therefore to circular economies as well as inclusive and peaceful societies. The Standard will also serve as an internationally recognized certification tool, requiring any project, plan, product, investment and/or process to be in compliance with the Blue Peace Standard in order to use it. This will allow e.g. investors to have a clear understanding on what they invest in, and it will give e.g. consumers a clear understanding on provided services and products (livelihoods assets and public goods).

7.11.4.4 The Adoption of Standards and Norms to Mitigate Inter-Sectoral Water Management Conflicts

Giving a voice to people affected by water scarcity is essential for sound water management and peaceful development.

The Geneva Water Hub analysed the potential effect of existing and in-development instruments, that are aimed at regulating responsible practices, including water, in socially and environmentally-sensitive businesses, in particular in the mining and metal industries; sectors that are challenging to influence. As such, and in line with the recommendations of GHLP-WP, the GWH developed, and started implementing a strategy to incentivize the use of responsible water practices in large-scale mining operations.

Multiple-issue standards applicable to large-scale mining, and including independent third-party certification mechanisms as a guarantee for compliance, may reduce the risk of conflicts between water used by mining industries and local uses. All standards do not integrate a significant water component, and some are limited in their geographical scope.

The GWH decided to support a process relating to standard setting through discussions with investors and international mining companies. This process aims at facilitating the adoption of high standards, showcasing the added financial value from the related adoption. In order to achieve this, the Geneva Water Hub will use new requirements from investors and the insurance sector as a leverage. These industries are concerned with, potential impacts of water-related risk on financial performance on one hand, and high costs resulting from water pollution or conflicts (operation delays, cancellation of licenses, reputation damages) on the other hand. Their concerns constitute real incentives for change in water practices and a certification is a viable quality assurance mechanism.

7.11.4.5 The Global Data System

Recommendations relating to the quality and quantity water data were a key aspect in both the High Level Panel on Water and the Global High Level Panel on Water and Peace. In 2018 and 2019, the World Meteorological Organization (WMO), and partners collaborated with the Geneva Water Hub and the Group of Friends on Water and Peace, to create a coalition of countries, and institutions to advocate the importance of investing in water data, for the sustainable water management and aversion of risk (https://public.wmo.int/en/media/news/wmo-advances-water-data-and-peace-agenda#:~:text=The%20World%20Water%20Data%20Initiative,water%20data%20by%20decision%2Dmakers). The question of data must be understood beyond the circle of specialists and should be a major theme in the preparation of the UN mid-term review of the Water Action Decade in 2023. This requires visible steps and the creation of a single UN Data Portal for Water.

Initiatives such as the Global Hydrometry Support Facility (WMO HydroHub), the WMO Global Hydrological Status and Outlook System (HydroSOS) and the World Water Data Initiative (WWDI) are important building blocks to help include the water data in the peace agenda. This initiative has the aim to build a common understanding of the issues as a common basis for discussion among countries. It will also help to strengthen the links between operational hydrology and policy.

Mobilizing a coalition for data on water and peace is crucial for meeting the challenges of our century (Muenger et al. 2020).

7.11.4.6 The Global Water Conventions

The Panel encouraged the use and adoption of International Water Law in transboundary water cooperation, by states. The two United Nations Conventions; the 1997 UN Watercourses Convention and 1992 UNECE Water Convention, provide the necessary legal basis for improved international cooperation. Transboundary water cooperation agreements should be concluded among countries sharing rivers, lakes and aquifers. Regional conventions and agreements for collaborative management of water resources should be encouraged, especially among countries that have decided not to accede to the global conventions (Tanzi et al. 2015; GWH 2016). Additional "soft law instruments" need to be developed where necessary, including in the area of inter-sectoral water management.

In addition, the developments in financial mechanisms have to be linked with the international water law framework, i.e. the transboundary cooperation financial mechanism among party members to these conventions.

7.11.4.7 Research and Education

Research is carried out by two research teams, the UNESCO Chair on hydropolitics and the Platform for International Water Law of the GWH. These two research teams focus on a better understanding of challenges related to water governance and on legal frameworks structuring water management. They conduct strategic analysis for evidence-based decision making.

Within this framework, and in order to understand the triggers for water cooperation, the Geneva Water Hub is currently implementing with UNIGE, ETHZ, Zoï and Oregon State University, a methodology combining different approaches, theoretical frameworks and techniques. It aims at monitoring international hydro political tensions, and identify key variables that could play a role in the production of tensions or cooperation. Anchored in a scientific perspective, this proposal combines large-N datasets, in-depth processes analysis and science-based visualization tools for the comprehensive and systematic examination of hydro politics. This diversity should increase the understanding of hydro political tensions and inform a wide range of audiences including, in particular, policy and decision makers, water management practitioners, scholars and the general public.

In terms of education, and with the purpose of investing in knowledge and capacity, the Geneva Water Hub through its five-year research and education function, has launched three online and in-class Massive Open Online Courses (MOOC), (i.e. MOOC in management and water policy, MOOC in international water law, MOOC in ecosystem services), training more than 28,000 students.

More than thirty institutions working on knowledge and capacity development in the field of water cooperation and diplomacy have joined the Universities Partnership for Water Cooperation and Diplomacy (UPWCD), launched and coordinated by the Geneva Water Hub. It aims at becoming a one-stop-shop on water cooperation and diplomacy. It integrates all relevant information and resources related to the theme. This includes: events, publications, databases, education material events, and joint research activities (Barua et al. 2019). And its objective is to facilitate cooperation and exchanges among like-minded institutions in order to make a real impact on the global water and peace agenda.

7.11.4.8 Culture

Water is strongly represented in every culture, and religion in the world. In addition to the rationale, political and scientific discourse, the GWH includes the cultural and artistic language to influence the water-peace agenda, through its various activities.

The Symphony on Water and Peace is now a central piece and cultural signature of the Geneva Water Hub and its key partners engaged in the water and peace discourse, and is a translation and clone of the GHLP-WP process, and development. It was developed in parallel, by composers and musicians from the 4 regions in which the GHLP-WP had their regional exchanges with the stakeholders. Accordingly, the Symphony on Water and Peace includes four movements, with a fifth Jazz one, developed in Brasilia calling for action to implement the recommendations (Youtube—Geneva Water Hub—Symphony on Water and Peace). This symphony is a real success and its "making" an excellent illustration of the work of the GHLP-WP. It aims to be the "jingle" of water and peace issues.

In February 2020, the Symphony was performed at the "Festival à Sahel Ouvert" celebrated, on the banks of the Senegal River, that was at the centre of the 1989 Senegalese-Mauritanian conflict. Water, peace, and security was the thematic of this Festival, and was expressed through various creations of art including videos, cinema music, photos. In addition, a philosophic reflection with the local population on the role of water in the sustainability of their societies, led by the eminent Senegalese philosopher Prof. Souleymane Bachir Diagne, and the GWH (Geneva Water Hub 2020d).

Beyond the specific musical piece, the Symphony encompasses the mobilization of arts, culture and philosophy of the GWH water and peace discourse.

7.11.4.9 Way Forward

At the time of fine-tuning this section, the world is still dealing with the outbreak of the COVID-19 pandemic in the beginning of 2021, which has both direct and indirect impacts on the water and peace local, regional and global agenda, at both the short- and long term. Beyond the sanitary aspect, COVID-19 has exposed the fragility and vulnerability of countries and societies (United Nations 2020; OECD 2020; Tignino and Kebebew 2020).

Basic hygiene is a prerequisite to limit the spreading of the virus and water is an essential component of any hygiene measure to be considered. Moreover, the indirect effects are likely to be severe as well and long lasting. Water availability and water infrastructure are vital for survival and development of societies, their agriculture, energy generation, and urban development. Where water availability and infrastructure are negatively affected by disruptions created by the pandemic and its economic consequences, the cumulative effect could be disastrous. It would be irresponsible to ignore these dangers. Every effort will have to be made to retain and strengthen the activities for good management of water resources, for adequate maintenance and development of water infrastructure and for the strengthening of the transboundary water cooperation.

Promoting water cooperation in its various forms has become an urgent task. Water should be used as an instrument of peace; violent conflicts related to water should be prevented. This is a moral imperative and a recognized political need of our era.

There is clearly a need to reinforce the dialogue between the water and the peace sectors. Although steps have been taken with the reflection induced by the GHLP-WP towards the water-peace nexus, yet the road ahead is a long one, but we are definitely on the right track. It is not surprising that in the current discussions on the UN Agenda 2030, the importance of SDG6 and ensuring water and sanitation for all, are already recognized as a priority. Every effort should be made to ensure that the centrality of SDG6 is strengthened and international cooperation in that regard is further developed.

In this context, it is important to recognize the link between water and peace. Water cooperation has historically been an important instrument of international cooperation and strengthening of peace. This function should be further developed. The role of water basin agencies is undoubtedly central in the sustainable and peaceful development of the region, with the view that conflict takes root in fragile contexts (Muenger and Ndour 2020). In the short-midterm, the operationalization of the Global Observatory on Water and Peace, with the analytic capacity and the safe space convening capacity of the various partners, the monitoring and compliance of the Geneva List, the use of innovative Blue financing mechanisms, will assist in engaging the UN Security Council, and UN General Assembly with concrete tools and mechanisms to use water as a vehicle of Peace.

The world has to face the drama of water in its many manifestations through a set of carefully devised and sophisticated strategies. These should involve individual states and governments, regional organizations, including transboundary water management systems and global organizations, including the United Nations system and global financial institutions. These should also involve more dialogue between the water and peace actors.

It is time to act, and the time is Now. After all, water is A Matter of Survival, and one of the biggest challenges of the twenty-first century.

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Léna Salamé graduated from the Sorbonne University in Paris as a lawyer in international public law. She specialized in conflict management and mediation, at a Harvard-MIT-Tufts joint programme and MWI, Boston, respectively. She served in the United Nations' system for 17 years as the strategic and operational coordinator of its programme on water conflict and cooperation.

Léna conceived around a 100 training courses and capacity building activities on international law, conflict management, confidence building and cooperation processes. She trained over 1500 persons on related topics. She also lectured in over 200 international events around the world. Her audiences encompass young, mid and high-level professionals, executive officers, as well as media professionals, decision makers and the civil society from all continents (i.e. South East Asia, Arab States, Africa, Europe, Latin America, Central Asia). She published a number of scientific articles and scientifically edited over 5000 pages of research related to topics of her competence. Because of this, she is credited for having played a central role in the development and promotion of the modern concept of hydro-diplomacy.

Daene C. McKinney is Professor of Civil Engineering at The University of Texas at Austin. Dr. McKinney's interests include sustainable management of water resources, especially the integration of engineering, economic, environmental and political considerations in transboundary basins. His current research focuses on climate change adaptation in major river basins, impacts of climate change in glacier-dominated river basins, sharing of transboundary aquifers, the development of water management decision support systems, and the application of cooperative game theory to transboundary river basin negotiations. He is Governor (Alternate) of the World Water Council.

Jerome Delli Priscoli was senior advisor at the U.S. Corps of Engineers' Institute for Water Resources. Over 40 years, he directed the Corps research, training and field assistance programs on; Social Assessment techniques, Public Participation, and Alternative Dispute Resolution (ADR). These programs set standards across the USG. The ADR program received the first U.S. Hammer award for efficiency in government from the US Vice President. He directed numerous high-level studies, designed, facilitated and served on many special committees in USACE and the U.S.G. Dr. Delli Priscoli became Chair of the Global Water Partnership (GWP) Technical Committee. He is on board of Governors of the World Water Council. Dr. Delli Priscoli has been advisor to the World Bank on water policy and to all UN water related agencies and IFI's and worked closely with Water Ministers worldwide. He was an original member of the U.S. delegation to the Middle East multilateral peace talks on water. He co-chaired the DG of UNESCO's world commission on Water and Freshwater Ethics. Dr. Priscoli is the Editor in Chief of the peer reviewed journal Water Policy. The American Water Resources Association awarded him the Icko Iben award for achievement in cross disciplinary communications in water.

Toshio Koike received the Bachelor, Master, and Doctor of Engineering, in 1980, 1982, and 1985, respectively, from the University of Tokyo, Japan. He was at the University of Tokyo, as a research associate in 1985 and a lecturer from 1986 to 1987, and at the Nagaoka University of Technology, Japan as an associate professor from 1988 to 1999 and a professor in 1999. In 1999, he joined the Department of Civil Engineering, the University of Tokyo, where he held the position of Professor until 2017. He is also working as Advisor to the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT). Since October 2014, he has been appointed as Director, International Centre for Water Hazard and Risk Management under the auspices of UNESCO (ICHARM), Public Works Research Institute (PWRI) in Tsukuba, Ibaraki, Japan.

His research interest includes the water cycle and climate sciences and their applications to water resources management, which can be classified into the following three components, establishment of satellite remote sensing, development of the data integration and information fusion system, and development of the hydrological down-scaling methods including satellite-based data assimilation. Aside from his scientific contributions to water cycle and climate sciences and water resources management, he has been leading the international water cycle science projects and the inter-governmental science and technology cooperation.

Some of the prominent awards he has won recently include the following: "Award for Contribution to the IPCC NOBEL Peace Prize" from "WMO and UNEP" in 2008, "Einstein Lecturer Award" in 2009 from Chinese Academy of Sciences, China, "Japan Water Award -International Contribution" in 2010, "Science Award" from by the Japan Society of Hydrology and Water Resources in 2015.

Jack Moss is retired, having been the Executive Director of AquaFed—The International Federation of Private Water Operators.

Mr. Moss has 30 years' experience in the private sector water services industry. This has taken him to work in water services development in many different situations and countries around the world.

He is particularly interested in the commercial, institutional, human rights, regulatory and governance aspects of water supply and sanitation. He has written papers and made presentations in conferences on these subjects, including for the OECD, World Bank, United Nations etc.

He was chair of the water group of the BIAC (Business and Industry Advisory Committee to OECD) and has been an active contributor to the OECD's work on water and related matters.

He was AquaFed's liaison person with UN Water. He served as a member of UN Water's Task Teams on the water in the post-2015 Development Agenda and contributed to the Open Working Groups deliberations on the SDGs.

He served in the WBCSD water working group and was spokesperson representing the "Major Group—Business and Industry" in the 5th, 6th and 7th World Water Forum political processes, building on previous action of a similar kind in the World Summit on Sustainable Development 2002 in Johannesburg, the CSD 12, 13, & 16 and Rio +20.

In 2002/3 he project managed a multistakeholder project on valuing water for the CEO Panel on Water and co-authored a publication "Valuing Water for Better Governance" that was launched at the 3rd World Water Forum in Kyoto.

Mara Tignino is Reader at the Faculty of Law and the Institute for Environmental Sciences at the University of Geneva. She is also the Coordinator of the Platform for International Water Law at the Geneva Water Hub. Dr. Tignino has been Visiting Professor in various universities including Renmin University of China and the University of Barcelona. She acts as an expert and legal adviser for States and international organisations and has given training workshops in Africa, Asia, the Middle East and South America. In 2017, she won the prize "Women Peacebuilders for Water" from "Fondazione Milano per Expo" for her research on international water law and her dedication to training and mentoring new generations of international lawyers.

Owen McIntyre Professor and the Director of the LL.M. (Environmental and Natural Resources Law) Programme at the School of Law, University College Cork (UCC) and a Co-Director of the UCC Centre for Law and the Environment. He has served as the inaugural Chair of the IUCN World Commission on Environmental Law's Specialist Group on Water and Wetlands, and as a member of the EBRD Project Complaints Mechanism, the Scientific Committee of the European Environment Agency, and the (Irish) Aquaculture Licences Appeals Board. He holds visiting positions at Wuhan University, Xiamen University, Charles University Prague and the University of Dundee, School of Law.

Hussam Hussein is a Postdoctoral Researcher at the Department of International Agricultural Policy and Environmental Governance of the University of Kassel (Germany) and he is focusing on water-food security in the Mediterranean region, with an interest in transboundary water governance. His past research focused on critical hydropolitics in the cases of Jordan and of Lebanon, exploring the role of discourses in shaping water policies. Dr. Hussein obtained his Ph.D. degree in 2017 from the School of International Development, University of East Anglia (Norwich, UK) and is member of the Water Security Research Centre and of the Tyndall Centre for Climate Change Research at the University of East Anglia since 2012.

Mahsa Motlagh is a research associate in the "Digitainable" Project at Bonn Alliance for Sustainability Research, Bonn, Germany. The focus of her research is on the cross-disciplinary interface of social and environmental aspects of digital transformation, sustainable development diplomacy, and capacity building for behavioural change. Holding a Ph.D. in transboundary water governance, Mahsa has specialized in diplomacy in conflict resolution and multi-stakeholder process, human security, and social inclusion.

Aaron T. Wolf is a professor of geography in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University. His research and teaching focus is on the interaction between water science and water policy, particularly as related to conflict prevention and resolution. He has acted as consultant to the US Department of State, the US Agency for International Development, the World Bank, and several governments on various aspects of transboundary water resources and dispute resolution. All told, he is (co-) author or (co-)editor of seven books, including Core and Periphery: A Comprehensive Approach to Middle Eastern Water, (Oxford University Press 1997), Transboundary Freshwater Dispute Resolution, (United Nations University Press 2000), Managing and Transforming Water Conflicts (Cambridge University Press 2009), and close to fifty journal articles, book chapters, and professional reports on various aspects of transboundary waters, from the local scale to the international. A trained mediator/facilitator, he directs the Program in Water Conflict Management and Transformation, through which he has offered workshops, facilitation, and mediation in basins throughout the world.

Lynette de Silva directs the Program in Water Conflict Management and Transformation at Oregon State University. She teaches courses in water conflict management; and water resources management; and has acted as a consultant to UNESCO, offering training to senior water professionals. Over the past 20 years, she has worked in areas emphasizing water resources and land management practices. She is a mediator and life coach. de Silva is the co-author of Resolving Environmental Conflicts: Principles and Concepts, Third Edition, published through CRC Taylor and Francis Group, LLC, released in 2019.

Natasha Carmi is an experienced water specialist in hydropolitics with a demonstrated history of working in highly sensitive and timely political environments. She joined the Geneva Water Hub in 2018, as the lead water specialist and contributes primarily to the establishment of the Global Water Observatory on Water and Peace, and the empowerment of women in water diplomacy. She works both on the global and regional aspects of the advancement of the water-peace discourse. Prior to that, she worked as water policy advisor to the Palestinian Negotiations Support Project, working closely with decision makers, and has experience in bilateral and regional water negotiations. Ms. Carmi has worked with water resources and environmental challenges in the Middle East for the past 20 years. She serves frequently as a faculty member for conferences and workshops dealing with transboundary water resources in general, and hydropolitics in particular, at which water is a core political issue and international water law is a necessary framework for resolving conflicts and identifying opportunities and solutions.

Danilo Türk is an Emeritus Professor of International Law, diplomat and politician. Prior to his term as the third President of the Republic of Slovenia (2007–2012) he was teaching international law at the faculty of Law, University in Ljubljana (1982–1992 and 2005–2007). He also worked as human rights expert, both in Slovenia and within the UN. Upon independence of Slovenia he was appointed Ambassador of Slovenia to the UN (1992–2000). He served on the UN Security Council in 1998–1999. Upon successful conclusion of his term, the then Secretary-General Kofi Annan invited him to serve as UN Assistant Secretary-General for Political Affairs (2000–2005). He returned to Slovenia in 2005 where he was elected third President (2007–2012).

In 2015–2017 he served as Chairman of the Global High Level Panel on Water and Peace. Since 2018 he is the Lead Political Advisor to the Geneva Water Hub.

François Münger is the director of the Geneva Water Hub, that is a global unit for water security and peace. The Geneva Water Hub is the Secretariat of the High Level Panel on Water and Peace. He left in December 2014 the direction of the Global Program Water Division of the Swiss Agency for Development and Cooperation—SDC-, that he created and profiled during eight years; the Global Program water being now in the center of the water strategy of the Swiss Federal Department of Foreign Affairs.

Eng. François Münger holds a diploma/M.Sc. in geophysics and mineralogy (University of Lausanne), a diploma/M.Sc. in hydrogeology (University of Neuchatel) and a European M.Sc. in environmental engineering with specialization in biotechnology (Swiss Federal Institute of Technology—EPFL-), as well as a post graduated certificate equivalent to an M.S. in geological and climate hazards (University of Geneva).

He is a senior expert in water, sanitation, and environmental issues. He has worked previously as a scientific researcher for the EPFL in charge of an international project of energy storage in aquifers, as director of a dams and deep boreholes project in Africa, as head of SDC Water Program in Central America and as a senior water specialist of the World Bank in HQ and in Africa. He has also launched various partnerships with public and private sector, NGOs and local authorities, as for example a large partnership on the reduction of the water footprint of twenty + multinational enterprises. Since six years he is supporting the development of capacities and of a portfolio in hydrodiplomacy within the SDC's global Program Water.

He has led various publications and high level meetings on the Human Right to water and supported strong global advocacy campaigns to highlight the importance of sanitation. He has work experience in different private or public institutions in Switzerland, Africa, Latin America, Central Asia and East Europe. In March 2015, with the title of Swiss Special Envoy for water, he took over the creation and launch of the Geneva Water Hub that is now a global center in Geneva and of which he is now the director general.

The Water Security Discourse and Its Main Actors

8

Robert G. Varady, Tamee R. Albrecht, Chad Staddon, Andrea K. Gerlak, and Adriana A. Zuniga-Teran

Abstract

This is a chapter about the advent and adoption by water scholars of a new term, "water security." How did this term appear, how is it defined, in which settings does it apply, what are its different facets and interpretations? Has it impacted water management and if so, how? The authors explore the discourse surrounding this term and the persons and institutions that have found it useful, channeled it, challenged it, and popularized it over the past century.

Keywords

Water security • Water insecurity • Water governance • Discourse • Soft path • Transboundary waters

R. G. Varady (✉)
Udall Center for Studies in Public Policy, University of Arizona, Tucson, USA
e-mail: rvarady@email.arizona.edu

T. R. Albrecht
School of Geography, Development and Environment, and Udall Center for Studies in Public Policy, University of Arizona, Tucson, USA
e-mail: talbrecht@email.arizona.edu

C. Staddon
Department of Geography and Environmental Management, University of the West of England, Bristol, UK
e-mail: chad.Staddon@uwe.ac.uk

A. K. Gerlak
School of Geography, Development and Environment, and Udall Center for Studies in Public Policy, Tucson, USA
e-mail: agerlak@email.arizona.edu

A. A. Zuniga-Teran
School of Landscape Architecture and Planning, Udall Center for Studies in Public Policy, University of Arizona, Tucson, USA
e-mail: aazuniga@email.arizona.edu

List of Acronyms

CFA	Cooperative Framework Agreement
CWP	Cienega Watershed Partnership
DALY	Disability Adjusted Life-years
DWC/CPWP	Dialogue on Water & Climate/Co-operative Programme on Water & Climate
EU	European Union
FAO	Food and Agricultural Organization
GEF	Global Environmental Facility
GEWEX	Global Energy and Water Cycle Experiment
GWI	Global Water Initiatives
GWP	Global Water Partnership
HWISE	Household Water Insecurity Experiences
IBWC	International Boundary and Water Commission
ICID	International Commission on Irrigation and Drainage
IGRAC	International Groundwater Resources Assessment Centre
IHD	International Hydrological Decade
IHP	International Hydrological Programme
IOI	International Outfall Interceptor
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
ISARM	Internationally Shared Aquifer Resource Management
JMP	Joint Monitoring Programme (of UNDP and WHO)
MDG	Millennium Development Goals
MRC	Mekong River Commission
NAFTA	North American Free Trade Agreement
NBI	Nile Basin Initiative
NGO	Non-Governmental Organization
NIWTP	Nogales International Wastewater Treatment Plant
OAS	Organization of American States

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OECD	Organisation for Economic Cooperation and Development
PCCP	From Potential Conflict to Cooperation Potential
SADC	Southern African Development Community
SDG	Sustainable Development Goals
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children's Fund
UNU-EHS	University Institute for Environment and Human Security
UNWC	United Nations Watercourses Convention
WCD	World Commission on Dams
WCW	World Commission on Water for the 21st Century
WHO	World Health Organization
WMO	World Meteorological Organization
WWAP	World Water Assessment Programme
WWC	World Water Council

8.1 Introduction: Water Governance Framings

This is a chapter about the advent and adoption by water scholars of a new term, "water security." Language is an organic entity and it grows and shrinks as some words and concepts enter, evolve, change meaning and, sometimes, disappear. Here, we explore the discourse surrounding this particular term and the persons and institutions that have found it useful, channeled it, challenged it, and popularized it.

We are writing about an extended conversation that has been taking place since the start of this century. We hope our narrative will yield some thoughtful insights, as we tell a story that is an account of the apparent need for a fresh way to characterize an aspect of water management and use.

8.1.1 The Advent of Framings and Paradigms in Global Water Governance

A review of the past half-century's literature on water shows that water security is hardly the first term to enter the vocabulary of water professionals and observers with the promise of new beginnings, fresh insights, and even intellectual revolutions. It has come on the heels of a cascade of competing notions, concepts, framings, and paradigms—all seeking some explanatory power over a ubiquitous, complex, and extensive phenomenon: the role of water in society.

Until the rise of the modern environmental movement in the 1970s, water was chiefly a subject of concern for hydrologists, hydraulic engineers, irrigation specialists, biochemists, sanitation engineers, public health professionals, and other technically-oriented practitioners. Most of these specializations are themselves relatively young, tracing their origins only to the mid- or late- nineteenth century. A key inflection point, the post-World War II period, was characterized as one of "boundless confidence in the ability of science and technology to transform society and adapt the landscape to human needs" (Varady et al. 2008; Staddon 2010). To be sure, there were interfaces between emergent water professions and populations, communities, households, and livelihoods. But for the most part, the literature of the period concentrates on public works, infrastructure, and what are termed "supply-side" or "hard-path" approaches to water management—approaches whose primary aim is to assure sufficient quantities of safe water irrespective of cost, social impact, or environmental consequence.

8.1.1.1 Soft-Path Approaches and the Growing Role of Governance

Already, by the late 1970s, Lovins, looking for unconventional approaches to management—albeit in his case, in the *energy* sector—coined the term "soft path" (Lovins 1977). In the water sector, by the late 1980s scholars like Brooks and Peters (1988) were exploring alternatives by considering what they called the "potential for demand management." A decade-and-a-half later, Wolff and Gleick, in their biennial publication, *The World's Water 2002–2003*, recognized that potential and, explicitly acknowledging Lovins, called their opening chapter, "The Soft Path for Water." At about the same time, Brooks (2003, 2005) had morphed his own demand-management approach towards the Wolff-Gleick concept of "soft paths for water," a phrasing that has since caught hold and refers to any measure that does not involve merely building new supply.

Since the mid-1990s, the soft-path approach to managing water that has been arguably the most notable has emphasized the interrelatedness of the various aspects of water management. This approach has become known as Integrated Water Resources Management (IWRM). Below, we will discuss IWRM in some detail and show how derivative thinking led from IWRM to water security, the theme of this chapter.

But understanding and appreciating soft-path approaches like IWRM, it turns out, requires a brief intellectual detour and a change in focus. Instead of seeing water management solely or largely as a means to provide more water, this view stresses the significance of "governance"—yet another term, also deeply complex, that has penetrated the modern vocabulary of water scholarship. Echoing the theme of ebb-and-flow of linguistic catch phrases, the Finnish scholar Tilhonen (2004), called governance "a term of the day," questioning its durability.

Unsurprisingly, like many such all-encompassing expressions, governance turns out to be a slippery and chameleon-like concept. The term has many definitions, but according to Bevir—a political scientist—in its broadest sense, governance refers to processes undertaken by "a government, market or network, … a family, tribe, formal or informal organization or territory and whether through the laws, norms, power or language of an organized society. In lay terms, it could be described as the political processes that exist in between formal institutions" (Bevir 2012). To this rather sweeping and comprehensive—if perhaps unwieldy—definition, Hufty, another political scientist, adds that governance relates to "the processes of interaction and decision making among the actors involved in a collective problem that lead to the creation, reinforcement, or reproduction of social norms and institutions" (Hufty 2011). Referring specifically to the water sector, Pahl-Wostl and her coauthors term governance, at the global scale, "the development and implementation of norms, principles, rules, incentives, informative tools and infrastructure to promote a change in behavior of actors" (Pahl-Wostl et al. 2008). The key contradistinction here is with "government," which refers to the formal institutions, usually defined by elites, that prevail within a community or nation.

Our own definition of governance (Megdal et al. 2015), also tailored to the water sector, is not very different from Pahl-Wostl's and is meant to be more functional and real-world applicable: "Water governance is the overarching framework of water use laws, regulations, and customs, as well as the processes of engaging the public sector, the private sector, and civil society." Understood this way, governance can include the coordination of administrative actions and decisionmaking at different jurisdictional levels, it can be informal as well as formal, and it can include long held cultural apprehensions about water which are often overlooked by analyses treating only of formally written laws, regulations, and policies. Governance, therefore, can capture what Staddon (2017), Turton and Meissner (2002) and others have referred to as the hydrosocial contract: the set of understandings and agreements, more or less tacit, that define the relations between those who make water decisions and those who must abide by those decisions. What's more, governance is not only the product of consensus-linked processes, institutions and viewpoints, but often incorporates levels of dissensus, as when state water schemes provoke opposition that must somehow be accommodated (or overridden). The clearest examples of these governance processes involve dam projects (e.g., Narmada in India in the 1990s) or water utility privatizations (e.g. Cochabamba in Bolivia in 1999–2000). These and similar projects were always at least as much about reformulating the hydrosocial contract as they were about a specific sort of structure (dams) or a policy prescription (utility privatization).

All of the above definitions of governance—from the broadest to the most specific—stress the role of institutions such as legal systems, organizations, laws, customs, and practices—in short, context-based societal attributes. In the case of water, these are seen to hold strong potential for influencing how much high-quality water can be, or ought to be, made available to a community or population or to the environment. Tilhonen (2004) stated that the broad use of the term is clearly an indication of "the need for a change from top-down governing towards more participatory and down-up governance." In this sense, these understandings of water governance deliver on Tilhonen's promise to address management in a less top-down manner and thereby afford more room for soft-path-*cum*-demand-management approaches.

8.1.1.2 Framing Mechanisms and Paradigms: An Entrée to Global Governance

The insight provided by the soft-path view of water governance is illustrative of the power of framings in shaping responses to water-related issues. But the soft-path paradigm has not been the only—or even the latest—such framing mechanism considered. Below, we consider other ways of looking at and conceptualizing water governance.

The conscious notion that water governance—and similarly water *management*, consisting of how elements of governance such as laws and policies are implemented via specific actions on-the-ground (Megdal et al. 2015; Varady et al. 2016)—might be considered at the global scale arose only in the years 2006–08 (Conca 2006; Newton 2014). This was not formally termed "global water governance" until 2008 (Pahl-Wostl et al. 2008; Schnurr 2008; Varady et al. 2008). But well before the use of the term, broad trends and framings in management approaches were influencing how water was governed around the world. As Varady and Meehan (2006) point out, after 1945 an "apertura" opened for increasingly global-scale, and globalized, water governance.

As Fig. 8.1 (updated from Varady et al. 2009) shows, since the end of the Second World War, global water management has experienced at least a dozen epistemological frameworks, half of them still current for at least some parts of the global community. These framings are epistemological rather than merely substantive inasmuch as they shape the channels in which debate can run, rather than directly shaping the debate itself. While such framings can

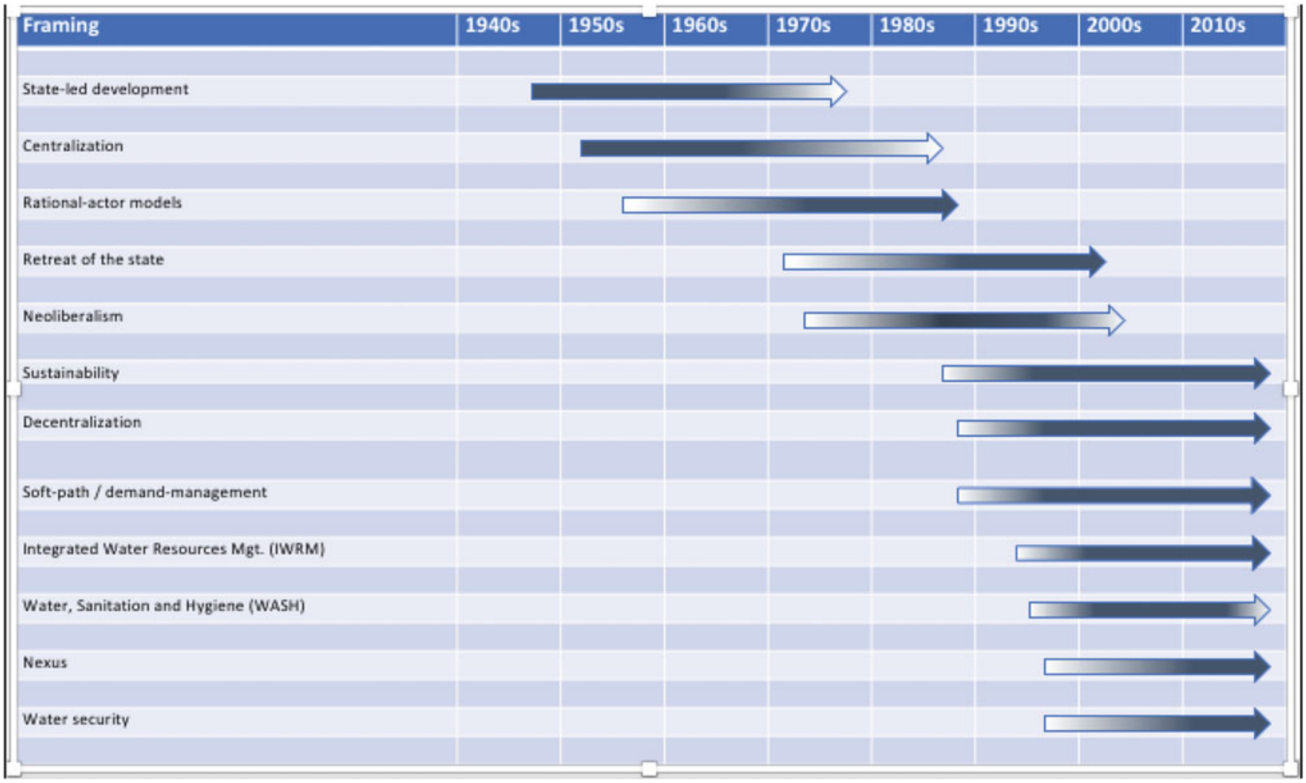

Fig. 8.1 Evolution of global water-management frameworks. *Note* Dark shading indicates periods of particular hegemony; light indicates increasing peripherality. Adapted from Varady et al. (2009)

sometimes coexist, often they cannot as they imply mutually exclusive conditions or outcomes. An example explored by Staddon and Everard (2017) discusses the implications for Indian groundwater management of the clash between "Nehruvian" epistemologies of centralized water management and "Gandhian" epistemologies of self-help and therefore local decentralized water management.

These approaches to water management have generally followed the *zeitgeist*. The narratives begin with postwar, strongly centralized, state-dominated, top-down processes mostly bent on expanding physical supply through increasingly grand dam schemes. A quintessential example of such large-scale, technocratic approaches with a "nation-building" undertone is the multipurpose development project in the Tennessee River Valley (Grey and Sadoff 2007; Staddon 2010). In the 1930s, a massive system of more than 40 interconnected dams and reservoirs was constructed to support navigable water use, provide flood control, and furnish affordable electricity for rural areas. Huge investments were made in similar large-scale irrigation, energy, and development projects in the U.S. and the former Soviet Union (e.g., the Big Volga Project) in the early 20th century under this 'hydraulic mission' to 'tame' and reap the benefits of nature (Molle et al. 2009).

Next, these framings passed through an extended period of neoliberalism that highlighted the economy and the private sector, again through dam schemes now recast as investment opportunities, as well as of projections of state prestige and modernity. Eventually they converged during a period of three decades in which decentralized approaches have held sway and featured such concepts as sustainability, demand-side approaches, cross-sectoral integration, social wellbeing, and equity (Staddon 2010). And finally, bringing the narrative up to the present day, two new framing concepts began to move center stage: the resource "nexus" (or the idea that is it important to analyze and manage the interactions between water, food, energy, and other critical domains) and "water security," the subject of the present chapter.

8.1.2 Global Water Initiatives: A Proxy for Global Water Governance?

8.1.2.1 What Are Global Water Initiatives?

The frameworks shown in Fig. 8.1 did not emerge spontaneously; they have resulted from long periods of experimentation, dialectic, institutional actions and reactions, and civil-society participation constrained by global-scale inertia. In the case of water—as with other sectors such as agriculture, public health, and energy—it has been organized interests that led the way in introducing new concepts and shaping them into management strategies. Collectively these efforts have been known as “global water initiatives” (GWIs), a grouping that international water-governance scholars, specifically Newton (2014), consider a subset of the larger concept, global water governance.

Why should these initiatives be termed “global”? First, because the discussions and deliberations that produced the framing mechanisms of Fig. 8.1 took place at a global scale, and on global stages with representatives from many nations. These efforts occurred at very particular venues and places, and within well-defined networks. Second, GWIs are global because their intended targets of action are situated across the globe. As noted above, in the last 40 years the global stage has become an increasingly important place for rethinking water governance. From IWRM to the water-energy-food resource nexus and water security, key framings have tended to emerge from global events and processes.

The first such interests were ***professional societies*** with roots in the mid- to late-19th century. These associations, which brought together experts in such water-related fields as navigation, glaciology, hydrology, hydraulics, and sanitation—and eventually human-dimensions fields such as law, policy, economics, and development studies—promoted their disciplines’ agendas in concerted ways. The list of such societies is long, but some prominent examples are the International Navigation Association (founded in 1885), the International Association of Hydrological Sciences (1922), the International Glacier Commission (1894), the International Association of Hydraulic and Environmental Engineering and Research (established in 1935 as the International Association of Hydraulic Research), the International Association of Hydrogeologists (1956), the International Water Resources Association (1971), and the International Water Association (1999)—many of these, as in these examples, employing the word “international” to indicate their intended global scope. These sorts of associations were the earliest types of global water initiatives (Varady 2004; Varady et al. 2008, 2009; Varady and Iles-Shih 2009).

If professional societies were the earliest manifestations of GWIs, the second set of movements intended to influence governance were not groupings of cognate professionals, but concerted attempts to shape public thinking via consciousness-raising set-aside periods of time. In the mid-1950s, a pioneering United Nations (UN)-led effort known as the International Geophysical Year (IGY)—involving scientists in professional societies of the type mentioned above—opened the door to this second type of GWI: the ***designation of periods of time*** to fan public awareness of different topics or causes. In the realm of water, the most notable successor to IGY was the International Hydrological Decade (IHD; 1965–74),[1] a full ten-year span during which scientists were charged with—most prominently—assembling water atlases, preparing water budgets, conducting hydrological surveys, and designing educational programs and curricula. Analogous time periods were subsequently designated, ranging from *decades*—like the International Drinking Water Supply and Sanitation Decade (1981–90) and the International Water for Life Decade (2005–15), to name just two of some dozen such periods—to *single days*, such as the annual World Water Days celebrated every March 22 since 1993. In 2018 UN-Water (a collective group including the water divisions of the major UN agencies) inaugurated the International Decade for Action ‘Water for Sustainable Development’ (2018–2028), with a specific charge to promote achievement of Sustainable Development Goal #6 (SDG6).

As the IHD was winding to a close in the early 1970s, the United Nations introduced a third type of GWI: ***special events*** meant to aggregate expertise and interest around broad themes. In the early history of such events, the most notable was the 1972 UN Conference on the Human Environment in Stockholm. Its theme was not water specifically, but the environment writ large, and it resulted in a 26-point declaration which has framed much of the global discussion ever since. Five years later, for the first time, water was addressed directly, explicitly, and globally at the 1977 UN Conference on Water, at Mar Del Plata, Argentina (Staddon 2010). The 1992 “Dublin Conference” (officially, the International Conference on Water and Environment and a preparatory meeting for the Rio Summit later that same year) was perhaps the first such event to take up such subsequently controversial themes as financing and private-sector involvement in water development and provision, formally codifying a powerful combination of participatory and market-led thinking in four principles:

Principle 1: ‘Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment’

Principle 2: ‘Water development and management should be based on a participatory approach,

[1]Also during this decade, the adoption of the 1966 Helsinki Rules formed a key moment in international-level arguments, from a legal point of view. The Rules established a global water-governance system that goes beyond the centuries-old system of treaties regarding navigation and rights of state access to waterways. The Helsinki Rules established a common legal framework guiding the use of surface water and connected groundwater in international drainage basins (Salman 2007).

involving users, planners and policy-makers at all levels'

Principle 3: 'Women play a central part in the provision, management and safeguarding of water'

Principle 4: 'Water has an economic value in all its competing uses and should be recognized as an economic good'

(Guiding principles. The Dublin Statement on Water and Sustainable Development)

It is no exaggeration to suggest that nearly every major event or declaration in the 'water world' since has been either an appreciation of, or a challenge to, the Dublin Statement. From then on, such special events proliferated, addressing a spectrum of water-related themes—or, often, water in the broadest sense. They grew larger in size, and through their ability to draw wide-ranging and eventually, diverse audiences, they gained in influence. The triennial World Water Forums are a prime, if extreme, example of these sorts of gatherings. Beginning modestly in 1997 in Marrakech, Morocco, there have now been eight such forums, the most recent in March 2018 in Brasilia, Brazil, which according to the *Rio Times* (Alves 2018) drew 40,000 attendees from 178 countries. What is important to note here is that venues such as Rio (and in the past, The Hague, Kyoto, Mexico City, Istanbul, Marseille, Daegu, and Brasilia)—as well as other recurring global events, including the World Water Week conferences held annually in Stockholm since 1991 and other regional derivative events —serve as GWI real-world nexus points. From these points, networks of knowledge transfer and communication and channels of power, decision making, and policy emanate. And through such networks of interlocking events, attended by much the same global water elite, a non-centralized, non-hierarchical form of global water governance occurs.

The soon-ubiquitous water-themed events, spawned partly by consciousness-raising time periods (we are currently in our third 'Water decade' since 1981), are fertile opportunities to establish and strengthen linkages among a new cadre of water elites. Members of disciplinary societies, water professionals, policymakers, managers, and representatives of civil society took advantage of the chance to connect to existing networks and to establish new networks. These otherwise diverse actors share common high-level interests in ameliorating modes of water management seen as outdated and inappropriate. They have coalesced within epistemic communities that facilitate their particular articulation of, and advocacy for tackling complex water-related problems via soft-path rather than hard-path approaches (Haas 1992; Conca 2006).

A palpable outcome of this opportunism was the establishment of a fourth type of GWI, ***global-level organizations***. Of course, some such organizations were venerable and already existed prior to the rise of the GWI phenomenon. Some of these were issue-oriented advocacy groups (e.g., ICID, the International Commission on Irrigation and Drainage). Others have been intergovernmental organizations, in some instances within the extensive UN network—such as IHP, the International Hydrological Programme; and the WWAP, World Water Assessment Programme, both hosted by UNESCO). Still others are quasi-intergovernmental organizations with national, subnational, and private-sector members (e.g., the World Water Council [WWC] and the Global Water Partnership [GWP], whose near-simultaneous origins in the mid-1990s marked a new chapter in the GWI period). Still others were non-governmental-*cum*-foundation-created (such as IWMI, the International Water Management Institute; originally and until 1996 the International Irrigation Management Institute).

The establishment of WWC and GWP were harbingers for what became a cascade of new organizations. These included more-or-less-permanent efforts like the WWAP, and more recently, the UN-based cooperation mechanism, UN-Water; international nonprofit research organizations like the Stockholm Environmental Institute; externally-funded multiyear projects such as the Global Water System Project (GWSP, which has merged into the even larger-themed Future Earth), and GEWEX (the Global Energy and Water Cycle Experiment); and limited-life funded projects such as the Dialogue on Water and Climate/Co-operative Programme on Water and Climate (DWC/CPWP). The UN Secretary-General and organizations such as the World Bank also established several high-profile commissions on water such as the World Commission on Dams (WCD 2000), formed in 1997, and the World Commission on Water for the 21st Century (WCW 2000), created in 2000. Collectively, these institutions contributed to the expansion of GWIs, yet individually, they tended to compete with other UN organizations for resources and attention. Finally, notable university-based efforts include the Global Water Future Programme headquarters in Brisbane, Australia, at Griffith University (the successor of the GWSP); and the Global Water Futures "consortium" led from Saskatchewan, Canada, which is currently the largest university-managed water program.

Taken together, the four main types of GWIs (professional societies, time periods, events, and organizations) identified above are prominent pieces of a much larger global water puzzle that includes national and subnational governments, transnational institutions such as river-basin commissions, international agreements and treaties, NGOs and community associations, utilities and water companies, research institutes, irrigation-management associations, and other organized sectoral interests. Within this construct that some have called the "world of water," following Lemos and Agrawal (2006), we understand water governance to include the full spectrum of diverse-yet-distinct networks of the kind of global-level institutions mentioned above. In this interpretation, GWIs can be seen as "key sites for decision-making, knowledge transfer, and conflict resolution —all core components of governance" (Varady et al. 2009).

8.1.2.2 Some Critiques of Global Water Initiatives

GWIs, as shown, have proliferated and gained influence, but they have been criticized for a number of seeming flaws, at least three of which continue to persist. First, observers say, there are too many of them and they have been increasing at too fast a rate to be accommodated or sustained. The graph in Fig. 8.2 shows the number of GWIs and their growth from the late nineteenth century to the mid-2000s, with a steep rate of growth over the last decade-and-a-half of that period.

Second, according to some critics, this expansion of the number and type of GWIs must surely lead to overlap, duplication, efforts at cross purposes, and inefficiency.

And third, engineers, economists, and development specialists often point out that while the goals and objectives of many of these initiatives may be noble and desirable, in the absence of reliable performance metrics, it is difficult to know how effective any of them really are.

Since there is no optimum number of GWIs, it's difficult to counter the first objection. How many are *too many*? Further, it is not clear that these institutions are continuing to multiply at the rate they did between the 1990s and mid-2000s. But the notion that there are too many GWIs leads directly to the assumption that therefore many of them must be doing more or less the same thing. Conceptual graphic representations suggest that there are multiple functional niches that can be occupied by GWIs (Newton 2014; Varady et al. 2008, 2009).

For example, the *scope* of a given initiative may highlight its thematic orientation, disciplinary thrust, temporality, geographic focus, or social-change mission. At the same time, its *programmatic orientation* may range from generation of ideas and concepts to basic research, applied research, monitoring and evaluation, policymaking and legislation, financing, and management and administration. And consider that *thematic orientation* alone allows for interests in such varied water-management-related topics as water supply and sanitation, urban water quality and use, rainwater harvesting, agricultural water productivity, river

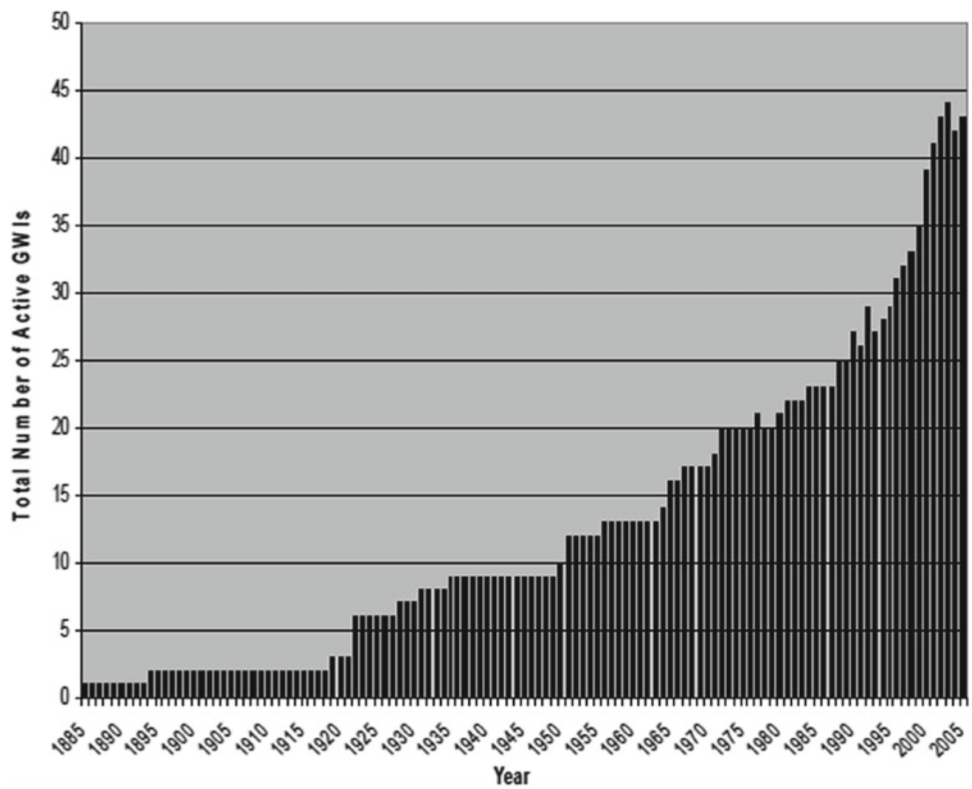

Fig. 8.2 Proliferation of GWIs, 1885–2005 *Source* Varady and Iles-Shih (2009)

basin and watershed management, and groundwater management. In addition, particular GWIs may specialize in particular water issues such as assessment of disasters, risk, and vulnerability; protection of ecosystem services; special needs of transboundary conditions; and approaches to conflict resolution, to name just a few.

It is clear that given all the above variations in motives, missions, programs, sizes, and organizational structure, GWIs selectively position themselves at specific places in a large, multidimensional space where each of the items listed above under "scope" and "programmatic orientation" is effectively an axis. And while the institutions may overlap somewhat, the space is so large and the motives so varied that each GWI's identity can be reasonably distinct.

The third critique—that there exist no reliable ways to gauge the effectiveness of individual GWIs or of the overall GWI phenomenon—is difficult to counter. Practitioners in the field of development have always been aware of the difficulty of proving their worth, especially to donor agencies that demand benchmarks, deliverables, metrics, and other forms of proof. The same is true of many of the approaches that have been employed—the frameworks shown in Fig. 8.1. Can sustainability be measured accurately? A number of related terms—e.g., adaptive capacity, adaptive management, resilience (to climate change and other perturbations), and, per the discussion below, *water security*—have found proponents in academia and in the field. Such terms are "seductive and usefully expressive of a desired outcome," but as Lemos et al. (2016) point out, they can also be problematic. To be most useful—that is, to assist progress toward established goals and guide policy—the use of such concepts should be accompanied by measurement and monitoring of outcomes (Varady et al. 2016; Sun et al. 2016). But for many who employ these and similar terms, they remain unable to quantify successes as chemists or geologists or economists might. This issue is addressed below, in Sect. 8.4.3 ("How Can Water Security Be Assessed and Measured?").

8.2 The Water Security Discourse

8.2.1 Conceptual, Disciplinary, and Pragmatic Antecedents of the Idea of Water Security

Having discussed the history and evolution of global water-governance paradigms in the previous section, we see how "water security" reflects the current thinking in water governance. While influenced by trends toward soft-path approaches and integrated management, it is prudent next to examine the use and implications of "water security"—in particular, how it supports existing frameworks and what new perspectives it brings to light. The term "water security," as Fig. 8.1 shows, entered the vocabulary of the water community at the beginning of the present millennium. Its conceptual, disciplinary, and pragmatic antecedents are to be found in the evolution of thinking that coursed through decentralization of decision making, recognition of the role of governance and especially its upscaling to the global stage, the imperative of sustainability, the importance of integrated (rather than siloed) management, increased public participation, and an appreciation of the social and institutional dimensions of water management (Bogardi et al. 2012).

How did the term "water security" originate, and why was there a need for such a notion?

We begin by examining one of the key framing mechanisms identified above, Integrated Water Resources Management (IWRM). This framing—promulgated since 1985 [when it was used by the Ministry for Transportation and Water in the Netherlands (Ministry for Transportation and Water 1985; Borchardt et al. 2016)], and after 1997 promoted by a prominent GWI, the Global Water Partnership (GWP 2000)—represented a leap forward in conceptualizing how water could be most effectively epistemologically framed.

IWRM was premised on the idea (as noted by Tilhonen) that water decision making needed to be decentralized by including stakeholders, while integrating social, ecological, and infrastructural systems (Lemos 2015). It combined this more palpably bottom-up approach with a strong commitment to sustainability (Setegn and Donoso 2015). IWRM also recognized most notably that: (1) development and management of water, land, and related resources were best achieved via institutional coordination; (2) ecosystems should be part of the management equation; (3) management regimes needed to be contextually-based and not uniform; and (4) surface and groundwater management ought to be considered in tandem (GWP 2011). All this was formalized and embedded in 2000 within what GWP calls the "IWRM ToolBox," intended as a Web-based practical manual for applying the principles of IWRM anywhere in the world (GWP 2013). The concept of "water security" drew on many of these foundational principles while also addressing gaps in the IWRM framework.

8.2.2 Definitions, Meanings, and Connotations of Water Security

8.2.2.1 Definitions in Use

From the literature, it appears that the first notable use of the term "water security" was in the early-1990s and was related to the convergence of water scarcity and political conflict in the Middle East (Staddon and James 2014). These concerns were of course not limited to the Middle East—other regions of the world were also dealing with scarcity, as well as the growing awareness of climate change and of water's integral role in an interconnected "environmental security" (ibid.). The UN Food and Agricultural Organization (FAO) took up the term in 1996 in the context of FAO's action plan for that year's World Food Summit and it was accordingly framed around the central imperative of food security. Still, FAO's conception of water security included seven themes: access, quality, quantity, health, economy, time, and preference, all of which appear in later definitions. These dimensions of water security would recur—though sometimes in modified terminology and with added elements—in others' understandings of the concept.

In 2000, GWP, the main formulator and proponent of IWRM, was perhaps the next major organization to take up water security as a framing concept. Recognizing that IWRM lacked certain features, GWP saw water security not so much as a practical tool (like the one codified in the ToolBox discussed above), but as a strategic imperative, in which "every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life while ensuring that the natural environment is protected and enhanced" (GWP 2000; Gerlak and Mukhtarov 2015). To the FAO definition, GWP added sustainable development, ecosystems, and hazards (Gerlak et al. 2018).

In 2007, in their widely-cited paper, Grey and Sadoff added the notion of livelihoods, an insertion that GWP also later adopted. Soon after, in 2009, UNEP, the United Nations Environment Program, continued the accretion process (though in some definitions, as some attributes were added, others sometimes fell off), incorporating the food/energy nexus, industrial resources, sanitation, and transportation. This was followed by Norman et al., who in 2010 introduced watershed-scale; and then, by the Organisation for Economic Cooperation and Development's insertion of a policy component (OECD 2011). Bakker (2012) and Cook and Bakker (2012), in another pair of influential publications, incorporated peace and national security; and in 2013, Scott et al. further added global change, resilience, and uncertainty to the definition. Table 8.1 (from Gerlak et al. 2018) identifies chronologically the content of each definition and meanings process and shows the relative frequency of each cited attribute.

Other works, especially the *Handbook on Water Security* (Pahl-Wostl et al. 2016), have also explored the many ways that water security is understood and framed. In that volume, water-security definitions are found to span multiple subject areas, from agricultural engineering to public health, and from environmental science to policy. Similarly, these authors found that definitions focus on various aspects, such as agricultural production, natural hazards, water access, contamination, water infrastructure, armed conflict, cross-sectoral linkages, demand management, and others (Cook and Bakker 2016: 24).

The variety of included attributes shows that the different definitions reflect varying understandings of the term. But as observed by Garrick and Hall (2014), those definitions and associated indicators can sometimes be seen as competing with each other. This competition, according to Garrick and Hall, mirrors "deeper, unsettled conceptual and methodological issues" which Staddon and James (2014) suggest

Table 8.1 Definitions of water security and their thematic attributes

Source/Attribute	FAO	GWP	Grey/ Sadoff	UNEP	Norman et al.	OECD	Bakker	UN-Water	UNESCO	Scott et al.	Total
Year	1996	2000	2007	2009	2010	2011	2012	2013	2013	2013	
Quantity	X	X	X	X	X	X	X	X	X	X	10
Quality	X	X	X	X	X	X	X	X	X	X	10
Health	X		X		X		X	X	X		6
Economic growth	X		X	X		X		X			5
Access	X	X	X	X	X	X	X	X	X	X	10
Time	X										1
Preference	X										1
Ecosystems		X	X	X	X	X	X	X	X	X	9
Sustainability		X			X	X		X	X	X	6
Risk/hazards		X	X				X	X	X		5
Livelihoods			X				X	X			3
Sanitation				X							1
Food/energy				X							1
Industrial resources				X							1
Transport				X							1
Watershed					X				X		2
Policy						X					1
Peace/national security							X	X			2
Global change										X	1
Resilience										X	1
Uncertainty										X	1
Total	7	6	8	9	7	7	8	10	8	8	78

Source: Adapted from Gerlak et al. 2018

manifests some fundamental tensions in relations between their constituent political, economic, and ecological domains.

8.2.2.2 Water Security as National Security: Realist and Post-realist Interpretations[2]

An important point emerges from Table 8.1: of the 21 characteristics shown in the left-hand column, only one deals with the contentious issue of "national security," and it is included in just two of the nine definitions examined. This is significant because national security concerns frequently poison relations among countries, especially neighboring countries. The term can conjure up phantoms of water-supply poisonings, military attacks on water infrastructure, unilateral seizure of upstream water resources, and other aggressive acts that can threaten a nation's internal as well as external security.[3] Such ideas can lead to countries adopting a defensive, or nationalistic, posture towards 'their' water that makes international cooperation more difficult. As a result of such fears, notions and terms that evoke such concerns are often shunned, especially by UN agencies and treated with suspicion by scholars (Staddon and James 2014).

Environment and security in transboundary regions are much more closely intertwined. Environmental processes in one country—such as droughts, floods, sewage flows, and air pollution, may become serious enough to harm the neighboring country either directly or indirectly. Conversely, one nation's actions to safeguard its own security—such as militarization, drug interdiction, fencing, and patrolling for cross-border immigrants can adversely impact the other nation's environment and natural resources. This interrelationship is further complicated by a deeper distinction between hard "traditionalist" or "realist" views of national security on the one hand—and softer, alternative, "non-traditionalist" or "post-realist" interpretations on the other hand.

Adherents of the realist, or neo-Hobbesian school of thought in international relations see security as a critical part of a nation's sovereignty and therefore as a fundamental, absolute right, with an obligation on the state to preserve it at any cost.[4] According to this interpretation, arising from age-old competition for territory and resources, the concept of "national security" is used to justify maintenance of armies, the development of new weapons systems, and the manufacture of armaments. Military strength—and in recent history, economic power, as well—is the trump card and the nation that possesses the greatest measure of it earns the right to protect itself from environmental insecurities of various sorts.

This perspective prevailed across the globe until the collapse of the Soviet Union and the ensuing end of the Cold War (Dalby 1992; Dinar 2000). By the late 1980s there was already a considerable coalition of realist foreign-policy experts linking state security to control over key water resources. In 1991 the foreign policy analyst Joyce Starr (1991, p. 19) explicitly linked "water" and "security" to the longer-term prognosis for stability in the Persian Gulf region, then still in the final throes of the First Gulf War stating that: "Water security will soon rank with military security in the war rooms of defense ministries." A few years later Canadian political theorist Thomas Homer-Dixon published the first of a series of articles and books claiming that environmental pressures caused by overpopulation, such as declines in freshwater availability, would cause conflict between nations (Homer-Dixon 1994). Staddon and James (2014) point out that, far from being exceptional, Starr and Homer-Dixon were merely giving voice to views held throughout the foreign relations policy establishment and even in some scholarly circles. This alignment is precisely why many progressive scholars seek to rehabilitate and reframe the water security concept.

8.2.2.3 Defining Security to Exclude the Realist Perspective

By the late 1970s and early 1980s, although the Cold War still raged, a number of writers—Lester R. Brown was among the vanguard—challenged the realist view of international relations and began in effect "rethinking security" (Brown 1977; Ullman 1983; Dalby 1992). In the early debates, the anti-realists argued for a radical expansion of the concept of security to include social, economic, demographic, agricultural, and natural-resources-related matters. Among those at the forefront of this movement to "securitize" environmental issues[5] were scholars writing about environmental change. Norman Myers and Jessica Mathews, both writing in 1989, were among the early proponents of this view. They contended that because security is contingent on stability and peace, environmental problems and

[2]Much of this subsection is drawn from an unpublished paper commissioned by the Puentes Consortium Mexico-U.S. Higher Education Leadership Forum in 2010. The version used here is "Environment and Security in the U.S.-Mexico Border Region: The case of water" (2012) by I. Aguilar-Barajas, R. G. Varady, and C. A. Scott.

[3]In a recent novel, *The Water Knife* by Paolo Bacigalupi, near complete desiccation of Mexico, Texas, and other parts of the southern US causes waves of refugees to flee towards Nevada and California.

[4]Extreme libertarians would argue that the security of external borders and one's citizenry is the only rightful task of a national government.

[5]That is, to consider the security aspects of these issues, with environment seen as either the cause of security concerns or as the possible object of security-related actions. A complementary term might be "environmentalizing security."

population growth were critical aspects of national security (Myers 1989; Mathews 1989).[6] Appreciating the nuances of the rapidly changing relationship between humanity and natural systems and resources, Brown, Myers, Mathews, and other anti-realists recognized tradeoffs between security and other values. Brown in particular was a key proponent of the view that in a resource-limited world, human security would ultimately lay with humanity's ability to live within limits.[7] Other such as Starr and Homer-Dixon, as we have already seen, took the more traditional realist view that resource limitations would, in time, necessitate militarized responses to attempts by others to wrest control of dwindling resources.

In the years since this initial redefinition of security, writers have continued to broaden the term to address food, climate variability and change, energy, and of course, water. This more holistic conception of security underlines environmental problems that threaten the health and wellbeing of individuals or economic security of countries (Falkenmark 2000). The joining up of water and security arose as a byproduct of the growing interest in environment and security, sparking the "Water Wars" genre of social science publishing. By the mid-1990s, it was common to see new articles and books on the theme of "water wars," (see Sect. 8.6.2) although the careful reader would spot that these authors could not point to clear causal links between water scarcity and military conflict. Instead they tended to limit themselves to speculations about potential future links and, like Ohlsson (1995) and Schulz (1991), posited the emergence of "hydropolitical security complexes." In August 1995, then-Vice President of the World Bank Ismail Serageldin (in)famously declared that "if the wars of this century were fought over oil, the wars of the next century will be fought over water—unless we change our approach to managing this precious and vital resource." We will be scrutinizing this claim later on in this chapter.

Expanding the understanding of security yet further, O'Brien and Leichenko (2000) and O'Brien (2006) proposed a linkage of globalization and climate change, terming the risk from those two combined forces, "double exposure." This initial pairing has grown to be multidimensional, linking multiple forces such as globalization, energy demand, poverty, disease, and conflict, which acting in concert, could severely impact communities, society, environment, and stability—in other words, by definition, *national security*.

This more comprehensive line of systemic thinking has been growing steadily in recent years. The environmental–human security dimensions were the reason behind the establishment of the United Nations University Institute for Environment and Human Security (UNU-EHS) in 2004. For UNU-EHS (2005) safeguarding human security requires a new approach, based more on the prospects for cooperation and sharing across boundaries and a more sophisticated understanding of many interrelated variables—social, political, economic, technological and environmental—which determine the specific impacts of extreme events—such as floods, landslides, and droughts.[8] The appeal of such broad redefinitions has even drawn in such neoliberal thinkers as Gary Becker, who conceded that "environmental protection and national security goals may well coincide" (Becker and Posner 2007).

In this essay, we have deliberately chosen to cast water security in the *non-traditionalist*, *post-realist* light described above. This view does not ignore raw political and economic power asymmetries, but concentrates instead on illustrating a tradition of peaceful, cooperative solutions to shared problems.

8.2.2.4 Our Definition of Water Security

It should be evident from the above discussion and from the conceptual variation shown in Table 8.1 that formulations of water security are continuously changing. Table 8.1 shows that none of the nine definitions we consider include every one of the identified 21 themes, though they all do include qualitative, and all but one, quantitative dimensions.

In this chapter, while recognizing and respecting the attributes of some of the most-cited definitions (e.g., by Grey and Sadoff, Bakker, and UN-Water), we use the one developed by Scott and colleagues (2013). That definition is succinct and includes seven of the 21 attributes; most importantly for us, it is the only one of the nine definitions that covers global change, resilience, and by implication, uncertainty. It reads as follows: "*[Water security is the] availability of adequate quantities and qualities of water for societal needs and resilient ecosystems, in the context of current and future global change.*"

[6]It's noteworthy that the 1977 monograph by Lester Brown, the 1983 article by Richard Ullman, and the 1989 piece by Mathews were respectively titled, *Redefining National Security*, "Redefining Security," and "Redefining Security." The Ullman and Mathews essays both were published in the influential journal *Foreign Affairs*, assuring a wide audience for these new, more liberal interpretations of security.

[7]An idea that reached its logical endpoint with John Rockstrom et al.'s 2009 paper on "planetary boundaries."

[8]The United Nations Development Programme has identified, since 1994, seven dimensions of human security: economic, food, health, environmental, personal, community, and political (UNDP 1994). As expressed in the 2009 Stockholm International Water Symposium, oriented to transboundary waters, "water security is a key element of human security, together with food security, energy security, health security, economic security, and freedom from fear" (Grobicki 2009, p. 14). The concept of 'freedom from hazard impacts' was first referenced in written material in 2005 (Günter Braunch 2005).

8.3 Water-Security Actors and Adopters

8.3.1 Water Security and Insecurity

Notwithstanding the array of definitions of water security shown on Table 8.1, if a single word were to characterize the essence of the water security concept, that word would be "access," which appears in all nine of our selected definitions. Access to what? To *adequate quantities* of water of *sufficiently good quality*—both of those attributes also appearing unanimously in the definitions. When used in the literature, the concept most commonly also suggests equal access for all (Gerlak et al. 2018).

So, if the common definition of water security implies equitable access, its obverse, insecurity, must be lack of equitable access. The UN's Millennium Development Goals (MDGs; UN 2015a) campaign was launched in 2000 identifying an ambitious set of eight categories, 21 goals and 60 indicators. The successor program to the MDGs, the Sustainable Development Goals (SDGs) program (UN 2015b), established 17 goals with a total of 169 specific targets, each with baselines and measurable benchmarks. That these initiatives have been deemed necessary shows that eliminating poverty, hunger, inequity, and resource sustainability persists as a global challenge.

In particular, the fact that clean water and sanitation have been allotted a dedicated SDG (number 6) attests to the current level of water insecurity in many regions. And while SDG 6 is intended to mount a coordinated, multi-front, global effort to improve access to potable water and to sanitation, numerous forces are confounding that access. Consider the following drivers at work:

- At hotspots across the planet, changing climate is raising temperatures and reducing precipitation and snow and ice packs, which in turn reduces surface-water flow and groundwater recharge.
- Natural disasters repeatedly exact major tolls on vulnerable landscapes and societies, compromising water-delivery and sanitation systems.
- In some developing countries, populations are growing more rapidly than available water supplies are being replenished, challenging efforts to enhance access.
- Agricultural and industrial activities, including changes in land-use and land cover, can complicate provision of safe drinking water, as can overcrowding in the world's proliferating megacities.
- Weak and inadequate institutions limit the benefits of good governance. And political instability and constrained financial resources impede efficient access to water.
- Finally, all the above factors and others affect not only human populations, but river flows, aquifer sustainability, habitat security, and overall ecosystem wellbeing.

Clearly if SDG 6 and related SDGs are to meet their benchmark projections, they must surmount these and other palpable drivers of water insecurity. In short, the answer to our question, "Does combatting mounting water insecurities offer possibilities for enhancing security of access?" is that it is impossible to achieve water security—however defined—without combatting the ubiquitous and persistent manifestations of water insecurity. The only possibility of achieving the SDG 6 goal is to overcome or at least address those core insecurities as vigorously as possible. Drawing on results from the first globally-validated scale to measure the experiences of households (Young et al. 2019), we suggest that the global challenge is both enormous and growing.

8.3.1.1 Some Caveats

The SDGs were ushered in amid cautious optimism, occasioned by the momentum of the partial attainment of some of the UN Millennium Development Goals (MDGs) launched a decade-and-a-half earlier, at the turn of the millennium. To magnify and accelerate the impacts of the just-completed MDGs, 193 UN member states felt that targets needed to be better delineated and articulated, more closely monitored, and more diligently pursued.

But there is a danger that the cautious optimism of 2015 may be overtaken by more recent, illiberal post-2015 global trends. The waves of anti-globalization, nationalism, and isolationism, populism, and financial retrenchment currently affecting the world complicate the achievement of sustainability as envisioned by the SDGs. Every one of the 17 SDGs is threatened by decreased investment, diminished cooperation, and anti-progressive sentiment—all occasioned and facilitated by a growing disregard for science and distrust of existing governance arrangements, particularly those driven or dominated by elites and experts.

8.3.2 The Actors: What Constitutes the User Community?

In the preceding sections, we have delved into the water-security discourse and recounted the antecedents of this discourse in the larger context post-war approaches to water governance and in particular, the rise of global water initiatives. We have considered multiple definitions of the term and discussed how these have been interpreted, understood, and employed. But until now, we've omitted an important consideration: interpreted, understood, and employed *by whom*?

In this section, we look at the individuals and institutions —actual and potential, within nations and across the world —that constitute the user community for the concept and application of “water security.” Accordingly, we refer here not to users of water resources, but to users of the notion of water security.

8.3.2.1 Local and National Actors

Within nations, government agencies and community and private-sector groups have a responsibility to citizens to assure their access to sufficient amounts of safe water (WWAP 2006). To varying degrees, these institutions also may attempt to safeguard supplies of water to benefit the environment. And in each case, whether for humans or for nature, they may seek to do this sustainably, for future as well as present generations. By and large, those are the key elements of most definitions of water security (see Table 8.1).

National governments are complex organisms and no two are identical. Typically, sectoral responsibilities are allocated to ministries. The environmental-consciousness movement of the 1970s originally was inspired by Rachel Carson’s 1962 book, *Silent Spring*, and spurred on by the Meadows’ et al. (1972) book, The *Limits to Growth*, and the first Earth Day in 1970—among numerous signal developments. Since then, in response to this movement, many countries have created water ministries to govern the use of their water resources—i.e., allocate quantities, limit withdrawals of groundwater, assure quality, secure flows, regulate private providers, and assure equitable, affordable water.

A half-dozen nations have water-specific ministries, ones that possess sufficient clout and financial resources. But many—including most prominently the United States, which has never had a federal water ministry—either do not follow this model or have weak, underfinanced ministries (e.g., Rogers 1996; Thompson 1999). In the U.S., for example, responsibility for water governance is spread across multiple federal ministries (called departments) and a large number of sub-federal or non-public-sector institutions. Thus, the Environmental Protection Agency sets and enforces water-quality standards; the Department of the Interior—via its multiple sub-departmental agencies—looks after water use on public lands; the U.S. Army Corps of Engineers is responsible for flood controls, levees, and related infrastructure; the U.S. Forest Service (within the Department of Agriculture) manages water in National Forests; the Department of State (the foreign ministry) oversees transboundary water resources … and so on (Rosenbaum 2013).

In the U.S., a nation that is a showcase for decentralized government, many day-to-day water-management responsibilities devolve to the states, and even further down the chain, to such entities as Indigenous nations, counties, municipalities, irrigation districts, groundwater-management districts, and quasi-governmental utilities (Megdal et al. 2015). To add to the complexity of this water-governance structure, NGOs, community organizations, public-health concerns, private-sector associations, water-basin associations, farmers’ and ranchers’ associations, and other interest groups all play roles in determining how water is managed.

This complex mosaic of federal, lower-level public-sector, private-sector, and civil-society responsibilities represents one extreme of the centralized-to-decentralized continuum of water governance. The other pole is found in nations—both democratic and not—with strong traditions of consolidated federal authority, for example China, the UK and South Korea. Between the two poles, most countries feature various configurations of ministries and other agencies operating at different spatial scales within a national framework.

The water-security user community—that is, the actors within the above entities—is a loosely-defined population of water experts. Where water governance is particularly complex, multi-tiered, and multi-sectoral, the community tends to be extremely diverse—ranging from elected officials to ministers, planners, agency heads, resource and public-lands managers, NGO representatives, managers of industries, agriculturalists, urban water and public-health officials, private water providers, and individual stakeholders. Elsewhere, where responsibility is consolidated in fewer institutions, the community typically is less varied, comprising mostly government officials, landed interests, and other elites—with sparse input from and participation by civil society.

But the relevant question is this: *Is water security a useful concept for those users?* If the term is understood in its most straightforward sense, the answer is likely affirmative. If we were to speculate, all of the above users—if they seek effectively to discharge their responsibilities to their constituents—would probably agree that the core elements of the definition of the term (sufficient quantities of sufficiently good quality water for humans and the environment, for now and for the future) are reasonable guideposts for their actions. While we know of no comprehensive research on the subject, recent studies suggest that the water security concept is growing in use by actors in government (e.g., Soyapi and Honkonen 2017; Staddon and James 2016), the private sector (e.g., Bakker 2018; Baleta and Winter 2017) and for public awareness raising by civil society (e.g., Sershen et al. 2016).

Do these users keep up with the latest twists in the literature? Do they advocate the UNESCO definitions versus the one proffered by the Global Water Partnership? Do they subscribe to the theory-steeped, power-relationship-focused arguments of certain academics—for example, how strategies to address local water security can, in effect, exacerbate water insecurity for indigenous communities (e.g., Boelens and Seemann 2014)—or do they prefer the practical assertions of on-the-ground development specialists, as demonstrated in community-focused water security framework of WaterAid (2012) or the World Bank's (2015) tools for implementation? Or, perhaps they ascribe to the more self-interest-based interpretations of economists, who call for the use of incentives to promote water savings, flexible water pricing or life-cycle approaches (e.g., Sahin et al. 2015)? We suspect that all these subtleties are likely lost on the vast majority of users and potential users. If they are at all aware of the term, they probably just pluck from it those elements that are most appropriate to their endeavors.

8.3.2.2 Transnational Actors

Local and national actors, as discussed above, respond primarily to issues within their constituencies—that is, communities, cities, jurisdictions, and nation-states. But how is water security interpreted and acted on when national borders do not constrain problems and concerns? In such instances, transnational institutions—such as global water initiatives, environmental treaties and agreements, UN agencies, regional associations, trade blocs, development agencies and banks, river-basin commissions and other multinational regulatory agencies, international NGOs and interest groups, and in modest way, water-governance researchers—are the agents for enhancing access to sufficient, safe quantities of water (see Table 8.2).

The types of transnational institutions identified above (and this is not an exhaustive list) are enormously varied. They pursue markedly different objectives: from diplomacy, to financing infrastructure, to regulating transborder water quality, to defending human rights and environmental values, to assuring scientific validity, to enhancing discourse and understanding.

With such a variegated palette of interests, it is unsurprising that interpretations of how to achieve water security do not converge. Yet in spite of the multiplicity of institutional objectives, Table 8.1 shows that there is general agreement on a handful of attributes of water security: assuring access to quantity and quality tops the list; but others such as safeguarding human health, protecting ecosystems, promoting economic growth, and achieving all those goals sustainably all are prominent.

Since the 1990s attention to transboundary basins and aquifers has shown that many concerns about what we now call water security transcend national borders (ISARM 2018; Varady and Morehouse 2003; Milich and Varady 1999; Ingram et al. 1994). As Sect. 8.4 points out, transboundary scenarios increasingly are being recognized as harboring more complex social, political and institutional challenges than ones within a nation-state that make addressing surface water and groundwater supply security difficult (Albrecht et al 2018b; Gerlak et al. 2018; Magsig 2009).

It is in regard to these transboundary areas that transnational institutions are most active and influential. This is the case because these are the areas where the legal and administrative reach of the nation-state is limited to its own territory. Confronted with the stark barriers imposed by nature and/or politics, even the best-intentioned and most effective governments may be unable to overcome barriers to their efforts to achieve water security. And this is where multinational, multilateral actors—organizations or instruments, inter-governmental or nongovernmental, formal or non-formal—come to the fore. Such is the case in transboundary contexts such as shared surface water on the U.S.-Mexico border and the multinational Guarani Aquifer, shared among four South American nations.

While the 1944 treaty (which is still in force) requires that the U.S. deliver 1.5 million acre-feet (MAF; or 1.95 billion cubic meters) of water annually to Mexico, it did not specify what degree of water quality—a key attribute of water security—is required for the water delivered to Mexico. In the 1960s, tensions arose when, due to increased salinity of the Colorado River, water deliveries to Mexico became too saline to use for irrigation, livestock watering or domestic use (Umoff 2008). The binational International Boundary and Water Commission (IBWC) played a critical role in resolving this issue, and although it took several iterations to arrive at a permanent solution, in 1973 the U.S. and Mexico agreed to add an amendment, or "Minute" (Minute 242), to the 1944 Water Treaty that requires the U.S. to maintain water deliveries of an acceptable quality by specifying a threshold value of salinity for water transfers (Umoff 2008). Since enacted in 1944, more than 300 minutes have been added to the Treaty to ameliorate specific transboundary water-related issues.

Across the South American continent, one of the world's largest groundwater bodies, the Guarani Aquifer, extends across the territories of four countries—Brazil, Paraguay, Argentina, and Uruguay. Through the collaborative efforts of diplomats, regional experts, and community representatives, and a guiding hand by UN agencies, the Organization of American States, and other multilateral organizations, the four nations concluded the 2010 Agreement on the South America Guarani Aquifer System (Sugg et al. 2015). After some political difficulties, that agreement is beginning to become operational, addressing the important water-security concerns of the residents who are dependent on the Guarani (Sindico et al. 2018).

Globally, we now have a reasonable understanding of transnational aquifers, which—at a time of rising populations and decreasing supplies of surface water—are becoming the main source of water. We have a clearer appreciation of how many such aquifers exist, where they are situated, and their areal extent. This knowledge is largely

Table 8.2 The landscape of transnational institutions and their role in water security

Institution	Relevant institutional objective	Sample institutions	How water security is manifested
Global water initiatives	Advancement of understanding	World Water Council, World Water Forums, Global Water Partnership, International Water for Life Decade	Meetings, conferences, white papers, procedures manuals
Environmental treaties and agreements	Diplomatic resolution of concerns	1960 Indus Waters Treaty, 1983 U.S.-Mexico La Paz Treaty, 1995 Mekong Agreement	Regulation of water-volume allocations, enforcement of quality standards
UN agencies	Follows mission of each agency	UNESCO, WMO, UN-Water, UNEP	Convening of forums, scientific investigations, development assistance
Regional associations	Harmonization of environmental regulations	European Union, SADC, OAS	Water-quality directives, regional studies
Trade blocs & associations	Promotion of economic interests	NAFTA, EU, WTO	Maintenances of trade regulations
Development banks & agencies	Support for advancements in developing nations	World Bank, Asian Development Bank	Guidance for development projects, requirements for funding
Multilateral commissions	Facilitation of cooperative resource management	Mekong R. Commission, Intl. Commission for Protection of the Danube R.	Bilateral and multilateral treaties, agreements, cooperative efforts
Intl. NGOs	Protection and conservation of resources and the environment	World Wildlife Fund, Intl. Union for Conservation of Nature	Guidance and policy positions
Intl. interest groups	Promotion of equitable access to and use of resources	Stockholm Intl. Water Institute, Intl. Water Management Institute	Research, policy guidance, white papers
Intl. communities of practice, e.g., water governance researchers	Support for the practice of the group	U.S.-Mexico Binational Working Group on Aquifer Assessment, Intl. Network of Basin Organizations	Research, conferences, academic exchange

due to ongoing research efforts, most notably that of the International Groundwater Resources Assessment Centre (IGRAC) that has compiled and synthesized knowledge about transboundary groundwater in the Transboundary Aquifers of the World Map (IGRAC 2015). IGRAC's research was made possible by the concerted work of UNESCO's International Hydrological Programme (IHP), its ISARM (Internationally Shared Aquifer Resource Management) program, and its Global Groundwater Governance Initiative, supported by key donors such as the Global Environmental Facility.

Elsewhere, there are innumerable examples of transnational actors helping address water-security issues in situations where nations and subnational institutions are hampered by their unilateralism. For instance, communities on either side of the U.S.-Mexico border informally—i.e., without reference to their foreign ministries or diplomats—have helped deal with clusters of contamination and environmental-health problems, water shortages for fighting fires, and cross-border trades of water rights for irrigation. On the Swiss-French border, a binational group of local, non-federal government agencies has been resolving issues in the Genevese Aquifer related to overpumping (de los Cobos 2018). In Southeast Asia, strong NGO action has sparked greater deliberation and collaboration, sometimes challenging more formalized scientific and governance processes of the Mekong River Commission (Lebel et al. 2005). And more generally, beginning in 2001, situations across the world experiencing water conflicts have benefited the experiences gained via from UNESCO's PCCP (From Potential Conflict to Cooperation Potential) initiative (PCCP 2018). Recognizing that education, training, and familiarity with conflict are essential to resolving disagreements, PCCP has commissioned case studies and thematic reports; assembled curricula, handbooks and training materials; convened workshops and training sessions; and publicized their work at large conferences and congresses (Castelein and Bogardi 2004; Delli Priscoli and Wolf 2009).

8.4 Water-Security Framings in Practice

It the preceding sections, we examined various definitions, conceptualizations, and epistemological framings of water security that have emerged in academic spheres and policy contexts. We also explored the types of actors and institutions that have, or could, engage with the notion of water security. The next step is to understand how water-security concepts and approaches are being used in practice, which leads to a number of salient questions. Does the actual practical use of water security match the growing discourse in policy and academia? What can we learn about water challenges by examining how water security is employed by individuals and organizations on the ground? How have these actors helped shape the discourse on water security?

At the core, we would like to know whether adopting a water-security approach helps advance our analytical appreciation of water challenges and thereby offers new solutions to address the SDGs. By seeing how this concept is applied, we can reflect on the most common issues encountered. That would help us learn which aspects of water security are most useful for addressing real-world challenges, and clarify the complex relationship between concepts, tools, and approaches—and improved water outcomes.

Via individual benchmarks and goals, the SDGs set a global agenda for improving the human condition as well as sustainability of the environment and resources. SDG 6 sets a specific goal for water: to improve access to clean water and sanitation. This objective is a central feature of, and is embodied in, the water-security discourse as discussed previously. Water security contributes to multiple SDGs by supporting the sustainability of ecosystems, food systems, cities and human health, as well as multiple cross-cutting themes, such as gender equity and growth (Adeel 2017; Gimelli et al. 2018). The SDGs serve to leverage global support for these aims, but to support the SDGs effectively, water security needs to be addressed at multiple governance levels, geographic scales, and social strata (Adeel 2017).

Attaining such progress will depend directly on what on-the-ground actions are taken. Yet the barriers to progress vary in different parts of the world—they may be due to physical water scarcity, lack of access, insufficient water infrastructure, or irregular and changeable water availability —to name only the most obvious obstacles. It follows that addressing these diverse and nuanced challenges will require a variety of approaches. How can water security be operationalized in practice to address the very real challenges that communities, cities, states, and nations face?

8.4.1 How Has Water Security Been Conceptualized and Framed?

The concept of water security is abstract, broad and multidimensional. As a result, the concept is challenging to operationalize. In an attempt to make water security relevant in practice, approaches for applying it have considered multiple aspects, dimensions, indicators, and measures (Gerlak et al. 2018). However, water-security framings were originally employed using simplistic, reductionist approaches. These framings defined water security narrowly and employed a limited set of parameters with which to describe it (Staddon and James 2014; Zeitoun et al. 2016). For example, a narrow framing might focus on easily-measurable attributes—such as quantity and quality—and utilize quantitative methods for assessing these attributes such as a water balance or risk assessment. Such approaches are useful in certain contexts—e.g., where a bird's eye view is needed at a national or regional scale. However, the use of more broadly-defined water-security framings that integrate the less-tangible attributes that more directly affect how individuals, communities, and nations use, experience and sustain water resources are growing in research and practice (Gerlak et al. 2018; Jepson et al. 2017; Zeitoun et al. 2016). These holistic and integrative approaches include attributes such as water access, water for sustaining livelihoods, and water governance, yet may also include attributes such as equity of access and water preference (Chenoweth et al. 2013; Sinyolo et al. 2014; Sojamo et al. 2012; Zeitoun et al. 2016).

Water governance is a key component of a broad framing of water security (Gerlak et al. 2018). Governance approaches—particularly those that involve participatory and bottom-up processes—contribute to water management that is not only more physically sustainable, but also produces more equitable and context-relevant solutions (Gerlak et al. 2018). Governance strategies that address all-important social, political, and economic aspects of water security are increasingly needed. In this area, we see clear points of tangency with the IWRM discourse, where two of the three founding principles explicitly call for participatory approaches that include often excluded groups in society, particularly women.

While a broad framing of water security tends to include water access, attention to justice and equity in these remains relatively underexploited (Gerlak et al. 2018). Water access as an indicator of water security most often focuses on access to water services, such as provisioning, sanitation, and wastewater collection (Gimelli et al. 2018). It remains difficult to determine how to implement measures of equity and justice on-the-ground (Asthana and Shukla 2014). Recent work has suggested—conceptually, but not yet implemented in empirical studies—a reframing of the concept of water security (Jepson et al. 2017; Gimelli et al. 2018) in ways that adopt the concept of hydrosolidarity, a term coined by Malin Falkenmark (in her Volvo Prize Lecture of 1998 in Brussels, Belgium) that stresses ethics and human behavior (Gerlak et al. 2011; Falkenmark 2005). Beyond securing a right to water as a physical substance, Gimelli et al. (2018) suggest reinterpreting access in a way that incorporates equity and a broad definition of human wellbeing whilst Jepson et al. (2017) approach the equity challenge from the point of view of "entitlements" versus "capabilities." Drawing on prior works such as Ribot and Peluso (2003) and Sen (2008, 2013), both studies argue for a reframing of access that includes not only a *right* to water but the *ability* to benefit from it.

8.4.2 How Has Water Security Been Employed in Different Contexts Around the World?

As described in Sect. 8.2.2 and Table 8.1, water security is characterized by multiple dimensions or attributes, including quantity, quality, access, effective management, water availability for the environment or ecosystems, and many others. Which water security dimensions are most influential varies case-by-case. It follows then that water security could be studied, measured, and evaluated by researchers from diverse perspectives across a variety of geographic scales. In a recent review and analysis of case studies of water security, Gerlak et al. (2018) found that such studies are conducted at every possible scale: the city, regional, national, community, and transboundary. They are also conducted by scholars from diverse disciplines including economics, anthropology, geography, political science, and the health sciences.

However, *how* water security is employed varies according to geographic scale. For example, when assessing *community* water security, researchers often incorporate qualitative indicators, such as water preference, access to water sources and local water governance strategies, in an effort to capture the site-specific qualities of water challenges and to understand local conditions (*ibid.*). By contrast, in studies of water security at the *national scale*, the use of quantitative indicators is more prevalent (*ibid.*), in part because quantitative measures are easier to synthesize at a larger scale of study, but also because water use and other water-resource data are generally more available at the national level than at other scales. These could include national water-use statistics by sector, regional climate forecasting to assess water availability or regional water balance calculations, and water-quality evaluation. At the transboundary scale, factors relevant to water security may include nation-to-nation geopolitics and regional goals. Much data at national and transnational scale is relatively easy to access through global portals such as UN Water and FAO.

Researchers also employ the concept of water security in diverse ways that elucidate the range of water challenges faced in different regions of the world. For example, studies conducted in China often highlight problems of urban-water provisioning and conflicts of water supply and access between urban, peri-urban, and rural water users (Sun et al. 2016). In the Middle East region, emphasis is often on expanding water supply through desalination or increasing water-use efficiency of agriculture and municipal users (Gerlak et al. 2018; Cook and Bakker 2012). Studies of water security in North America reflect a broader spectrum of community, agricultural, and urban water issues. And, in Sub-Saharan Africa, water security is most often evaluated at the community-level, defining site-specific water security indicators that reflect local needs (Gerlak et al. 2018). More recently a global consortium of scholars, the Household Water Insecurity Experiences (HWISE) Consortium, has emerged specifically to direct attention to the household scale, where there has been historically much less attention (Jepson et al. 2017; Young et al. 2019).

While most regions struggle with not only single, but multiple water issues, the unique combination of physical, social, economic, and political attributes that are relevant in different contexts likewise suggests that an array of strategies for improving water security will be relevant around the globe. The pertinent attributes vary from place to place, and from context to context (Gerlak et al. 2018; Gober et al. 2015; Garfin et al. 2016; Wilder 2016). Thus, approaches to increasing water security—or reducing water insecurity—also must be context-specific (Gerlak et al. 2018; Jepson 2014). For example, in the U.S. water is governed at the state level, whereas Mexico features a nationwide water-management regime and in many east African nations water law expressly empowers community-scale "Water User Committees" to make meaningful interventions (Terry et al. 2015). These disparate legal and management structures influence which strategies are both available and effective in these countries to address water security. Similarly, surface water pollution might be a key challenge in urban areas of Europe, whereas water scarcity may be more problematic in the arid regions of the Middle East.

Acknowledging that water-security challenges are multi-dimensional and site-specific, what is needed next is a way to assess, or measure, these various attributes. But how do we define the threshold between what is "secure" and what is "insecure"? Indicators need to be identified that can help define and measure water security.

8.4.3 How Can Water Security Be Assessed and Measured?

We have explored how water security is characterized by multiple dimensions and aspects. But how can progress towards a state of improved water security be appropriately assessed? It turns out that assessment of levels of or progress towards water security is a considerable challenge, not least due to the complex multi-factorial conception of water security swirling around academic, practitioner, and political communities (cf. Table 8.1).

In their review of assessment methodologies Sun et al. (2016), show that the number of water security indicators proposed by scholars and development agencies ranges from 6 up to 106, while 92% of the studies they reviewed had fewer than 30 indicators. Frequently selected indicators include:

– Total renewable water resources
– Gross domestic product
– Industrial water withdrawal
– Individuals without reasonable access to a water source (an MDG, now SDG target)
– Vulnerability to water-related disasters

While such indicators have an internal logic, they are relatively crude when it comes to assessing potential impact of different sorts of water insecurities on people and the environment. Of course, there always exists a compromise between having a sufficiently large number of indicators to characterize water security comprehensively versus having a small enough number of indicators such that they can be easily managed. Some researchers suggested that a water security index should ideally have no more than 12–15 sub-indicators, and an index with more than 20 sub-indicators may only be applicable to particularly data-rich areas (Global Water Partnership 2014).

Following this logic, and working largely at the national/international scale, there have been several attempts to create a robust water security assessment tool. One of the better-known attempts, by the Asian Development Bank, develops a water security framework with five key thematic dimensions: household water security, economic water security, urban water security, environmental water security, and resilience to water-related disasters, and provides the first quantitative and comprehensive view of water security in the Asia-Pacific region (ADB 2013; Thapa et al. 2014; Sun et al. 2016). A similar approach, but with a greater emphasis on risks to water insecurity, was proposed by the OECD at about the same time (OECD 2013). Both approaches have tended to be operationalized through national-scale data trawls and composite-indicator construction. Although visually quite attractive, careful examination of the underlying datasets often reveals unresolved problems of data provenance, quality, structure, and therefore commensurability. In the ADB approach for example, data from the Joint Monitoring Programme (JMP)'s[9] monitoring of MDGs (now SDGs) progress towards better access to "improved" water and sanitation is merely imported into a new "Key Dimension" indicator that includes also a measure of Disability Adjusted Life-years (DALYs) linked to diarrheal illness. Together these three interval variables are transformed into a single ordinal variable indicating where a given nation is relative to other nations on a five-point scale.

But there is a serious problem with most indicators-based approaches to water security—they tend to emphasize the sorts of things that states are most comfortable measuring because they are less likely to be seen in a bad light. Though not specifically about water security, the MDGs provide a good example of this. The key water-supply access MDG called for countries to halve the proportion of their populations without access to "improved" water sources by 2015.[10] Collection of the data necessary to provide data returns to the JMP required only observation-based returns by national authorities of the numbers with/without such access. However, water security is not a binary (you either have it or don't) phenomenon. Rather, it is fluid in the sense that it is related to many other factors including local social, economic, and political dynamics (who can access these improved sources, when and under what conditions?). National- or even district-level summary statistics obscure as much as they reveal, for example Uganda's declaration that the nation achieved the water-supply MDG before the deadline may hold up when looking at national statistics, but disaggregating such summary top-line numbers by district, urban/rural and by ethnic group shows a much more fragmentary, indeed "messy," picture (Staddon et al. 2018a, b).

[9]JMP; the global organization, managed by UNICEF and the WHO, vested with responsibility for collating data for the water-related MDGs.

[10]'Improved' sources are those that are potentially capable of delivering safe water by nature of their design and construction. These include piped water into the dwelling, yard or plot; public taps or standpipes; boreholes or tubewells; protected dug wells; protected springs; packaged water; delivered water and rainwater. Unimproved sources include unprotected dug wells and unprotected springs.

As Jepson et al. (2017) point out in their recent critique of mainstream approaches, the critical element of water security involves the capabilities of target populations to achieve water security on their own terms: "we propose that a dynamic and relational view of water security can be further developed and informed by the capabilities approach of Amartya Sen and Martha Nussbaum" (Jepson et al. 2017). What this means, in essence, is that we need to shift attention away from the mere presence or absence of "access" at a given moment in time and instead look at the underlying capabilities that make access (and therefore water security) more or less precarious. Moreover, simply measuring distance to tap stands or other physical infrastructure tells us nothing about whether relative access to physical water may or may not be transformed into the services ["functionings" in Nussbaum and Sen's (1993) terminology] such as hydration, hygiene, and happiness that are surely more to the point.

The HWISE Consortium has undertaken to develop the world's first cross-culturally validated metrics-driven tool for assessing the realities of household scale water insecurity. Through two phases of scale development to date the consortium has surveyed more than 7,000 households in 29 locations around the world. The locations surveyed cover a range of geographical, climatic, urban, and rural contexts and therefore allow for generalization of findings. Through this process much valuable data about the complex intersectionalities linked to water (in)security has been collected and an initial scale comprising more than 30 items has been reduced (through rigorous mathematical analysis) to only 12 making the scale easier and cheaper to implement (Young et al. 2019).

8.5 Some Examples of Water Security in Practice

In the preceding section, we explored the many ways that water security is framed, measured, and implemented in practice. We concluded that the concept is best represented by a combination of many attributes and should ideally be implemented in site-specific ways employing multiple indicators for assessment.

We believe that examples of specific water-security challenges and their site context are useful for understanding the diversity and breadth of water-security challenges on-the-ground. This section presents selected case studies of examples of water-security challenges and strategies in context. Rather than picking different examples from around the world, which would require a contextual explanation for each case, we chose five examples from the same geographic region—the southwestern U.S. and northern Mexico—where social and environmental conditions are very similar.

The examples presented exemplify different types of water-security challenges, many of which are likely to be pertinent to other parts of the world, particularly in arid and semiarid areas. The diversity of issues demonstrated in these examples also shows how—even within a single geographic region—water-security challenges are profoundly context-specific.

8.5.1 A Story of Water Security in Tucson, Arizona

The first example in this chapter describes the landscape of water security in the city of Tucson, Arizona, a metropolitan area of about one million inhabitants located in the arid southwestern region of the U.S. In this water-scarce environment, the city's water security has multiple facets—including the sometimes conflicting needs to obtain supplies from a diversity of sources, protect water quality, and provide access to water supplies for all. The relative importance of each of these aspects has also changed over time as different water management strategies have been employed—from water treatment, to aquifer recharge, to conservation.

Tucson is located in southern Arizona (Fig. 8.3), in a semiarid climate that receives an average of 310 mm of precipitation per year (Carlson et al. 2011). Because surface water has long disappeared in this area, groundwater has become the main water source. However, excessive pumping over the years led to land subsidence and concerns about aquifer depletion prompting state officials to look for ways to protect the groundwater supplies. In 1980, the Arizona Department of Water Resources was created to manage the Groundwater Management Act—a complex piece of legislation that aims to protect groundwater resources. Yet in spite of this law, groundwater levels continued to decline and water managers and state officials sought ways to diversify the water portfolio in Tucson (City of Tucson Water Department 2013; Megdal and Forrest 2015). One early approach used to increase the City's water supply involved the purchase of farmland in Avra Valley in the 1970s and 1980s. With these purchases, the water utility company secured water rights for the city. As the city grew, water managers needed ever more additional sources. In the 1990s, after a long legal fight among the states in the lower Colorado River Basin, Tucson began receiving water deliveries from the Colorado River via the Central Arizona Project (CAP). This 540-km-long canal is an impressive conveyance system that pumps water uphill a vertical distance of 730 meters, all the way to Tucson. The plan was to use CAP water and effluent from a then-newly-constructed treatment plant as the main water sources for the city, leaving groundwater (by then badly depleted) as a back-up source. However, water quality issues caused by the reaction

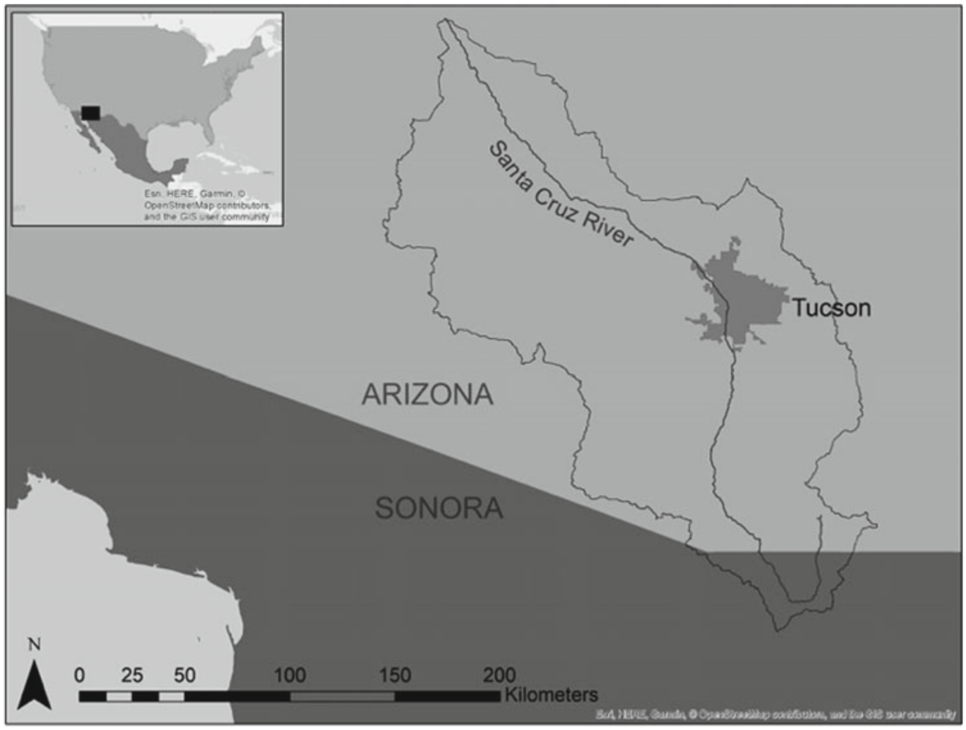

Fig. 8.3 Location of Tucson, AZ (*Map* by A. Zuniga. *Photo credit* Tucson Water, with permission)

of the municipal supply pipes to the different water pH levels in CAP water resulted in public outrage. People were getting red-colored water from the tap, and many filed complaints. In response, the local government mandated that the utility company returned to groundwater as the main water source in 1994 (City of Tucson Water Department 2013; Megdal and Forrest 2015).

Even though the treatment plant had nothing to do with water quality issues, citizen activism made it impossible to use the plant again. Water managers faced a unique situation—they had surface water brought from afar (CAP water) that they could not use and the aquifer was being depleted. Their solution was to use CAP water to recharge the aquifer. They converted their Avra Valley farmlands into two recharge facilities (Fig. 8.4) and directed CAP water to newly built infiltration ponds. This way, Tucson residents would still get groundwater in their homes and CAP water could be used to replenish the aquifer. This innovative solution is known as "water banking" and has been a model for groundwater management around the world (Megdal et al. 2014).

This water incident in Tucson also resulted in a strong conservation ethic among the population that has allowed for stringent regulations to reduce demand, including a local ordinance that prohibits the use of high water use plants; a land-use plan that limits development in protected areas; incentives of water use during non-peak hours and the efficient use of water; and rebates for adopting rainwater harvesting technologies (Cleveland et al. 2015). In addition, Tucson created a reclaimed water system—a network of purple pipes—to irrigate golf courses, and other greenspace (City of Tucson Water Department 2013). Such "dual pipe" supply systems are becoming a common choice in contexts where the significant investment capital required is readily available.

Over the past few decades the water portfolio for Tucson has grown from solely relying on groundwater to using surface water (via CAP), reclaimed water, and rainwater. Tucson currently supports its population through a combination of massive infrastructure projects, changes in water use, innovative legal mechanisms, technological advancements, and conservation efforts. However, these strategies will certainly be tested when climatic changes reduce the region's water budget.

8.5.2 Hard- Versus Soft-Path Approaches: The Politics of Desalination in Guaymas, Sonora, Mexico

Ultimately, it always seems that there is no single "magic bullet" policy that can deliver water security in any locality. Instead, a combination of approaches is needed to address water security across its multidimensional attributes (Lemos et al. 2016). Researchers have discovered over the past decade or so that governance approaches, including well-crafted policies and laws, are critical for achieving beneficial outcomes—technical fixes alone are insufficient (Rogers-Hayden et al. 2011; Gerlak et al. 2018). As Staddon

Fig. 8.4 Avra Valley Storage and Recovery Project (*Photo credit* amay.org)

et al. (2018a, b) put it: "excellent engineering is necessary, but not sufficient by itself to deliver greater urban resilience." In most cases, a combination of both hard-path and soft-path approaches is needed to achieve sustainable solutions. Hard-path approaches include water infrastructure such as water transport structures and water treatment facilities that increase usable water supplies. In contrast, soft-path approaches include increasing water-use efficiency by improving water management and legal frameworks, increasing efficiency of water use (household, irrigation, e.g.), innovative economic approaches such as flexible water pricing, adaptive management of multiple water supplies, resolving competing water-rights claims, and expanding water access to underserved populations (see Sect. 8.1.1, above).

Guaymas is one of the driest municipalities in the Mexican state of Sonora and has long experienced severe water problems. The main water source for this region used to be the local aquifer until it was depleted and experienced seawater intrusion. Then, water managers sought water sources from afar, such as the Yaqui River located 120 km away. The state water agency—the State Water Commission—conveys water through pipes and water pumps all the way to Guaymas and the neighboring town of Empalme.

In addition to water scarcity, the aging infrastructure in both Guaymas and Empalme leaks significant volumes of water, approximately 50%, reducing the efficiency of the system. The quality of the water that remains is often so deplorable that water users refuse to pay their water bills, arguing that they have to buy bottled water for potable needs. Lack of effective water metering aggravates the situation because water managers do not have enough resources to repair the infrastructure (Ramos Luna 2018).

Instead of choosing soft-path approaches to water management (e.g., reducing water losses in existing systems through better management, ensuring the revenue of the utility company with appropriate metering), the state government chose a classic 21st century hard path approach and invested heavily in a desalination plant. They purchased 200 hectares of land around a nearby beach in the municipality of Empalme to build the plant (Fig. 8.5). They financed the project through a public-private partnership with funds that amount to $767 million pesos (more than $40 million USD) in a desalination plant that will produce 200 L per second and is expected to benefit 225,664 people (for more information, visit http://desaladora.sonora.gob.mx/).

Given a history of corruption scandals from the previous state administration, and water conflicts that arose from a previous inter-basin water transfer, this project has followed stricter transparency policies. Their websites contain normative frameworks, laws, decisions, programs, financial statements, community groups, technical studies, issued permits, providers, and land acquisitions. Although intentions to "do things right" are evident, it remains unclear how the water utility company will make users pay for desalinated water that will be much more expensive than the current option? If users do not pay, how are they going to maintain operations of the desalinated plant that will use a huge amount of energy? Because the infrastructure has not been upgraded, water leaks are expected to continue. Therefore, resources will be used to desalinate seawater, and 50% of desalinated water will likely end up in leaks.

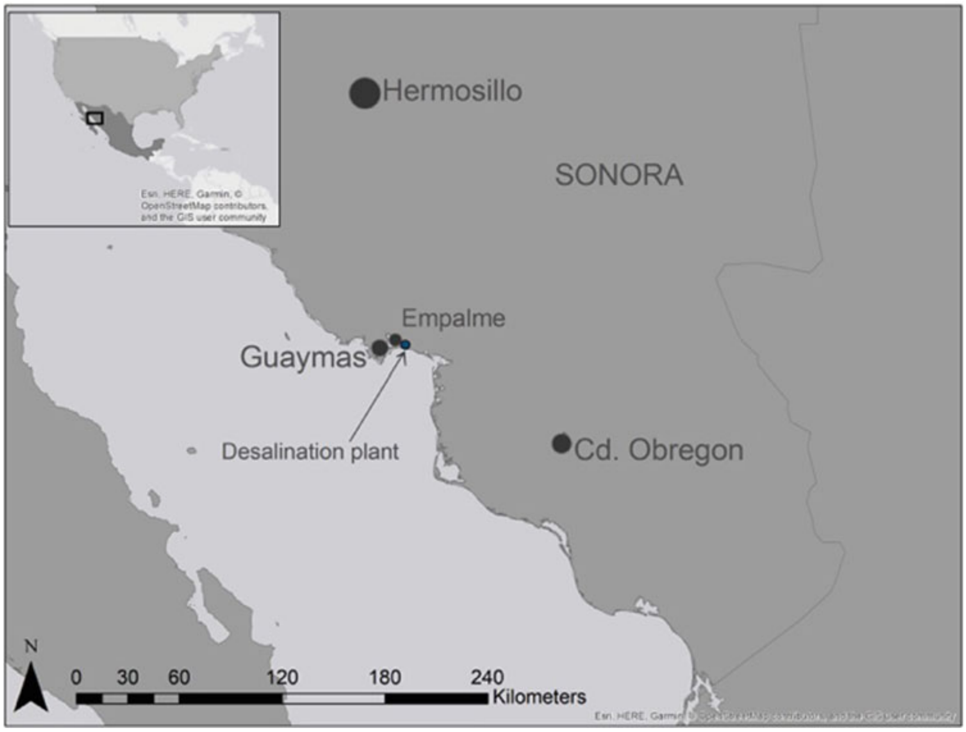

Fig. 8.5 Location of the desalination plant in Guaymas-Empalme, Sonora, Mexico (*Map* A. Zuniga)

It is a fact that politicians do not benefit from upgrading leaky distribution infrastructure. These types of projects are not very popular because the streets are opened up and residents suffer from a messy environment though a prolonged time —not to mention the burden on the public purse. Once completed, the street looks like it did before and there is not a palpable legacy for the politician. In contrast, large-scale infrastructure works, such as a desalination plant, are very popular because they depict a future-oriented politician that brings prosperity to the people. But in reality, hard-path approaches should be the last resort for water management. Soft-path approaches should be first in line to solve water management problems, particularly in communities such as Guaymas-Empalme that have severe problems that will remain there after the plant provides more potable water to the region.

8.5.3 Adaptive Management for the Cienega Watershed in Southern Arizona

As noted above, water security cannot be characterized or measured by a single indicator. Instead, multiple indicators are needed to paint a complete picture of the social, political, physical, and environmental aspects contributing to overall water security. But, determining how to select the appropriate indicators is not easy and needs to be addressed on a site-by-site basis. Approaches to water security are more effective when they incorporate the perspectives of local stakeholders and the community context (Gerlak et al. 2018). Instead of reducing water security to a few convenient indicators, the broader context should be incorporated (Gerlak et al. 2018; Zeitoun et al. 2016). One way to do this is to involve local stakeholders in water-security assessment through the sorts of local deliberative processes discussed above. In the next example, we explore how water-security indicators were developed for the Cienega watershed in southern Arizona.

The Cienega Watershed is located in south-eastern Arizona, U.S.A. and provides multiple ecosystem services, including groundwater for the Tucson Metropolitan Area. This watershed contains five of the rarest habitat types in the U.S. Southwest: marshlands—or cienegas in Spanish—cottonwood-willow riparian forests, sacaton grasslands, mesquite mosques, and semi-desert grasslands. This area also contains the Cienega Creek, one of the few remaining perennial streams in southern Arizona that provides critical habitat for wildlife, including some threatened and endangered species. In terms of human activities, this watershed has been used historically for ranching operations and is an attractive visitor destination for its scenic landscapes and cultural heritage (Fig. 8.6).

Population growth combined with climate change has resulted in a decrease in perennial surface water and groundwater levels, threatening riparian ecosystems. This situation has raised concerns among stakeholders, who created the Cienega Watershed Partnership (CWP)—a citizen-based non-profit organization that serves as a steward

Fig. 8.6 The Cienega Watershed (*Photo credit* M. McNulty, with permission)

of the land. Government approval for a new copper mine in this area has triggered additional concerns for the future health of the watershed. Faced with these challenges, CWP sponsored an adaptive management project to monitor the state of the watershed by relying on their partners, who are people from organizations already working on land monitoring activities.

But what is the best way to assess the state of a watershed? There are so many indicators to choose from. CWP members have involved their stakeholders in this effort. They have used participatory methods first to establish the criteria for the indicators and second to reduce the list to a manageable number. Once the list of indicators was identified, they followed an iterative process to further refine the list and compile data on each indicator. The final agreed list includes 20 indicators related to climate, water, ecological, and socio-cultural factors. Stakeholders get together once a year to review the data and analyze the meaning of these data for the state of the watershed. During each iteration, some indicators are dropped from the list and others added or refined, depending on the feedback from the stakeholders.

Having a periodic assessment of the watershed not only helps with the monitoring of ecological and social processes on the land, but also brings stakeholders together. This process enables data sharing and collaboration way beyond the scope of this project. For example, as a product of this collaborative process, archaeologists from federal, state, and municipal agencies defined a form that captures impacts to be used by all of them during their monitoring activities. Once the copper mine starts operations, the group of stakeholders is ready to monitor the effects that this new economic activity will have on the land and its water resources. Together, stakeholders have a strong voice on protecting what happens on this land.

8.5.4 How Is Water Security Manifested in Rural Environments Versus Urban Settings?

In rural areas, access to sufficient quantities of water of adequate quality can be a challenge, especially for poorer households. Rural case studies might focus on the household or community-level or address the needs of agricultural water users. In rural areas, legal frameworks for groundwater governance may be non-existent and access to water conveyance infrastructure may be prohibitively expensive or politically-challenging to secure. Indicators of water security should be developed with community input in order to best represent local needs and challenges—local indicators might include community capacity, environmental needs, water delivery systems and health, and wellbeing (Dickson et al. 2016). The typical indicators are often not those that are utilized at the local scale (Norman et al. 2013). Instead, indicators that reflect the site-specific nature of water challenges—such as community resilience, environmental, and social appropriateness—are needed (Dickson et al. 2016).

The next case study offers an example of conflicts that may arise when water resources are shared by rural and urban water users. Where urban areas experience rapid population growth, water resources that used to serve rural areas and agriculture may be reallocated to cities—creating geographical disparities in water security between rural and urban communities. The example below discusses such a situation where water is transported from rural areas to serve the growing needs of the city of Hermosillo, in Sonora, Mexico.

8.5.4.1 Conflict from Inter-basin Transfers in Sonora, Mexico

The capital of the Mexican state of Sonora, Hermosillo, is the fastest growing city in the state and relies on groundwater and surface water from the Sonora River for municipal and agricultural uses. However, during the past decades, population growth combined with climate change impacts have resulted in a severe reduction of water supply.

The local dam dried out and the aquifer was depleted. Residents of Hermosillo suffered water rationing on a daily basis (Radonic 2017).

To face this critical situation, the state government along with water agencies at the state and federal levels approved funding of $3,860 million pesos (more than $200 million USD) for the "Independence Aqueduct" in 2010 (Pineda 2017). This massive project conveys water from the Novillo Dam, located on the Yaqui River Basin in the southern part of the state, to Hermosillo via an underground 150 km long aqueduct to deliver 75 million cubic meters of water (Pineda 2017; Radonic 2017). Using state-of-the-art technology, this massive infrastructure project has improved water security for Hermosillo. This extra water has enabled population growth, periurban development, business and industry expansion, and increased irrigation (Pineda 2017).

However, the project was not free of conflict. Farmers of the Yaqui Valley along with Yaqui indigenous people and citizens of Ciudad Obregon (located in the southern part of the state, Fig. 8.7) were not happy with this project which they saw as taking much-needed water from their county. From 2010 to 2015, they protested the construction of the aqueduct, blocking the international highway and stopping traffic sometimes for several hours at a time (Fig. 8.8). They formed a civic movement named "Movimiento Ciudadano por el Agua" (Citizens' Movement for Water) and published several inserts on local and national press venues. They also filed several lawsuits against this project. Concerns of these groups were legitimate. These include restrictions to cultivate a second crop as a consequence of reduced water supply for the farmers, inability to expand irrigation area for the Yaqui tribe, and lack of business growth in Ciudad Obregon. The judge at the 10th Judicial District of Sonora ruled in favor of the Yaqui tribe on May 2, 2011, and demanded the interruption of the construction of the aqueduct. But the state government simply ignored this legal judgement. After a sustained and fierce fight in the media, courts, and highway, the opposition lost the fight when the aqueduct started operations in April 2013 (Pineda 2017; Radonic 2017).

The conflicts for the Independence Aqueduct highlight social and political tensions in Mexico. The benefits of this project are enjoyed by the affluent elite of Hermosillo, who control the periurban land that is now able to develop, and the farmers of Hermosillo who found their aquifer replenished.

This project also portrays a centralized approach, where the capital of the state grows economically while the rest of the state declines (Pineda 2017). While the rich benefit and the capital grows, the poor maintain their status, and the elites of Ciudad Obregon along with the Yaqui people witness how the winners take it all.

In urban contexts, water-security challenges may include not only conflicts among users, but also water pollution, wastewater treatment, equitable provisioning, flooding, and supporting ecosystems. While the relationship between cities and water security is complex and often fraught, increased population density seems always to exacerbate many dimensions of water insecurity (Jensen and Wu 2018; Mekonnen and Hoekstra 2016). Urban areas are by nature unable to provide sufficient natural resources for their populations from within their land area, and thus must access resources derived from outside the city, what French water scholar Bernard Barraqué calls the "more from further" paradigm for urban water (Barraqué et al. 2008, p. 1156). This creates dependence on imported resources and products —through water transfers and importation of water-dense products such as food (Hoekstra et al. 2018). Urban water governance requires not only infrastructure to secure sufficient water resources to reduce risk to the densely populated area, it also requires good governance in terms of analysis, planning and integrated policy (Hoekstra et al. 2018; Prichard and Scott 2013).

Using Singapore and Hong Kong as example cities, Jensen and Wu (2018) devised water-security indicators for urban contexts, which include: availability, diversity of sources, quality, capacity, sustainability, affordability, flooding risk, public health risk, and governance (including planning, disaster management, and regulation). These indicators reflect the specific water security challenges encountered in quite unique urban settings. In other cities, other indicators may be relevant.

The next example describes the case of the Lower Santa Cruz River in Tucson, Arizona. Here, stormwater originating from urban areas poses flood-control and sedimentation problems for reaches further downstream.

8.5.4.2 Urban Stormwater Management in the Lower Santa Cruz River Along Tucson, Arizona

Even though precipitation is not abundant in the Sonoran Desert, stormwater management is still a critical issue in the

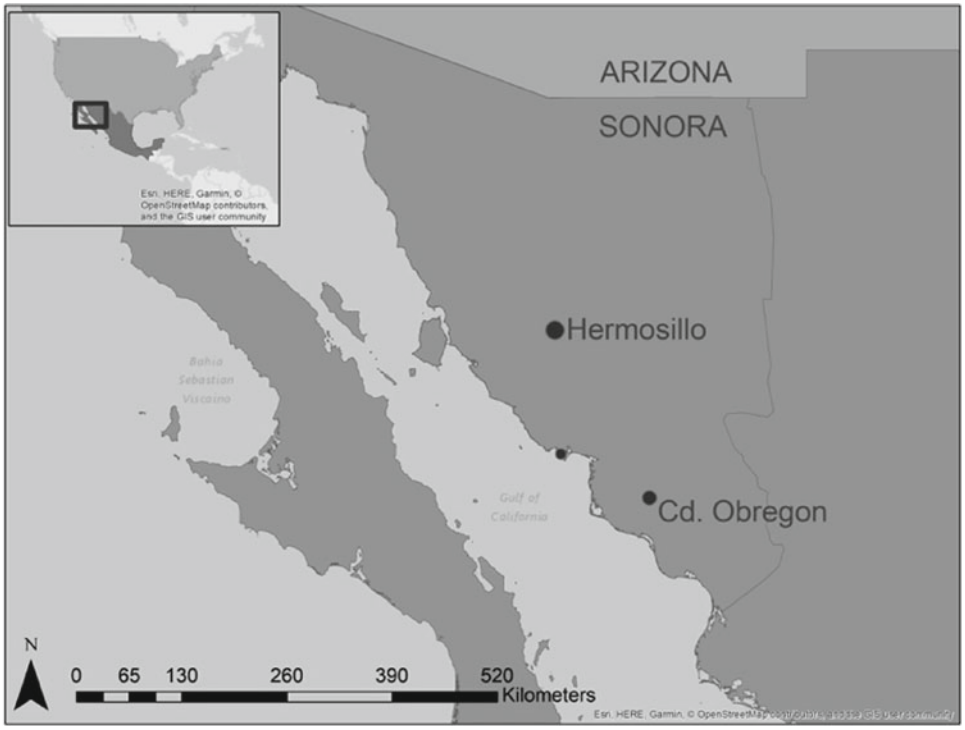

Fig. 8.7 Location of Ciudad Obregon and Hermosillo in Sonora, Mexico (*Map* A. Zuniga)

Fig. 8.8 Blockade of international highway near Ciudad Obregon (*Photo* V. Ivish, with permission)

Lower Santa Cruz River that runs northbound through the City of Tucson and its metropolitan area. As did to other cities in the U.S., Tucson solved flooding issues in the 1980s by lining some segments of the natural drainage system.

In 1982, the City of Tucson lined some 2 km of the banks of the dry Santa Cruz River downtown, leaving the riverbed in its natural state and converting it into a river channel (Davis 2017, 2018). Other segments of creeks and washes

Fig. 8.9 Rillito River near downtown Tucson (*Photo* C. Bristain, with permission)

throughout the city followed this trend, some of which were entirely lined. This type of grey infrastructure discharges stormwater rapidly away from the city allowing the development of land along the natural floodplains. Although flood-control measures have provided safety and recreational amenities to the residents in the form of walking and biking paths (Knott 2018), the property now located in this area desperately needs flood protection (Fig. 8.9).

After 30 years, sediment has deposited along the river bank and has raised the riverbed by 3 m (10 feet), overtopping the banks during a storm events and threatening the infrastructure located along floodplains. This vulnerable area along 6.5 km (4 miles) of floodplain contains 173 structures that are worth $84 million USD. If nothing is done, this area would be designated as Special Flood Hazard Area, which means that residents of this areas will be vulnerable to flooding and property owners that have federally guaranteed mortgages would have to buy flood insurance. The solution to this problem, from the engineering perspective, is to remove sediment from the dry river bed (along with trees and other riparian vegetation) to increase the depth of the channel for the sake of public safety and flood protection. This work started in May 2018, with a duration of two months, and with a cost of $860,000 USD (Davis 2018).

Environmentalists and neighborhood activists are not happy with this approach. From the environmental perspective, this flood-control approach represents critical habitat loss that will affect many species. Although the plan is to maintain certain portions of vegetation along the riverbed, the removal of trees and vegetation will negatively affect many species, particularly birds. Since 2004, 125 bird species have been recorded along the river, including the threatened Yellow-billed Cuckoo. Although the start of the project was planned for early 2018—before the bird-nesting season—project delays due to lack of city approval prevented works to start in a timely manner. There is urgency to finish works before the coming monsoon season, when severe storm events usually happen. In the meantime, environmentalists work diligently to relocate animals (e.g., lizards, snakes, rodents) to other riparian areas (Davis 2018). Neighborhood activists protest this work, mainly because they were not consulted properly. County officials thought they had opened channels of communication with the community, but in fact, had not. County officials held an open house on April 19, 2018, to inform the community about the project that was scheduled to start four days later, not allowing time for any input (Davis 2018).

This type of stormwater infrastructure work is considered by some as a "band-aid" solution because it will need to be repeated again in about a decade when the sediment builds up again (Davis 2017, 2018). A more comprehensive and holistic approach is needed. Green infrastructure, if widely implemented throughout the city, has the potential to decrease stormwater volume and sediment build up in the river, avoiding constant repair works to the river bed as well as neighborhood opposition (Zuniga-Teran and Staddon 2019; Hawkins 2017).

8.6 Water-Security Framings for International and Transboundary Cooperation

8.6.1 Internationalizing Water Security

In prior sections, we have seen the variety of ways that water security has been employed at different geographic scales. In this section, we focus on the use of water security in a transboundary context—looking specifically at contexts where water resources are shared across international borders—and the unique challenges this brings to the fore. Studies operationalizing water security at the transboundary scale are fairly uncommon overall, yet studies of those regions are becoming more prevalent (Gerlak et al. 2018: 82; Albrecht et al. 2018a). Magsig (2009: 61) even suggests that the challenges of achieving water security may "[manifest] themselves most perceptibly" at the transboundary scale where vulnerability and complexity are high.

Transboundary waters link populations both within and between countries and create hydrological and economic interdependencies (UN-Water 2008). With more than 2.7 billion people worldwide today dependent on resources from transboundary river basins (De Stefano et al. 2012), water security in transboundary contexts will have far-reaching impact. Indeed, transboundary waters pose enormous challenges for achieving water security (UN-Water 2013).

The contemporary perception of water security as a regional shared concern supports the notion that a regional or sub-national approach to their water-security challenges not only benefits the region as a whole, but also, when taking a long-term perspective, it constitutes the best option for the parties' respective national security interests (Magsig 2015: 198). Securitizing water discourse in transboundary settings—or tying water issues to high politics—is generally regarded as negative for decision making, however some exceptions in international contexts, have been observed where securitization has helped empower new voices, gain attention for issues and, in some cases, provide an opportunity for international agreement based on tradeoffs between water and security/border issues (Fischhendler 2015: 251). This suggests the need for critical examination of water security, particularly its post-realist frame, and its use at the transboundary scale. This section examines how a water security discourse has evolved in transboundary waters from an early focus on national security to a broader emphasis on regional cooperation and cross-sectoral linkages beyond the water sector.

8.6.2 How Has a Water Security Framing Evolved in Transboundary Water Contexts?

8.6.2.1 From National Security to Regional Cooperation

Approaches to internationally-shared water are deeply rooted in state-centric approaches. In transboundary contexts, water security has been employed to advance securitization of water resources at the nation-state level or to promote water security via international cooperation (Leb and Wouters 2013).

We have seen in Sect. 8.2.2 above that the post-realist view of security is a kind of environmentalization of security that does not dwell on military or other threats to national security. One notable result of this insight was a rise in the importance of environmental issues and the consequent attention to cooperative approaches to transboundary conflicts (Dinar 2009, 2011; O'Brien 2006). In this vein, Aaron Wolf, in a seminal 1998 essay (and in two decades of work since), effectively refuted the notion that international water conflicts will inescapably lead to water wars; he demonstrates that historically, cooperation on transboundary waterways disputes has been far and away the prevalent outcome for more than two millennia (Wolf 1998, 2007).

Key mechanisms for transboundary water cooperation include international law, bilateral or multilateral treaties, and basin-level institutional capacity. While water security seemingly integrates well with the aims and intentions of established approaches, the discourse of water security in some cases presents challenges—and in others, new opportunities.

Water security is often framed at the national level, even where transboundary watercourses are concerned. In a study of transboundary water security in Israel and Palestine, Brooks and Trottier (2014) examine shared surface water and groundwater. They highlight the defects of quantitative ways of sharing water, the dominant approach to sharing water in the region where available water is divided among the riparian nations by a quantitative formula involving absolute or percentage shares. Among other things, Brooks and Trottier argue that quantitative approaches to sharing water increases securitization of water in the region. They suggest that instead of treating water resources as a matter of national security, transboundary institutions for joint water management are needed to monitor conditions and mediate conflicts among riparian nations. They propose an institutional structure without quantified allocations of shared water, linking water security to national security or utilizing rigidly quantified water allocations act as "barriers to more efficient, equitable, sustainable and implementable management of transboundary water" (Brooks and Trottier 2014: 213).

Others similarly employ a water-security framing to promote transboundary water security via cooperation, international water law and treaties. Wouters et al. (2009) argue that international water law, specifically the UN Watercourses Convention, plays a key role in addressing water security in international contexts. Framed in terms of water availability, access, and the need to address conflicts of use, the principles of international water law can be mapped to water security (Wouters et al. 2009; Leb and Wouters 2013). The principle of equitable and reasonable use addresses water availability by defining rights and obligations, the principle of "no significant harm" promotes access to water of reasonable quality by both upstream and downstream users, and the duty to cooperate supports development of dispute resolution mechanisms (Leb and Wouters 2013). International law can guide efforts toward addressing transboundary water security, yet how such principles are implemented can be influenced by social and political relations and power dynamics that may influence water security outcomes.

The principles of the UN Watercourses Convention are implemented in transboundary basins via international agreements. Treaties provide a platform for nations to agree on specific measures and approaches and allow for enforcement. Treaties can address water security by providing mechanisms to adapt to change and mitigate risks such as, for example, the agreement to notify neighboring nations of emergency conditions such as infrastructure failure that might affect the downstream country (Leb and Wouters 2013). Treaties also allow for agreements to be made in terms more specific to the basin's hydrological characteristics and socio-economic conditions through data sharing (Leb and Wouters 2013). For example, the 1992 UNECE (UN Economic Commission for Europe) Convention on the Protection and Use of Transboundary Watercourses and International Lakes focuses on transboundary cooperation and coordination which can be interpreted as mechanisms to promote regional water security for Europe (Bakker and Morinville 2013).

Petersen-Perlman et al. (2017: 106) utilize a water-security framing to further arguments on transboundary water conflict and cooperation. The authors argue that system changes affecting human and water security—for example, dam development or climate change—can have regional impacts. They suggest that to address conflicts regarding water sharing and management, institutional capacity at the transboundary scale, such as international treaties and river basin organizations, should be expanded, but also ensured to be effective. Effective institutions equitably distribute benefits, provide conflict resolution mechanisms, utilize clear yet flexible allocation criteria, and have an adaptable structure (Giordano and Wolf 2003).

However, inserting water-security discourses into existing transboundary dialogue may make cooperation more difficult. Representing the start of a new phase of cooperation, the Nile Basin Initiative (NBI) aims for a shared vision of "equitable utilization of, and benefits from, the common Nile Basin water resources" and offers a platform for negotiating a shared legal framework. After a decade of negotiation on the Cooperative Framework Agreement (CFA), progress stalled, provoked by the use of water-security discourse. The CFA's Article 2 defined water security as "the right of all Nile Basin States to reliable access to and use of the Nile River system for health, agriculture, livelihoods, production and the environment." Wanting to protect their existing uses, the basin hegemons, Egypt and Sudan, requested an addendum requiring that each riparian "not to adversely affect the water security and current uses and rights of any other Nile Basin State" (Salman 2013: 21). Non-hegemons in the basin saw this addendum as maintaining the status quo of inequitable allocations and did not agree (Salman 2013). In part, the use of the term "water security" caused problems due to its ambiguity, and particularly its lack of a legal definition (Mekonnen 2010). However, the underlying disagreement on allocations persisting from the colonial era existed far prior to negotiating the CFA (Zeitoun 2011). It was not necessarily the concept itself that was the problem, but rather how and when it was used and interpreted.

Finally, binational institutional capacity is key for facilitating cooperation. When employing water security to analyze water challenges at the transboundary scale, scholars often call for increased, and more appropriate, institutional capacity to address social, political, environmental and institutional aspects of water security. Wilder et al. (2016) examine water-security strategies in the western U.S.–Mexico border region that include expanding supply to meet increased demands for dwindling supplies through new technologies, such as desalination. Recognizing the potential of desalination systems to increase water supply in the region, they examine the associated consequences, costs, and constraints. They find that desalination systems alone do not constitute a sustainable approach to achieving water security in the Upper Gulf of California region. In a binational setting, building a sustainable desalination system means "paying attention to the multiple, non-technological attributes of desalination systems, including the environmental, financial, social, institutional, legal, and political" (Wilder et al. 2016: 770). Ultimately, they argue that a successful desalination system for the U.S.–Mexico border region is dependent upon sustained positive relations and robust binational institutions with appropriate capacities (e.g., for registering, metering, billing, and collecting water fees) to address structural problems and ensure that more water does not merely amplify existing inefficiencies and promote unsustainable growth.

When considering transboundary groundwater, a water-security framing sheds light on the dual need for both protections of the physical resource and improved governance (Albrecht et al. 2017). Groundwater is particularly vulnerable to degradation because impacts—such as pollution or overuse—are difficult to monitor and may occur slowly over many decades. Furthermore, remediation of polluted groundwater bodies is more difficult and time consuming than in case of surface waters. Water-security framings support a focus on protecting groundwater supplies from these risks (e.g., Zeitoun et al. 2014). Groundwater aquifers vary dramatically in regard to their physical characteristics, and while they can extend across international borders, they are often limited in spatial extent. For these and other reasons, international law, legal frameworks, and other cooperative mechanisms for groundwater have developed more slowly than that for surface water—however, the principles of the UNWC have influenced shared groundwater practice. For example, studies of transboundary groundwater emphasize the need for on-going collection and exchange of data and information to address to improve understanding of the resource, promote cross-border cooperation, and enhance water security (Comair et al. 2013; Petersen-Perlman and Wolf 2015).

Improved institutional capacity is also a key factor in enabling international cooperation on groundwater (Conti 2014) and is recommended at both the local and binational level to address transboundary groundwater security (Albrecht et al. 2017). For example, in the Guarani Aquifer System in South America, while an agreement exists, increased institutional capacity is needed to enforce groundwater regulations at a national level, and facilitate cross-border exchange of information (Petersen-Perlman and Wolf 2015; Sugg et al. 2015). Local agreements can be particularly relevant for addressing transboundary challenges in small aquifer systems (Eckstein 2013) and can be more effective when implemented within the context of broader international agreements (Rivera 2015).

8.6.2.2 Transboundary Wastewater Management in the U.S.-Mexico Border

The U.S.-Mexico border provides many examples of transboundary water security challenges, regarding shared surface water, cross-border groundwater aquifers, and transboundary pollution. In the Upper Santa Cruz watershed that extends across the international border between Arizona and Sonora, transboundary wastewater management has been a challenge for the water security for the border region of Ambos Nogales—the sister cities of Nogales, Sonora, and Nogales, Arizona (Fig. 8.10). The Upper Santa Cruz River is problematic in this border region because of wastewater contamination issues that are difficult to solve.

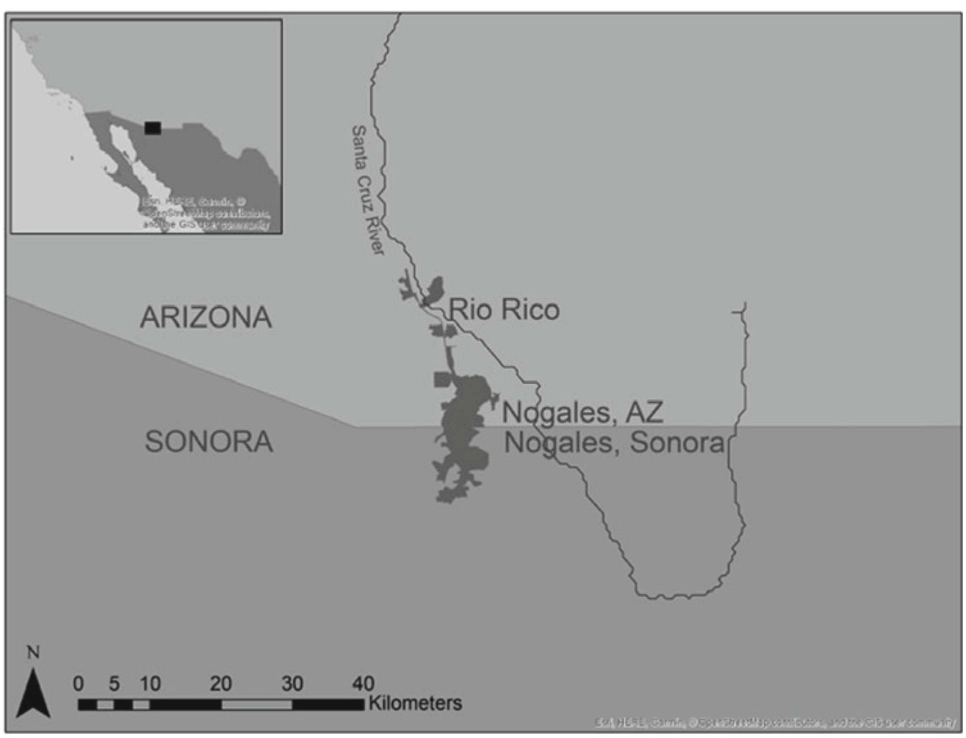

Fig. 8.10 Map of Ambos Nogales—Nogales, AZ, and Nogales, Sonora (*Map* A. Zuniga)

The City of Nogales, Sonora, has a sewer system that runs along the natural drainage system that have been converted to roads. During storm events, stormwater and everything it carries with it, get into the sewage system. These episodes severely affect the U.S. side of the border because Mexican sewage is conveyed and treated in the Nogales International Wastewater Treatment Plant (NIWTP)—located in Rio Rico, Arizona, which is 14 km north of the international border. In addition, the topography of the region causes stormwater runoff to flow northward, into the U.S. The conveyance system that carries Mexican raw water (and trash, gravel, sediment and other solids during a storm event) from the border to the NIWTP is referred to as the International Outfall Interceptor (IOI) tunnel, and desperately needs repairs.

Although repairing the IOI seems like a straightforward solution to the ongoing water contamination problems in the Nogales Creek, it remains unclear whose responsibility it is to pay for the repairs and maintenance of the IOI tunnel. This 14.5 km (9 mile)-long tunnel that runs beneath the Nogales Wash (Fig. 8.11) is disintegrating and its crumbled pipes leak sewage into the wash, posing serious health problems to the population (Kapoor 2017). According to a budget request issued by the International Boundary and Water Commission (IBWC) in 2013, it would cost $100 million USD to repair the IOI tunnel. Neither the City of Nogales nor the U.S. government has reached an agreement on the payment for the repairs. A district court settlement from 2004 ruled that the City of Nogales should be the entity paying for the repairs. But the city refuses to pay not only for the repairs but also for the treatment of its sewage arguing that the 14% of the sewage treated by the NIWTP belongs to the City of Nogales, Arizona and they are charged the equivalent to 23%.

In March 2017, Arizona lawmakers tried to finally establish responsibility for the IOI tunnel and introduced a bill called "The Nogales Wastewater Fairness Act," which states that the IBWC should be responsible for its repairs. The IBWC is part of the U.S. State Department and is responsible to manage boundary issues related to water. This way, the City of Nogales would only cover the costs related to the sewage it produces. However, neither the IBWC nor the City of Nogales has initiated repairs to the IOI (Kapoor 2017).

Mexico is supposed to pay for its wastewater being treated in the NIWTP at the price and amount originally agreed, but the City of Nogales, Sonora, regularly exceeds its agreed amount—particularly during the rainy season—and has not paid the increased cost of treatment because the exceeded amount is billed at a much higher price. Mexican effluent does not come back to Mexico; instead, it flows north along the Santa Cruz River bringing ecological

Fig. 8.11 Nogales Wash lies above the International Outfall Interceptor (IOI) (*Photo* T. Albrecht, with permission)

benefits to the region north of the plant. Effluent sustains riparian vegetation benefitting flora and fauna (including endangered fish species Gila Topminnow), along with property prices along the greening river. Bringing effluent back to Mexico is out of the question because of the huge energy costs that pumping effluent uphill would entail, and the land-tenure issues related to a conveyance system.

Mexico has tried to address the excess sewage sent to NIWTP by building a wastewater treatment plant in a neighboring watershed that does not flow north to the U.S. side. This plant—named "Los Alisos"—started operations in 2012 and its effluent is also bringing ecological benefits in the Mexican side (Flores and Bravo 2012). Nevertheless, during storm events, Mexico will still be sending an exceeding amount of raw water combined with stormwater to the NIWTP through the damaged IOI, polluting the Nogales Creek in the U.S. side of the border.

8.6.3 Cross-Sectoral Water Security Linkages

At the international level, water-security discourses are tightly linked to the notion of the water-energy-food security nexus. Water, energy, and food resources are innately interlinked, and their production and use create tradeoffs in other resource sectors—thus understanding water security must also consider energy and food sectors (Albrecht et al. 2018a, b; World Economic Forum 2011; Zeitoun 2011; Shah et al. 2003). The notion of the water-energy-food security nexus was introduced in the early 2000s as an approach to identify tradeoffs and synergies among water, energy, and food systems (Shah et al. 2003; Hoff 2011; Albrecht et al. 2018a). The nexus security framing suggests that water, food and energy systems must be considered together in order to optimize resource use and economic efficiency, increase policy cohesion across sectors and advance sustainable outcomes (Albrecht et al. 2018a; Wada 2017). However, water, energy, and food systems each operate on different spatial and temporal scales and are mobilized in the global economy in different manners based largely on their different physical characteristics (Bijl et al. 2018). Thus, international trade is an important mechanism through which water-scarce regions to increase their effective water security via importation of water-intensive goods, or "virtual water" (Allan and Mirumachi 2013).

Water-energy-food security nexus approaches (see also Chap. 17) have been promoted via transboundary water management vehicles, for example nexus assessments of transboundary river basins were planned as part of the 2013–2015 work program of the UNECE Water Convention (de Strasser et al. 2016; UNECE 2012). Water-energy-food system linkages are being assessed in pilot transboundary basins worldwide in an effort to evaluate cross-sectoral tensions and test a nexus assessment methodology at the transboundary scale (de Strasser et al. 2016). Researchers found that a nexus approach allowed participants to traverse politically-sensitive issues and provided a broader range of tradeoffs by incorporating multiple sectors in negotiations (de Strasser et al. 2016: 17). By integrating key economic sectors into the transboundary water dialogue, this effort aims to examine how a nexus approach can improve transboundary water cooperation.

In their research of "security" framings within one well-known river basin organization, the Mekong River Commission (MRC), Gerlak and Mukhtarov (2016) found an anthropocentric framing of security that places emphasis on water for human needs like agriculture, energy production, and fisheries. Yet, they also observe a heightened attention to multiple forms of security, including food, energy and water security, and the linkages between these types of security. Their work uncovers an emphasis on security and the links it brings to food and energy security at the regional level of water governance, placing an emphasis on the MRC to help countries address water insecurities.

In the Nile River Basin, a market-based approach allows limited freshwater supplies in Egypt and Sudan to be augmented by imports of 'virtual water' embedded in food products that have high water requirements for production (Zeitoun et al. 2010). By highlighting the magnitude of water leaving and entering states "virtually," the approach "obliges policy-makers to think beyond the basin and reconsider the concept of water security within broader political, environmental, social and economic forces" (Zeitoun et al. 2010: 229). This research calls attention to sub-basin political and economic dynamics, suggesting that water and food security analysis would benefit from a shift away from the more dominant and less flexible inter-state basin-wide approach.

We have traced the discourse of water-security in transboundary water contexts, exploring how state-centric frames have evolved into interstate cooperation and regional collective approaches. In some cases, the water-security discourse supports cooperation toward sustainable and shared water-resources management in international basins. But at other times, such discourse complicates advances toward the underlying goals of the concept—access, availability, and sustainability.

When the water-security discourse is conflated with national security, or when it privileges the national scale within a transboundary context, it can be a barrier to effective water management. A key to promoting a broad and equitable approach to water security in international basins will be focusing on regional collective concerns, high levels of participation at multiple levels, and improved institutional capacity to address binational and multinational cooperation.

8.7 Conclusions

We opened this chapter by stating that we intended to explore the advent and adoption of a term, "water security," with rising popularity in academic and policy circles. In particular, we wished to determine whether water security—a concept with multiple definitions and as many understandings—could serve as a useful framing mechanism that does not contain too many "hostages to fortune" that could get in the way of progressive scholarship and practice.

To attempt to answer that thorny question, we first delved into the various and diverse framings and paradigms of water governance that have emerged and gained favor over the past half-century or so. The importance of history to understanding the evolution of these framings cannot be overstated. New paradigms like 'water security' do not happen in isolation. They are connected to all sorts of contexts, actors, activities, trends, and other path-dependencies that make them more or less tractable and more or less impactful.

The collection of framings we chronicled led us to the central theme of this chapter: *the water security discourse*, whose antecedents wind through a web of paths—conceptual, disciplinary, and practical. After surveying the not inconsiderable range of available definitions, we arrived at our own composite understanding: "*Water security is the availability of adequate quantities and qualities of water for societal needs and resilient ecosystems, in the context of current and future global change.*" (see also Sect. 8.2.2).

Next, we examined the larger field of actors and adopters, looking closely at local and national as well as transnational water-security user communities. We wanted to know the range of practical uses and interpretations of water security. Then, we sought to come to terms with a commonly asked question: *Can water security be reliably assessed and measured? And if so, how effectively and how reliably?* Next, we offered some real-world examples of water security—urban and rural settings, hard-path vs. soft-path approaches, adaptive management opportunities, and conflictual situations. We ended our exploration by examining water-security framings for international and transboundary cooperation.

Having reviewed and discussed the above facets of water security, we pose, and attempt to answer, a number of concluding questions.

First, *is water security a useful framing mechanism?* We see distinct usefulness in the concept because it adds a purpose for water-management approaches. The notion has been picked up by international organizations as a way to focus on a common agenda item—to make the world less insecure—in this instance, by providing sufficient quantities of clean water to people and to the environment, now and in the future. We also see this concept as having been adopted by global water initiatives—most notably the Millennium Development Goals (through 2015) and Sustainable Development Goals (from 2016). These ambitious global efforts, complemented by numerous worldwide conferences and events, have built on previous concepts such as IWRM and thereby promoted sustainable water management.

We then ask, *has water management been enhanced by applying water-security framings in actual settings*? The diversity of actors and the scope of their involvement in water security is perhaps its most noteworthy feature—at all levels, including the transnational level. This diversity isn't uncommon in the world of water more generally, but it is significant that so many institutions and users have plucked ideas that they consider beneficial to their missions and objectives from the water-security "basket." Among those attributes, a critical one is the growing acceptance of the *community context* of water management and governance. According to this view, water security should be used and shaped by the community, relative to the definition adopted and how it is employed. It also suggests that the community—and most particularly, stakeholders—should determine which indices or measurements are adopted and how they are employed and interpreted. This applies to transboundary watersheds as well. In international settings, water-security framings are best utilized to inspire regional cooperation on collective beneficial action (Appelgren and Klohn 1997).

Given the distinct differences—especially regarding water use—between rural and urban settings, our next question is: *is water security useful in both urban and rural situations?* While the concept has been used more commonly in rural settings (e.g., farming, ranching, mining, habitat protection), with rapidly increasing urbanization, we see urban environments as having growing impact on watershed management. As land-use change, climate change, and expansion of urban infrastructure alter the hydrological cycle, cities are intrinsically linked to water-resources management. In addition, as cities grow and water demand increases, reclaimed water and rainwater are increasingly being seen as potential water sources. Here, green infrastructure has risen as a promising approach to enhance water security in cities and beyond.

So finally: *is water security likely to be an enduring concept?* Predicting the future of concepts is a hazardous endeavor. Certainly, it must be acknowledged that water security as a framing device, while it has proven useful in many settings, has some built-in limitations. As we have seen, global water-management frameworks, like other such categorization devices, are subject to social and intellectual movements, paradigm shifts, and political winds. New concepts and framings are being added continuously. Water security, like all such formulations can be seen as amorphous, imprecise, and hard to measure. Its effectiveness in any given context will always depend on which of its many definitions is considered and by whom. Water security has demonstrated considerable staying power and resilience, yet it remains difficult to know whether the concept is an ephemeral one or if it will remain in the lexicon. We believe that the crux of the notion has universal appeal and will likely endure.

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Robert G. Varady is Research Professor of environmental policy at Udall Center for Studies in Public Policy at, where he was previously director, and is also adjunct professor of Hydrology and Atmospheric Sciences and in the School of Natural Resources and the Environment—all at the University of Arizona. He obtained his Ph.D. in 1981 in modern history at the University of Arizona, and holds M.S. and B.S. degrees in mathematics from the Polytechnic Institute of Brooklyn and the City College of New York, respectively. Varady's work mostly has addressed water governance and policy in arid regions, with an emphasis on transboundary issues. He has co-edited 13 volumes and journal special issues; published some 225 articles; and made more than 250 presentations at conferences, symposia, seminars, workshops, and other venues.

Tamee R. Albrecht is a Ph.D. Candidate in the School of Geography, Development and Environment and a Graduate Research Associate with the Udall Center for the Studies of Public Policy at the University of Arizona. She earned her M.S. in Hydrology from the Colorado School of Mines and B.S. in Geology from the University of Massachusetts-Amherst. Her research focuses on water governance and interactions among water, energy, and food resources, particularly in transboundary contexts.

Chad Staddon raised in Vancouver, Canada, and educated in Canada and the USA, Chad has worked and researched North and Central America, Western and Eastern Europe and, to a lesser extent, in Asia and Africa. His key areas of expertise are resource economics and policy, water conservation and water related technology and engineering for urban resilience. His current teaching is almost entirely in the areas of water resource efficiency, water services in the developing world and water-related resilience. Staddon has over 80 publications, has given more than 100 invited lectures and seminars worldwide and has held research grants from Canadian, US, UK and EU sources. He is currently Professor of Resource Economics and Policy at the University of the West of England, Bristol, and Founder-Director of the International Water Security Network.

Andrea K. Gerlak is an Professor in the School of Geography, Development and Environment and Interim Director and Research Professor at the Udall Center for Studies in Public Policy. Her research and teaching focus on institutions and environmental governance. She examines cooperation and conflict around water, including questions of institutional change and adaptation to climate change in rivers basins, and human rights and equity issues in water governance. Gerlak is a senior research fellow with the Earth System Governance Project and serves as a co-editor for the *Journal of Environmental Policy and Planning*. She holds a B.A. in political science from the University of Nevada, Las Vegas, and a Ph.D. in political science from the University of Arizona.

Adriana A. Zuniga-Teran is an Assistant Research Scientist at the University of Arizona's Udall Center for Studies in Public Policy and the School of Landscape Architecture and Planning. With a background in architecture and expertise in neighborhood design, Adriana combines knowledge-building with problem-solving of real-world challenges in her research projects. Adriana works with stakeholders and community partners to answer questions related to water security, urban resilience, and environmental justice, by focusing on greenspace/green infrastructure across the urban-rural continuum. Adriana is originally from Monterrey, Mexico. She did her undergraduate studies on architecture at Monterrey Tech (ITESM) and worked as an architectural designer in Mexico for several years. She holds two advanced degrees from the University of Arizona: A Master of Architecture degree with a concentration in design and energy conservation, and a doctoral degree in Arid Lands Resource Sciences with a minor in Global Change.

Water Governance and Policies

9

Claudia Pahl-Wostl, Ines Dombrowsky, and Naho Mirumachi

Abstract

Failure at multiple levels of governance rather than the resource base itself is at the origin of the water crisis. Despite increasing scholarly research on water governance and efforts towards policy reform the overall situation has not substantially improved and major transformations in water governance are yet to be implemented. The chapter summarises and addresses multi-level and multi-sectoral challenges for water governance by reviewing and discussing several key concepts in science and policy. An analysis of basin scale approaches and their effectiveness and a discussion of the importance of scale and of multi-level governance approaches shows that crossing boundaries is essential to tackle complexities of sustainable water governance and management. The concept of the WEF nexus is introduced and critically analysed concerning its potential to overcome sectoral fragmentation and sectoral power imbalances. Crossing boundaries also implies governance across national borders. The sub-chapters on transboundary water management and on global water governance address these international and global dimensions. Overall, the chapter highlights from different perspectives the importance of linking and of governing across scales from the local to the international and global.

Keywords

Multi-level water governance • River basin management • Water-energy-food nexus • Transboundary water governance

List of Abbreviations

EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
GWP	Global Water Partnership
INBO	International Network of Basin Organisations
IWRM	Integrated Water Resources Management
MDGs	Millennium Development Goals
MRC	Mekong River Commission
OECD	Organisation for Economic Co-operation and Development
OMVS	Organisation for the Development of the Senegal River
RBOs	River Basin Organisations
RBM	River Basin Management
SDGs	Sustainable Development Goals
TVA	Tennessee Valley Authority
UNFCCC	United Nations Framework Convention on Climate Change
UNSGAB	United Nations Secretary-General's Advisory Board on Water and Sanitation
UN-WATER	United Nations Water
WEF	Water-Energy-Food
WFD	Water Framework Directive
WTO	World Trade Organisation
WWDR	World Water Development Report

C. Pahl-Wostl (✉)
Institute of Geography and Institute of Environmental Systems Research, Osnabrück University, Osnabrück, Germany
e-mail: cpahlwos@uni-osnabrueck.de

I. Dombrowsky
Programme "Environmental Governance and Transformation to Sustainability", German Development Institute/Deutsches Institut für Entwicklungspolitik (DIE), Bonn, Germany
e-mail: ines.dombrowsky@die-gdi.de

N. Mirumachi
Department of Geography, King's College London, London, UK
e-mail: naho.mirumachi@kcl.ac.uk

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9.1 Introduction

The crisis of water is largely a crisis of governance (OECD 2011). Many water related problems can be attributed to governance failure at multiple levels of governance rather than to the resource base itself. Despite increasing scholarly research on water governance and efforts towards policy reform the overall situation has not substantially improved and major transformations in water governance are yet to be implemented (Pahl-Wostl 2017).

The history of water governance can be summarised as an evolution towards increasing complexity to do justice to the issues pertaining to a sustainable governance and management of water resources. This complexity poses a major challenge not necessarily owing to the lack of physical water availability. The development of water governance reflects the overall, though gradual, shift in our understanding of the role of government as the central actor in water policy to one that is increasingly embedded in a more comprehensive context of water governance. A diversity of meanings and interpretations is coming along with the increasing popularity of the water governance concept. The original version of a now widely used definition can be attributed to the United Nations (UN): "The governance of water in particular can be said to be made up of the range of political, social, economic and administrative systems that are in place, which directly or indirectly affect the use, development and management of water resources and the delivery of water services at different levels of society" (United Nations 2006). This definition highlights that water governance is a complex multi-actor and multi-level process. The definition has a descriptive rather than analytical focus. Based on a review of a range of definitions on governance in the environmental field, Claudia Pahl-Wostl introduced the following definitions: "**Water governance** is the social function that regulates development and management of water resources and provisions of water services at different levels of society and guides the resource towards a desirable state and away from an undesirable state. A **water governance system** is the interconnected ensemble of political, social, economic and administrative elements that performs the function of water governance. These elements embrace institutions as well as actors and their interactions" (Pahl-Wostl 2015). The notion of governance as "a social function centred on steering human groups toward desired outcomes and away from undesirable outcomes" introduced by Oran R. Young highlights the role of governance in a societal context—in particular in contrast to the steering role of government (Young 2013). It also highlights the normative character of governance as a societal function with a certain purpose. This purpose and how it should be achieved needs or should be negotiated among the various stakeholder groups involved. The evolution of water governance systems is characterised by a general trend of shifting from command-and-control as the guiding principle towards embracing as well market-based and participatory approaches. Thus, it is meaningless to devise universalised models of water governance guiding policy reform and critiques have been made towards seeking panaceas (Ingram 2011). Diverse historical, political, societal, economic and environmental contexts result and may need also different water governance systems (Pahl-Wostl 2015; Pahl-Wostl et al. 2012). In contrast, water management refers to the activities of analysing and monitoring water resources, as well as developing and implementing measures to keep the state of a water resource within what has been negotiated as desirable bounds (Pahl-Wostl 2015).

The shift towards embracing complexity is also reflected in the integration of spatial scales and issues. Whereas water had traditionally been perceived as a local problem, the river basin was promoted as the preferred spatial scale at which water should be managed. The emphasis on a preferred scale is being increasingly countered with the insight that water governance is a multi-level challenge and increasing efforts are devoted towards vertical and horizontal integration. Integrated Water Resources Management (IWRM) has been a dominant paradigm for sustainable water management since the 1990s. However, it has become increasingly evident that integrated water management cannot be realised by the water sector on its own. The concept of the water-energy-food nexus aims at overcoming sectoral boundaries. But it may fail if there is little consideration of the political dimensions and power constellations that transcend multiple scales and boundaries and if other sectors where water is used are not accounted for. The political dimension becomes particularly prominent in international river basins. A nexus concept is also essential for an effective implementation of the Sustainable Development Goals (SDGs). These are formulated as individual goals but the Agenda 2030 specifies that these can only be implemented if interdependencies, synergies and trade-offs are taken into consideration. The SDGs may be powerful drivers towards more sustainable water governance (Bhaduri et al. 2016). However, this requires a strengthening of water governance at the global scale and at the same time, a closer inspection of how SDGs translate at the local level.

The chapter addresses these multi-level and multi-sectoral challenges for water governance by reviewing and discussing several key concepts in science and policy. After an analysis of basin scale approaches and their effectiveness, the importance of scale and of multi-level governance approaches is discussed in more depth. During these elaborations, it becomes already evident that crossing boundaries is essential to tackle complexities of sustainable water governance and management. The concept of the WEF nexus is then introduced and critically analysed concerning its potential to overcome sectoral fragmentation and sectoral power imbalances. Crossing boundaries also implies governance across national borders. The sub-chapters on transboundary water management and on global water governance address these international and global dimensions. Despite this focus, both sub-chapters highlight as well the importance of linking and of governing across scales from the local to the international and global, an insight that guides the whole chapter.

9.2 Basin Scale Approaches and River Basin Organisations

9.2.1 The Concept of River Basin Management

For a long time, water management and related governance had mainly been perceived as a local issue (Molle 2009). However, since the second half of the 18th century, the concept of the river basin as a hydrological drainage area developed (Molle 2009). Since that time, the river basin has repeatedly been put forward as a spatial unit to manage and govern water resources, even if that was done with varying motivations (ibid.).

The concept of River Basin Management (RBM) calls for a management of water resources at the level of river basins. The call for RBM frequently goes along with the demand for the set up special purpose organisations that govern and manage water at the river basin scale, so called River Basin Organisations (RBOs) (Rogers 1997; Serageldin et al. 2000). Economists have long argued that the river basin provides—at least theoretically—an opportunity to internalise externalities and to develop water resources in an optimal manner (Rogers 1997; Sadoff et al. 2002; Kneese and Bower 1968). Ecologists have argued that a basin perspective is needed for an ecologically sustainable use of water (Newson 1992). In contrast, as explained further below, political scientists often also point to obstacles towards RBM given that the basin scale and the administrative scale of political jurisdictions usually do not match. This raises the question how effective RBOs prove to be as governance mechanisms.

In the 19th century, RBM largely remained a utopia in countries such as Great Britain, France, Spain or the United States (Molle 2009). However, the first half of the 20th century saw the setup of different types of RBOs in several industrialised countries, mostly in order to promote the hydraulic mission (Allan 2003) of 'marshalling' of water resources for industrialisation, agricultural development and energy generation, and partly, to deal with pressing water pollution issues. In the USA, the famous Tennessee Valley Authority (TVA) was established in 1933 as a means to promote economic development of the hitherto poor region based on complex hydraulic engineering works. In France, the *Compagnie Nationale du Rhône* was founded in 1921 and in Spain, *Confederaciones Sindicales Hidrográficas* in 1926 with similar missions. In the highly industrialised state of North-Rhine Westphalia in Germany, several smaller scale multi-actor river boards or associations (*Wasserverbände*) were created in order to develop water resources and deal with industrial pollution. In the United Kingdom, in the 1930s, Commissioners of Sewers were abolished and drainage districts erected based on 47 catchment areas, to be transformed into all-purpose Regional Water Authorities in 1974. The French *Agences Financières de Bassin* were set up in 1964 (Molle 2009; Kneese and Bower 1968; Teclaff 1996; Barrow 1998). As, François Molle lays out, most of these organisations experienced several transformations and served different political interests and purposes over time (Molle 2009). This notwithstanding, after World War II, all over the world attempts were made to copy the TVA as development model in developing countries (UN 1958), albeit with mixed results (Rangeley et al. 1994). Examples include the Organisation for the Development of the Senegal River (OMVS), the Mekong River Commission (MRC) and its precursor organisations, and lately, the so far unsuccessful attempt to convert the Nile Basin Initiative into fully fletched RBO, given the failure so far to reach a basin-wide agreement (e.g. Cascao 2009; Tawfik and Dombrowsky 2018; Schmeier 2013; Motlagh et al. 2017). From the late 1970s to the early 1990s, a certain dismissal of the river basin concept could be observed as pollution problems dominated in many industrialised countries, which were mainly dealt with through the treatment of point-sources (Molle 2009). Also, at a global scale the environmental and social impacts of large engineering works became ever more apparent.

However, since the early 1990s, RBM gained new momentum as part of the discourse on Integrated Water Resources Management (IWRM), this time with a greater emphasis on ecological sustainability. IWRM evolved as a response to shortcomings of narrow engineering and sectoral solutions to water governance (Hartje 2002). It calls for more integrated approaches to water management and governance, including the integrated management of water quantity and quality, surface water and ground water, water and land resources, human and ecological demands, upstream and downstream uses as well as different water using sectors (GWP 2000). The Global Water Partnership defines IWRM as "a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP 2000). By emphasising coordination processes, the GWP definition of IWRM implicitly points at the fact that IWRM cannot only be understood as a management, but also a governance concept (Horlemann and Dombrowsky 2012).

While the GWP definition of IWRM does not explicitly refer to the basin scale, IWRM is usually associated with management of water resources in river basins. More specifically, RBM was explicitly mentioned as an underlying concept of the 1992 Dublin Principles on IWRM and Agenda 21 and has been advocated by the 1993 World Bank Water Policy, the US Environmental Protection Agency and most international water conferences in the 1990s and 2000s (ICWE 1992; EPA 1996; World Bank 1993; UNCED 1992). In terms of the global diffusion of IWRM and RBM, the Plan of Implementation of the 2002 Johannesburg World Summit on Sustainable Development called upon all countries to develop "integrated water resources management and water efficiency plans by 2005, with support to developing countries", including "strategies, plans and programmes for integrated river basin, watershed and groundwater management" (UN 2002). However, the short timeframe for preparing these plans has subsequently been heavily criticised (e.g. Molle 2008). In Europe, RBM has been enshrined as legal requirement of the European Water Framework Directive which seeks to establish a good ecological status for all European water bodies (even if it has been disputed that the WFD suffices the IWRM concept (Rahaman et al. 2004; Beveridge and Monsees 2012; Heldt et al. 2017; EU 2000). A further actor promoting RBM is the International Network of Basin Organisations (INBO), a network of basin organisations, government entities in charge or water and bi- and multilateral cooperation agencies, established in 1994 (INBO 1994). In the IWRM- and WFD-related conceptualisations of RBM, the emphasis is less on economic, but more on sustainable development and ecological integrity. It is hence being argued that taking the river basin as management unit allows for reconciling upstream and downstream interests as well as economic, social and ecological demands on water resources and as such for a sustainable use of water resources (Molle 2009; Newson 1992).

Consequently, and in particular in response to the Johannesburg Plan of Implementation, many additional countries have started to institutionalise RBM, partly also in response to respective demands by donor organisations. In 2012, 113 of 130 countries (or 87%) reported in an UN-survey they have started to set up mechanisms for RBM, and 44% of the countries stated that implementation was advanced (UNEP 2012).

9.2.2 The Institutionalisation of RBM and Types of River Basin Organisations

GWP and INBO put forward that a river basin organisation's main mandate is to be the 'leading voice' on river basin management and to take a 'big picture' perspective on basin-wide water issues (GWP and INBO 2009). The design, jurisdiction and scope of responsibility of RBOs can, however, vary considerably and various types and forms of river basin organisations exist in national and international river basins worldwide. Even terms such as 'basin commission', 'basin council' or 'basin authority' can have different meanings from case to case (Teclaff 1996; Burchi 1985) and can therefore not necessarily be associated with a particular type of organisation. Bruce P. Hooper identifies a total of nine different categories that are being used to describe RBOs (Hooper 2006).

From a conceptual point of view, Erik Mostert distinguishes two 'archetypes' of RBOs operating within countries (Mostert 1998). In the 'hydrological model', special river basin organisations equipped with specific executive powers, budgets etc. are being set up. In the 'coordinated model', river basin commissions coordinate existing general-purpose jurisdictions at the river basin level. Volkmar Hartje observes that while several unitary states including France, Spain and the United Kingdom adopted what Erik Mostert refers to as hydrological model of RBOs, federal countries seem to be more inclined towards the coordinated model (Hartje 2002). For instance, when Germany had to decide how to institutionalise the WFD, the Federal Government and the Federal States ('Länder') responsible for water management from the beginning opted for the coordinated model, in order to avoid constitutional problems associated with setting up new agencies that cut across the Federal States (LAWA 2001; Moss 2012; Petry and Dombrowsky 2007). Similarly, in the USA the Federal States tend to coordinate water resources management through river basin compacts (Schlager and Blomquist 2008).

Dave Huitema and Sander Meijerink further refined Erik Mostert's typology, suggesting four ideal types, drawing upon Elinor Ostrom's grammar of institutions (Kiser and Ostrom 1982; Huitema and Meijerink 2014, 2017). On this basis Dave Huitema and Sander Meijerink distinguish autonomous RBOs, agencies, coordinating RBOs and partnerships depending on certain combinations of authority, boundary, aggregation, information and pay-off rules: "Autonomous river basin organisations have a constitutionally guaranteed independent position and have their own mechanisms for democratic control. Agencies (…) are created by the state to perform a limited number of specialised tasks at arms' length from the government; they are accountable only to (parts of) government. Coordinating river basin organisations are collaborations of the founding government partners and respond to them. Partnerships are bottom-up initiated governance arrangements which are accountable to their participants, which include civil society organisations" (Huitema and Meijerink 2014).

Dave Huitema and Sander Meijerink compared RBOs in basins in eleven developed and developing countries, responsible for the management of river basins or sub-basins

Table 9.1 Characterisation and performance of RBOs in eleven basins

Name of RBO	Country	Type of RBO	Performance measure	
			Coordination	Environmental effectiveness
Mackenzie River Basin Board	Canada	Coordinating	Poor	Poor
Oregon Watershed Enhancement Board	United States of America	Agency	Good	Average
Westcountry Rivers Trust	United Kingdom	Partnership	Good	Good
Erftverband	Germany	Agency	Good	Good
River Basin District Authorities	Portugal	Autonomous	Average	Unknown
Breede-Overberg Catchment Management Agency	South Africa	Agency	Good	Unknown
Western Bug River Basin Administration + Council	Ukraine	Agency + Coordinating	Poor	Unknown
Lower Kunduz and Taloquan River Basin Agencies + Councils	Afghanistan	Agency + Coordinating	Poor	Poor
Mongolian River Administrations + Basin Councils	Mongolia	Agency + Coordinating	Poor	Unknown
Ping River Basin Committee + Mae Kuang Sub-basin working group	Thailand	Both Coordinating	Poor	Poor
Murray-Darling Basin Authority + Ministerial Council + Community Committee	Australia	Agency + Coordinating + Coordinating	Average	Unknown

Source Adaptation based on Meijerink S, Huitema D (2017)

that lie within single countries (Huitema and Meijerink 2014, 2017; Meijerink and Huitema 2017) (see Table 9.1). While these cases represent RBOs the authors of the edited volume were familiar with and not a random sample of a total population of RBOs, it is interesting to note that the large majority of these cases are either agency or coordinating types, and the selection included one autonomous and one partnership type RBOs only. In addition, several basins have both an agency and a coordinating type of RBO in place in parallel. Overall, the authors conclude that the cases do not provide evidence of a shift of power from the nation state to the RBOs. They rather see RBOs are examples of 'institutional layering', meaning that a new institution is added in addition to existing general-purpose jurisdictions without replacing them (Meijerink and Huitema 2017). They also do not find a linear pattern of RBO development. In the cases studied, decisions in RBOs were either made by unanimity or consensus. The geographical scope of most RBOs was not based on hydrological criteria only and in most RBOs decision-making was primarily based on scientific as opposed to traditional or experimental knowledge (ibid.).

In addition to RBOs for basins within single countries, for transboundary rivers, often international RBOs have and are continuously being set up (e.g. Schmeier 2013; Dombrowsky 2007) (see Sect. 9.5). To the knowledge of the authors, no comprehensive compilation of RBOs worldwide exists. However, it is worthwhile to mention that jointly with INBO, Ariel Dinar and colleagues identified a total of 197 national and international RBOs worldwide (Dinar et al. 2005; Dinar et al. 2007).

9.2.3 The Problem-Solving Capacity and Effectiveness of RBOs

From a social science perspective, RBM can be understood as a response to so called problems of spatial fit that may arise as a result of a mismatch between institutional arrangements—in this case general-purpose jurisdictions—and biophysical systems and their properties (Young 2005). Problems of spatial fit occur when a "lack of fit causes spatial externalities, benefiting free riders and harming others beyond the spatial reach of the responsible institution" (Moss 2004). The assumption is that the better the fit between administrative and natural systems, the more effective the institution and the more sustainable the outcome will be (Young 2005). The conventional answer to problems of spatial fit in water management is to internalise spatial externalities through the management of water resources at the river basin level (Rogers 1997; Moss 2004; Mitchell 2005; Dombrowsky 2008; Herrfahrdt-Pähle 2010). RBOs are often considered as a means to do so (even if externalities may also be internalised through other means). However, while RBOs may solve 'problems of spatial fit' between hydrological and political boundaries, it has been argued they may create new problems of spatial fit between RBOs and existing general-purpose jurisdictions which in turn can also be interpreted as 'problem of institutional interplay' (e.g. (Horlemann and Dombrowsky 2012; Moss 2004; Herrfahrdt-Pähle 2010; Moss 2003). Hence, the question arises how effective RBOs may prove to be.

Overall, measuring the effectiveness of RBOs is conceptually and empirically demanding (Huitema and Meijerink 2017). This pertains in particular to issues of attribution since outcomes may be influenced by many factors beyond RBOs and due to potential time lags between the establishment of an RBO and the implementation of measures. In addition, for various reasons (e.g. leadership, strategy, context) the effectiveness of an RBO may vary over time. While numerous single case studies on various aspects of RBM exist countries, more rigorous comparative work on RBOs and their effectiveness remains limited. Karin E. Kemper, William Blomquist and Ariel Dinar carried out a combined quantitative and qualitative study on the decentralisation of water management in river basins (Kemper et al. 2010). Their econometric analysis of decentralisation processes in 83 river basins finds that the success of the decentralisation process in basins critically hinges on the budgets of the RBOs, with continued central government support as well as revenues generated and remaining within the basin proving to be important explanatory variables (Dinar et al. 2007). However, interestingly they also find that basins with higher budget per capita did not necessarily outperform those with lower levels and that decentralisation of water management was more successful in basins in federal than in unitary countries (ibid.). This was complemented by a comparative qualitative analysis of eight RBOs in developed and developing countries. Based on this analysis, William Blomquist, Ariel Dinar and Karin E. Kemper conclude that "[v]ery different institutional and legal structures may lead to positive performance results" (Blomquist et al. 2010).

Edella Schlager and William Blomquist studied the politics of watershed management in several basins across the United States (Schlager and Blomquist 2008). They conclude: "it appears to us that effective management of watersheds cannot be comprehensive and integrated into a single jurisdiction, but neither can it be the job of non-governmental collaborative partnerships alone" (Schlager and Blomquist 2008). Instead, what seems to work in the USA is a polycentric, federal governance style that is characterised by nested and overlapping jurisdictions, differentiation among organisations by functions and scales, representation of diverse communities and various modes of decision-making (Schlager and Blomquist 2008; Bogardi et al. 2012).

To our knowledge, the most rigorous comparative analysis of the effectiveness of RBOs within single countries has been presented by Dave Huitema and Sander Meijerink (Huitema and Meijerink 2014). The RBOs in eleven countries presented in Table 9.1 were analysed in terms of their ability to enhance coordination, accountability, legitimacy and environmental effectiveness. Overall, the cases show a very mixed result for each of these performance measures, including instances of good, average and poor performance for the various categories (see Table 9.1, illustrated for coordination and environmental effectiveness). While one important argument for the establishment of RBOs is that they may support coordination between different sectors, interests and levels of government, coordination was rated as good in four, average in two and poor in five of the eleven cases. Assuming that RBOs take ecological issues more seriously than general-purpose jurisdictions, the criterion environmental effectiveness referred to attaining a good ecological status. Rating environmental effectiveness turned out to be challenging, not least due to issues of attribution and potential time lags between the establishment of an RBO and the implementation of measures that improve ecological status. Hence, while two RBOs were rated as good and one as average for this criterion, three were rated as poor and in five cases environmental effectiveness remained unknown. This reinforces that studying the effectiveness of RBOs remains challenging methodologically and that our knowledge on the environmental effectiveness of RBOs remains limited. Still, overall three RBOs were rated good for all or almost all criteria, including the German Erftverband, the British Westcountry Rivers Trust and the American Oregon Watershed Enhancement Board. In contrast, many of the RBOs that performed poorly in all or many categories were found in developing countries (for the Mongolian case see Dombrowsky et al. 2014).

Hence, there is growing consensus that many forms may work. However, no superior form of RBO can be found in the literature. Still, an increasing number of authors question what Dave Huitema and Sander Meijerink refer to as autonomous and agency type RBOs. Similar to Timothy Moss (Moss 2012; Moss 2004), Sander Meijerink and Dave Huitema conclude that "spatial fit between problems and institutions is no guarantee of good performance" (Meijerink and Huitema 2017). Instead, given that RBOs usually constitute an additional layer on top of existing multi-purpose jurisdiction, the effectiveness of RBOs hinges much more on their ability to manage 'institutional interplay' with and their connectivity to the existing institutional environment. A further prerequisite for their effective functioning are sufficient financial resources (Meijerink and Huitema 2017; Dinar et al. 2007). However, Sander Meijerink and Dave Huitema warn that the establishment of strong autonomous or agency type RBOs with strong powers and resources may end up being a Pyrrhus victory, given that more opponents may be inclined to regain power or to hinder the RBO's success. They believe that "lighter, coordinating or partnership types of RBOs is a more effective strategy in the long run because such RBOs meet with less resistance" (Meijerink and Huitema 2017). Jeroen Warner, Philipus Wester and Alex Bolding argue that "[m]oving towards sustainable river basin management requires much more emphasis on developing, managing, and maintaining collaborative relationships for river basin governance, that build on existing organisations, customary practices, and administrative structures, rather than the current focus on the establishment of unitary river basin organisations" (Warner et al. 2008). Bruce Lankford and Nick Hepworth point out that a polycentric model of RBM may be more appropriate for regions such as Sub-Saharan Africa which is "institutionally, organisationally and geographically more decentralised, emphasising local, collective ownership and reference to locally agreed standards" (Lankford and Hepworth 2010). This, however, means that it is not so much the form of RBM which matters, but what matters is that various actors in water governance and management have coherently defined and coordinated tasks, and that the process of water governance and management is well coordinated and managed (Dombrowsky et al. 2014). In any case, it is likely that the "…endless search for elusive governance systems that would unite nature and society" will go on (Molle 2009), even with very limited prospect to find the silver bullet solution. However, this does not mean that careful design of RBOs would not matter.

9.3 Scales and Geographies of Water Governance

9.3.1 Multiple Levels of Scale in Water Governance

The previous section on river basin management described how the hydrological boundaries have been used as a way to organise the scale at which water is managed. However, it has been argued that water governance analysis has a tendency to focus on a singular level of scale when in fact governance needs to be multi-levelled to deal with complexities (Pahl-Wostl et al. 2008). Indeed, as the critiques of the previous section showed, while river basin organisations aim at overcoming problems of spatial misfit between jurisdictions and hydrological systems, RBOs themselves may create new problems of spatial misfit (or problems of interplay) with existing government agencies (Moss 2012). Taking a multi-levelled approach begins to recognise how to address scalar (mis)fit.

While the river basin scale has been the main focus in the institutionalisation of water management in the examples above, local, national and global governance also exist. The local level is characterised by decentralised efforts of water governance for context-appropriate solutions with attention to local rights, needs and stakeholders involved (e.g. van den Brandeler et al. 2018). National level governance seeks to ensure gains for the state and its people, often laying out framework conditions for using water or for the provision of basin public goods. In addition, at global level a range of formal and informal structures involving both state and non-state actors exist to manage global dimensions of water (see Sect. 9.6). These levels of governance are not mutually exclusive and shed light to water issues unique to spatial levels but are influenced by and influencing matters at other levels (Pahl-Wostl et al. 2008). In this regard, the problem of scale misfit should not direct water governance to seek remedies per se. Rather this problem indicates that we ought to be "paying less attention to the structure of an authority responsible for managing a river basin and far more to the interactions among the multiple organisations affecting water use within a basin" (Moss 2012).

Despite the debate on water governance increasingly shifting in its focus away from a single level to multiple levels of governance, there is no clear, broadly adopted definition of multi-scaled water governance. Multi-scale often emphasises spatial considerations. Temporal scale is also important as hydrological and climatic conditions change. Within a spatial or temporal scale, an intervention at a particular level can result in changes at other scales, causing cross-scale impacts (Dore and Lebel 2010). Joyeeta Gupta, Claudia Pahl-Wostl and Ruben Zondervan argued for *glocal* water governance where a global normative framework acknowledging the global drivers of water demand and global influences on hydrological systems are contextualised and adapted at the local level of implementation (Gupta et al. 2013). This notion reflects an idea that scales of water governance are "a joint product of biophysical and social processes; they are not unambiguously defined by the physics of flows, the dynamics of ecosystems, or social institutions" (Dore and Lebel 2010). Critical perspectives of water governance go further to suggest that these biophysical and social processes can also be used to exercise political power, making scales of water governance a politically charged issue. Based on political ecology, Alice Cohen and Karen Bakker argued that scales are not given or natural. Instead, they are socially constructed to facilitate environmental management (Cohen and Bakker 2014). In fact, governance can be rescaled so as to seemingly address environmental problems but divest responsibilities or place burdens, resulting in uneven development (Cohen and Bakker 2014). In this regard, there are 'winners' and 'losers' that emerge from the 'politics of scale' (e.g. Swyngedouw 1997; Lebel et al. 2005; Houdret et al. 2014).

Understanding water governance as a process involving multiple scales enables a more detailed analysis on this very element of power relationships. From a political economy perspective, Suvi Sojamo and colleagues presented a critical insight to the power disparities within the global agro-food supply chain (Sojamo et al. 2012). They argued that a very small number of agribusinesses and supermarket chains can determine how the global food market operates. This market simultaneously represents the flows of virtual water from exporting to importing countries through agricultural products. Four agribusinesses dominate the virtual water flow of staple food commodities, including wheat, corn, soya, sugar, and cotton. Their dominance has hitherto been supported by a web of links with national trade organisations, infrastructure and shipping sectors and investment banks, resulting in strong ties between the private market and political, economic elites. This condition enables food prices to be kept low at the expense of environmental stewardship and a selective crop production that can put farmers in a precarious position. The study by Sojamo et al. demonstrates that the power to govern water resources can be exercised by private actors, specifically businesses that would not traditionally be seen as 'water managers'. The businesses have strong networks and capacity to influence at multiple spatial scales, particularly in what farmers produce and what individual consumers demand.

As such, focusing on the scale of governance demonstrates that there are multiple geographies of water resources use and management (Moss 2012; Del Moral and Do 2014). The river basin organisation represents a hybrid of a physical and political spatiality, while the virtual water flows in the global agro-food supply chain demonstrates a distinct economic space. Scale thus includes not just the place (i.e. watershed) but also the actors and the relational aspect between these actors and places (O'Lear and Diehl 2007). Through the perspective of multiple geographies, it is possible to consider governance with options not simply within the water sector. In other words, as the United Nations World Water Development report called for, there needs to be comprehensive consideration of options within and outside of the 'water box', or the water sector (United Nations 2006). This notion is increasingly picked up in ideas of the water-food-energy nexus, as highlighted earlier (see also Sect. 9.4).

9.3.2 The Politics of Scale in Water Governance

The problem of spatial misfit, especially in the case of river basin organisations, has brought up the ways participation can be better utilised. On one hand, academic scholarship has suggested that participation can improve effectiveness, particularly through the involvement of facilitating actors and intermediary agencies. On the other hand, such participation may suffer from lack of legitimacy due to issues of representation (Newig et al. 2016). Empirical findings from efforts at implementing the EU Water Framework Directive in two areas within Germany showed that participation can address to some degree issues of spatial misfit, but inclusiveness to suffice representation of stakeholders was problematic (ibid).

However, stakeholders are not predetermined to a particular scale and can actively work across different scales as well as levels within a scale to demonstrate influence. The former is considered to be scale jumping, where a stakeholder has sufficient influence such that decision-making of another scale can be shaped. The latter refers to scale bypassing which does not follow the hierarchical notion of scalar levels (e.g. small to large scale; local to global scale) (see also Gupta 2008, 2014; Hüesker and Moss 2015). Here, Jens Newig and Timothy Moss remind that scale is not merely a discursive construct but also about practices that shape and refine behaviour (Newig and Moss 2017).

The active rescaling of governance is another example in which the relational aspect of stakeholders and places are changed. For example, for indigenous communities such as those along the US-Canada border in the Coast Salish region, scale can be devised to establish an identity of peoples that breaks from existing notion of sovereignty. Moreover, by identifying a scale not along the conventional international boundary, it counters territorial views of governance and works to develop postcolonial geographical space (Norman 2015).

In contrast, the scales of water governance can be used to resist regional territories to be established and instead further nation-building and nationalistic notions of water control. This is the case of Turkey, which rejects constructing a 'Middle East region' based solution for water management, including the management of the transboundary Tigris-Euphrates river on which it is an upstream state (Harris and Alatout 2010). Instead, the management of these rivers is tightly bound up with the strategies that attempt to make natural the national scale management, over which the government has control (Harris and Alatout 2010). In these cases, scale operates to underpin a certain idea of how people and place relate. Margreet Zwarteveen and Janwillem Liebrand emphasise the performativity associated with scale, showing that it can have the effect of producing a certain vision of development (Zwarteveen and Liebrand 2016). In their case study of irrigation in Nepal, ordering of irrigation activities through scale is based along notions of modernity espoused by the decision-making elite. The implication for water governance is that state power can be executed through these practices of managing water. The performativity of scale demonstrates the inclusion of stakeholders (and thus exclusion of others) and the interwoven power relations. Water governance thus represents the ways state power is demonstrated as well as contested.

Rescaling of water governance shows that there are power dynamics that bring together or separate multiple geographies of water. Certainly, configuring scale is an act of exercising power. New scales can empower stakeholders such that power can also be a product of rescaling, as Frank Hüesker and Timothy Moss point out (Hüesker and Moss 2015). Multi-scalar water governance is not necessarily a hierarchical concept of territorial units: these units can be challenged or used deliberately to discount other levels of scale. The fluidity of scale in water governance reinforces the complexity that both the academic and policy debates are concerned with. More importantly, the fixed, rescaled, misfitting features of scale indicate how water governance analysis needs to carefully follow how, where and by whom scale is established and changed, and the impacts it has.

9.4 Nexus Approaches Linking Water to Other Fields

9.4.1 The Water-Energy-Food (Security) Nexus

The previous section addressed the importance of different scales and thus the vertical dimension of water governance. This section has a focus on the horizontal dimension and the need to integrate different interrelated and frequently competing sectors in water governance. The introduction of IWRM was a response to the insight that sustainable management of water cannot be achieved from within the water sector alone. Despite the attempt of IWRM to initiate fundamental governance reform and to integrate water with other policy objectives, decisions made in other sectors still neglect the potentially serious consequences for water resources (Pahl-Wostl et al. 2011; Newig and Challies 2014; GWP 2004; Biswas 2004; Jeffrey and Gearey 2006; Medema et al. 2008; Schreiner 2013). The concept of the Water-Energy-Food (WEF) nexus aims at an integration of sectoral policies and at holistically approaching different policy fields from the outset (Benson et al. 2015). The nexus should be governed with a focus on interaction between policy fields and not on policy fields in isolation.

Initially, the WEF nexus concept had a strong focus on water security. In contrast to IWRM that was initially promoted by an expert and scientific community, the WEF nexus was first promoted by business at the World Economic Forum, where water security became a central topic of global concern in 2008. Subsequent reports promoted a nexus approach (WEFWI 2009, 2011). The World Economic Forum emphasises threats and opportunities for business and sees market mechanisms and the green economy as effective and efficient solutions for dealing with resource scarcity. The German government took the lead in promoting the WEF nexus concept in policy circles in the run-up to the Rio+20 sustainability summit by organising a conference on "The Water-Energy-Food Security Nexus: Solutions for the Green Economy" in Bonn in 2011. Despite the focus on the green economy, this stream of discourse adopted a broader framing of the concept and emphasised wider policy implications and environmental, social and economic sustainability (BMU 2011; Hoff 2011). The WEF Security Nexus was not taken up by the Rio+20 sustainability summit and was not addressed explicitly in formulating the Sustainable Development Goals (SDGs). Despite the holistic and transformative ambition of the 2030 Agenda, the SDGs—as formulated—have hardly any explicit connection between the water, energy and food goals and their targets (Bhaduri et al. 2016; Le Blanc 2015).

Will the WEF nexus concept be just the next fashionable but transient concept in the series of water management paradigms? Or will it indeed help to overcome prevailing governance failures (viz. lack of coordination, ineffective implementation of policies) and will a framing in security terms be supportive in this respect? Jeremy Allouche, Carl Middleton and Dipak Gyawali put forward a more sceptical view and argue against too much optimism attributed to the nexus perspective (Allouche et al. 2015). In their opinion, nexus thinking is not really novel, lacks engagement with the respective market logics within sub-nexuses and the difficulty of integration and disregards the politics of knowledge in policy framing. Indeed, so far the framing of the WEF nexus is rooted in a scientific and technical rationality on requirements for integration. This is also evident from the recommendations of the Bonn conference on how to make the nexus work, which include (Bonn Conference 2011): "While the opportunities of the nexus perspective and their social, environmental and economic benefits are real, implementation requires the right policies, incentives and encouragement, institutions up to the task, leadership as well as empowerment, research, information and education. Accelerating the involvement of the private sector through making the business case for sustainability and the nexus is essential for driving change and getting to scale". Implementation may fail if the concept is not sensitive to power constellations, political economy issues as well as transaction costs and how they vary at and across different spatial scales (Pahl-Wostl 2019).

The WEF nexus aims at ensuring a level-playing field for all sectors. One barrier in this respect is the power imbalance among the sectors such as the prevailing dominance of agricultural policy over environmental policy and the traditionally strong lobbying power of stakeholder groups from the agricultural sector. The situation is not much different for the energy sector. Economic interests associated with hydropower development have dominated considerations of environmental and social sustainability (Pahl-Wostl et al. 2013; Zarfl et al. 2015). A WEF nexus perspective implies to attribute equal importance to all three domains, which might be perceived by some stakeholders in the field as the undesirable loss of a privileged and powerful position.

Despite such caveats, it should be noted that promising developments can be perceived with respect to a broader adoption of the WEF nexus concept. The FAO devoted some considerations to the role of the WEF nexus for food security and for their work (FAO 2014). The International Renewable Energy Association (IRENA 2014) promoted the nexus as important concept to guide the transformation of energy systems towards renewable energy sources. The biofuel debate emphasises the link between agriculture and energy (Raman and Mohr 2014).

9.4.2 Governance Challenges Related to the WEF Nexus

9.4.2.1 The Role of Security

What does it mean to address water-energy-food security from a nexus perspective? Given the diverse interpretations of food, water and energy security, it is by no means evident. As discussed by Claudia Pahl-Wostl the three concepts follow overall a quite different logic and emphasis (Pahl-Wostl 2019). Food security has traditionally focused on an emphasis on stopping hunger in the world. At the same time, this is connected to a strong global dimension, to economic interests and markets as drivers of change as being evident from the Green Revolution and the importance of the World Trade Organisation (WTO). Energy security has a distinct geo-political and strategic focus. This may derive from the unequal distribution of fossil energy sources and the concern of industrialised countries to assure energy supplies. Furthermore, climate change and the UNFCCC process have strengthened the global dimension. Currently, one observes a paradigm shift with the transformation of energy systems towards renewable energy sources. This paradigm shift strengthens decentralised energy production by small-scale local facilities. The increased importance of diverse scales in energy production requires a much stronger vertical coordination across governance levels. It has implications for the interactions with other sectors (e.g. biofuels, hydropower).

As mentioned above, IWRM entailed the introduction of the hydrological principle and emphasised the river basin as appropriate scale at which water should be managed. In contrast, security concerns have often been voiced at the national level. The global dimensions of water security have gained centre stage only in recent years. Water security was defined by David Grey and Claudia W. Sadoff as: "Water security refers to the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies" (Grey and Sadoff 2007). Water security embraces the most encompassing and integrated approach regarding the dimensions of sustainability which reflects the multifaceted and ubiquitous nature of water (Grey and Sadoff 2007; Pahl-Wostl et al. 2013; Bogardi et al. 2012). Compared to the different definitions and framings of water and food security, energy security has paid the least attention to environmental sustainability, the environmental implications of energy systems.

Nevertheless, balancing the different sustainability dimensions of water security has already been identified as problematic due to the different logics of how to determine what acceptable risks are (Pahl-Wostl et al. 2013). Balancing water, energy, and food security is even more challenging given the diverse definitions and interpretations of the security concepts, the absence of effective governance structures to support negotiations, and the lack of systemic governance instruments even within the sectors involved and even more in considering cross-sectorial issues. Claudia Pahl-Wostl argued that (1) a more holistic approach of using the ecosystem services concept could support the development of a systemic understanding among actors and the identification of innovative ways of cooperation and collaboration and that (2) an effective implementation of the approach would require a combination of governance modes —collaborative networks, market based approaches and regulatory frameworks (Pahl-Wostl 2019). A combination of governance modes would also be required to address and integrate the different framings of the security concepts in the different sectors.

9.4.2.2 Cross-Sectoral Coordination and Cooperation

The demand for more inter-sectoral coordination in water governance is not new (OECD 2011), even though the WEF nexus lends new impetus to this. Since to date no experience exists on institutional arrangement designed to govern the WEF nexus it might be useful to reflect on experience in the field of environmental governance and policy that face similar challenges regarding sectoral and institutional integration. In particular experience from Europe is very interesting as coordination challenges in a multi-level governance system are particularly pronounced.

The EU's Fifth Environmental Action Program "Towards sustainability" covering the period 1992–2000, can be described as the firm manifestation of the sustainability principle at EU level (Lenschow and Zito 1998). It signified a gradual shift from 'command and control' style environmental policy making to both economic and communicative policy instruments as well as more participatory forms of decision making, both at EU and national level (Holzinger et al. 2009; Wurzel et al. 2013). Concurrently, it set the operational requisites for environmental policy integration advancing an institutional and procedural framework such as intra- and inter-institutional coordination strategies and structures apart from concrete policy instruments such as obligatory impact assessments and sustainability appraisals (Jordan and Schout 2006; Bina 2008; Steurer 2008). To cope with problems of spatial 'misfit' between resource management issues and governance scales (Young 2002), functionally specific governance institutions have increasingly been implemented on scales that correspond to the geographic boundaries of environmental problems (Durner and Ludwig 2008). Following this trend, governance in the EU is characterised by a multiplicity of vertical, horizontal and functionally specific levels of decision-making (Hooghe and Marks 2003). However, recent attempts to bridge the gap between supra-national policy making and local policy implementation, including efforts to acknowledge spatial scales of environmental problems that do not correspond to political or administrative boundaries, have not yet led to the desired results (Newig and Koontz 2014; Lenschow et al. 2017). Similar to these problems of vertical coordination across levels of government and/or ecologically defined spaces, also horizontal coordination across policy fields (or policy integration) like environment, agriculture and energy remains largely deficient (Jordan and Lenschow 2008; Jordan and Lenschow 2010). Networked forms of governance have increasingly been promoted, and play an increasing role in European environmental governance (Bodin and Crona 2009; Klijn 2008; Newig et al. 2010; Pahl-Wostl 2009). Though touted as having great potential for learning and resolving resource management issues, their effectiveness is still disputed. Likewise, effects of public and stakeholder participation on environmental governance outcomes are still largely unclear (Newig and Fritsch 2009). At the same time, evidence tends to be limited to the OECD world, focuses largely at administrative and policy tools at national (and EU) level and thus neglects related issues of vertical integration as well as the potential of non-state-led "new" instruments (for an exception see Goria et al. 2010). Research tends to focus on the introduction and application of policies and procedures without investigating systematically their effectiveness with regards to achieving sustainable results. In conclusion, empirical evidence to date suggests that policy integration has remained an elusive undertaking.

Similar conclusions were drawn by Nina Weitz and colleagues in their assessment if and how insights from integrative environmental governance can support the closing of governance gaps in the WEF nexus (Weitz et al. 2017). They argue for a stronger focus on policy processes rather than outcomes. This entails elaboration of shared principles that can guide negotiation and decision making processes and the need to overcome the technical-administrative view on governance that dominates nexus literature (Weitz et al. 2017).

The WEF nexus offers a promising approach to reframe problem perspectives and could support more balanced negotiations of interests between sectors and engage diverse actors. It shifts the emphasis onto relationships and feedbacks between sectors. What is required is an approach that allows diagnosing trade-offs and security problems in the WEF nexus and that is meaningful at different levels and different stages of governance processes. However, such diagnosis would not yet solve the coordination challenge. Efforts to implement WEF nexus governance arrangements would be well advised to adopt a more gradual approach to policy implementation with a focus on processes of negotiation and decision making and the need to include the possibility for learning.

9.5 Transboundary Water Governance

9.5.1 Conflict and Cooperation in Transboundary Water Governance

Transboundary rivers or internationally shared rivers have been subject to various projects that divert, transfer and reallocate water. These projects can be part of cooperative efforts at managing the river. At the same time, existing riparian tensions can intensify. The problem of access and allocation of water is a challenge when river systems spatially and temporally distribute water unequally. However, developing a river not only influences physical distribution but are also inherently political enterprises, shaping and changing the power to control where, when and how water should flow.

In recent years, there has been a global rise of dam development (see Zarfl et al. 2015). In transboundary river basins, dam development can become the vehicle to challenge and change existing politics on the use and allocation of water. Notably, the Grand Ethiopian Renaissance Dam in Ethiopia marks a paradigmatic shift in the development of the Nile where upstream development has been hitherto nascent (Tawfik and Dombrowsky 2018; Nasr and Neef 2016; Cascão and Nicol 2017). The Rogun Dam in Tajikistan is also another attempt at solving water scarcity issues where river basin planning has been drawn-out by upstream and downstream tensions (Menga and Mirumachi 2016). The Chinese investments in the Myitsone dam in Myanmar and the subsequent postponement of this dam construction demonstrate how dam developers, activists and regional intergovernmental organisations like the Association of Southeast Asian Nations (ASEAN) play a role (Chan 2017; Sun 2012; Kiik 2016; Kirchherr et al. 2017). The politics of transboundary water development is not limited to governmental actors.

In many of these cases, there are power asymmetries between riparian states but also between donor agencies, financial institutes and investors that fund projects, host communities of the infrastructure and civil society organisations. While the global governance of transboundary rivers has marked a milestone with an international framework, the United Nations Convention on the Law of Non-Navigational Uses of International Watercourses (hereinafter UN Watercourses Convention), originally adopted by the UN General Assembly in 1997 and entering into force in 2014 for ratifying parties, the practice of transboundary water governance is increasingly diverse. It is diverse both in the kinds of actors involved but also the changing political economy and political ecologies in which these actors operate. Transboundary water governance thus encompasses transboundary water interaction between states that are underpinned by global norms, regional drivers, national interests and power struggles between actors within and beyond the hydrological river basin boundaries.

To understand transboundary water governance, a starting point is to analyse the coexisting conflict and cooperation between riparian states (Mirumachi 2015). Rather than identifying instances of conflict or cooperation, the focus on the coexistence of the two demonstrates how riparian interactions change over time. These changes are facilitated by multilateral institutions for water governance (such as international RBOs discussed earlier in Sect. 9.2), national regulation and policy as well as influenced by broader political events unrelated to water per se. Analysis of transboundary water governance is thus contextualised, providing a richer account than noting the incidences of conflict or cooperation. This approach also provides more precision in the scale and locale specific implications of water use and allocation, rather than treating governance in a universalised fashion.

9.5.2 Governance Mechanisms for Coexisting Conflict and Cooperation

Treaties and international agreements are common mechanisms to manage and regulate shared water access and use. The number of agreements has grown over time, demonstrating the geographical spread of governance efforts across transboundary rivers. There were 250 treaties in addition to a significant body of agreements, amendments, protocols and other documents in 2007, much of which has been established in the last half century (Giordano et al. 2014). In addition, there has been a trend where treaties have become more comprehensive over time including multiple purposes and sophisticated mechanisms for enforcement and conflict resolution (Giordano et al. 2014). This trend also corresponds with the way national water management has become more integrated over time, with as mentioned earlier, IWRM points out the interconnectedness of water and related resources as well as the diverse stakeholders with vested interests in managing these resources. Empirically, the track record for achieving transboundary IWRM is patchy at best (Dombrowsky 2007; Hooper and Lloyd 2011). Achieving transboundary IWRM is particularly challenging because of the complex integration required between sectors across spatial scales (Mirumachi 2013). Nonetheless, it can be argued that the debate on transboundary water governance is better attuned to such complexity.

A case in point is the increasing recognition of knowledge co-production. In order to solve complex problems, it has been suggested that rather than relying on one type of knowledge, plural knowledges are better suited (Armitage et al. 2011). In the case of transboundary river basins, this implies that knowledge is not limited to basin-wide analysis but also locale specific understanding. Knowledge comes in different forms: in formal scientific, tacit, experiential or indigenous insights. Consequently, regarding the state as the primary actor may not be sufficient to capture the ways knowledge is used and communicated in transboundary water governance. Where there is a mix of state and non-state actors, governments are not necessarily the sole authority of decision-making and knowledge. Instead government is required to act as facilitators in pluralistic decision-making (Armitage et al. 2015).

As explained earlier, while international RBOs focus on international level decision-making, informal governance mechanisms are more flexible in establishing networks of actors across scale. Boundary organisations can bring together state and non-state actors and have the effect of facilitating features of formal institutions, such as conflict resolution. Informal networks can also be another mechanism through which different kinds of knowledges are brought together (Armitage et al. 2015). This plurality of water governance is particularly pertinent when transboundary RBOs are institutionalised enough that they have specific functions and responsibilities, however not independent of national government powers (Schmeier 2015). National interests can get in the way of resolving contentions and make sub-optimal ecological outcomes as a political compromise. Water governance can provide alternative ways of influencing and regulating the national interests of riparian states, which can make agreement implementation contentious and provide sub-optimal outcomes for ecological sustainability.

9.5.3 Transboundary Water Governance for What Ends?

The gradual shift of transboundary water governance taking into account complexity and plurality reflects the varied goals, demands and interests regarding transboundary river basin management. Concurrently, governance becomes a continual process of mediating value conflicts as hydrological, ecological, political, socio-economic conditions change. It thus constantly needs to grapple with challenging questions on the objective of managing and developing river basins. When environmental issues began to rise on the political agenda in the 1990s, sustainable use of water resources were often related to the issues of pollution and water scarcity that prevented human needs and development. In this regard, sustainable use was a way to serve anthropocentric goals. This anthropocentrism is also reflected in principles such as equitable use of the UN Watercourses Convention, which requires a socio-political interpretation rather than a technical measurement.

Public participation has been lauded as a way to enable governance that would mediate these value conflicts. According to IWRM, public participation would empower stakeholders in the process of decision-making. At the same time, it would help shift state actors being regarded as the sole central authority. However, as Christian Bréthaut demonstrated with the case study of the Rhone river basin, the proliferation of public participation initiatives do not necessarily yield efficiency of decision-making and can in fact contribute to further fragmentation of these efforts (Bréthaut 2016). It has been found that even if collaborative governance processes are set up, state actors often have advantages such as human resources. This enables them to exert power over other actors at multiple stages of the policy cycle, thereby significantly influencing decision-making (Brisbois and de Loë 2016). Because institutions do not emerge in an institutional vacuum, different mechanisms are at play for governance. Thus, public participation to facilitate the new water institutions may be used to the advantage of local elites who are already well embedded and established in existing institutions, as in the case of the Volta river basin where traditional chieftaincy coexists along with a newly established river basin authority (Wong 2016).

Transboundary water governance is not unique for its features of power dynamics at play. The issue of equity is bound up in the way power is used and exerted by different actors just like water governance within a national river basin. Along with equity, the attention to water (in)justices are useful to further the achievement of water governance. However, transboundary water justice is still nascent in both academic and policy discussions. There needs to be scrutiny not only on the process but also outcomes of transboundary water negotiations because those with power can put into place seemingly fair processes that ultimately result in outcomes that serve their interests at the expense of those with less power (Zeitoun et al. 2016). The issue of transboundary water justice is particularly vexing when national governments have little regard for justice and rights within their own territory. As Lyla Mehta and colleagues put it, many faults and problems need to be contended with: "the contradictory nature of the state and its disregard for marginalised people, unequal experiences of citizenship in the periphery, elite biases in policy making and planning, resource capture by powerful players as well as significant distributional, recognition and procedural problems" (Mehta et al. 2014). Questioning the ends of transboundary water governance thus also requires a hard look at the inconsistences across and between scales in the practice of equity and justice.

9.6 The Global Dimension of Water Governance

9.6.1 The Need for Addressing Water Challenges from a Global Perspective

Over the past decade, the global level—for a long time dismissed as irrelevant in the water sector—has been acknowledged as an important governance dimension (Gupta and Pahl-Wostl 2013; Gupta et al. 2013). Nevertheless, debates about its relevance are still ongoing (Vörösmarty et al. 2015; Hering et al. 2015).

A global perspective is required, since many water related environmental and societal problems as well as water use related conflicts elude appropriate solutions at local level or within national or basin boundaries. The driving forces behind this concept are the growing attention given to multilateralism in the international politics of water (Varady and Iles-Shih 2009; Gleick and Lane 2005; Conca 2006) and the recognition that local, national and basin-level water issues are interlinked within a global water system (see Sect. 9.3) (Pahl-Wostl et al. 2002; GWSP 2005).

Four arguments underscore the need for adopting a global perspective (Pahl-Wostl et al. 2008). First, the hydrological system is a global system and exchange processes occur at global level over relevant time periods (e.g. climate change impacts, teleconnections between deforestation and precipitation).

Second, global environmental change and socio-economic phenomena at the global level increasingly create situations in which the driving forces behind water related problems and conflicts lie outside the reach of local, national or basin oriented governance regimes (e.g. global trade impacts on water).

Third, many local environmental and social phenomena occur globally such as erosion, eutrophication, urbanisation, biodiversity loss, and the introduction of invasive species on the one hand and health and welfare issues resulting from poor access to water and sanitation in poor countries. Such local phenomena may imply alarming global trends, e.g. the construction of dams leads to a fragmentation and flow alteration of the world's river basins with major and sometimes irreversible impacts on associated freshwater ecosystems. Furthermore, lessons learnt in one part of the world, could be useful and relevant for other countries and comparative learning justifies a global approach.

Finally, many direct and indirect impacts of relatively reduced quantities and qualities of water are likely to be global (e.g. the reduction or change in the distribution of food production, impacts on migratory birds).

9.6.2 The Fragmented Nature of Global Water Governance

Global water governance is fragmented and characterised by the absence of a binding UN-convention and leadership (Pahl-Wostl et al. 2008; Gupta and Pahl-Wostl 2013; Gupta et al. 2013). Global water governance has the nature of a "mobius-web" system characterised by bottom-up, top-down, and side-by-side governance and by networked and hierarchical interactions including many actors (Pahl-Wostl et al. 2008). Despite its potential for coordination, such governance is prone to functional fragmentation because of weak connections, lack of leadership, and difficulties in compartmentalising. Each governance body focuses on specific aspects; i.e., the UN Human Rights Council focuses on the human right to water, and the World Health Organisation on water standards. Diverging interests lead actors to promote different policies in different venues; e.g., the World Bank promotes liberalisation in water. The lack of common norms, i.e., norm fragmentation, leads actors with different interests to choose venues that coincide with their own normative framework (Gupta and Pahl-Wostl 2013).

The lack of integration was also recognised by the United Nations and UN-Water was established in 2003 as a "mechanism" to overcome this coordination gap. UN-Water is an interagency mechanism to strengthen coordination among the 24 UN agencies working on various aspects of freshwater and sanitation. In an assessment of the role of UN-Water in global water governance, Thomas Baumgartner and Claudia Pahl-Wostl concluded that UN-Water has not yet had any significant impact on global water governance processes (Baumgartner and Pahl-Wostl 2013). However, it has the potential to act as a bridge between the expert-centred, knowledge-producing background and the political foreground of global water governance. In addition to the formal membership of the UN agencies, UN-Water has established links to a wide network of actors in global water governance. As an interagency coordination mechanism UN-Water lacks the direct control of an intergovernmental governing body and thus formal decision-making power. At the same time, the institutional setup obliges UN-Water to account for concerns related to diplomacy and political correctness. UN-Water cannot, like many other organisations, unilaterally address controversial issues. Instead it has to embrace the broad spectrum of political and scientific complexity of global water challenges and find solutions that are acceptable to all of its member organisations—and ultimately to all member states. The mandate of UN-Water would have to be extended so that is could develop a role as an effective bridging organisation linking network and hierarchical governance modes. One may question how realistic this proposal is given the power constellations in the UN-context. However, there is no doubt that such bridging organisations are needed. In their analyses of processes in global water governance, Claudia Pahl-Wostl and colleagues identified some highly important missing links between knowledge generation and policy framing and between knowledge generation and rule-making (Pahl-Wostl et al. 2013). The absence of effective global coordination in the water field has been highlighted by the United Nations Secretary-General's Advisory Board on Water and Sanitation (UNSGAB) as serious caveat for the implementation of the SDGs in general and the water SDG 6, in particular (UNSGAB 2015).

9.6.3 The UN Sustainable Development Goals

By the end of 2015 the Millennium Development Goals (MDGs) expired. The MDGs guided global development policy for more than a decade. The MDGs were replaced by the Sustainable Development Goals (SDGs) adopted in September 2015 by the United Nations.

The MDG process placed water back on the global political agenda in 2000. MDG 7 had as its target the halving of the number of people without access to safe drinking water and basic sanitation by 2015. The MDGs process can be judged as by and large successful (Pahl-Wostl et al. 2013). It circumvented the lengthy procedures of formal rule-making as a necessary condition for new political attention. By setting clear and measurable targets it helped mobilise resources, commitments, and greater coordination. However, the MDG process also shows clear deficiencies. Policy framing lacked comprehensiveness which is reflected in the MDG's negligence of universal access. A more comprehensive approach to the water challenge may be more beneficial to long-term sustainability than declaring success on the number of people gaining access to safe drinking water every year. Furthermore, measuring the achievement of targets only with statistics provided by governments casts a degree of doubt on the validity of the assessment of progress. The SDG process would have the potential to capitalise on the insights gained during the implementation of the MDGs.

The SDGs adopt a more comprehensive approach by moving away from a development focus towards a broader sustainability framing. Under which conditions could the SDG process become a global process driving transformative change towards sustainability? Maarten Hajer and colleagues caution against "cockpit-ism" (Hajer et al. 2015). By cockpit-ism they refer to complete reliance on a hierarchical governance mode where national governments and intergovernmental organisations play the key role. In particular, those societal groups most affected by the implementation process should be empowered and encouraged to actively participate in implementation and monitoring (Pahl-Wostl et al. 2015).

The SDG process also poses a significant task for science to develop appropriate indicators and monitoring processes. Here there is scope for the science community to become more actively engaged in the global governance process of SDG implementation (Bhaduri et al. 2016). This is particularly pertinent when one decade of global water research has provided clear evidence of the global dimension of the water challenge and has identified the key problems within it. However, such evidence has not contributed to transformative change in policies and a reversal of global trends. Research in the past has emphasised the identification of problems more than the identification of solutions. Furthermore, current global assessments (e.g., World Water Assessment Programme and their flagship product, the World Water Development Report—WWDR) seem to be insufficient for informing policy leading to effective action. The WWDR is used as source of reference by many scientists and policy advisers but does not have a significant policy impact. Hence, neither science nor policy seem to be ready to take on the SDG challenge.

Further research could and should become more active in the process of SDG implementation and make the transition to developing knowledge for action, and to identifying solutions in a co-production of knowledge process. If the water community would succeed in getting its act together it could establish a think-tank providing global leadership in the identification of knowledge gaps and in promoting recognition of important research findings. To overcome the missing links in global water governance, such a think-tank needs to combine a high level of legitimacy in its role as knowledge generator and assure representativeness (Bhaduri et al. 2016; Pahl-Wostl et al. 2013).

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Claudia Pahl-Wostl is professor for resources management at the Institute of Geography and Director of the Institute of Environmental Systems Research at Osnabrück University, Germany. She is an internationally leading scholar on governance and adaptive and integrated management of water resources and the role of social and societal learning. Research interests include the water-energy-food nexus, SDG implementation and social-ecological-network analysis. She has published numerous papers in peer-reviewed journals, chapters in edited books and two monographs. Her emphasis on interdisciplinary and community-building work is reflected in her role as editor of five books and seventeen special issues in peer reviewed journals. She has been member of numerous science advisory and evaluation panels and steering committees of research programs.

Ines Dombrowsky holds a Ph.D. in Economics and an M.Sc. in Environmental Engineering and heads the Research Programme 'Environmental Governance and Transformation to Sustainability' at the German Development Institute/Deutsches Institut für Entwicklungspolitik (DIE). Her research is grounded in institutional economics and political sciences with a particular thematic focus on water and the water-energy-food-climate nexus. Dr Dombrowsky has published widely on water governance issues from transboundary to local scales. She has prior work experience with the Helmholtz Centre for Environmental Research—UFZ (2001–2010), the

World Bank (1997–2001) and the Deutsche Gesellschaft für technische Zusammenarbeit (GTZ) (1995–1997).

Naho Mirumachi is Reader at the Department of Geography, King's College London, UK. She leads King's Water, an interdisciplinary research hub on water, environment and development. Her research focuses on the politics and governance of water resources, particularly in developing country contexts. She has published extensively and is the author of *Transboundary Water Politics in the Developing World* (Routledge 2015) and co-author of *Water Conflicts: Analysis for Transformation* (Oxford University Press 2020). Dr. Mirumachi recently served as lead author on freshwater policy for the 2019 UN Environment GEO-6 report. She is Associate Editor of *Wiley Interdisciplinary Reviews: Water*. She has experience in training policy makers on water security and water cooperation.

10 Economics of Water Security

Anik Bhaduri, C. Dionisio Pérez-Blanco, Dolores Rey, Sayed Iftekhar, Aditya Kaushik, Alvar Escriva-Bou, Javier Calatrava, David Adamson, Sara Palomo-Hierro, Kelly Jones, Heidi Asbjornsen, Mónica A. Altamirano, Elena Lopez-Gunn, Maksym Polyakov, Mahsa Motlagh, and Maksud Bekchanov

Abstract

In the immediate future, accessible runoff of fresh water is unlikely to increase more than the demand forecasted. It will have an impact on economic growth as it may reduce the per capita income of countries and create water conflicts. Such global threat creates a policy conundrum of how to meet basic needs and maximise the benefits from water resources. This chapter investigates different economic instruments in alleviating water-related risks and dealt with associated impacts.

Keywords

Water market • Investments for watershed services (IWS) • Blockchain technology • Non-market valuation • Urban water design • Transboundary conflict

A. Bhaduri (✉)
Sustainable Water Future Programme, Griffith University, Brisbane, Australia
e-mail: a.bhaduri@water-future.org

C. Dionisio Pérez-Blanco
Universidad de Salamanca, Salamanca, Spain
e-mail: dionisio.perez@usal.es

D. Rey
Cranfield University, Bedford, UK
e-mail: d.reyvicario@cranfield.ac.uk

S. Iftekhar
Griffith University, Brisbane, Australia
e-mail: m.iftekhar@griffith.edu.au

A. Kaushik
Water Solution Lab at Divecha Centre for Climate Change, Bengaluru, India
e-mail: adityakaushik00@gmail.com

A. Escriva-Bou
PPIC Water Policy Center, San Francisco, USA
e-mail: escriva@ppic.org

J. Calatrava
Universidad Politécnica de Cartagena, Cartagena, Spain
e-mail: j.calatrava@upct.es

D. Adamson
The University of Adelaide, Adelaide, Australia
e-mail: david.adamson@adelaide.edu.au

S. Palomo-Hierro
Department of Applied Economics, University of Malaga, Málaga, Spain
e-mail: sara.palomo@uma.es; sara.palomo@uco.es

K. Jones
Colorado State University, Fort Collins, USA
e-mail: kelly.jones@colostate.edu

H. Asbjornsen
University of New Hampshire, Durham, USA
e-mail: Heidi.Asbjornsen@unh.edu

M. A. Altamirano
Deltares, Delft, Netherlands
e-mail: Monica.Altamirano@deltares.nl

E. Lopez-Gunn
ICATALIST, Madrid, Spain
e-mail: elopezgunn@icatalist.eu; elopezgunn@gmail.com

M. Polyakov
Manaaki Whenua-Landcare Research, Lincoln, New Zealand
e-mail: polyakovm@landcareresearch.co.nz

M. Motlagh
Bonn Alliance for Sustainability Research/Innovation Campus, Bonn, Germany
e-mail: mahsa.motlagh@gmail.com

M. Bekchanov
Center for Earth System Research and Sustainability (CEN), University of Hamburgity, Hamburg, Germany
e-mail: maksud.bekchanov@uni-hamburg.de; maksud.bekchanov@yahoo.com

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List of Abbreviations

ACCC	Australian Competition and Consumer Commission
BCR	Benefit-Cost Ratio
BWSSB	Bengaluru Water Supply and Sewerage Board
California Bay-Delta Program	CALFED
DBCA	Department of Biodiversity, Conservation and Attractions
EMRC	Eastern Metropolitan Regional Council
GSAs	Groundwater Sustainability Agencies
GSPs	Groundwater Sustainability Plans
IWRM	Integrated Water Resources Management
IWS	Investments in Watershed Services
LID	Low Impact Design
MCs	National Mekong Committees
MDB	Murray-Darling Basin
MWD	Metropolitan Water District
NAS	Natural Assurance System
NMCS	National Mekong Committee Secretariats
NPV	Net Present Value
OMVS	Organization pour la Mise en Valeur du Fleuve Sénégal
PES	Payments to Ecosystem Services
PVID	Palo Verde Irrigation District
TN	Nitrogen
TP	Total Phosphorous
UWA	University of Western Australia
WSUD	Water Sensitive Urban Design

10.1 Introduction

10.1.1 Economic Dimensions of Water Resources Management

It is quite evident now that the cause of global water insecurity largely stems from population growth and economic development rather than global climate change (Vörösmarty et al. 2000). The gap between freshwater supply and demand will widen further during the coming century as a result of increasing consumption of water, and may fail to guarantee water security. In the next three decades, accessible runoff of fresh water is unlikely to increase more than 10 percent, yet the world's population is expected to grow by one third. It will have an impact on economic growth as it may reduce the per capita income of countries (Barbier 2004). In regions that have already (over) allocated their water supplies, this global threat creates a policy conundrum of how to meet basic needs and maximise the benefits from water resources.

Conservation and efficient usage are considered to be critical elements in the demand side of water management. A water market is theoretically conceived as a powerful instrument to induce efficient use of water (Tate 1994; Dinar and Subramanian 1997; Johansson et al. 2002; Rogers et al. 2002). Water markets provide one approach to reduce water scarcity and reallocate water to high-value uses, but questions remain concerning if market structures provide the capacity to include all parts of society. Water market is influenced by the political and economic conditions. Politicians may tend to favour low- water priced structure. Thus, water prices are fixed and determined administratively at a low level in many countries. It reflects neither the supply cost nor the scarcity value.

There are also different viewpoints on how water prices should be determined economically. Efficient water pricing is determined where the marginal benefit is equal to the marginal social cost, including environmental externalities and other opportunity costs (Lund and Israel 1995; Rogers et al. 2002). Despite the concept of water market's apparent simplicity, measuring the opportunity cost of water is difficult. In the absence of well-functioning water markets, opportunity cost assessment requires a systems approach and a number of assumptions about the real impacts and the responses to these impacts (Briscoe 1997).

The adoption of water markets and water trading has occurred in some parts of the world, and each country has implemented different market rules, trading agreements, institutional structures, and participant access, with mixed levels of success.

The first section of this chapter reviews some successful experiences of water trading in Australia, western US and Spain, describing how markets have helped in alleviating water-related risks and dealt with associated impacts. Despite these successful experiences, the potential of water trading is still underdeveloped in most cases due to several factors and barriers to trade. Policy makers confront multiple, conflicting criteria and objectives before implementing water market. Moreover, there are institutional constraints that often stand as obstacles to the implementation of water pricing, which can include legal restrictions, informational asymmetry and the perception of water as a basic right (Saleth and Dinar 2005; Le Blanc 2008). This section also provides some insights in relation to how to increase the success of a market for water.

Development of a water market is susceptible to market distortions typically caused by information asymmetry and high transaction costs. These market distortions lead to barriers to trade and thus prevent markets from functioning efficiently. Such market distortions can incur a significant social cost. Thus, water markets have been historically a complicated economic policy instrument to implement. The second section of this chapter explores how block chain-based solutions can be used by regulators to reduce information asymmetry and high transaction costs and help in the development of efficient and transparent water markets. The section illustrates how in a blockchain-based water market context; the price of good quality water goods will increase substantially. It can lead to the creation of an exclusive market with only a few participants who are able to afford the products. In addition, sellers of poorer quality water goods will have an incentive to move to a non-blockchain-based market, which will result in market segmentation.

There are several other economic instruments available for ensuring water security. Such economic instruments act as incentives designed to align individual and collective behaviour with the objectives of achieving reliable quantity and quality of water and mitigating water-related risks.

Economic and financial instruments for water security can include a wide array of arrangements such as markets, charges, subsidies, insurance, investments in watershed services and non-pecuniary cooperative agreements. The third section explores the economic rationale behind the use of economic instruments for water security, critically assesses their characteristics, and provides examples on their performance in alternative settings. The section addresses the need to go beyond market competition and underlines coordination and governance as necessary factors to attaining the incentive compatibility that makes possible human welfare and well-being improvements both at a private and public level.

Water security is associated not only with the concept of sustainable development as emphasized by the ministerial declaration of the 2nd World Water Forum in 2000. It has also been defined in the context of conflict prevention based on geopolitical concerns over water availability and its implications to human security. Economic instruments can play a significant role in allocating common (or shared) water resources and resolving water disputes, internalizing externalities, and act as a negotiating and implementing tool to manage and share water resources. The fourth section addresses different economic instruments in resolving water conflict based on economic principles and perspectives based on the integrated water resource management principle, benefit-sharing, and side payment approaches with different case studies.

The section addresses the specific benefits of transboundary water cooperation, and how different economic instruments as a tool can mitigate water conflicts and enhance collaboration between countries in water sharing. It is based on many factors, including the geographical position, demography, the levels of economic development and trade, water dependency, and governance structures. The section recognizes the need to identify and understand the range of often interrelated benefits derived from the cooperative arrangements and development of transboundary river basins is key for economic water security.

In the 21st Century, the urban areas will likely face water insecurity as a result of climate change and the various impacts of urbanisation. Water sensitive urban designs such as rain gardens, constructed wetlands, and living streams provide many tangible and intangible benefits. However, the formal investment decision-making process often does not include non-market benefits due to the lack of monetized information, which makes these types of projects less favourable for investment. Often organizations (such as water utilities, local governments, government agencies) involved with these types of projects do not have adequate resources and time to commission or conduct primary non-market valuation exercises. In such situations, the benefit transfer method could be a suitable low-cost alternative as it allows the use of existing non-market values after appropriate adjustment. The last section of the paper shows the value of assessing non-market benefits in decision making process and demonstrate the application of benefit transfer techniques to assess the non-market benefits of water sensitive urban designs using a case study in Perth, Australia. This section finds that non-market benefits could be substantial, and they need to be considered in the formal decision making and benefit-cost analysis.

10.2 Inside Stories of a Successful Water Market

10.2.1 What Is the Role of Water Markets?

Globally, many freshwater ecosystems are suffering from significant overexploitation (Bates et al. 2008; Bogardi et al. 2012; European Commission 2012). As water resources are essential for the preservation of life, livelihoods, and ecosystems, this combination of overexploitation, continuing increasing demands for water, and uncertainty associated with future water supply has allowed conflict over a shared resource to emerge. Conflict will continue as a combination of inequal income and population growth; urbanisation; changes in consumption habits; and the uncertain impacts of a changing climate, that will exacerbate problems related to future water availability (IPCC 2014a). Water insecurity and inequality pose substantive threats to social, economic, and environmental resilience globally.

Water scarcity is not unique to arid and drought-prone areas, as it is evident in more humid and temperate regions where traditionally rainfall has been abundant. Water management is often driven by institutions and their regulations, but in many cases, they have failed to keep pace with the changing nature of water demand and supply. Governments are re-evaluating their strategies for dealing with water insecurity and water inequality for this and future generations. In some basins, all available water resources have been already allocated to different users (irrigators, urban suppliers, industries, environment), and is not possible to fulfill more demands. When institutions prevent access to more water, a basin is considered closed (Molle et al. 2010). In closed basins, when water demand increases, the only way to meet this new demand (apart from water use efficiency gains) is through the reallocation of the existing water resources among competing needs. Even in basins that have not achieved the closure point, reallocation of water resources —either temporal or permanent— might be useful to serve more essential needs and to avoid expensive supply investments or environmental crisis during shortages. With the expected effects of climate change on water supplies and demands, some authors have pointed out to water markets as a cost-efficient adaptation mechanism (Escriva-Bou et al. 2017).

A water market is "an institutional framework which allows water right holders, under certain established rules, to transfer their water rights to other economic agents or water users, receiving an economic compensation in exchange" (Sumpsi et al. 1998a). As Getches (2004) pointed out "the great virtue of creating property rights in water is that it can be bought and sold". Water markets institutionalize water trading, allowing for more efficient use of available water resources, reallocating water from low to high-value uses, provided the right regulatory framework. Market prices provide useful information to all parties about the economic value of water, creating incentives for its conservation, to invest in local infrastructure to reduce conveyance losses from evaporation and leakage, and to coordinate infrastructure needs (Hanak and Stryjewski 2012). Whereas short-term transfers—sometimes called leases—are used for coping with droughts, permanent transfers are a demand-management tool to reallocate water. In Australia, California and Spain, transfers have been used for different purposes: to buy back water for the environment, to offset the risk of drought to capital, to increase the reliability of urban water supply, or to reallocate water from low- to higher-value crops (Wheeler et al. 2014; Hanak and Jezdimirovic 2016; Palomo-Hierro et al. 2015; Adamson et al. 2017). In most of the cases, a majority of sellers are farmers with higher reliability in their property rights and lower economic benefit in their water use application, whereas buyers are much more diverse.

10.2.2 Why, When and Where a Market for Water Has Been Established?

Establishing water markets can improve water economic efficiency. However, very few countries have established formal water markets and in countries where water markets are regulated and authorized, exchanges are not quantitatively that important (even in the most developed regions, trading represents a small share of total water entitlements). Water markets exist in different parts of the world, mainly in those areas with water scarcity problems or with an irregular distribution of water resources among seasons, users or regions. Australia, Chile and the USA, including California and other western states, are home to long-active water markets, yet they have very different structures, designs, institutional settings and degrees of the market intervention (Grafton et al. 2009). For example, in Chile and Australia, the management of these markets is more decentralized. Australian water markets are probably the most developed in the world, and in some basins, exchanges can be ordered, managed and monitored electronically. Despite these differences in market design and implementation, similarities exist in these countries: problems in the definition and registration of water rights and their supply reliability; the predominant role of agriculture as the main water seller, the prevalence of temporary exchanges of water; prices dispersion; and increasing concern for the environmental impacts. Many of these resemblances can also be found in other regions like Spain, Mexico, Canada or South Africa, where water markets have also been created but their use has been very limited to date (Palomo-Hierro et al. 2015; Bjornlund et al. 2007).

In many arid and semi-arid developing countries, with limited social and institutional capacities, the adoption of markets for permanent water rights has been slow; while informal markets for temporary transfers have been more widely adopted since no change of ownership takes place (Bjornlund 2003). Such is the case of China, India and Pakistan, where informal groundwater markets between farmers, characterized by the lack of official government administration, have spontaneously emerged (Hadjigeorgalis 2009a; Stickney 2008).

While there is not such a definitive set of requirements that need to be in place for water markets to occur and success, an analysis of the experiences and research reveals certain preconditions that point to the effective operation of water markets. These include, among others:

- The existence of resource scarcity along with differences in water productivity between potential buyers and sellers, as well as sufficient willing market participants (Qureshi et al. 2009).

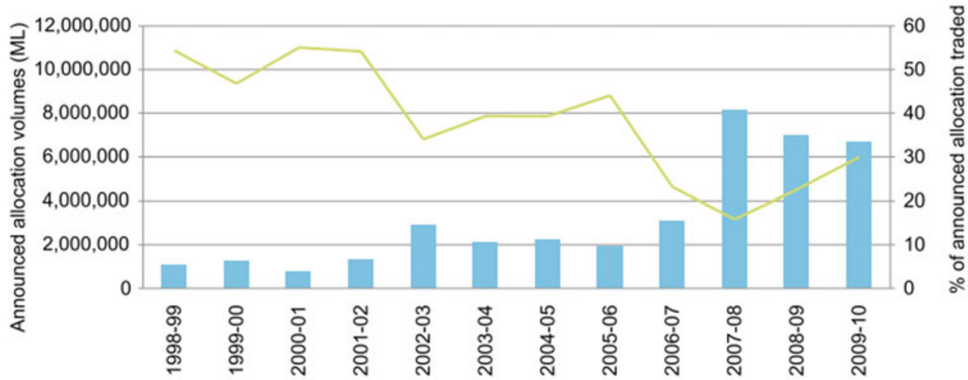

Fig. 10.1 Water allocation sales (blue bars) as a percentage of water allocated (green line) in the Southern MDB 1989–99 to 2009–10. *Source* NWC (2011b)

- The establishment of an effective cap on total sustainable extractions and then allocated among users (Burdack et al. 2014).
- Well defined property rights in a manner that they are completely specified, monitored, enforceable, transferable and legally secured (Saliba and Bush 1987).
- Unbundled water rights (access, use, and delivery components) separated from land rights (Young and McColl 2003).
- The presence of physical infrastructure so that the purchased water can be transported, at a reasonable cost, to the new owner (Easter et al. 1999).
- A sound regulatory and governance framework within which water trading can take place including the existence of enforcement and sanctioning mechanisms, including the constitution of water trusts (NWC 2011a).
- The availability of information on water concessions and water market prices and volumes traded in a fashion manner so that transaction costs may be reduced (e.g. electronic platforms) (Palomo-Hierro et al. 2015). The degree to which each of these preconditions are achieved in the alternative water markets is, of course, a continuous variable. Nonetheless, it seems that the fulfilment of these preconditions has been instrumental in explaining the different degrees of success -or failure- of different countries in using water markets (Easter 1994). For example, in Australia's closed basins, property rights design and desire to use markets for water reform have resulted in clear market rules, regulations and transparency to make the market as functional as possible. All these changes, together with the political will and the willingness to allocate real resources towards solving the over-allocation problems has allowed this water market to develop.

A transition towards water markets has usually taken place gradually as water demand increases and freshwater becomes scarcer. Yet, there have been other circumstances that prompted the adoption of this economic instrument as a tool to reallocate water, such as the occurrence of extreme events (e.g. droughts), changes in environmental regulation, or because of economic feasibility (Marston and Cai 2016). In Australia, the first tentative steps towards water trading took place in the 1980s, although water marketing did not gain traction until the Millennium Drought (1997–2010) changed preconceptions and expectations about known water supply in the Murray-Darling Basin (MDB), Australia's food basin. By 2006, the drought provided the political impetus to force regulatory changes and to develop the 2007 Water Act. The Water Act, amongst other issues, proposed both the development of a plan (the MDB Plan) to establish environmental rights and to establish institutions to identify and negate barriers to water trade (Loch et al. 2014). This legislation allowed the rapid growth in water market volumes, transfers and allowed irrigators to learn about the real price of water (Fig. 10.1).

The MDB is home to one of the most mature water markets in the world, accounting for over 80% of all entitlement trade and seasonal allocation trade in Australia, representing around 30% of water allocated in a given water year (NWC 2011b). Overall, the MDB has proven to be a mechanism to: provide private wealth by engaging in trade (local, regional and inter-state); provide a facility to help mitigate drought risk, and provide a solution to offset adverse outcomes from the use of water, but the market and its rules will continue to evolve.

Although to a different extent and with different outcomes, the transition towards water markets in California has followed a similar pattern of gradual development triggered by the occurrence of droughts and the increasing environmental concern (Hanak 2015). Water markets were first envisioned in California in the late seventies when the combination of scarcity, urban expansion, and intensive agricultural production raised awareness on the necessity of adopting measures to guarantee water supply and agricultural production. In this context of water scarcity and changing water demands water markets were primarily encouraged as a means to enhance water efficiency.

However, it was not until the late 1980s and early 1990s when a major drought accompanied by several water reforms took place that water markets started to be broadly adopted. Apart from this significant drought episode and similar to Australia, environmental concerns and subsequent environmental water trading also played a major role in boosting water market activity in California during the years 1995–2002. During this period, environmental purchase increased three times faster than the market as a whole, mainly due to the rise in environmental water purchase through federal and state programs such as the USBR's new Water Acquisition Program and the CALFED's new Environmental Water Account (Hanak 2015). These and other measures and legislative changes have allowed water marketing in California to grow significantly over the past three decades. Today, water trades represent about 5 percent of all water used in the state. Trade has developed into an invaluable tool for helping California manage its scarce water resources more efficiently and sustainably over the long term, as well in its ability to cope with periodic droughts.

The transition towards water market adoption in Spain provides a different picture. Law 46/1999 incorporated formal water markets into the Spanish legal and regulatory framework in 1999, allowing for spot water markets and water exchange centres to be developed. Though it has been fifteen years since water trading was allowed, limited improvement has taken place in the performance of water markets. Since their implementation, there have been relatively few water transactions, most of them during the drought period (2005 to 2008) in a spot market and among agricultural users (Palomo-Hierro et al. 2015; Rey et al. 2014).

In view of the above, Australia and California seem to illustrate a similar approach to water markets. In these regions, water markets are not considered an exception, even if they represent a small share of the total amount of water used like in California (Casado-Pérez 2017). The opposite is true in Spain where, as showed by evidence, water markets are regarded as exceptional rather than representing a major institutional change, use of water markets have mainly constituted a "disaster management strategy" (Zetland 2011). A deeper insight into the specifics, outcomes, and examples of each of these case studies is provided in the next section.

It is worth stressing that although successful examples of water market implementation and performance do exist, they are relatively scant. Most of the countries adopting water markets have made an effort in removing barriers to trade to enable the market to re-allocate water to its highest use-value. However, water markets implementation is still hindered by social, economic, environmental, physical and cultural barriers that have proven difficult to overcome (see Sect. 10.4 of this chapter). It is also worth mentioning that despite in real-world water markets generally deviate from an ideal textbook market, these do not preclude the possibility of a well-functioning and socially beneficial water market as case studies provided in the next section illustrate. As it happens in other natural resources markets, the potential performance of water markets will ultimately depend on their broader contexts and preconditions, i.e. legal rules, political choices, economic and geographic conditions as well as cultural practices (Bauer 1997).

10.2.3 Water Trading Experiences—A Story of Success?

Currently, water trading activity is helping to alleviate water scarcity problems in many regions worldwide (Griffin et al. 2013). This section presents some examples of successful water trading experiences in Australia, California, and Spain, to highlight the benefits of implementing a market for water as a reallocation mechanism. Besides, the reasons that limited the water trading potential are discussed.

10.2.3.1 Water Markets in Australia (Focusing on the Murray-Darling Basin)

To explore the development and evolution of water markets in Australia, this section builds on Alex Marshall's (2012) key intertwined components of market design that include: allowing market rules and strategies to evolve over time; property rights; legal settings; corporations and intellectual property; physical environment; and the necessity for, by adding political will, transparency and environmental holder.

The Murray-Darling Basin (MDB) is Australia's natural experiment in water reform and water markets. The MDB: covers and area greater than over 1million Km2; has over 50% of all water used for irrigation in Australia; and has over 65% of Australia's irrigated land (Australian Bureau of Statistics 2000). Water resources in the MDB are over-allocated and the transition towards market-based solutions is a political recognition that the supply-based measures do not solve environmental problems (Loch et al. 2014). Adding complexity to the markets is that the MDB has the 2nd most variable inflow in the world (Love 2005) and water markets are considered as a key risk management tool to combat drought (Grafton and Horne 2014).

Legal Settings, Institutions and Property Rights

While books have been dedicated to explaining the legalities of water market development in Australia (Guest 2016), this section has limited its discussion to the three major reforms that identified that:

- an upper limit (or cap) on water extractions had to be implemented and that water trading must have consistent rules between all states (1994 COAG Water Reform Framework, Environment Australia 1994).
- that for trade to work water entitlements must: specify the product, be legally recognised by all states and territories; be able to be traded or leased; understand that the product is subject to climatic variability; that the market needed clear rules to minimise transaction costs; and be free of current barriers to trade (2004 National Water Initiative, Council of Australian Governments 2004); and
- the 2007 Water Act (Commonwealth of Australia 2007) that enacted: The National Water Commission to identify and help remove barriers to trade; allowed the Australian Competition and Consumer Commission (ACCC) to rule if there were unnecessary charges or fees that prevented individuals from engaging in trade; and provided detailed instructions on the development and implementation of market rules (see Section 4 of the Act).

The on-going development reflects the learning about how to set up markets and these legal settings were harmonised between all states to ensure that legal status of property rights. The 1994 'Cap' on water extractions essentially closed the MDB. While this closure was a step forward, it also highlighted that there was value in un- and under-developed property rights. Consequently as rights were decoupled from land, these rights were traded and subsequently utilised and exasperated environmental degradation (Crase et al. 2011). Yes, property rights and trade can increase environmental harm.

To deal with the inherent variability of water supply, three classes of water rights exist within the MDB. These classes define the reliability of the property rights to provide water: high, general and supplementary water in a given catchment. Consequently, the bundle of rights within each catchment in the MDB is unique both in terms of the composition (i.e. number of rights by class), and the reliability of each right class. In other words, rights do meet the 2004 National Water Initiative guidelines, as the structure of these rights means that both buyers and sellers are aware of the 'marginal value' each right class by catchment has to their production system. This provides clarity to the market to help price property rights.

Corporations and Intellectual Property

While the rules pertaining to trade including participation terms are defined by the government, private companies have been allowed to construct the clearinghouses to facilitate trade between private individuals. Consequently, trading platforms are designed and operated by private companies to make a profit. Not only do they offer a place for individuals to engage in allocation or entitlement trade but they also offer information concerning the market, current water supply and links to forecasts and industry-based information. The success of the private interaction in shaping the functionality of the market has allowed these platforms to be exported overseas (Austin 2016)

Evolving Market Rules and Strategies

Market rules and strategies evolve over time as Marshall (1920) wrote…

> Again, markets vary with regard to the period of time which is allowed to the forces of demand and supply to bring themselves into equilibrium with one another, as well as with regard to the area over which they extend. (Book V, Chapter 1, Section 6, page 192)

As individuals and private companies adapt and learn to manipulate market rules, legal frameworks, property rights, and the physical environment, over time, new rules and legal settings are introduced to fine-tune the market and enforce rights. While the overall design of the markets attempts to minimise transaction costs, they are nevertheless evident (Loch et al. 2018).

Current market rules: define where and how water can be traded (surface, groundwater, and the trade between surface and groundwater) between catchments; if penalties (i.e. changes to volume) are applied to reflect the conveyance loss of water as it moves along the river (or between conjunctive sources); and provide the necessary legal frameworks to engage in permanent or allocation trade.

Market Transparency

Unawareness allows supernormal profits to be made in markets (Knight 1921). To prevent this, the development within Australian water markets, a combination of purchasing rights for the environment (i.e. the buyback) (Loch et al. 2014), and the public release of market information has prevented information asymmetry. The Restore the Balance (or buyback) process in Australia helped irrigators discover the price of water in the MDB that the government was willing to pay (Wheeler and Cheesman 2013) and in turn, informed the private market of prices.

Reviews (monthly or annually) of water markets (volume traded, prices, where trade occurred) can be downloaded from government websites and from private companies. Such information then helps individuals plan new strategies for dealing with water markets.

Environmental Holder

The development of the Plan has created some uncertainty in water markets, as the government is now the single largest owner of water. The Plan follows the concepts of common-property (Adamson 2015) to deal with the over-allocation of water in the MDB. The Environmental Holder will eventually manage between 2,750 to 3,200 GL of water for the environment and this will comprise of a set of property rights that are identical to irrigators' rights (i.e. as discussed the buyback was one economic instrument designed to transfer water from irrigators to the Environmental Holder).

As the Environmental Holder: has to meet a range of environmental objectives; can trade water to reallocate its permanent portfolio; and engage in temporary trade to either buy or sell water to and from irrigators, the market will again face a series of new challenges and strategic responses. Inevitably, comments suggesting that the Environmental Holder will act in a predatory manner (buyer or seller) will have to be explored.

10.2.3.2 California

Introduction

The first major drought widely experienced by Californians occurred in 1976–77. It provided a wake-up call that exposed the inadequacy of past water supply planning and changed how policymakers thought about water (Mitchell et al. 2017). The drought prompted major policy changes, and given the extensive supply plumbing already existent in California, demand management strategies were proposed as innovative solutions.

In a report to review California Water Rights Law (Governor's Commission 1978) the Governors' Commission proposed "The Market Approach" to improve water use efficiency and identified the regulatory changes needed to encourage voluntary transfers of water rights. To achieve this, the Commission proposed three critical tasks. One, ensure the security of the right, to incentivize water reclamation and avoid the risk of forfeiture under the "use it or lose it" doctrine. Two, ensure the flexibility of the right to change the place of use, point of diversion and purpose of use and some other restrictions. Three, implement administrative reforms to speed up the permitting process.

Most of these recommendations were set forth in the water code in the following years, and the first actual water trades started in the early 1980s.

Water Market Stages

The coincidence of the beginning of the California water market with a wet cycle limited the initial amount of trading in the early 1980s. However, another drought, between 1987 and 1992, spurred the market activity and cities, farms and the environment started to benefit from water transfers.

The establishment of the California Drought Water Bank in 1991 was a major institutional breakthrough, with the state approving and administering water trading (Zilberman et al. 2011). The Department of Water Resources, in charge of operating the State Water Project that provides water supplies for 27 million Californians and 300,000 ha of irrigated farmland, started purchasing water to offset lower deliveries to its contractors and wildlife refuges. Overall, during the period 1987–1994, state and federal agencies purchases for resale and environmental uses accounted for nearly half of the market activity (Hanak and Stryjewski 2012).

The growth of the market continued during the second half of the 1990s, even though during these years California experienced one of the wettest cycles in the 20th century. While most water purchases during the 1987–92 drought went to Californian cities, during the second half of the 1990s farmers in the San Joaquin Valley dominated water purchases. Environmental purchases also grew significantly during the wet cycle of the late 1990s.

The market achieved its maturity with the new century, and since then the amount of trading has not changed significantly. However, the composition of the trades has changed. During the 20th century, a majority of the trades were short-term leases (nearly 80%). The 21st century has seen a stable growth of long-term leases and the appearance of a small but quasi-constant share of permanent sales (between 2001 and 2014 long-term leases accounted for 44%, long-term leases for 43% and permanent sales for 13%) (Fig. 10.2).

Some Shortcomings

Infrastructure and legal barriers hinder California's water market. As a result, trades among agencies that have rights to use water within the same large projects (CVP, SWP, and Colorado River) continue to dominate the market, accounting for over 60% of all trades since the mid-1990s, and 80 percent of trades not involving direct state or federal government purchases (Hanak and Stryjewski 2012). Less than 20% of the activity in the market can be attributed to the "open market": agencies within different projects or not belonging to projects at all.

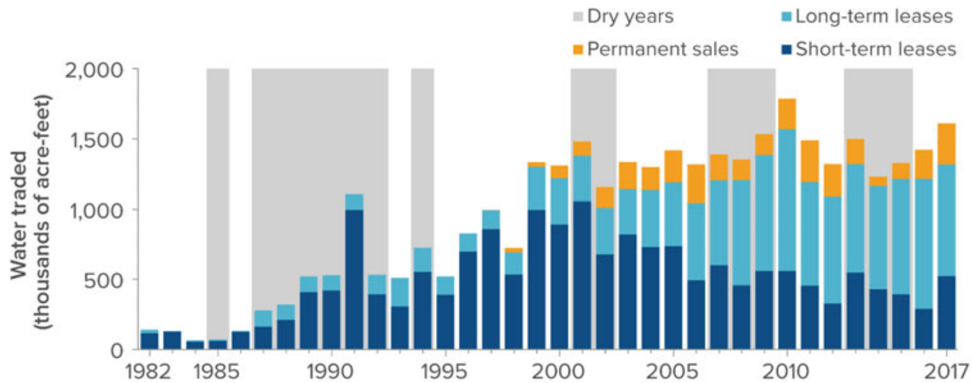

Fig. 10.2 Water traded in the California water market. *Source* Hanak and Jezdimirovic (2016)

The stagnation of the total amount of water market activity during the 21st century might also reflect the high transaction costs involved in the process. Some authors point out to the lack of clarity on priority beyond water rights (Gray et al. 2015), the need for different government roles (Casado-Pérez 2015), the lack of information on water rights, water available for trade, or prices (Escriva-Bou et al. 2016), or the need for expanding some conveyance and storage capacity (Newling et al. 2002).

Innovative Strategies: Increasing Urban Flexibility While Addressing Unintended Consequences of Trading

Metropolitan Water District (MWD) is the largest wholesaler of treated drinking water in the United States, supplying water to 19 million people in Southern California. It owns and operates an extensive water system and imports water from the Feather River, in Northern California, and the Colorado River to supplement local supplies. Palo Verde Irrigation District (PVID) provides water to more than 50,000 ha of farmland in Riverside and Imperial Counties, with a water right from the Colorado River of 555 hm^3.

In 2005, MWD and PVID signed a 35-year agreement to fallow annually between 7 and 28 percent of PVID land, depending on MWD necessities. Farmers that participate receive an up-front payment of $3,170 per acre from participating in the program ($1283/hectare) plus an annual payment of $600 per acre fallowed each year. More than 90% of PVID landowners accepted to participate. Between 30,000 and 120,000 acre-feet (37–148 hm^3) or water is made available to MWD customers annually (Doherty and Smith 2012). This agreement, an option contract where MWD has the right to purchase different amounts depending on its necessities, gives MWD flexibility to adapt to changing conditions in other supply sources.

But trading can result in unintended consequences. In a previous pilot trading program developed between the same entities between 1992 and 1994, an estimation of 60 full-time agricultural jobs and $4 million were lost in farm-related services in the Palo Verde Valley. This prompted the establishment of a $6 million local development fund to mitigate the negative impacts of the current water transfer agreement (Doherty and Smith 2012). The Community Improvement Fund included in the agreement has supported the creation and retention of farm-related jobs caused by the fallowing program, and awarded public benefit grants totalling $1.4 million as of June 2018 (MWD 2018).

The trading agreement between MWD and PVID was innovative because included an option contract increasing the flexibility of water supplies for MWD, and considered and tried to mitigate the unintended consequences of trading. Option contracts have emerged in other parts of California. This is a clear example that water reallocation can be a much cheaper option than investing in new supply sources (i.e., infrastructure) when dealing with temporal shortages, but also with a structural deficit in supplies (see Hansen et al. 2008; Gómez-Ramos and Garrido 2004; Howitt 1998 for more formal risk analysis). Similarly, mitigation funds have been included in trading agreements between other urban agencies and irrigation districts in Southern California.

The Emergence of Groundwater Markets to Ease the Transition to Sustainability

In California, groundwater depletion has been a concern since the early 20th century, but its impacts—including land subsidence, dry wells, reduction of surface flows and associated environmental impacts among others—worsened during the 2012–16 drought (Poland et al. 1975; Pauloo et al. 2020; Hanak et al. 2017). To address these issues, the state adopted in 2014 the Sustainable Groundwater Management Act (SGMA). This set of laws requires the formation of local groundwater sustainability agencies (GSAs) to develop and implement groundwater sustainability plans (GSPs) to transition to sustainability within 20 years (by 2040 for critically overdrafted basins, and by 2042 for the remaining high and medium priority basins).

To transition to sustainable groundwater use, groundwater basins have to expand supplies and/or reduce water use.

Given that the amount of affordable new supplies are limited, the consequences of the potential reduction of agricultural production for local economies are going to be significant. Just in the San Joaquin Valley, which generates more than half of the state's agricultural output, more than 200,000 ha of farmland could be abandoned causing billions of dollars of farm revenue loses annually. Expanding water trading, both on surface and groundwater sources, could reduce these losses significantly (Hanak et al. 2019).

To implement successful groundwater trading programs there is a need to develop trust in groundwater management through an inclusive and transparent process, ensure efficient and accurate collection of appropriated data, devise a fair groundwater allocation, craft trading programs to reflect local hydrologic conditions, and address concerns over funding management activities (Babbitt et al. 2017).

Some adjudicated basins—basins where a dispute over legal rights to the water ended with a court ruling known as an adjudication of water rights before the passage of SGMA—have allowed for the transfer of pumping allocations in California. The Mojave Basin, the Chino Basin, the Tehachapi Basin, and Seaside Basin, have shown how groundwater markets can increase flexibility in demand management by using different extraction limits, allocations and transfer rules. Similar concepts are used in other states, such as the Edwards Aquifer in Texas, and the Upper Republican Natural Resource District in Nebraska (Nylen et al. 2017).

SGMA has intensified the interest for groundwater markets in many basins. The Fox Canyon Groundwater Management Agency in Ventura County and the Rosedale-Rio Bravo Water Storage District in Kern County are some of the most advanced examples. Both of them are developing web tools which allow for individualized accounting and trading platforms. It is expected that many more basins in California will allow groundwater trading to ease the transition to groundwater sustainability.

10.2.3.3 Spain

Legal Framework

With the declared objectives of providing flexibility to the Spanish system of public water use rights (concessions), increasing the economic efficiency of water use and reducing the economic impact of scarcity, the Spanish Parliament passed in 1999 the Water Law Amendment (Law 46/1999), which legislated and regulated the operation of water markets in Spain. Law 46/1999 allowed, subject to the application to and the authorization by the corresponding river basin authority, for the voluntary water trading between concession holders entering into a private agreement to temporarily transfer their water use rights for a price or "compensation", through what is referred to as a temporary lease contract (Calatrava and Martínez-Granados 2016). Before this reform, only private groundwater rights could be traded, either leased or sold (Rey et al. 2014). To maintain the public nature of water use rights, prevent speculation and protect the rights of third parties and the environment, Law 46/1999 established restrictions in the direction, volumes and spatial extent of the exchanges. For instance, water cannot be sold from consumptive to non-consumptive users and the other way around, from higher to lower priority users or to non-right-holders (Rey et al. 2014). Inter-basin contracts are restricted to drought periods and to those basins that are already interconnected, requiring the authorization of the Spanish Government. The volume that can be sold is restricted to the real water consumption of the selling right-holder rather than the volume defined in the concession. Apart from lease contracts between users, Law 46/1999 provided for the possibility of river basin authorities setting up water use rights exchange centres to launch public water rights purchase offers to holders interested in temporarily or permanently transferring their water concessions, which would be transferred to other interested right-holders, in the manner of the water banks operating in the United States of America (Loomis et al. 2003; Garrido et al. 2013a).

Water Trading Experiences

The reader can find descriptions of the experiences with formal water markets in Spain in Calatrava and Gómez-Ramos (2009), Garrido et al. (2013a), Rey et al. (2014) and Palomo-Hierro et al. (2015). Garrido et al. (2013a) and De Stefano and Hernández-Mora (2016) address the barely documented issue of informal water trading agreements, while Montilla-López et al. (2016) does the same with water banks experiences. Calatrava and Martínez-Granados (2016) and García-Mollá et al. (2016) provide detailed descriptions of the functioning of water markets in the Segura and Júcar basin respectively.

The activity of water markets in Spain since they were formally regulated in 1999 has been limited, both in the number of operations and volumes traded, clearly below what was initially expected in view of the characteristics of the Spanish water economy. Even in the driest years, traded water represents less than 1% of all annual consumptive uses (Rey et al. 2014). Unsurprisingly, with some exceptions, most trading has concentrated in the southeast quadrant of Spain where most water-stressed areas are located (Palomo-Hierro et al. 2015). Agricultural users have been the main water sellers, whereas, with the exception of a handful of large purchases by urban suppliers and the public buybacks of rights, a majority of water resources have been also purchased by farmers.

Until 2005, when a severe drought started and water markets became more active, the formal trading activity was very limited. In fact, only 46.66 GL were traded in Spain (Palomo-Hierro et al. 2015), 20 GL of which corresponded to a one-off purchase by an urban supplier and 10.1 GL to lease contracts within the Segura basin (Calatrava and Gómez-Ramos 2009). Later on, during the 2005–08 drought, the Spanish Government authorized inter-basin lease contracts using the existing transfer infrastructures, as an exceptional emergency measure to abate water supply problems in the hardest-hit areas (Garrido et al. 2013a). This resulted in several annual agreements between users from the Segura and Tagus basins (using the Tagus-Segura Transfer) and between users in the Almanzora and Guadalquivir basins (using the Negratín-Almanzora Transfer). The prices in origin ranged from 0.15 to 0.28 €/m^3, and involved a very small number of trading partners. These agreements were renewed with similar conditions during several years (Rey et al. 2014; Calatrava and Martínez-Granados 2016).

The activity of intra-basin lease contracts, the only ones that functioned once the drought was over, increased in the period 2009–2014 with respect to 2000–2005. When a new drought situation recurred in 2014, the Spanish Government authorized again the celebration of lease contracts between users from different basins. However, in absence of published data for the whole country, the available evidence for the Segura basin, the major destination of inter-basin contracts, suggests that traded volumes have been significantly reduced with respect to those in the previous drought, partly because the Spanish Government is following a stricter application of the legislation (Calatrava and Martínez-Granados 2016).

Regarding they water exchange centres (as per their name in Spanish, Centros de Intercambio de Agua), they did not enter into operation, and only in the Guadiana, Júcar and Segura basins, until at the start of the 2005–2008 drought, when the Spanish Government reinforced their effectiveness by allowing them to cater for other demands, such as securing environmental uses. The water authorities of these three basins issued several public water rights purchase offers between 2006 and 2008, which had limited success. In the case of the Júcar and Segura basins, all the purchased resources were used to maintain environmental river flows, but the budgets were not used up because there were not enough suppliers that met the set requirements and the purchase price was not attractive for farmers (Rey et al. 2014). The aim of the Upper Guadiana water rights purchase offers, the largest-scale experience to date in Spain, was to raise the water tables in a severely over-exploited aquifer. In this case, the budget was fully allocated, but purchased rights were reallocated to other users in the form of new public concessions, and groundwater pumping was hardly reduced at all (Garrido et al. 2013a). None of these water exchange centres has operated again.

At a national level, the activity of water markets has been concentrated in drought periods (Calatrava and Martínez-Granados 2016). The sources of most of the volumes traded are inter-basin lease contracts and public buyback of rights through water exchange centres. Palomo-Hierro et al. (2015) estimate the total volume traded in Spanish water markets between 2001 and 2011 to be 590 GL, 81.5% of trade took place during three drought years (2005–2008). Inter-basin agreements totalled 39.9% of the volumes traded in that period, while public water rights purchase orders and intra-basin lease contracts accounted for 26.5% and 33.6% of these, respectively. In addition to the reduced number of trading partners and operations, the traded volumes are insignificant, moreover if we compared them with those in countries with more active water markets. Even considering 2007, the year with the largest market activity, traded volumes amount to less than 1% of total water use in the country, far below Chile, Australia and even California, and similar to the South African Republic (Palomo-Hierro et al. 2015). This figure rises up to between 2.5 and 4.5% for the most water-scarce basins.

The available evidence also shows that there is a considerable price spread in lease contracts (Palomo-Hierro et al. 2015; Rey et al. 2014), even within the same basin and years (Calatrava and Martínez-Granados 2016). Prices have ranged between 0.06 and 0.30 €/m^3 at source, net of transportation costs and losses. This, together with the relatively low number of market participants and transactions, suggests that there is a thin market, typical of situations where relevant barriers to trade exist (Saleth et al. 1991; Tisdell 2011).

Barriers to Trade

Several studies have pointed at some of the reasons for the limited functioning of water markets in Spain (Palomo-Hierro et al. 2015; Rey et al. 2014; Garrido et al. 2013a, b, c; Ariño and Sastre 2009; to cite a few). Many of the barriers to trade highlighted by these authors are similar to those in other countries, such as Australia, Chile or the USA: rigid legislation, spatial restrictions, slow administrative procedures, difficulties in finding trading partners, market thinness and price dispersion, etc. However, the evidence from these countries shows that their water markets are more flexible and that the traded are volumes relatively greater (Rey et al. 2014; Grafton et al. 2011), suggesting that barriers to trade could be more restrictive in Spain.

In addition to the restrictive regulatory framework, the most relevant barriers to trade in Spain would be the lack of market transparency, the insufficient definition of the volumes potentially tradable, and the fact that the administrative authorization process is not only slow but its outcomes are uncertain. However, the major barrier is probably the increasing opposition of some stakeholders, including those in the areas-of-origin, environmental organisations, etc. (Garrido et al. 2013a, b), which results in conflicts between different users and regions and political interferences. All these barriers to trade have resulted in thin markets with monopsonistic and monopolistic behaviours (Garrido et al. 2013b).

Most of the above-cited studies are in response to the need of an improved and more flexible regulatory framework, similar to the reforms included in the 2010 Andalusian Water Act. Reforms should also include a clearer definition of tradable resources and criteria under which exchanges would be authorised, a more agile administrative process with more predictable outcomes, less political interferences, and more transparency.

In addition, the Spanish Government should go beyond lease contracts between right holders and foster other trading mechanisms, especially in more water-stressed areas. For instance, water supply option contracts could reduce uncertainties and transaction costs (Rey et al. 2014; Garrido et al. 2013c). Similarly, using Water Banks for something else than very occasional environmental water buybacks could reduce transaction costs and increase market participation (Montilla-López et al. 2016), while allowing for better public monitoring of operations (Garrido et al. 2013a) and increased market transparency (Palomo-Hierro et al. 2015).

Finally, these barriers to trade that constraint on the permanent transfer of water rights result in the role of formal water markets being taken by the sale and lease markets for land with irrigation rights, and by informal water markets functioning mostly in the most water-stressed southern and eastern areas (Calatrava and Martínez-Granados 2016; Garrido et al. 2013a). Informal water markets are those that are not covered by the provisions of Law 46, and that include exchanges between members of the same WUA (Water Users Association) and, to a larger extent, the lease and selling out of private groundwater rights (De Stefano and Hernández-Mora 2016). Their activity suggests that the current regulatory framework does not respond to the changing needs of water users, especially during droughts.

An Overall Assessment of the Spanish Water Markets Experience

It would be far from true to consider the Spanish experience with water markets to date as a successful story, as there are both positive and negative aspects. Obviously, a positive issue is that water resources have been reallocated to higher-value uses and to more water-stressed areas, thus generating ample gains in welfare, especially in the case of inter-basin operation (Calatrava and Gómez-Limón 2016). Moreover, the water exchange centres briefly operating during the 2000s have provided environmental benefits through the public water rights purchase offers, which, like the public water banks of California, Australia or Canada, have been used exclusively to achieve environmental goals (Loomis et al. 2003; Docker and Robinson 2014). However, the notable gains-from-trade of inter-basin operations may have been smaller due to the alleged environmental impacts in the basins of origin of water and the indirect public financial support during the 2005–2008 drought in the form of water tariff rebates (Hernández-Mora and Del Moral 2015).

Gains-from-trade may have outweighed possible negative environmental impacts, which, are yet to be quantified. There is still a disputed debate about this (Garrido et al. 2013b), due to the general lack of transparency in which Spanish water markets operate. As the traded volumes were small and some applications were rejected based on potential environmental impacts, we can assume that these impacts have been insignificant for intra-basin operations. In the case of inter-basin leases, the environmental impacts may have been greater, although, as commented, this is a conjecture. However, in most operations, water authorities have required that a share of the exchanged volume be left in the watercourses of the area-of-origin (Garrido et al. 2013a, b). Another negative aspect is that the increasing opposition of some stakeholders has resulted in conflicts between different users and regions and political interferences (facilitated by the unsecured criteria for authorising trading operations).

In this sense, in our view, there might have been some political ambiguity towards water markets. The current regulatory framework gives water authorities a lot of leeway for political intervention. The Spanish Government played a relevant role by actively supporting inter-basin trading during the 2005–2008 drought (Garrido et al. 2013b), and promoted successive legal reforms aimed at extending trading opportunities (Hernández-Mora and Del Moral 2015). However, they have not clearly committed to harnessing the potential of water markets. Moreover, the Spanish Government seems to be increasingly reluctant towards inter-basin lease contracts (Calatrava and Martínez-Granados 2016). Should the Spanish Government decide to turn water markets into a more used and efficient tool, the instruments defined in the 1999 Water Act should be better designed and developed. Lease contracts needs more security and faster administrative procedures, while water banks should function permanently.

Despite the mixed picture, many experts and stakeholders consider water markets as a useful tool to facilitate water re-allocation in Spain, with potential to solve critical water scarcity situations, as long as they are adequately regulated and monitored. However, they must not be seen as the solution to structural water scarcity problems in the country (Garrido et al. 2013a), and in no case a substitute for a water authority action. Nevertheless, there is consensus in the need of deep reforms for water markets to provide their full potential without threatening the public interest (Rey et al. 2014).

10.2.4 What Can We Learn from Our Experience Trading Water?

In 1920 Alfred Marshall provided clarity to economic thought via the introduction of intersecting supply and demand curves to explain producer and consumer surplus. By illustrating how marginal utility changed demand and supply price elasticity, consumer and producer behaviour could then be explained. Markets are then a place where individuals interact in an attempt to maximise their utility over time. Marshall notes that markets can range in both size and structure from: open international market places; to 'secluded' where all external influence is frozen out; and the majority of markets that economist must study, lie somewhere between the two. Subsequently, markets are often considered as the panacea to economic problems. However, markets are not a naturally organic creation, markets are designed and this requires government intervention to deal with the complex problems of market failure and missing markets (Bromley 1989). Thus a single market can be used to 'solve' a myriad of social and economic problems while acting as a clearance house to link buyers and sellers together. Without a clear design, guidance, and rules of participation, markets can fail.

Apart from the MDB in Australia, in all countries where water markets have been established, trading activity remains relatively limited (typically 1–5% of allocated volumes). Water markets provide some flexibility, but their potential has been limited. Market limitations are contextual and historic political and policy decisions (that frame the markets design, private and public participation, legal frameworks, and institutional structures) create a legacy of obstacles that inhibit swift reform. While this inability to enact reform benefits existing right owners, the time required to enact change, if utilised properly, can be used to obtain more information to design better markets and ultimately lead to a better outcome for society. However, care is needed as trade can lead to increased environmental harm.

For markets to be established there needs to be political will (Loch et al. 2014). The transition towards a closed basin, capping extractions, allocating property rights and putting markets into place can only occur if either the public sees the need for change and directs political action, or if the policy process is being done to improve welfare for society (Rostow 1959).

Several studies have provided insight into identifying physical and institutional factors that are currently hampering the activity of water markets in different countries (Qureshi et al. 2009; Marston and Cai 2016; Garrido et al. 2013a; Zhang 2007). Among these, the study of Marston and Cai (2016) seems to provide the most comprehensive and updated review of the existing barriers. According to their research, the major difficulties faced in undertaking water trading schemes are:

- The lack of well-defined and enforceable water rights, mainly resulting from the existence of some financial, administrative and cultural factors which difficult the adoption of water reforms aimed at breaking the linkage between water rights and land rights.
- Third-party effects arising from water trading, i.e. the impact that water market transactions can have on users not directly involved in market decision-making processes or negotiations, or their social stability, or the environment (e.g. instream flows, water quality, area-of-origin equity, return flows).
- The lack of information support and limited stakeholder involvement, which prevents potential water users from market participation, and therefore narrowing the market.
- Transaction and transition costs that may outweigh any difference in the marginal productivity of water between buyer and seller, hampering potential water transfers. Examples of transaction costs may include the cost derived from gathering information, identifying trading opportunities, negotiation, conveyance, monitoring, enforcement and third-party impacts mitigation; while transition costs correspond to those institutional costs to shift from the previous institutional structure to one more favourable to markets (Rosegrant and Binswanger 1994). If transactions costs are greater than gains from trade, the transactions will not be profitable and will not take place (Beare et al. 2003; Martin et al. 2008).
- Unsustainable institutional structure and operation including excessive or over restrictive regulations or rules that prevent water transfers to other uses or places.

In places where water markets have matured and expanded (e.g. Australia) there is growing interest in the potential for more flexible trading mechanisms ('secondary markets' as termed by the Australian NWC), such as water derivatives. Water derivatives (forward contracts, futures and options) have several economic, institutional and risk-related benefits in comparison with traditional water trading mechanisms. They are already being used in some countries, helping urban water suppliers to secure water for different uses, environmental regulators to guarantee minimum environmental flows during water shortage periods, and irrigators to plan their activities knowing that they will have water available later in the season. Several authors have also demonstrated the potential benefits of water derivatives for countries where they do not currently exist, like Spain (Gómez-Ramos and Garrido 2004; Cubillo 2010; Rey et al. 2015a, b). The implementation of these mechanisms increases the risk management alternatives available and reduces risk management costs, enables water users to tailor water access to their requirements, and encourages more efficient utilisation of water rights and associated capital.

10.2.5 Concluding Remarks

The review of successful water trading in different countries highlights the benefits of markets as a tool to reallocate water and contribute to solving water availability issues. However, as the presented case studies also show, in reality markets are far from perfect and must be carefully designed and implemented to release their whole potential and avoid negative externalities. Due to increasing water availability pressures and a shift from supply to demand-focused water management approaches, we believe water markets could play a more important role in water reallocation in the future in many countries, once the prerequisites for their implementation are met in those areas. Learning from existing systems, like we are doing here, could improve future market experiences and increase their success.

10.3 Future of Water Markets Using Blockchain Technology

10.3.1 Introduction

In a world with expanding populations and a changing climate, new opportunities to unlock additional value from smart water market could be a game changer to address the increasing stress on scarce resource. Water markets where water assets are treated as a tradable commodity are cited as a solution to better allocate water and address the problem of water scarcity. Development of any market, especially to manage a good like water, is susceptible to market distortions typically caused by information asymmetry and high transaction costs. These market distortions lead to barriers to trade and thus prevent markets from functioning efficiently. As water is unlike any other commodity and is essential for life, these market distortions can incur a significant social cost. Thus, water markets have been historically a complicated economic policy instrument to implement. The purpose of this section is to explore how block chain-based solutions can be used by regulators to reduce information asymmetry and high transaction costs and help in the development of efficient and transparent water markets.

10.3.2 Water Market

Water market allows buyers and sellers of a water-related good (wastewater, rainwater, groundwater, water rights, or entitlements) to interact and facilitate an exchange. The primary purpose of a water market is to facilitate efficient allocation of water resources between buyers and sellers by allocating water resources in accordance to the strength of the buyer's water demand (Le Moigne et al. 1992). Water markets allow users with high marginal value to purchase water from users with low marginal value. In other words, water is transferred from low water use areas to high water use areas, allowing for allocation efficiency. The price of water determined by the interaction between buyers and sellers can also influenced by environmental and economic considerations. When markets functions efficiently, the market price of water sends signals about the scarcity of water and thus incentivizes buyers and sellers to increase or decrease their demand and supply. Typically, water is managed as a public good where the price of water is determined by public agencies who are reluctant to change the price based on quantity or quality available. Thus, it often leads to distortions where water is being under-priced and over-consumed. Some of the more successfully functioning water markets exist in the United States (California's central valley), in Australia (the Murray-Darling Basin), and in Chile (the National Market) (Hadjigeorgalis 2009b). Water markets are typically created to either meet additional water demands, to limit water use, to improve economic productivity and/or to protect natural ecosystems.

10.3.2.1 Conditions Necessary for an Efficient Water Market

Information asymmetry (Akerlof 1978) revolves around decisions made during transactions in a typical water market. In a water market setting, there are underlying gaps in the data ecosystem and institutional mechanisms which contribute to three main kinds of information asymmetries. First, there is inequality to data access issue. For example, some market participants might have better access to data than others, or the data that is available is of inferior quality, or data is available but key data is not accessible and open, thus leading to an adverse selection (Wilson 1991; Blume et al. 2008). Adverse selection occurs when some participants are able to make better decisions than others due to access to certain kind of information. For instance, a seller of treated wastewater has more information about the product quality than the buyer, thus putting the buyer at a disadvantage. The buyers will be unable to decide whether the price quoted is optimal or not *vis-à-vis* the quality of water supplied. Adverse selection can act as a barrier to entry for new buyers and can also result in inferior quality water weeding out good quality water over time. Second, when the data ecosystem is susceptible to tampering and institutional infrastructure does not have the necessary checks, balances, and penalty enforcement mechanisms; it can lead to the problem of moral hazard (Kotowitz 1989; Blume et al. 2008). The moral hazard problem occurs when entities participating in a trade transact in lack of faith, provide misleading information, or change behaviour post-contractual agreement. For instance, during a transaction, one of the parties can misrepresent the quality of the product and the other party is unable to validate the quality, thus promoting mistrust and perpetuating opaqueness in water markets. Third, the creation of monopolies of knowledge can lead to severe distribution effects (Ledyard 1991; Blume et al. 2008). For instance, a buyer of a large amount of water, by virtue of access to more and better information, can affect the price and quantity of the water traded. Thus, such information asymmetries lead to market failures. Symmetric information exchange between buyers and sellers is a necessary condition for the creation of efficient water markets.

10.3.2.2 Low Infrastructure and Transaction Cost

Development and maintenance of a water market comes with other associated costs. Infrastructure costs include: (1) Initial cost of setting up an enabling mechanism of water markets; (2) Development and deployment of water entitlements; (3) Connecting buyers and sellers; (4) Monitoring and evaluation of water use and externalities; and (5) Enforcement mechanisms for penalty and reward. Transaction costs include: (1) Participation fees; (2) Information search costs of willing buyers and sellers; (3) Negotiation and bargaining costs; (4) Cost of registration for an exchange; (5) Enforcing contracts; and (6) Cost of checking veracity of the product. High infrastructure costs and associated maintenance costs act as a barrier in setting up a water market (Brookshire et al. 2004). High transaction costs can lead to thin markets (Freebairn and Quiggin 2006).

10.3.2.3 Stringent Regulation and Distribution of Water Entitlements

Regulators act as principal agent to set the framework and rules for establishing a water market. They play a key role in identifying and vetting participants, issuing water rights, administering trade, monitoring and evaluating water use, and externalities; and developing enforcement mechanisms for deterring rule breakers. Regulation is subject to bureaucracy and corruption that can prevent water markets from functioning effectively. In a water market setting, if there are different rules for different participants, and if the buyers and sellers do not perceive equal opportunity gains from transactions, then a market failure can occur (Dinar et al. 1997). A robust regulatory mechanism with necessary checks and balances is necessary for developing, implementing, managing, and sustaining a complex economic instrument such as a water market.

Water entitlements are tradable rights held by users for exclusive use of a water resource as defined by the regulators. Clarity over water rights and a history of water assets are a necessary condition for the functioning of a water market. Information asymmetry and high transaction costs lead to significant market distortions in any market. Its effects are even more magnified when managing water assets in a market-based setting. A robust regulatory process along with a clear system of water rights is necessary to overcome these distortions in order to create an efficient water market.

10.3.3 Blockchain Solution and Analysis

Traditionally, in a regulated market place, market distortions such as information asymmetry and high transaction costs are tackled through a system of institutional solutions such as: (1) The establishment of norms and standards that act as binding rules and requirements vis-à-vis processes and quality of the goods; (2) The disclosure and transparency mechanism that requires participants in a market to report process adopted, quality of product produced, cost associated, and so on; (3) The monitoring and traceability provisions that allow for tracking of products, quality, and liability allocation (Hobbs 2004); and (4) Contingent contracts that allow for a trade to be completed when specific conditions are met (Bazerman and Gillespie 1999). However, the effectiveness of these institutional solutions depends on several intermediaries, an individual's ability to access these intermediaries, an ability to leverage the available data, and the integration of several disparate systems and stakeholders (Verhulst 2018). In addition, these solutions are susceptible to inefficiencies, corruption, bureaucracy, human errors, and tampering (Fig. 10.3).

In order to make these institutional solutions more resilient and adaptive and make regulators more accountable, while also setting the conditions that would allow participants to trade, this section explore the value addition of blockchain-based solutions in a water market setting. These solutions can be used as a governing tool that can replace intermediaries, modernize the regulatory processes, and act as an accounting, auditing, interlinking and trading platform that enables water markets to function effectively.

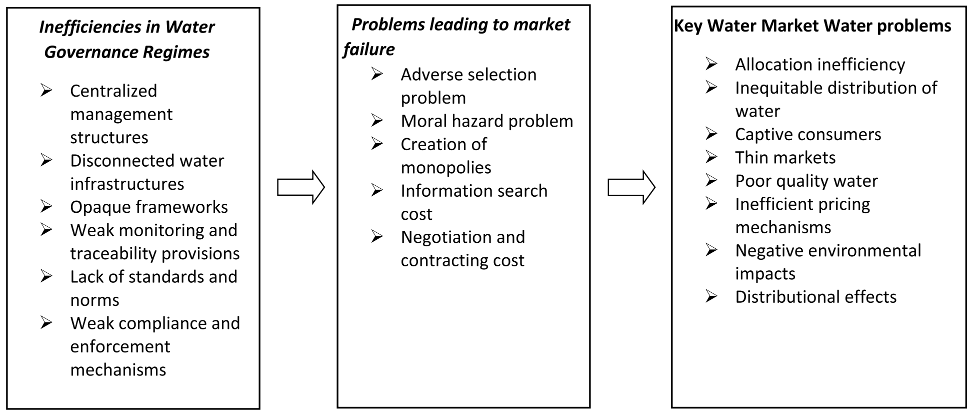

Fig. 10.3 A process flowchart that illustrates the relationship between inefficiencies in water governance regimes, types of market distortions and its relation to urban water problems

10.3.3.1 Blockchain Technology

Blockchain technology might sound like just a trendy buzzword but it is being regarded as the best innovation since the internet technology. Even though the optimism should be handled with caution, blockchain's key features and potential applications seem well worth the hype. Blockchain is a distributed, decentralized, peer-to-peer database network that allows for fast, secure, and transparent transactions of digital assets. It is a network of ledgers with the capacity to record information, and compute and transact, with each ledger holding an up-to-date copy of the entire network. Each ledger acts as a node in a network. Unlike in a centralized system, where transactions are validated by a single server acting as a central authority, with blockchain, the veracity of transactions is validated by distributed consensus. For example, if a majority of nodes verify and authenticate a transaction, then the transaction is accepted. This updated version of the transaction is stored in a block. Each block stores a series of transactions and is linked to the previous block of transactions through hashing functions. Through cryptography and complex mathematical puzzles, the blockchain network is virtually immutable. Thus, it can be used to store information and facilitate transactions in a transparent, efficient, and a tamper-proof manner (Brakeville and Perepa 2018) (Fig. 10.4).

10.3.4 Blockchain for Water Markets

The capabilities of blockchain technology can be divided into three fundamental features. The first feature is a shared ledger system that is virtually immutable through a combination of cryptography and distributed consensus algorithm. It protects against misuse of data and opens up several possibilities in domains where privacy and trust is of critical importance. One of its primary applications is in securing digital identities. This allows for the creation of a common tamper proof database that facilitates assembling data from multiple sources in a seamless manner. Its distributed consensus mechanism and inherent traceability provisions allow for checking the veracity of this data and validates data sharing. This promotes trust amongst different stakeholders and participants, increases transparency, improves data reliability and reduces audit time. This common tamper proof database facilitates accounting for trades and transfers, prevents double counting, and promotes efficiency in the system. The second feature is tokenization, which is the ability to create coins or tokens that are a digital representation of assets i.e. a unit of a token represents a specific amount of an asset. This paves a path for token economics and allows for faster transactions with better tracking, trading, and transferring of digital assets. The third feature is a "smart" contract, which is a digital protocol that self-executes when certain conditions are met (Gopie 2018). This allows disparate parties to transact in a transparent and a trusted manner without a need for an external enforcement mechanism or intermediaries. It facilitates compliance of participants, enforces negotiations of contracts, and renders transactions traceable. Smart contracts can help reduce transaction costs, human errors, and corruption through automation and thus increase the robustness and resilience of the system (Fig. 10.5).

In a water market setting, the convergence of the three features of blockchain—a shared ledger to store information in an immutable fashion, the ability to create currencies paving a path for token economics, and smart contracts to execute automated functions when certain conditions are met—makes it a useful tool to reduce information asymmetry and transaction cost. Blockchain based peer to peer trading platform called the Water Ledger conducted a feasibility study on whether blockchain technology can increase transparency and improve efficiency in the water trading market of Murray Darling basin in Australia (Civic Ledger Pty Ltd | Australian Water Partnership n.d.). The finding of the study suggests that the complexities of the water market

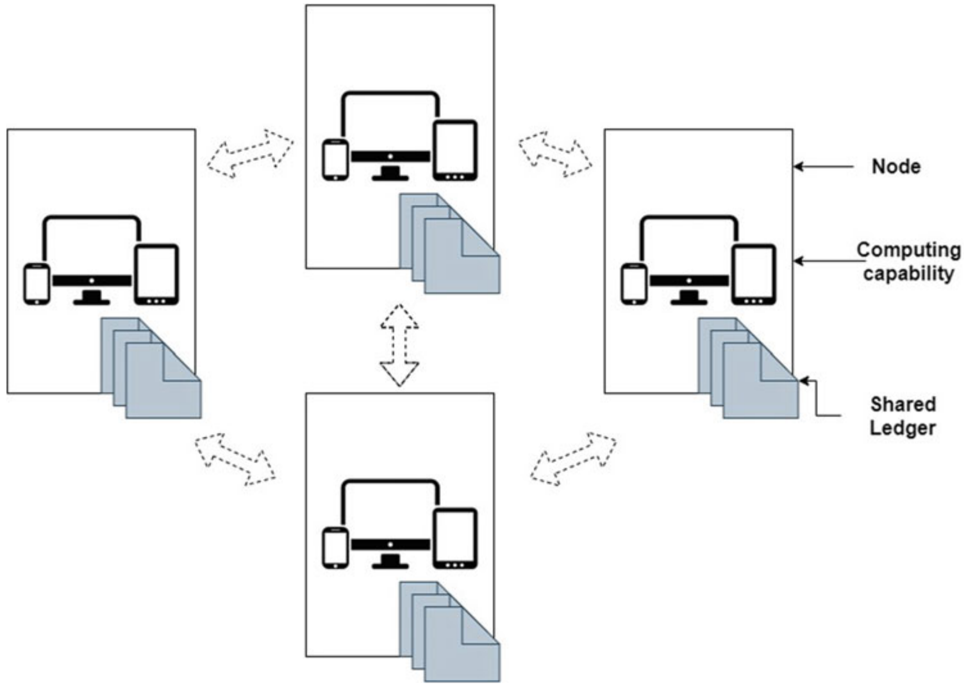

Fig. 10.4 Blockchain network

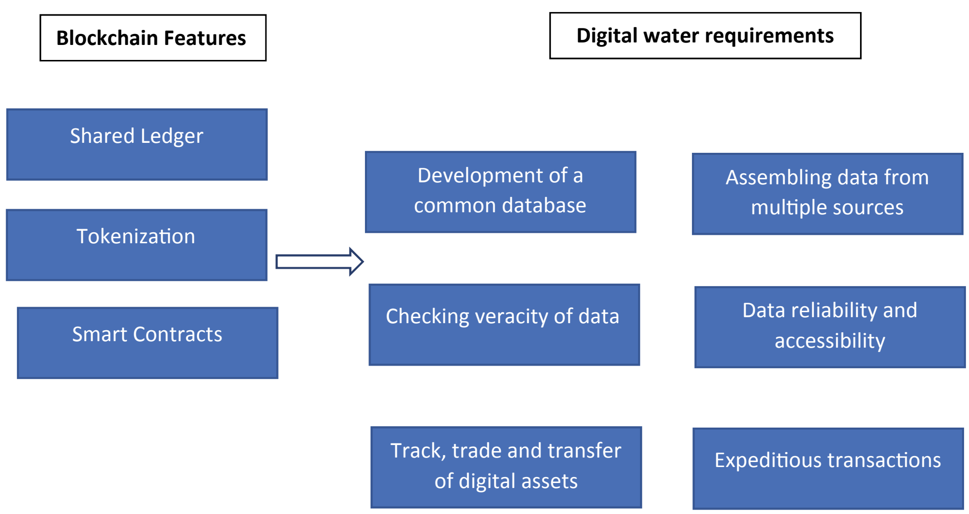

Fig. 10.5 Mapping of blockchain features with digital water requirements

in Murray Darling basin with business and operational rules, lack of available water information and presence of intermediaries excluded around 75 percent of potential participants. These excluded participants were reluctant in participating in water trades as they were not able to understand or have the confidence in how the market operated (OECD Blockchain Policy Forum Distributed Ledgers: Opportunities and Challenges 2018).

The water trading mechanism in Murray Darling Basin allows for buying and selling of water entitlements—permanent rights to share of water and water allocation shares—seasonal rights to share of water distributed to an entitlement holder (Water Markets and Trade 2015). Through a system of tokenization i.e. by mapping a physical asset such as allowable water allocation shares to a digital signature in the form of a token, the Water Ledger platform provides clarity over the ownership and history of such a water asset. This makes tracking, trading, and transferring of water assets transparent. Through its system of consensus algorithms, Water Ledger verifies all water trades and updates all shared digital ledgers and public registries in real time (How Water Ledger Works n.d.). Thus, such a tamper-proof blockchain network with robust traceability provisions will prevent misrepresentation of transactions, or prevents participants from backing out of a trade after a contract is signed. This provides the participants with confidence in the robustness of such a trading system and tackles the problem of moral hazard (OECD Blockchain Policy Forum Distributed Ledgers: Opportunities and Challenges 2018). In addition to all trades being published in real time, business and operating rules are built into the blockchain system. This reduces uncertainties amongst participants. Any change in the rules of trade will immediately be visible to all users (How Water Ledger Works n.d.). Thus by allowing equal access to information and making all changes to the market rules visible to all, such a platform promotes trust and transparency in the water market ecosystem. This reduces the problem of adverse selection that participants face in a water market and prevents the creation of knowledge monopolies.

The intermediaries in a typical water market setting play a variety of roles. They manage operations such as connecting buyers and sellers, providing information, and registering trades. These intermediaries charge a fee to manage these operations. The Water Ledger platform allows buyers and sellers to come together in a single market place without any intermediaries and all information is provided at no cost to participants (How Water Ledger Works n.d.). This reduces the transaction cost and transaction time (OECD Blockchain Policy Forum Distributed Ledgers: Opportunities and Challenges 2018). The platform also integrates with other related departments' data that determine a buyer's need such as rainfall data and agricultural throughput. Thus, allowing buyers with range of options optimized to their needs. This reduces information search cost. The process of trading is inexpensive and is simplified through a combination of smart contracts and optimized choices based on selection of specific parameters that is presented to the participants. Automatic execution, settlement and enforcement of contracts based on complex water market rules eliminate costs associated with negotiating and enforcing trades. Finally, the platforms allow for trades to be published in multiple ledgers simultaneously thus reducing the cost of maintaining and reconciling multiple ledgers. Reduction of transaction cost and transaction time allows more participants to participate as well as allows for more transactions to actualize. This improves the liquidity in the water trading market (OECD Blockchain Policy Forum Distributed Ledgers: Opportunities and Challenges 2018). Thus, the Water Ledger platform provided a single ecosystem without intermediaries that brought buyers and sellers together and facilitated the participation of excluded participants (OECD Blockchain Policy Forum Distributed Ledgers: Opportunities and Challenges 2018).

To summarize, Blockchain can be used as an effective tool to eliminate market distortions and pave the way for smart water markets to address the problem of water scarcity. Blockchain would act as: (1) An accounting platform that maintains a ledger of accurate tamper-proof information on water rights, quantity, quality, buyers and sellers; (2) An auditing platform that allows regulators to track transactions and penalize rule violations; (3) A trading platform that connects buyers and sellers and facilitates transactions of water assets; and (4) A networking/interlinking platform that allows for seamless interaction among different agencies and stakeholders.

10.3.5 Challenges of Using Blockchain

10.3.5.1 Use of Other Technologies

*There are s*everal different types of databases that record digital transactions, version control software packages that keeps track of every changes made to a file, audit management packages to assist in continuous monitoring and scrutinization, trading tools to facilitate transactions and accounting tools for book-keeping purposes. These individual tools offer specific features that can rival or supplant blockchain. It is possible that these tools are individually cost effective and offer a faster execution speed. However, integration of multiple such tools to operate across different functionalities as in the case of water markets creates inherent complexities that can lead to inefficiencies and higher costs. As illustrated in the previous section, the Blockchain database through its decentralized shared ledger system, consensus algorithms to verify transactions, tokenization to track assets and smart contracts, provides an integrated functionality of accounting, auditing and trading and thus provide seamless integration while adding value across the ecosystem.

10.3.5.2 High Energy Consumption and Increased Transaction Time

Blockchains are divided into public or private based on who is allowed to participate in the network. In public blockchains, anyone is allowed to participate without permission —in the consensus validation process, in sending transaction over the network or in viewing all transactions. Thus, public blockchains offer true transparency and decentralization. Such a blockchain system works well in certain applications such as managing digital currencies. However on the downside, public blockchains increase transaction time and reduce the network speed as there is significant cost vis-a-vis computational power and time associated with verifying transactions through a distributed consensus protocol. As illustrated in the previous sections, blockchain does reduce cost related to data storage, data capture, search cost and so on. But it increases cost significantly during the verification process as anyone is allowed to participate. For public blockchain to function efficiently and to scale, significant computational power will be necessary to facilitate faster transactions. However, in a water market setting, selected participants are allowed to engage in trade while regulators play a role in deciding the rules of the trade. In such a setting, a private blockchain-based model with a permissioned access setting that puts a limit on the number of participants would be an ideal protocol to use. A system with limited players can reduce the inherent cost associated with verifying transactions, allow for faster execution of transactions and thus provide better scalability options (Jayachandran 2017).

10.3.5.3 Not Truly Decentralized

Use of a permissioned blockchain system does not eliminate the role of a central authority and thus is not truly decentralized. However, regulators and institutions play a significant role in the management of water markets. They set the rules of the water markets for participation, compliance, operation, and trading. They also continuously monitor water use, take into account water quantity and quality considerations, and observe externalities and third-party effects. All this in addition to developing a penalty and reward system to ensure compliance. In short, they play a role in preventing market failures. A permissioned blockchain protocol offers a way to make the regulators more accountable, make regulations more robust, and help reduce market distortions.

10.3.6 Exploring the Need for Water Markets in Los Angeles and Bengaluru

10.3.6.1 Los Angeles County

The water management infrastructure in Los Angeles county, with the help of 215 community water systems, serves over 10 million people (DeShazo and Gregory 2016; U.S. Census Bureau QuickFacts n.d.). Each of the community water systems is administered by governmental agencies or privately-owned bodies. The water systems are of different capacities in terms of the volume of water that they can hold and number of customers they cater to. Each of the water systems is unequally supplied with different water resources. The supply of water to each of the water systems is not determined by need, equity, efficiency or the environment, but rather by historical processes. Different water systems are supplied with water from various sources resulting in differences in quality. Also, by being dependent on a particular water resource, water systems are susceptible and vulnerable to shocks such as droughts or contamination. In addition, due to an unequal allocation mechanism, some water systems contain more water or less water than the other systems. This results in different pricing mechanisms for each system. There are some water systems that supply water at $2,000 per year for certain households whereas comparable households in other water systems pay around $200 per year (Water Management in Los Angeles 2015).

These water systems differ in governance regimes, jurisdictional boundaries, and regulations. They are completely decentralized in their management, fragmented in their architecture, and disconnected in their operations. The water systems act as a natural monopoly, since consumers have no ability to switch to other suppliers. In addition, there is no systematic or standardized regulatory framework. There is a lack of standardized and accessible databases (Water Management in Los Angeles 2015). This results in lack of supervision, transparency, and accountability in the system, which can lead to an inadequate understanding of water quality and distribution. Governing agencies make assumptions on how to distribute water rather than adequately projecting for future demands and risks. There is also lack of coordination and oversight as each of the suppliers set their own prices and policies (Water Management in Los Angeles 2015).

Developing a regional blockchain-based water market that provides a robust regulatory mechanism and an efficient trading platform can help: (1) Reduce inequity by facilitating water systems with surplus water to trade with systems that have a deficit; (2) Develop new revenue streams and local water sources by incentivizing water systems to explore opportunities to tap into new supplies such as rainwater, wastewater, and storm water; (3) Improve resilience to climate change impacts by facilitating water systems to diversify its supplies; and (4) Creating incentives for water systems to recycle wastewater (DeShazo and Gregory 2016).

10.3.6.2 Bengaluru

The population of Bengaluru stands at over 10 million; similar in size to that of Los Angeles county (Bengaluru Water Board, Blueprint for Future n.d.). However, unlike Los Angeles county, the major supplier of fresh water is a centralized governmental agency called the Bengaluru Water Supply and Sewerage Board (BWSSB). The BWSSB primarily imports water from a single source, the river Kaveri (Bangalore Water Supply and Sewerage Board n.d.). With growing demand and a changing climate, reliance on a single source will make the water system infrastructure vulnerable. The distribution of water by BWSSB is based on a piped water network. There is inter-regional inequity in water distribution as significant number of urban communities in Bengaluru is not connected to a piped water supply managed by BWSSB (Bengaluru Water Board, Blueprint for Future n.d.). Instead, they rely on water supplied by unregulated private companies. These private companies typically extract and sell groundwater (Ranganathan 2014). Since they can

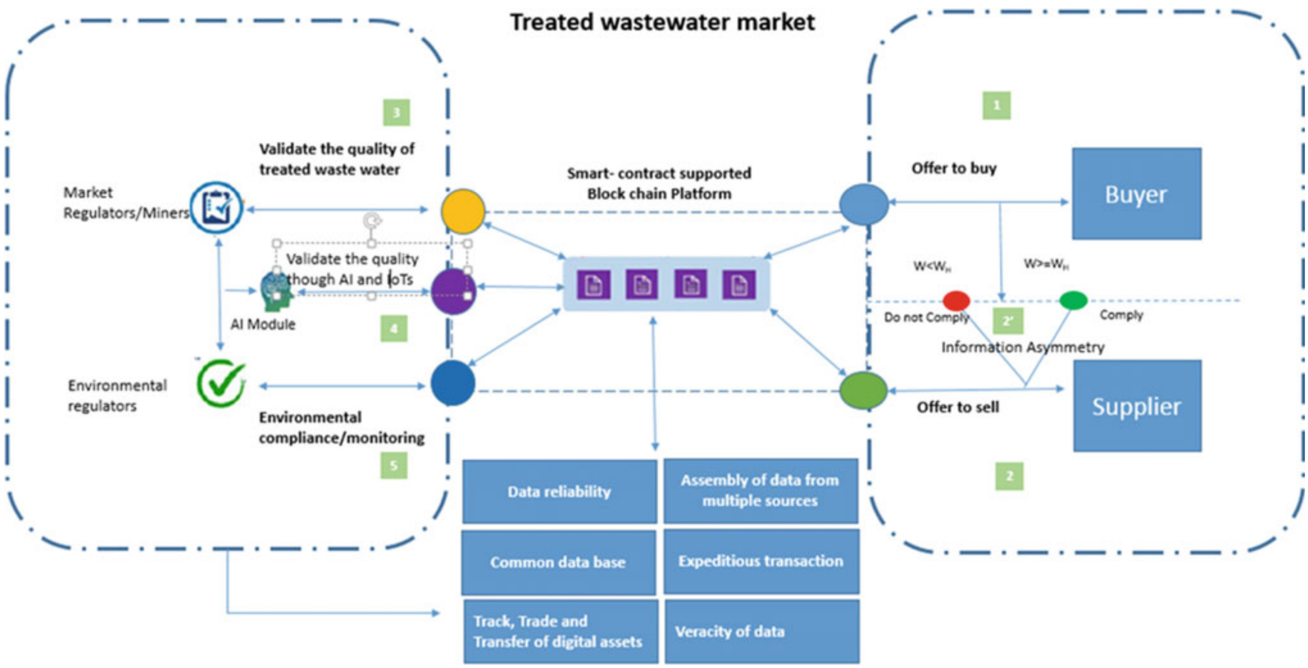

Fig. 10.6 Blockchain based system workflow

operate under an informal market setting, there is no systematic reporting or regulatory framework to hold them accountable for the quality of water that they supply or the environmental impacts (like falling water tables) that they inflict. In the areas where BWSSB supplies water, the tariffs are low. Such an inefficient pricing model leads to apathy and lack of awareness amongst consumers resulting in overuse and wastage (Fig. 10.6).

In order to reduce the dependence on a single source, there is a need to diversify BWSSB's water resource portfolio. Thus, there is an opportunity to develop recycled wastewater, catchment and household-scale rainwater, and storm water as supplementary sources. Financial considerations and management inefficiencies are usually an impediment to developing new local sources. Developing a blockchain-based smart water market that provides a robust accounting, auditing, and trading platform to manage these local sources will bring in new revenue streams, provide access to newer and cheaper water supply options to consumers, improve allocation efficiency, and reduce risk exposure *vis-à-vis* imported water. These market-based instruments for local water sources can be expanded to include private players who manage groundwater, thus formalizing the informal water market (Fig. 10.7).

10.3.7 Policy Implications: Beyond Water Markets

10.3.7.1 Creation of a Prosumer Market

In light of current water scarcity problems, alternate sources are being tapped to address water needs. Rain water harvesting and wastewater reuse are popular alternatives. A blockchain-based system can be used to create peer-to-peer trading platforms where water users can be incentivized to also act as producers. This lays a foundation for a prosumer market, i.e. production by consumers. Development of a prosumer market reduces dependence on surface and groundwater, incentivizes consumers to use less water thereby assisting in conservation, and creates a socially, economically, and environmentally conscious citizenry.

10.3.7.2 Monitoring Water Quality Levels

A blockchain system can be built to acquire water quality data from quality measurement equipment and can be used by authorities to monitor the levels of water purity in the distribution system. Through smart contracts, an automatic

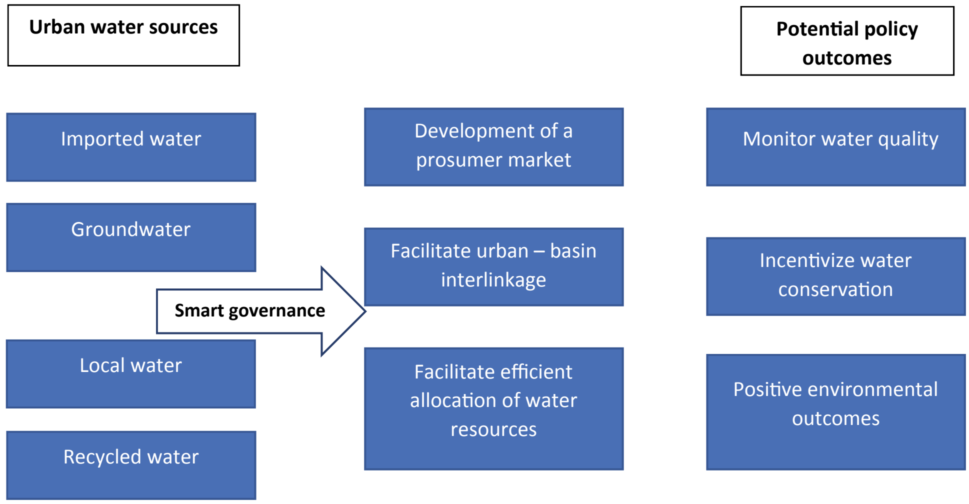

Fig. 10.7 Policy implications of using the internet of things, big data, and predictive analytics integrated in a blockchain network in urban water management scenarios

system can be developed to send alerts to relevant authorities and citizens if water quality level falls below permissible limits. Such a mechanism can help avoid a crisis related to water quality as seen in Flint Michigan in the United States where there was an unprecedented level of lead in water.

10.3.8 Conclusion and Future Research

Water resources are finite and are becoming increasingly scarce in light of natural and anthropogenic stressors such as extreme weather phenomena, population explosion, rapid urbanization, and consumerism. Regulators who manage water are faced with challenges such as inefficiencies in water allocation, apathy amongst consumers, overexploitation of water resources, and pollution. Water markets are cited as a solution to address the problem of water scarcity and its associated problems. They are instruments that are used to dynamically allocate water-related goods efficiently. However, water markets are a complex economic instrument to implement, manage and sustain as they are susceptible to market distortions especially due to information asymmetry and high transaction cost. A robust regulatory mechanism is necessary to prevent these market distortions. The research paper makes a case for a blockchain-based system to be used by regulators of water markets as an accounting, auditing, trading and an interlinking tool to reduce information asymmetry and transaction costs. This paper also explores the potential of a blockchain-based water market to address the problem of inequitable distribution of water in the community water systems of Los Angeles county; and underdeveloped local water sources and unregulated private players in the city of Bengaluru. A blockchain-based smart water market will be able to effectively allocate water resources; empower consumers by providing economic and social value; and incentivize conservation and provide positive environmental outcomes. Thus, acting as an effective policy instrument to reduce water scarcity.

The future work could focus on the economic implications of a blockchain-based water market on the society. To illustrate this a bit further, one of the key findings of this paper is that using blockchain as an underlying technology to manage water markets reduces market distortions due to information asymmetry. An interesting question that this finding unlocks is how will a water market operate when buyers and sellers have access to perfect information? Based on the "market for lemons" concept (Akerlof 1978), when perfect information is available to buyers regarding different grades of quality of goods that are available, over time poor quality goods will be weeded out due to perfect signalling. This can result in either fewer seller participating in such a market or fewer products albeit higher quality ones available to meet the demand. In a blockchain-based water market context, with fewer goods available, the price of good quality water goods will increase substantially. Such a scenario can lead to the creation of an exclusive market with only a few participants who are able to afford the products. In addition, sellers of poorer quality water goods will have an incentive to move to a non-blockchain-based market, which will result in market segmentation. Thus, the future research work will look to answer questions such as whether a blockchain based water market will increase or decrease welfare in society.

10.4 Economic Instruments and Finance for Ensuring Water Security

10.4.1 Introduction

Sustainable access to adequate quantities of acceptable quality water is necessary for food security, human well-being, education and capacity building, protection against water-related risks, ecosystem preservation and socio-economic development (UN 2017). Yet, in many areas of the world the combined effects of climate change, population growth and changing distributions of wealth mean that the balance between these needs are increasingly difficult to maintain (IPCC 2014b). By 2030, 25% of the population is expected to live in a country affected by water scarcity and/or recurring droughts, to add to the increased likelihood of more severe floods and extreme events (UN 2015). In this context, ensuring water security necessitates a substantial increase in water use efficiency across economic sectors (OECD, 2015a; UN 2017; WEF 2017).

Water is a finite and vulnerable resource, and its scarcity is increasing globally. Thus, water is amenable to being managed through economic and financing principles and instruments (ICWE 1992a). When analyzed from the lens of economic goods, efficiency improvements through new technologies and/or reallocation from less to more productive water uses could create welfare enhancing opportunities that can be used to minimize harm from droughts, floods, and other threats to water security, and in some cases create additional income that can be used to compensate those users that end up worse-off (Kaldor-Hicks improvement) (Hicks 1939; Kaldor 1939; Pigou 1932). Yet, the complexity and uniqueness of water as a resource means that realizing these opportunities is often challenging (van der Zaag and Savenije 2006). Water is essential for life, fugitive and bulky, private, collective and public at the same time, heterogeneous, and variable across space and time. Interspersed water bodies are interconnected at a basin level, as part of an intricate system in which environmental, social and financial uses coexist. As a result of this complexity, the straightforward application of basic economic principles to water can lead to undesirable outcomes (Hahn 1989). Much evidence shows how the welfare-enhancing opportunities offered by water markets or subsidies for irrigation modernization can go to waste as a result of uninformed or poor governance, and in some cases even backfire, giving rise to relevant negative externalities in the form of water overuse, the depletion and pollution of water bodies, and degraded riverine and related ecosystems (Connor and Kaczan 2013; Rodríguez-Díaz et al. 2012). Sensible and conscientious governance, supported by economics, adequate finance and interdisciplinary water resources approaches are necessary to make these opportunities work for individual users, society and the environment (OECD 2013).

The centrality of water to the multiple dimensions that condition human well-being means managers and water planners in water scarce and drought-prone areas face difficult choices on water allocation to balance multiple trade-offs (Hanemann 2006). The adoption of a holistic and coordinated management of water and related resources through an Integrated Water Resources Management (IWRM) is necessary to ensure that social welfare and well-being are maximized in an equitable and sustainable manner—thus effectively contributing towards greater water security (Gomez et al. 2017). Properly designed, economic instruments can both create welfare-enhancing opportunities for private users, and leverage them to coordinate and align individual decisions with the social objectives of achieving reliable quantity and quality of water and mitigating water-related risks embedded in the water security concept.

This section is structured as follows: in Sect. 10.2.2 we present different economic instruments for water security, provide examples, and critically assess their characteristics and performance, drawing on the available evidence on the performance of economic instruments; in Sect. 10.2.3 we discuss how they may contribute in the future to achieve greater water security; Sect. 10.2.4 concludes by summarizing lessons learned and identifying persistent gaps in the design and implementation of economic instruments, including financial ones.

10.4.2 Economic Instruments—Rationale and Taxa

Public intervention in water allocation can benefit from, and typically includes, a wide array of economic instruments, notably water markets, charges, Investments in Watershed Services (IWS), insurance and non-pecuniary agreements. Below we summarize the main features of these instruments, and illustrate how they can contribute to water policy objectives offering some evidence on their observed performance.

10.4.2.1 Water Markets

The term ‘water market’ does not have a precise definition (Brown 2006). The USA National Research Council defined a water transfer as any change in the point of, in the type or in the location of water use (National Research Council 1992). Sumpsi et al. (1998b) defined a water market as “an institutional framework which allows water right holders, under certain established rules, to transfer their water rights to other socio-economic agents or water users, receiving an economic compensation in exchange”. A market for water “permits the temporary, long-term, or permanent transfer of water from the existing rights-holders to other water users in exchange for payment” (Hanak 2003, p. 2). Water trading will only occur if there is a difference, after transaction, transport, and risk costs, between buyer’s willingness to pay and a seller’s willingness to accept payment for not having that water available (Calatrava and Garrido 2005).

Designing efficient market institutions to replace traditional water allocation rules is a daunting task, as market and legal rules, as well as social norms, must be established to make trading efficient and at the same time to protect other water users and to enhance the conservation of the resource (Garrido 2007). Similar to other allocation mechanisms, water markets have some advantages and disadvantages that should be considered. They reveal the opportunity cost of water, allowing for a more efficient use of the available resources through the transfer of water from low to high value uses (Adler 2009). Water markets could generate significant gains for buyers and sellers that would not otherwise occur. These gains increase when water availability is low (Garrido and Gómez-Ramos 2009; Grafton et al. 2010). On the other hand, economic criticisms of water markets are based on the argument that transactions costs may be higher than those derived from other water allocation mechanisms (Pujol et al. 2005), and that they could generate third-party externalities, exceeding in some cases the social benefits derived from trading (Rosegrant and Binswanger 1994).

Water markets have been implemented in those areas with water scarcity problems or with an irregular distribution of water resources among seasons, sectors or regions. In many developing countries, with limited social and institutional capacities, the adoption of markets for permanent water rights has been slow; while informal markets for temporary transfers have been more widely adopted, since no change of ownership takes place (Bjornlund 2003). In USA, Australia, Chile, Mexico and Spain, formal water markets operate under very different frameworks and rules. Water trading has been mainly proposed as a flexible means for mitigating water-supply shortages to non-agricultural users, by transferring water resources from agriculture (main water abstractor in most countries) to other sectors, and reducing the negative economic impacts of water shortages (Ranjan 2010). In countries like India and Pakistan, but also in developed countries like Spain, informal water markets have arisen, being characterized by the lack of official government administration (Hernández-Mora and De Stefano 2013).

10.4.2.2 Water Charges

Water charges differ from prices in that they are a levy on the use of the resource, defined through an administrative procedure rather than through the interplay between supply and demand in a market environment. They can be structural (fixed rate) and/or incremental; urban, industrial or agricultural; volumetric and/or based on a proxy (such as irrigated surface); and address financial, resource and/or environmental costs. Charges often combine different levies (e.g. fees and tariffs) and tranches. They can contribute to water security through a reallocation of the resource, in case users relinquish their right to use water; or through the recovery of the costs of water use, in case revenues are earmarked towards actions aiming to enhance water security.

Charges are by definition an effective tool. Water complies with the law of demand and displays a negative relationship between charges and quantity demanded, meaning higher charges tend to reduce withdrawals (Yoo et al. 2014). Charges are instrumental in addressing the negative externalities related to water use (i.e. costs accruing to third parties that did not choose to incur on them), but this can be challenging due to limited evidence on the relationship between the charges and the quality and availability of the water resources, as well as other ecological functions and services (de Jalón et al. 2017). More importantly, since charges are often set through administrative procedures, they tend to fall below the estimated marginal cost of resource use and have a limited impact in rationing withdrawals. Sensible cost-recovery that has the ability to enhance water security can be challenging to achieve, as demonstrated by the European experience, where despite major regulatory and water resources planning initiatives charges remain on average below marginal costs (EC 2000, 2012). This is especially visible in agriculture, the largest water user, and that concentrating the least productive uses of the resource. Irrigation water charges are typically much lower than in other sectors, and often appear decoupled from actual water use (e.g. irrigated area instead of volumetric payments), being thus insufficient to recover the costs. Cost recovery levels in water insecure basins of S and SE Spain can be as low as 54%, and these figures do not include the relevant environmental and resource costs of the resource (Maestu and del Villar 2007). In practice, observed charges appear to be guided by users' ability to pay rather than the costs derived from the activity. For example, the ratio of industrial to irrigation water charges in the Lombardy Region in Italy equals 166.7, with industrial uses representing 5% of water use and 63% of revenue raising—a gap that cannot be solely explained on the basis of higher costs (Santato et al. 2016).

On the other hand, the multidimensionality of water implies a straightforward application of full cost-recovery charges may not be desirable, either. Agriculture still plays a fundamental and strategic role in terms of food supply independence, habitat and landscape protection, soil conservation, water basins management, carbon dioxide sequestration, biodiversity conservation and food security (OECD 2014). Sensible and informed policy design is necessary to ensure these multiple tradeoffs are properly balanced once economic instruments are deployed. In the worst possible scenarios, autonomous adaptation may lead to inelastic demand in which water use is not responsive to charges, thus worsening economic outputs without reducing water use (Pérez-Blanco et al. 2015).

10.4.2.3 Investments for Watershed Services (IWS)

Investments in watershed services (IWS) are a category of economic incentive approaches where the user or beneficiary of watershed services exchanges financial value for the provision of protection, rehabilitation, or enhancement of watershed services or land uses from sellers or providers (Asbjornsen et al. 2015). IWS create financial value for these activities, internalizing the positive externalities that occur when upstream providers of watershed services protect or enhance green infrastructure. IWS are considered efficient solutions to water management problems if the benefits received by downstream beneficiaries are greater than or equal to the financial incentives required to attract sellers of watershed services into these programs (Jack et al. 2008; Wunder 2015).

IWS programs encompass a broad range of policy mechanisms referred to in the literature, including payments for ecosystem services, payments for hydrological services and compensation for watershed services, among others (Wunder 2015). In watershed management IWS has become the more common term and is more inclusive of programs that do not use monetary payments but also include other forms of financial value. A recent compilation of IWS programs includes water quality trading and offsets, as well as water quantity markets, under the IWS label (Bennett and Franziksa 2016). In this section, we focus on the exchange of financial value or other means of compensation provided in exchange for specific actions that contribute to the protection, rehabilitation or enhancement of watershed services from changes in land use management. These investments in green infrastructure include both user-driven investments, where the users themselves act on behalf of their customers or constituency, and public subsidies for watershed protection.

As of 2015, there were more than 400 IWS programs operating in over 60 countries (Bennett and Franziksa 2016). The financial value of these programs was more than \$25 billion and a land area one and a half times the size of India was being protected or rehabilitated through these programs (~486 million hectares). The rise in IWS programs parallel growing interest in investing in natural capital or green infrastructure to secure ecosystem services (Jack et al. 2008). In addition to economic efficiency, these approaches are often promoted due to the potential generation of co-benefits (Bremer et al. 2016). Co-benefits of IWS programs include enhancing other ecosystem services, such as habitat protection or carbon storage, and or social benefits, such as increased incomes in rural areas.

One of the most famous examples of a user-financed IWS program is the New York City-Catskills example (Chichilnisky and Heal 1998). This example involved the City of NY investing in natural capital in the Catskills and Delaware watersheds instead of building a more expensive water filtration plant. Today these investments in source water protection are common throughout the world with more than 40 cities in the United States involved in some type of IWS program (Bennett et al. 2014). The type of land management activity being targeted by these programs ranges from forest conservation to reforestation to wildfire risk mitigation, and involves incentivizing watershed services on both private and public lands. For example, the U.S. Forest Service has developed a number of partnerships through its Forests to Faucets program that leads to financial resources for management of public lands for watershed services. Outside of Denver, Colorado, Denver Water and the U.S. Forest Services have teamed up to invest more than \$30 million in wildfire risk mitigation activities on public lands to reduce impacts to water quality after catastrophic wildfire (Jones et al. 2017).

Most funding for user-driven IWS programs comes from the public sector, with water utilities being a major player. Non-governmental and private sector organizations are often part of the mix, but represent a much smaller proportion of total funding (Bennett and Franziksa 2016; Bremer et al. 2016). There are relatively few examples of user-funded IWS programs where private industry is the sole buyer; one exception to this is the case of Vittel (Nestle Waters) in north-eastern France (Depres et al. 2008). The bottling company developed an IWS approach after being faced with increased nitrates in the watershed after farmers began switching from traditional hay crops to corn. There was a clear business case for Vittel to work with farmers upstream and the example highlights the complexity and long time frame that is often necessary to develop a successful IWS approach. User-financed IWS programs increasingly involve a group of organizations contributing jointly to affect watershed services, referred to as a collective action fund, versus individual groups acting as sole buyer.

Public payments for watershed protection are an IWS approach where government is the only buyer and can involve supranational, national or state governments (Bennett and Franziksa 2016). These programs are often larger in scale than user-financed IWS. The U.S.'s Conservation Reserve Program is included under this category since the government provides financial incentives to farmers to take lands vulnerable to erosion out of agricultural production (Jack et al. 2008). China has one of the largest public subsidy programs for watershed services. The Conversion of Cropland to Forest Program pays farmers to take sloping land out of production and afforest in order to decrease soil erosion and flooding (Gutiérrez-Rodríguez et al. 2016). Mexico also has a national payment for hydrological services program aimed at improving water security and water quality. At the national level this IWS approach provides monetary payments to landowners that agree to conserve forest. Mexico has also developed a decentralized version of this program where local governments, non-governmental groups and the private sector come together, with a match from the national government, to implement the IWS approach (Asbjornsen et al. in press; Muñoz-Piña et al. 2008).

Despite the rapid growth in IWS programs they face a number of challenges and critiques. Few rigorous evaluations of IWS programs exist—even though there is expressed interest in monitoring and evaluation, most programs lack the technical ability or funding to implement effective monitoring, especially across ecological, social and economic dimensions (Asbjornsen et al. 2015). A recent integrated assessment of expected return on investment from an IWS program in Colorado found that the potential financial returns to beneficiaries was positive, but also found that these returns would vary considerably by site characteristics and only hold under assumptions of worst-case scenarios (Jones et al. 2017). Very few studies have gone beyond measuring changes in land management or land cover to linking these activities to changes in watershed service provision (Naeem et al. 2015). This lack of monitoring is problematic since the scientific relationships between some land use practices and watershed services remain contested (Asbjornsen et al. 2015). An added concern in incentivizing changes to land management is whether the harmful activities they are trying to address (e.g., deforestation, agricultural practices) will simply be displaced to other areas. Referred to as leakage, a handful of studies have found evidence of leakage in programs that pay for forest conservation (Alix-Garcia et al. 2012; Velly et al. 2015).

Another common criticism of IWS stems from concerns about the equity of using financial incentives in some rural, developing contexts (Pascual et al. 2014). There is also the social concern is whether financial incentives will crowd out intrinsic motivations to protect and rehabilitate watersheds, and whether this will undermine long-term conservation outcomes (Rode et al. 2015). This is closely related to issues of permanence, and whether IWS programs will lead to sustained changes in watershed services, especially if the payments stop. There are few long-term studies of IWS but preliminary evidence suggests that IWS focused on forest conservation is not likely to lead to sustained changes after payments end, if the underlying drivers of deforestation are not changed; however, incentives that lead to rehabilitation or enhancement of land might lead to sustained impacts if the program ends (Börner et al. 2017). The issue of permanence is important to consider when setting up an IWS program since initial and long-term financing has been identified as one of the largest barriers to IWS (Bennett and Franziksa 2016). The trend toward collective action funds may help address this concern, since having multiple investors is more sustainable than public subsidy programs that are vulnerable to political changes.

10.4.2.4 Financing Water Security and the Insurance Value of Ecosystems

The insurance value of an ecosystem results from "the system itself having the capacity to cope with external disturbances and includes both an estimate of the risk reduction due to the physical presence of an ecosystem (e.g. area of upstream land/number of downstream properties protected) and the capacity to sustain risk reduction (i.e. the resilience of the system)" (EC 2015). This approach is based on the recognition of the multipurpose role of ecosystems, which can be analysed from the perspective of its insurance value. According to Baumgärtner and Strunz (2014), "an ecosystem's ability to maintain its basic functions and controls under disturbances, is often interpreted as insurance: by decreasing the probability of future drops in the provision of ecosystem services, resilience insures risk-averse ecosystem users against potential welfare losses". Capturing this value necessarily relies on the integration of physical, social, institutional and economic aspects to understand the insurance value of ecosystems. This approach also requires giving due attention to enablers and barriers for the uptake of innovative institutional, economic and financial mechanisms that internalize the insurance value of ecosystems into current practices. In insurance language terms, financing water security through insurance is conditional on the potential for ex-ante intervention to reduce the damage costs by putting value into ecosystem functions that can reduce risk. Financing water security through insurance encompasses a complex interplay between regulatory frameworks, economic incentives, financial resources, viable business models and providers of green infrastructure services to encourage the use and uptake of nature-based solutions as part of the risk reduction portfolio of water conservation measures.

Thus developing economically and financially viable schemes that capture the insurance value of ecosystems (regulatory functions and their resilience to shocks) would increase water security by reducing vulnerability to water risks like floods and/or droughts. For example, by slowing down the flow of flash floods through e.g. river restoration and/or afforestation for slope stabilisation, or by protecting the storage capacity of aquifers acting as "natural reservoirs" for use during drought "acting as a powerful climate adaptation option, a natural insurance mechanism, and not just a component of freshwater supplies" (OECD 2015b, p. 10).

Depending on the institutional setting and the particular risks the presence of the ecosystem helps mitigating, the implementation of a Natural Assurance System (NAS) will depend mainly on: a) the development and uptake of new (private and/or public) insurance schemes or insurance sector-driven innovative financing mechanisms such as CAT bonds and weather derivatives, or “resilience bonds”, provided they take the disaster risk reduction impact of Nature-Based Solutions into their estimation of risk profiles. Derivatives are end-products of a process known as securitization that transforms non-tradable (natural catastrophes or weather related) risk factors into tradable financial assets. As a result, the markets for these types of products are often incomplete; or b) a long term collective contract between the public authority responsible for the watershed and key beneficiaries of the insurance services of the ecosystem, which align incentives, allows for a fair allocation of benefits, costs, risks and returns over time. At present for example there is a global initiative to develop Nature Based Standards for climate bonds to facilitate investment into ecological or natural infrastructure with a degree of investor assurance on the investments made (Bottio and Rosembuj 2016).

The relative weight of one option or the other depends on the current levels of service and the role of the public and private sector in a particular society concerning disaster risk management for a particular water risk: floods, droughts or water quality.

The design of the collective contract and/or the choice for private or public insurance schemes will be influenced by whether the particular risk reduction service given by the ecosystem in a local specific institutional context can be considered a private, a public, a common or club good. Often this classification will also be influenced by the historical levels of services provided by the state. Depending on the classification given to the service different funding sources (taxes, tariffs or transfers) and value-capturing strategies could be drafted to ensure the financial sustainability of the NAS.

Private companies around the world driven by the exacerbation of water risks due to Climate Change and aiming to ensure their license to operate and continuity in water supply are already investing considerable amounts of money into beyond the fence actions under the concept of Water Stewardship (WWF 2017).

The insurance value of ecosystems is an approach that starts from a risk frame to water risks and security, aiming to identify and validate the risk reduction potential of ecosystem regulatory functions. The shift towards NAS does involve a change in paradigm and the acceptance of the fact that given the increasing frequency of extreme events it is no longer possible to rule out all disasters even with the highest level of investments in prevention measures, such as dikes and coastal defences. The shift towards NAS, therefore, requires a combination of sustainable watershed and green infrastructure measures with well-functioning early warning systems and a renegotiated allocation of risks and responsibilities between the public sector, private sector and civil society. The Netherlands, a country with the highest levels of investment in flood prevention, is now in the process of negotiating this new collective agreement as part of the so-called Spatial Adaptation Programme within the “Delta Plan” (Kabat et al. 2005). Another example is the case of the city of Copenhagen and the financing of its Cloudburst Plan. A cloudburst event in 2011 in Copenhagen left the city with losses amounting to more than EUR 1 billion (Rasmussen 2017). The current Cloudburst Management Plan will be financed through an increase in the water rates of Copenhagen citizens, who in turn will benefit from reduced insurance premiums due to the estimated damage loss reduction from better prevention into a number of measures to increase the resilience of the overall system (including aquifer storage services).

10.4.2.5 Non-pecuniary Agreements

Non-pecuniary economic instruments for water management involve negotiated arrangements among public and/or private agents to achieve public policy objectives through the use of non-monetary incentives and truly voluntary agreements—i.e. excluding rewards, penalties and other regulated obligations (Lago et al. 2015). The centrality of water to economic and social activities, as well as natural processes, means that in areas where the resource is scarce the opportunities in which non-pecuniary instruments can lead to non-coerced, acceptable reallocations for all the parties involved (including the environment) may be difficult to find. Yet, these opportunities exist and are well documented.

In the absence of water markets, non-pecuniary agreements through collective action are the conventional instrument to manage drought events in European Mediterranean countries, where traditional command-and-control approaches are being complemented with decentralized and collective management of water, in which users voluntarily reallocate the resource so as to mitigate present and future losses (EC 2008). A good example can be found in France, where farmers need to constitute a Single Collective Water Management Association (in French: Organisme Unique de Gestion Collective) that reallocates the resource within the maximum threshold set by the Local Water Committee (in French: Commission Locale de l’Eau, consisting of representative stakeholders) or public institutions (Montginoul et al. 2016). Non-pecuniary agreements can also be found at a wider basin scale. This is the case of Italy’s Po River Basin, where drought management has shifted from the traditional command-and-control approach in which the Civil Protection Department (in Italian: Dipartimento Protezione Civile) sets specific allotments for users to a coordinated approach in which water allotments are defined through voluntary and participatory processes in a Drought

Steering Committee (in Italian: Cabina di Regia), sanctioned through a formal Memorandum of Understanding (in Italian: Protocollo d'Intesa) (PRBA 2003).

Transformational solutions, as opposed to incremental ones, can help create innovative environments in which win-win solutions can be adopted—sometimes through spontaneous non-pecuniary agreements (Kates et al. 2012). This may be the case of green infrastructure and nature-based solutions that outperform conventional grey technologies (see e.g. Baro et al. 2015; Demuzere et al. 2014; Mazza et al. 2011). One example of the use of non-pecuniary agreements for the adoption of nature-based solutions to enhance water security can be found in the Lower Ebro Basin in Spain. In this area, the hydropower operator voluntarily accepted to release artificial or pulse floods designed to partially restore the river regime, which in turn led to public (risk abatement, macrophyte removal, habitat enhancement) and private benefits (mitigation of the clogging of intakes for hydropower generation and irrigation water pumping, inclusion in the hydropower operator's social responsibility strategy) at the expense of comparatively marginal costs (Gómez et al. 2014).

10.4.3 What Role for Economic Instruments?

Achieving water security—the provisioning of reliable quantity and quality of water to society—is becoming one of the major challenges many regions throughout the world face today, while the unique mixed public, community and private character of water resources makes voluntary actions to address this problem unlikely. Consequently, economic instruments (including financial ones), which change the costs or benefits associated with choices about water use, provide a viable and promising opportunity to incentivize desirable decisions and behaviors by diverse watershed actors. In this chapter, we defined instruments for water security as incentive-based mechanisms designed to align individual behavior with the objectives of achieving sustainable water provisioning and mitigating water-related risks. We discussed in detail several broad categories of such instruments, including markets, charges, subsidies, insurance, IWS, and non-pecuniary cooperative agreements. Selecting the most appropriate instrument will depend on the particular situation, including factors such as the cultural context, existing regulatory framework, the values, beliefs, and motivations of local people, adequate financing mechanisms, and the specific issues surrounding the supply and demand of water resources. In other words, there are no silver bullets, or one size fits all, but rather, all of these instruments play an important role within the larger mix of water policies. There is much opportunity to learn from the experiences of others, and to modify and adapt instruments and to package them in different combinations that best suit the context and that appear particularly promising to best fit the local conditions.

In this chapter, we highlighted several important considerations that strongly influence the effectiveness of various instruments for water security in achieving their goals. Incentives and the behavior triggered in the key actors, and how this contributes to water security goals, is key. Transaction costs associated with implementation of different instruments may also be critical, as these can be quite high for some instruments (e.g., water markets) such that the costs may actually outweigh the benefits—either from an economic or a social perspective. Efforts should be made to enhance the adaptability and flexibility of particular instruments in ways that minimize transaction costs. Another important aspect when designing instruments for water security is ensuring compatibility between the incentives and different groups of interest, such that the incentives match the particular motivations and priorities of target groups, and include all relevant users (e.g., public, private, community based or collective) in ways that are perceived as equitable, transparent, fair, and consistent. Oftentimes, public-private partnerships offer a valuable mechanism for actively engaging diverse water users in working towards common goals while maximizing economic efficiencies. Finally, viable financing schemes such as insurance are also a key element often forgotten in the equation that should be considered alongside the policy mix being considered to align behavior with water security objectives.

We also highlighted several key challenges in effectively designing and implementing these instruments. Perhaps one of the greatest challenges is the possibility that an instrument will generate interactions and feedbacks between different components of the social, economic, and biophysical systems that may lead to unexpected negative consequences. Thus often rather than a single instrument, the right policy mix has to be designed to achieve stated policy objectives. In order to ensure objectives are met, continuous monitoring and evaluation of key indicators using an interdisciplinary approach should be conducted, and the information incorporated into an adaptive governance framework such that the instruments can be adjusted as needed. Another critical challenge, especially in water scarce or high water risk regions, is balancing multiple trade-offs associated with different policy decisions. For example, providing water to certain groups or geographic regions may limit the availability of water to others. Or in some cases, maximizing water quality or quantity benefits may result in negative impacts on other important watershed services, such as flood mitigation or habitat quality for aquatic or terrestrial organisms. In addition, it is also important to consider interpectoral impacts (e.g. through the so called water-food-energy nexus). An important challenge which will become more prominent due to increased pressure on water resources relates to achieving equity in water resource allocation, looking at, e.g., "distributive impacts" and affordability. Finally, because water is considered by many people and in some regulatory frameworks to be a human right and a public good, attaching economic value or subjecting water resources to market forces can elicit strong resistance and even protest among some stakeholder groups that need to be taken into account when working to introduce economic instruments for water security and their financing options.

10.4.4 Conclusion

In summary, economic instruments for achieving water security vary greatly in their objectives, structure, design, underlying assumptions, and target populations. Their effectiveness is strongly dependent on sound knowledge about the complex interactions and feedbacks between the socioeconomic and biophysical systems within the watershed, as well as on the ability to continually monitor, evaluate, and adjust policies to changes in circumstances and new information. Key areas for future research include:

- Inter-, multi- and trans-disciplinary research to address the multifaceted nature of complex socio-bio-hydro-economic systems;
- Comparative analysis of different economic instruments within varying socioeconomic and biophysical contexts, to identify underlying common principles/guidelines that determine success;
- Enhancing quality data that helps to monitor and evaluate the effectiveness of the instruments and the overall policy design;
- Considering not just the efficiency of economic instruments but also who will pay (the beneficiaries), and the financing of the different options and their fairness, which is often not considered;
- Aspects related to incentives and human behavior, i.e. a deeper understanding on the "social acceptability" of the different economic instruments;
- Under an aegis of water security, distributive and equity issues, which also consider ecosystem functions.

10.5 Role of Economic Instruments in Water Sharing

10.5.1 Introduction

Nearly half of the world's population lives in transboundary river basins (TFDD 2016; Jacob et al. 2017). The desire for control of water resources becomes a fertile ground for conflicts as with growing population, climate change, and poor water governance, scarcity of water has resulted in increased demand for water resources. It is anticipated that achieving agreements over the allocation of scarce water resources maybe even more complicated in the case of many nations, given the interdependencies that such shared resources imply. Water conflict regions with poor water governance and policies generally take a longer time for a sustainable solution. Delay in the resolution of conflict often intensifies the water scarcity (Sarker and Blomquist 2019). A recapitulation of the history of international waters suggests protracted water conflicts occur when with limitations of efficient water management policies and agreements are imposed; for example, the Indus treaty took ten years of negotiations, the Ganges thirty, and the Jordan forty (Figueres et al. 2003). During these negotiations, water availability may plummet to a point where it intensifies the water scarcity, reducing the per capita income of downstream countries. The problems tend to be worse as the effect of water conflict gains in intensity.

There are many conventions, declarations, and legal statements concerning the management of international transboundary water bodies, and countries sharing river basins have established integrated basin management initiatives. However, many international river basins and other shared water resources still lack any type of joint management structure, and some international agreements and joint management arrangements need to be updated or improved (Barbier and Bhaduri 2015).

Transboundary water allocation creates a unique economic problem in the presence of externalities. An international river is a common property shared among the basin states and the water used in river basins has the property of a unidirectional externality where the upstream country affects the volume or/and quality of a downstream country's water, but the downstream country cannot do the reverse (Roger 1997). It is assumed that most externalities can be captured by analyzing the river basin as a single unit through an Integrated Water Resource Management (IWRM) where available water resource is distributed (or redistributed) to legitimate claimants, and the resulting authorization for use is granted, transferred, reviewed, and adapted as a water use right (Bird et al. 2008). It entails the coordination of water resources management intending to maximize economic and social benefit and distribute equitably without compromising the sustainability of vital ecosystems and the environment.

The principles of IWRM can also be observed through achieving joint, optimum utilization of water resources, which can help to avoid disputes over the shared waters. IWRM, in the context of the Dublin Principles (ICWE 1992b) assumes water as an economic good and suggests an allocation mechanism that will create more value for the society through balancing equity (i.e., distribution of the total wealth among water users) and fairness (i.e., symmetry in the distribution of water use-derived gains) across different economic groups (Dinar et al. 1997; Neal et al. 2014). Several attempts have been made to develop general rules of international law to guide the sharing of water in transboundary settings (Helsinki Rules 1966; UNECE Helsinki Convention 1992; Salman 2007 also see Chaps. 6, 9, and 12). The principles generally hinge on the notions of equality, reasonableness, and avoidance of harming one's neighbours. However, given countries' increasing demand for water resources, there is limited scope for cooperation to resolve such transboundary water conflicts. Currently, only a few transboundary water agreements include water allocation provisions, and some of the agreed allocation frameworks are challenging to be implemented as the agreed allocation mechanism is not robust and flexible enough to deal with climate change impacts, and environmental conservation concerns, such as environmental flows.

Some countries possess comprehensive powers to deal with interstate conflicts and promoting cooperation in management within their territory. When water is shared by many countries, however, the problem of externalities takes a different dimension because the river basins shared by more than one country cannot be efficiently planned and developed as a single unit unless all of the riparian countries agree. Only in a few cases, this has been attempted, and a leading case, the Columbia River Basin shared by Canada and the United States, yielded mixed results (Krutilla 1966; Roger 1997). When water is shared by more than one nation and the externalities involved cannot be physically internalized, the problems of defining water rights appear. Within one nation, the issue of optimal water allocation can be managed by the definition of water rights and institutions devised for equitable usage of the resource. In the western United States, water property rights are well defined and governed by prior appropriation. In the transboundary water sharing setting, however, the notion of property rights does not hold between countries, and institutions of law for water sharing are enforced by agreement between countries, not by a "supranational authority."

In such situations, economic instruments can play a significant role in allocating common (or shared) water resources and resolving water disputes, internalizing externalities, and act as a negotiating and implementing tool to manage and share water resources. Concerns over the potential for disputes and conflicts over transboundary freshwater resources have sparked increased research into international river basin cooperative management and focused on bilateral and even multilateral, cooperative water agreements (see for recent reviews in Gómez et al. 2018; Garrick et al. 2019; Farquharson et al. 2017; Acquah and Ward 2017; Barbier and Bhaduri 2015; Bhaduri and Bekchanov 2017; Bhaduri and Liebe 2013; De Bruyne and Fischhendler 2013; Dinar and Hogarth 2015; Dombrowsky 2010; Kilgour and Dinar 2001).

Under certain conditions, there is a possibility of attaining bilateral or even multilateral agreement on international river basin management through "linking" the agreement between the parties to an additional issue of mutual interest. Countries favor having specific benefits of transboundary water cooperation, which though may seem obvious, differ significantly according to many factors, including the geographical position, demography, the levels of economic development and trade, water dependency, and governance structures. Identifying and understanding the range of often interrelated benefits derived from the cooperative arrangements and development of transboundary river basins is the pillar to improved management of the basin. A creative combination of approaches, being able to quantify the benefits of cooperation in the short and long term, localized for each case, in an equal and transparent manner, is what riparian states of a basin need to initiate (Barbier and Bhaduri 2015).

For example, issue linkage can facilitate agreement on several international river basin issues. Issue linkage involves either side deals, such as additional trade or aid agreements, or "credible threats," such as the imposition of economic or trade sanctions. In the case of unilateral diversion by an upstream country, however, economic threats by the affected downstream country will only be credible if the latter is the dominant trade and economic power in bilateral relations.

Similarly, the likelihood of successful side deals, such as agreements for increased compensation through trade or aid for the downstream country, is directly related to the economic power of the latter in existing bilateral economic and trade relationships. When the downstream country is the economically "weaker" partner, it is the upstream country that always has the "credible threat" of unilateral water diversion (Just and Netanyahu 1998). Therefore, any cooperative water-sharing agreement is likely to result in an outcome where the poorer downstream country ends up compensating, the richer upstream country to prevent the diversion from occurring (Bennett et al. 1998). Hence, issue linkage and benefit-sharing approach may provide a foundation for greater cooperation and avoiding conflict by giving the understanding of how the physical unit of the basin interconnects with the economic, social, and political aspects. Among those approaches, benefit-sharing mechanisms and issue linkage measures are selected as practical economic instruments to promote and support cooperation in transboundary water management frameworks.

Based on the integrated water resource management principle, benefit-sharing, and side payment approaches with different case studies, this section explores different economic instruments as a tool to mitigate water conflicts and enhance collaboration between countries in water sharing.

10.5.2 IWRM and Water Sharing

The interdependence of the water users within a basin increases the importance of system-wide coordination of the resources to minimize potential conflicts and achieve socio-economic targets with minimal environmental repercussions. Conflicts arise when the water supply to environmental systems decreases due to prioritizing economic development, or the welfare of downstream users depends on the quantity and quality of upstream return flows. An Integrated Water Resources Management (IWRM) framework has gained attention to consider these water use and flow interdependencies and address the interests of multiple water users for effectively resolving potential conflicts and achieving optimal outcomes (GWP 2000).

IWRM initially appeared in water legislation and official guidelines as an instruction to the administrative and technical staff of water departments to manage water resources in an integrated manner (see Chaps. 3 and 12 for further reference on IWRM). The IWRM was popularized; however, after the Water Conference in Dublin in 1992, where four main principles of the IWRM concept were postulated (ICWE 1992b; Ibisch et al. 2016):

- freshwater is a limited and essential resource for sustainable economic activities and ecosystem functioning;
- water resources management is conducted through a participatory approach involving all users, water managers, and policymakers of all levels;
- women play a crucial role in managing and protecting water resources;
- water is treated as an economic good due to competing demands for water, and the value of water should be considered for more efficient water uses.

IWRM is considered as a generic framework in which policymakers can co-work to achieve water solutions and coordinate the implementation of economic and policy instruments. Due to historical, cultural, socio-economic, and geographical differences across the countries, a single blueprint for implementing the IWRM to specific local context does not exist. Therefore, IWRM can be adapted to address the issues raised in the local context.

IWRM is based on a decentralization approach that allows for diversified structures at different water governance levels instead of top-down approaches to water security (Lenton and Muller 2009). Grass-root level initiatives are encouraged to achieve effective resolution of local water security issues. The involvement of local communities in decision-making processes also allow consideration of specialized knowledge, generation of a broader pool of solutions based on diversified opinions, and achievement of broader stakeholder support (Loux 2011). The use of incentive-based marketing instruments becomes important rather than the command-and-control mechanisms in water system developments. This, in turn, shifts the focus from water supply developments such as large-scale water reservoirs and inter-basin water transfers to more cost-effective and innovative water demand management interventions.

Water allocation and water system development assessments based on economic concepts such as consumer surplus and marginal costs of water use became popular with the increasing application of water-economic modeling approaches (Harou et al. 2009; Bekchanov et al. 2017). These studies consider the river basin as a relevant unit for water system analysis due to the possibility of effectively tracing interdependent water supply, flows, uses, and pollutant fluxes within a basin (Ringler et al. 2004). Scarce water resources are to be allocated among competing economic sectors and different stakeholders over time, considering the economic value of water, the costs of water supply, and environmental impacts. IWRM concept thus lies at the core of these modeling assessments. The water-economic models consequently became effective tools for addressing interdependent water management issues such as controlling floods, reducing drought risks, preventing water pollution, sustaining human and environmental security, transboundary management of resources, and coordinating intensive and extensive developments across the economic sectors (Rosegrant et al. 2000; Cai et al. 2003; Ringler et al. 2004; Dinar et al. 2007; Bekchanov et al. 2015a, b).

In economic literature, the interdependencies of the economic actors (groups, parties) and the essence and transaction costs of coordination were postulated by Ronald Coase in the 1960s, much earlier than the popularization of the IWRM concept (von Braun 2016). Negative or positive externalities may occur due to the interdependencies of the economic actors (Coase 1960). Negative externalities cause damage costs to the affected actor; in contrast, positive externalities generate additional benefits. When applied to the water system, negative externalities occur; for instance, if upstream return flows with heavy pollution may damage downstream riparian ecosystems and increase water-borne disease incidents. On the other hand, positive externalities emerge when groundwater seepage and return flows from irrigation projects maintain the proper water level of the surrounding lakes, which are essential for sustaining fishery. The externality of the same action can be either disruptive or beneficial, depending on the quantity, quality, and timing of the change. For instance, in regions where irrigation is seasonal, upstream water reservoir for hydropower generation can prevent winter-and early spring flooding and maintain sustainable irrigation supply in summer, generating positive externalities. Nevertheless, these reservoirs can also be used to increase hydropower benefits in winter when energy demand is high, consequently extending winter floods and leaving less water for irrigation in summer (Bhaduri and Bekchanov 2017).

Economic instruments such as taxes and tariffs can be used to reduce negative externalities, while subsidies can be used to award positive externalities. For instance, taxing or increasing tariffs for water overuse, incentivize more efficient water uses, reduce water demand, and enhance improved flows to ecosystems. Pollution charges through fining polluted water discharges into freshwater bodies also contribute to improved quality of water ecosystem services and downstream livelihoods. In support of water conservation, subsidies can be considered to water users who invest in improved water use technologies. Similarly, industrial return water reuses by irrigation and wastewater recycling activities can be subsidized to improve resources use efficiency and lower the costs of the production when human and environmental health risks of such action are infinitely small (Bekchanov and Mirzabaev 2018). Payments to ecosystem services (PES) are also the type of subsidy that supports environmentally friendly production practices such as organic farming, agroforestry, and watershed protection that helps to protect land and water ecosystems and can be less costly than the implementation of advanced water treatment options.

The economic instruments applied at the production system level also may have implications for water system changes. For instance, taxing production or trade of water-intensive crops such as rice may increase water availability to alternative economic activities. Meantime, subsidized rice farming or higher market prices for rice commodities can boost rice cropping, consequently reducing lower amounts of water for the remaining production activities. Upgrading value chains closely linked to agriculture systems also may have a strong impact on water systems (Bekchanov et al. 2016). Promotion of the adoption of technologies that reduce food losses in food and livestock processing or allow to produce more outputs per unit of leather or fiber material, for instance, may indirectly reduce demand for irrigation water. Improving fertilizer use efficiency may reduce fertilizer demand, consequently decreasing water-energy requirements and pollution impacts of fertilizer production and reducing ground and surface water pollution due to fertilizer overuses. As coined in the tele-coupling concept, economic policies beyond the particular river basin may have an influence on water uses and ecosystem quality in the basin since the economies are being closely connected across the world (Lenzen et al. 2013).

The IWRM also has several shortcomings, including the lack of clear definition of the concept, time-consuming and costly processes required to achieve mutual consent and cooperation, and the increasing complexity of the coordination when developing large projects. Lack of a single blueprint to implement IWRM makes the implementation difficult, and the adoption of a diverse set of instruments yields different outcomes. Consequently, evaluation of the efficiency of IWRM compared to the alternatives becomes challenging (Biswas 2008). Also, ensuring collaboration among the stakeholders has high transaction costs both in terms of time and money. In regions with inadequate institutional capacity and non-transparent rules, it is even more challenging to maintain collaboration and achieve just and effective solutions, especially when aiming at investing in large scale interventions.

10.5.2.1 Application of IWRM in Central Asia

Following legal and economic reforms aiming at the transition towards a market economy, a wide range of policy changes have taken place in water and land use sectors of Central Asia aftermath of independencies. The IWRM principles have been adopted to enhance cooperation among riparian water users and improve water system efficiency (Dukhovny et al. 2013). Integrating international practices and local expertise, regionally specific IWRM principles were developed for supporting secure livelihoods, ensuring environmental sustainability, and enhancing social harmony:

(a) Hydrologic units based on the morphology of a river basin and irrigation network are accepted as proper boundaries for water management replacing the previous system based on administrative boundaries;
(b) Water use activities across sectors (horizontal) and all levels of governance (vertical) should be adequately coordinated;
(c) All stakeholders are required to participate in financing and maintaining the water system in addition to its management;
(d) Water from all sources (precipitation, surface reservoirs, groundwater aquifers, and return flows) and potential climate impacts should be accounted in water management processes;
(e) Environmental flow requirements should gain adequate prioritization in water management decisions;
(f) Measures of water conservation and prevention of unproductive water losses should be implemented when relevant;
(g) Transparent water governance and openness in information sharing should be maintained;
(h) Financial security of water management organizations should be ensured with proper pricing of their services and implementing economic instruments in grass-root level water management.

Following the IWRM principles allow for minimizing unproductive water losses and reduced water demand considerably in the region (Dukhovny et al. 2013). Effective water uses and equal distribution of water along the irrigation network enhanced agricultural production outcomes significantly.

10.5.2.2 Transboundary IWRM Implementation Challenges in the Mekong River Basin

IWRM concepts gained greater emphasis on establishing the Mekong River Commission (MRC), which is comprised of four governmental representatives from Vietnam, Thailand, Cambodia, and Laos (Suhardiman et al. 2012). The Secretariat of the MRC operated to implement various development programs supported by different international funding agencies. These programs are linked with the development plans and policies of national ministries through the National Mekong Committees (NMCs) of the member states. To ensure participation of various national ministries in the development processes and increase the likelihood of adoption of program activities designed by MRC at the national level, the National Mekong Committee Secretariats (NMCS) play a mediatory role in channelling MRC program components to relevant national ministries.

However, the programs of MRC focused on sustainable development rather than enhancing regional economic development potential. Consequently, the MRC's program activities mainly differ from the development interests of the national ministries. The MRC also focused on supporting knowledge accumulation and sharing information related to water systems management rather than playing the role of development agent that channels donor funds to member countries. This, in turn, reduces its influence on national ministries in adopting MRC program activities. Bureaucratic competition by sectoral ministries at the national level for regulating a higher portion of water flows and gaining higher access to funds further degrade the coordination role of NMCS. The emergence of financially-independent and private developers also diminishes the role of MRC in influencing the changes in the basin. Private developers can invest in development projects (hydropower, irrigation, mining) in agreement with national governments, yet neglecting potential transboundary effects.

For improving the effectiveness of the MRC in the sustainable management of transboundary water resources, the national interest of development should be taken into account in IWRM programs. In support of the IWRM platform, economic sectors should be able to see noticeable benefits from basin-wide information sharing and resource coordination. Given the increased impact of private developers in the basin, their external effects on the ecosystems and other users should be appropriately evaluated and regulated.

10.5.3 Benefit-Sharing Framework: Sharing Benefit Instead of Sharing Water

Benefit-sharing refers to the transboundary use of direct and indirect achievements of the optimized allocation of the shared waters, including all water-related social, environmental, and economic activities within a basin. The use of benefits of water, rather than the allocation of water itself, provides an enhanced scope for identifying mutually beneficial cooperative actions (Dombrowsky 2008). Establishing arrangements and fostering synergies between the associated benefits of joint management of the basin is vital to advance transboundary water cooperation and to create the opportunity for accessing the multiple benefits beyond the water domain.

The origin of the benefit-sharing framework is what has been known as the "mutual gains" approach in the peace and conflict study since the 1980s. There are pieces of evidence that shifting the focus of negotiation from water quantity to benefits derived from its allocation assists in easing the pre-existing tensions between riparian countries (Nkhata 2018). The rationale is that once the focus shifts from a narrow perception of quantities of water to the broad vision of possible extra benefits from its optimal use, room for constructive dialogue can emerge, which encourages the for collective action to explore that potential. However, the perception by all countries that a collaborative basin development and management plan which maximizes overall benefits are "fair" is essential to motivating and sustaining cooperation (UNESCO 2013). Riparian countries should focus first on agreeing and employ water management approaches to optimize the generation of basin-wide benefits, and secondly, on sharing those benefits in a manner that is agreed as fair and equitable (Brochmann and Gleditsch 2012).

From an economic perspective, benefit sharing is an efficient method to persuade cooperation as it helps riparian countries to realize win-win positions. Traditionally, transboundary water management involved allocating shared waters among states for various utilization practices. Most of the time, fixed water allocation arrangements can trap riparian countries in a 'win-lose' position with a high level of competition, with little room for compromise and joint actions (Tilmant and Kinzelbach 2012). While allocating transboundary waters, it has been more beneficial to focus on the benefits from the water rather than the fixed amount of water being shared, which means a shift from the zero-sum of water sharing and shift to the positive-sum of benefit-sharing (Phillips 2009). This implies that the potential of the approach is mainly excessive for the riparian parties if deliberate in bringing in a multi-sectoral perspective beyond the water sectors. Therefore, benefit-sharing provides a more flexible basis for nexus thinking that can intensely increase the range of cooperative opportunities and expand economic gains in an equitable manner by looking into the interrelations of correlated domains, rather than viewing any in isolation.

The benefit-sharing framework includes the responsibilities concerning the shared basin, fair distribution of benefits, reciprocal rights and regulation, cost and externalities consideration, efficient response to water-related disasters, and risk reduction. Effectual water resource management practices can increase the availability of water in the distribution system, hence its productivity (Alaerts 2015). Consumptive and non-consumptive water uses are explored during the negotiation process; decision-makers can decide on areas of benefits of cooperation and agree on the composition of available options. However, there is no comprehensive universal benefit-sharing strategy framework; therefore, benefit-sharing arrangements tend to be derived from case-to-case negotiations and settlements where sharing benefits requires context-specific redistribution and compensation. Water Diplomacy mechanism can promote the speed and success of the negotiation processes but needs time to lead to benefit identification, scheme creation and associated trade-offs recognition, which is regularly lengthy and exhaustive (Daoudy 2013).

Measuring potential benefits to be shared requires mutual agreement on the validity and approval of data. In transboundary basins, however, data is one of the primary sources of dispute among riparians (Soliev and Theesfeld 2017). Furthermore, multiple purposes and diversity of benefits create a prioritization challenge for parties, which leads to a distinct basis for assessing the value of water in different allocations patterns. Moreover, risks and uncertainties regarding the projected scope of benefits and the exact time of materialization of those benefits in the future hamper benefit-sharing negotiations.

For successful benefit-sharing applications, case-based approaches have to be developed for dealing with data contestation, the capability to identify and coordinate national priorities based on an agreed valuation system. Those approaches need to consider strategies not only to reduce the level of uncertainty in assessing the benefit but also to deal with a certain level of risk that will remain. Such strategic approaches could include providing financial as well as political guarantees.

10.5.3.1 Successful Benefit-Sharing Practice: Senegal River Basin

The Senegal River, the second-longest river in Western Africa, is shared by Mali, Mauritania, Guinea, and Senegal. The riparian countries agreed to share the development costs and benefits of joint infrastructure, employing a benefit-sharing framework to reach and maintain a successful transboundary collaboration (Hensengerth et al. 2012).

Periodical floods and droughts have threatened riparian populations since always and have been a significant cause of food insecurity and an impediment to socio-economic development in the region. In response to particularly devastating droughts in the early 1970s, the three downstream states (Mali, Mauritania, and Senegal) decided to jointly engage in water resource exploitation projects that would exceed their respective unilateral capacities. To do so, in 1972, they established the "Organization pour la Mise en Valeur du Fleuve Sénégal" (OMVS), a supranational organization charged with the development of the river's resources to support the economic development of its riparian states as well as economic cooperation and regional trade (IUCN 2014). In the beginning, the OMVS's efforts mainly focused on three areas: irrigated agriculture, hydropower, and navigation. In the following years, two dams were built, Manantali Dam in western Mali and Diama dam on the Senegal-Mauritania border. Both dams delivered enormous benefits concerning dependable river water flows for irrigation, power generation, enhanced river navigability, and flood control for the four cooperating countries, and in particular, for the river basin populations. OMVS has adopted a Water Charter and is a rare example of joint ownership of large dams worldwide.

As a successful benefit-sharing framework implementation, through the Senegal River Basin Development Authority, a transparent methodology has developed first to quantify and then allocate the benefits and costs of multipurpose investments across the entire basin. OMVS performs as a regional strategic evaluation of options for hydropower development and of water resources in the Senegal Basin (Senegal River Convention 1972). Access to all the potential benefits has been possible eventually through an interlocking and pioneering web of inter-state agreements among the three riparian states starting by the signing of the Convention on the Statute of the Senegal River in 1972 until the adoption of the Senegal Waters Charter in 2002. The scale of benefits derived and the perceived fairness of the benefit-sharing arrangements, together with the political ideal of solidarity between the three countries, have sustained substantive cooperation and an active river basin organization (Tignino 2016).

Environmental and social challenges have arisen as a result of changes in the basin ecosystem due to the construction and operation of the dams, climate change, and the new paradigm of the development spectrum (Mbengue 2014). Nevertheless, through cooperation, the countries have realized, and allocated benefits, which they would not unilaterally have been able to achieve.

10.5.3.2 The Success Story of Benefit-Sharing Practice Between India and Bhutan

There is a successful case of regional cooperation in benefit-sharing between India and Bhutan. Himalayan rivers have an enormous hydropower potential that is still not exploited entirely for the benefit of the region. India experiences perennial energy shortage with increasing energy demand from rising population and economic growth. India entered into a benefit-sharing arrangement with the neighboring country, Bhutan, on hydropower projects and provided technical and financial assistance to develop numerous hydropower projects in Bhutan. India benefits from the supply of hydroelectric energy resources from Bhutan, while the latter country gains from the revenues earned from the export of power. India and Bhutan signed a bilateral agreement as early as in 1974 for the construction of the 336 MW Chukhahydel project across river Wangchu in Western Bhutan for meeting internal power demand and exporting the surplus electricity to India (Biswas 2008). India undertook the costs and risks of constructing the hydroelectric dam and power plant in exchange for a reduced purchase price of electricity from the completed facility. India invested close to 2 billion US dollars (at 2008 price) for hydropower projects in Chukha, Tala, and Kurichu hydroelectric projects creating a total installed capacity of 1,410 MW in Bhutan. India and Bhutan have recently signed an agreement to develop an additional 5,000 MW of hydropower generating capacity. India enjoys several benefits without relying on scarce fossil fuels while obtaining a real economic internal rate of return of at least 14%. The present value of net economic gains in 2008, evaluated at 2008 prices, has been 2.3 billion USD for Bhutan and 2.5 billion USD for India. India has also recovered its capital investment along with its opportunity cost through loan repayments and the share of hydroelectricity rent generated at the project because of lower import prices. Considering all the economic costs and economic benefits, Bhutan and India share the benefits from the Chukha Hydroelectricity Project in the proportion of 48:52 (Dhakal and Glenn 2013).

10.5.4 Bargaining Power on Water Sharing and Side Payments

A downstream county often balances the asymmetric water sharing with the aid of institutional arrangements to mitigate water scarcity in the absence of any water-sharing agreements or treaties, such as water market or market-based inter-basin water transfer. However, pure market solution rarely provides the best outcome not only because infrastructure is insufficient to make markets operate efficiently, but also water markets in the downstream country alone cannot resolve the problem of water scarcity without upstream country's intervention (Netanyahu et al. 1998). However, if the downstream country bargains with the upstream country over water resources, it could lead to the resolution of conflict and may create a possibility of a long run sustaining water-sharing agreement.

It is evident from a review of past transboundary water sharing cases that a record of cooperation has consistently prevailed over acute conflict related to global water resources (Wolf et al. 2003). Wolf et al. (2003) also have cited that the last (and only) war fought specifically over water took place 4,500 years ago, between the city-states of Lagash and Umma along the Tigris River. Over the last 50 years, there have been 1,831 interactions (both conflictual and cooperative). During the same period, 157 treaties were negotiated and signed; only 507 events were conflict-related; 1,228 were resolved cooperatively (Wolf et al. 2003). Shared interests along a waterway seem to consistently outweigh water's conflict-inducing characteristics and induce countries for a cooperative bargaining solution. Side payments play a positive role in sustaining cooperation (Roger 1997).

In basins where water is scarce, a downstream country can acquire additional water from the upstream country, using non-water transfers (Bhaduri and Barbier 2008). Such transfers could be in the form of lump-sum payments, for instance in the 1960 Indus Waters Treaty (India, Pakistan), India agreed to pay Pakistan a one-time £ 62 million lump-sum payment for allocating the eastern tributaries of the river to India and the western tributaries to Pakistan (Beach et al. 2000). These transfers can also be annual payments, as in the Lesotho Highlands Water Project (Lesotho, South Africa), where South Africa pays Lesotho non-water transfers over time. In a cooperative solution, however, the possibility still exists that a country chooses to deviate from the agreement after it is in place. The sustainability of an agreement, in the long run, may depend on both sides possessing sufficient retaliatory actions (credible threats) to make continued cooperation in sustaining the agreement. The problem with the cooperative approach is that it does not explicitly model the incentives to abide by the agreement in the long run. Both the countries (upstream and downstream) have an incentive to deviate because monitoring is difficult.

Sometimes the downstream country may not pay a side payment directly. Instead, it may provide other benefits to the upstream country like the reduction of trade barriers and other trade benefits. As sometimes benefits are hard to covert in monetary terms, countries also use of in-kind transfers linking to other issues that provide a benefit. For instance, the Netherlands linked the issue of water allocation in the Meuse river to the issue of navigation on the Scheldt river. The Netherlands would gain from the water allocation treaty, while Belgium would gain from the improved access to the Antwerpen harbor.

Countries' time preference can be either symmetric or asymmetric and play an essential role in influencing the structure, tenure, and continuity of the agreement. However, generally downstream countries are more impatient than the upstream country as it faces more water scarcity than the latter country. Moreover, the downstream country may also face environmental problems like a saline intrusion, which has long term effects. If the environmental consequences are taken into account, then the downstream country may pay higher compensation or side payments to the upstream country to reach an agreement. The upstream country may be more impatient if it faces a higher marginal cost of withdrawing water from the river.

When countries have asymmetric preferences, one country can have a larger share of the benefits relative to the other. A country's bargaining power increases with its discount factor or with the increase in preference to having a negotiation later than earlier and also with the decrease in other country's discount factor (if the country prefers to have a negotiation earlier than later) If a country does not wish to accept any particular offer and instead would like to make a counteroffer, then it is free to do so but has to incur the cost of waiting. The smaller is the discount factor or the higher preference of a country to have a negotiated preference; the smaller is the cost of waiting. The country with a lower discount factor will be impatient and is likely to reach the agreement quickly (UNESCO 2013). In this process, the country may need to compensate for the relatively patient country for reaching an agreement more quickly and, as a result, may receive a lower benefit.

If the upstream country has a higher discount factor, it will not deviate once an agreement is struck, but if it is more patient than the downstream country, then it can ask for higher side payments or will retain a larger share of water for itself. It is like a scissor problem for the downstream country. If the upstream country is impatient, then the chance of deviation after an agreement is struck is higher. It means that the downstream country has to pay higher side payments or demand a lower level of water diversion in the downstream to induce the upstream country to accept an agreement. This also resolves the problem of deviation, as with higher compensation upstream country will have lesser chance to deviate.

The problem would be less severe if both countries have similar time preference. The countries, then, will not waste time in haggling and would be equally eager to reach an agreement early. After an agreement is reached, the upstream country will also not have any incentive to deviate, and the agreement will be continued in the long run.

When water flow is deterministic, then there exists perfect information about the flow of water. The upstream country can have an incentive to deviate from the agreement being the second mover in a given period. But with perfect knowledge of the flow of water, the downstream can detect the deviation in the next period.

Uncertainty in the flow of water may affect the negotiated outcome. Considering the stochastic nature of water flow, the upstream country has a higher chance of deviation because the downstream country may not detect the deviation, and an existing agreement may continue. The chance of defection will be lower if the probability of water consumption falling below a certain critical level is low. The chance of triggering the breakdown phase will be high if the threshold level of water allocation is high or if the negotiated share of water in the agreement is high. So, if the downstream country is not willing to pay higher side payments, then it will settle for a lesser share of water, and then the chance of breakdown of the agreement will be high (Poast 2013). The agreement will be sustained if the downstream country demands a higher share of water and pays high side payments to compensate the upstream country.

Uncertainty of the flow of water can also act as an incentive for the countries to reach an agreement if the variability of water flow is high. The main force that causes the countries to reach an agreement is the fear that negotiation will break down or be delayed because of the stochasticity of water flow. If it is assumed that an agreement outcome is always preferable to breakdown the outcome, the country will have the incentive to reach an agreement earlier. However, it entails a cost for the downstream country: the upstream country will have a higher chance to deviate from the agreement, and the downstream country cannot detect it.

Dinar et al. (2010) explore the impact of water supply variability on treaty cooperation between international bilateral river basin riparian states. The study used economic and international relations data to identify incentives for international cooperation in addressing water supply variability. The authors find that small-to-moderate increases in variability create an impetus for cooperation, although large increases in variability would reduce incentives for treaty cooperation. Stronger diplomatic and trade relations support cooperation, while uneven economic power inhibits cooperation.

10.5.5 Market-Based Water Allocation and Transfer

A market-based water transfer is relevant in resolving the trans-boundary water conflict in a river basin. Many articles (Howe et al. 1986; Saleth and Dinar 2001; Howitt and Hanak 2005) have identified two fundamental ways to meet water scarcity. First, water scarcity can be met by augmenting the supply of water from alternative sources, including water transfers from neighboring river basins. Creating new sources to augment water supply requires significant investments and effective institutions for allocating water. The implementation of these measures requires cooperation and coordination between regions. Second, water scarcity can be mitigated by managing the demand for water. One approach frequently cited in the past literature is the use of water markets (Kaiser and Phillips 1998; Green et al. 2001; Howe et al. 1986). In many parts of the world, water has been treated as a free public good with no charges made for withdrawing water. Since water can be withdrawn freely, excessive usage of water creates a shortage of water in the downstream country. Subject to certain conditions, a water market would guarantee efficient usage of water, and the problem of externality would be less severe.

Howe et al. (1986), discuss in detail the weakness of the water markets. The main problems with the water markets are issues of water quality externalities and the existence of third party effects. When there is a transaction in water markets, both the buyer and the seller are better off, but the third party effects are overlooked. From an equity point of view, a losing third party needs to be compensated. In a transboundary water sharing setting, where countries can buy water rights on behalf of their citizens, these problems are less severe (Howe et al. 1986); and under such conditions, there is a possibility to mitigate water scarcity in a downstream country using a market-based water transfer.

In the presence of scarcity of water, the downstream country can have a provision to buy water. The upstream country can sell water to the downstream, sacrificing its own water consumption, but the upstream country, confronting the scarcity of water in the river basin faces negative domestic political pressure in selling water to the downstream country. The downstream country may also find it unreasonable to buy water from the upstream country, given the water rights of the downstream country in fair use of the river water. Agreeing over water use rights in shared river basins is perhaps one of the most challenging issues that consequently impede water rights trading. Maintaining transparent management and negotiation processes, monitoring water flows and uses, and running the market platform can also come at a cost, and trading water rights can be useful only when the additional gains are higher than the transaction costs of the trading (Bekchanov et al. 2015a, b).

Suppose the downstream country, facing water scarcity, could choose to buy water from a water resource-abundant third country; for instance, Turkey, Ethiopia, and Nepal, where water is abundant even after meeting their domestic agricultural needs. The third country can supply water at a price to the downstream country to meet its excess demand or to mitigate water scarcity. An additional benefit of such transactions may be created by the revenue that the third country generates from selling water, which can act as an incentive for efficient water use. The downstream country entails a cost for buying water at a price, also inducing an incentive for efficient usage of water. Thus, in addition to mitigating the water scarcity problem, a market-based water transfer may also provide an incentive for efficient water use within the countries.

There are two ways in which a third country can transfer water to the downstream water-scarce country, based on the geographical location of the third country relative to the downstream country: First, water can be directly transferred to the downstream country from a third country without influencing the upstream country and its water consumption. Second, there are cases where water can be transferred to the downstream country only through the political boundaries of the other riparian countries. A less efficient outcome will be achieved when the third country charges a high price of water as the downstream country buys less water. The problem of externality faced by the downstream country in water availability, however, would be less severe than in the case without any market-based water transfer.

The best scenario is where both the upstream and downstream countries could supplement the water-sharing treaty with an additional provision of water transfer from a third country. In this case, water transfer can guarantee a potential Pareto improvement and facilitate the water-sharing agreement between the upstream and downstream countries to be sustained in the long run.

10.5.6 Conclusion

This section addresses different economic instruments in resolving water conflict based on economic principles and perspectives. The specific benefits of transboundary water cooperation, differ significantly according to many factors, including the geographical position, demography, the levels of economic development and trade, water dependency, and governance structures. Identifying and understanding the range of often interrelated benefits derived from the cooperative arrangements and development of transboundary river basins is the pillar to improved management of the basin. A creative combination of approaches, being able to quantify the benefits of cooperation in the short and long term, localized for each case, in an equal and transparent manner, is what riparian states of a basin need to initiate (Willis and Baker 2008). All around the globe, the flow of data is massively increasing, and data are increasingly available without or with limited restrictions. While innovative approaches in science and technology expand the availability of quantity and quality of water, they bring new information and decision-support systems to solve transboundary cooperation challenges that intersect with the needs of societies and concerns the sustainable development goals at the same time. However, technical solutions alone cannot solve the world's transboundary water challenges since sustainable solutions require integrated approaches, addressing technical, institutional, financial, social, and environmental issues simultaneously. To address these complex water problems at the transboundary scale, methods that go beyond applications of technology and scientific theories, as well as the implementation of management strategies, are required to connect the dots. Such nexus thinking may provide a foundation for greater cooperation and avoiding conflict by giving the understanding of how the physical unit of the basin interconnects with the economic, social, and political aspects. Among those approaches, benefit-sharing mechanisms, issue linkage, and market-based water transfer are some of the economic instruments to promote and support cooperation in transboundary water management frameworks. Cooperation can be reinforced by starting to share knowledge and experience of gaining benefits from successful transboundary water cooperation while facilitating the cooperation process through promoting multi-criteria capacity-building initiatives.

The above discussed economic mechanisms focus on effective water allocation in terms of quantity. Future studies should address the role of economic instruments to regulate both water quantity and quality at the basin scale. Moreover, considering the transaction costs of implementing such mechanisms based on real data and the ways of reducing them, greatly enhance the usefulness of these instruments to deal with water management issues. Increased availability of data and broader uses of digital technologies ease data collection and management processes reducing information asymmetries existent in the system significantly. Information technologies and their role for complex assessment of water values and externalities should be further investigated to bear the benefits of institutional innovations of water system management.

10.6 Application of Benefit Transfer to Estimate the Non-market Value of Solution-Oriented Approaches: A Case Study of Water Sensitive Urban Designs[1]

10.6.1 Introduction

Rapid urbanization in many parts of the world means an increase in impervious surface area which results in increased storm flow frequency, magnitude and volume, and increased non-point source pollution of the aquatic bodies (Elmqvist et al. 2013). Conventionally, centralized systems have been adopted to tackle this problem (Montalto et al. 2013). Implementation of a centralized system has been often guided by the desire to remove stormwater from the community as quickly as possible to protect human health and property (Arnold and Gibbons 1996). However, the adoption of centralized systems has resulted in the collapse of freshwater urban ecosystems which were dependent on the surface runoff in many places such as in Chesapeake Bay in the US and Port Phillip Bay in Australia (Paul and Meyer 2001).

Recognizing the limitations of the conventional centralized approach of stormwater management in many cities (such as Philadelphia, New York, and Melbourne), water utilities are using or investigating the feasibility of using Water Sensitive Urban Designs (WSUD). Such designs are also known as low impact design (LID) in the USA and New Zealand and sustainable urban drainage systems (SUDS) in the UK (Burns et al. 2012). WSUD is a planning and designing approach that integrates water cycle options to reduce pollution and stormwater run-off (Radcliffe 2019). By implementing WSUD, it is possible to reduce imperviousness of the surface and facilitate retention and infiltration of runoff at or near the surface (Montalto et al. 2013). Thus WSUD can restore critical natural flow patterns and reduce the occurrence of floods (Poff et al. 1997). Further, by using infiltration practices, it is possible to reduce non-point source pollution to the rivers and other aquatic systems (Phillips et al. 2003; Bratieres et al. 2008).

[1]An earlier version of the section has been published as Iftekhar, M. S. and Polyakov, M. (2019). Assessment of nonmarket benefits of WSUD in a residential development: Belle View case study. IRP2 Comprehensive Economic Evaluation Framework (2017–2019). Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities. The study was supported by the CRC for Water Sensitive Cities. The authors gratefully acknowledge the support provided by the Case study partners and other project members. M S Iftekhar acknowledges funding support from the Australian Research Council's Discovery Early Career Researcher Awards grant (ARC DECRA grant number DE180101503).

Despite having such potential, WSUD has been implemented in only a few places (Radcliffe 2019). Most cities in Australia and the US still rely on conventional centralized stormwater management system (Roy et al. 2008). Lack of evidence-based information on the benefits of implementing WSUD could be one of the primary reasons (Pataki et al. 2011). As Roy et al. (2008) highlighted, "research is particularly needed in the area of costs and benefits of WSUD; we need more on-the-ground data comparing WSUD to conventional approaches" (page 355). There are additional reasons why we need information on the costs and benefits of WSUD even when they are well recognized in the policy frameworks. The planners must decide on what scale and where to implement these designs. However, unless they have the information on the full range of benefits, their decision will be biased. For example, Friedler and Hadari (2006) based on a case study in Israel observed that on individual consumer level on-site greywater reuse systems were not economically feasible unless benefits occurring at a regional/national scale considered. Similar findings were reported by Molinos-Senante et al. (2011) on their cost-benefit analysis of wastewater treatment plants in Spain.

The benefits provided by WSUD could be tangible (such as water savings, reduction in flood risk) and intangible (e.g., amenity, recreation, and ecological improvements). Because there are well-functioning markets for tangible benefits, it is possible to use market prices to monetize them. However, a large portion of the benefits provided by WSUD is intangible and not traded on the market, which makes it difficult to monetize these benefits (Leonard et al. 2019). For example, while it is understood that many people value the experience of clear waterways, there are no market prices that directly reflect these values. As a result, intangible benefits are often ignored in the formal investment decision framework (Gunawardena et al. 2017).

Economists have developed various non-market valuation techniques to assess intangible benefits. Two main groups of methods are revealed preference and stated preference. In revealed preference methods, the data about past behaviour are analysed to estimate non-market values. One of the revealed preference methods is hedonic analysis. It uses the prices people pay to buy houses to infer the value they place on amenities. It assumes that the value of a house consists of the values of its components. These components include characteristics of a house, such as the number of bedrooms or size of the lot, as well as the features of the neighbourhood, such as proximity to and quality of the parks. By analysing data of multiple transactions, researchers can estimate how much people are willing to pay to live near a beautiful park, clean waterway, or in a leafy suburb. In contrast, stated preference methods involve asking people. For example, in a choice experiment, people are asked to make choices between project options and non-market values are estimated from their choices. However, both methods could require substantial time and financial commitment.

Another method that relies on data already collected is called the benefit transfer. Benefit transfer is useful when decision-makers face time and resource constraints as such methods allow extrapolation of existing nonmarket values to new contexts (Iftekhar et al. 2018). Benefit Transfer method allows one to predict values for an "application site" by extrapolating the results of the estimates of nonmarket values for an original "study sites" (Johnston et al. 2015). Two of the most common approaches are unit value transfer and benefit function transfer (Boyle et al. 2010). In a unit value transfer, point estimates from the study site are applied in the context of the application site after appropriate adjustment. On the other hand, a function transfer involves using the benefit function (the relationship between nonmarket value and a set of variables) of the study site and apply it to the application site (Loomis and Rosenberger 2006). While there are some studies where benefit transfer method has been used to calculate the total value of green infrastructure projects in Australia and elsewhere (Mekala et al. 2015), not many studies have used the benefit transfer method for WSUD projects.

In this section, we contribute to the knowledge-base by investigating the economic benefits of a WSUD project. The objective of the study is to demonstrate the application of benefit transfer for the assessment of intangible benefits of WSUD in a private residential development in Perth, Western Australia. We apply the estimated benefits in a formal benefit-cost analysis to understand the implications of using non-market values in such an analysis. There are not many studies that have conducted a benefit-cost analysis of WSUD projects. For example, see Carter and Keeler (2008), Polyakov et al. (2017a), Nordman et al. (2018) and CRCWSC (2020). Our study contributes to this scant set of literature. In the following section, we present the methodology used for the transfer of benefits, followed by the results of the assessment and a discussion section.

10.6.2 Methodology

This section describes the application of benefit transfer methods for a specific site, Belle View Estate, in Western Australia. Belle View Estate is a proposed 44 ha residential development located in Bellevue, 16.5 km north-east of Perth (Coterra Environment 2017a, b). The water sensitive urban design (WSUD) technologies considered in this development are constructed wetlands and living stream. Constructed wetlands are extensively vegetated water bodies that use sedimentation, filtration, and biological uptake processes to remove pollutants from stormwater. A living

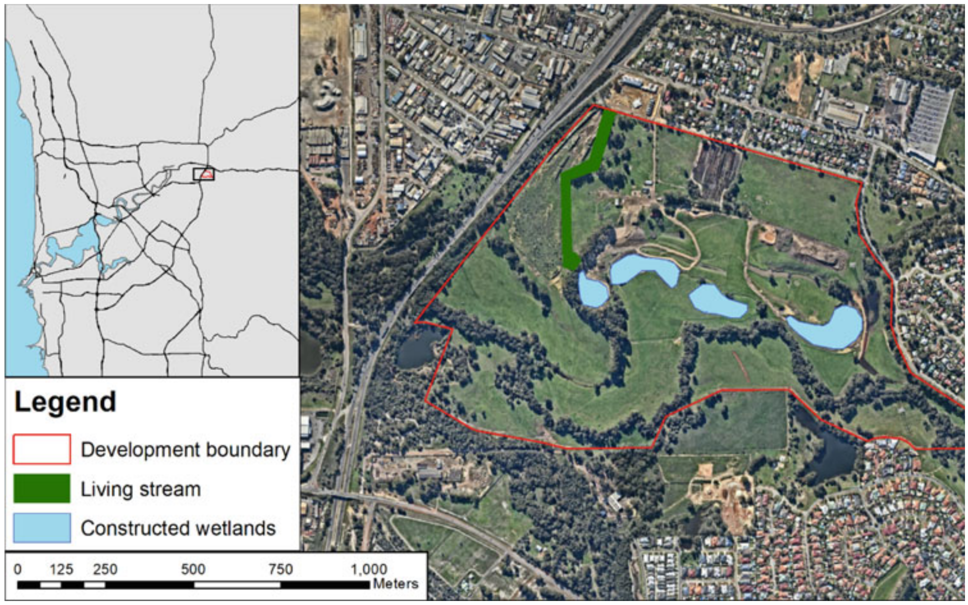

Fig. 10.8 Location of the site with sites for constructed wetlands and living stream. *Source* Own calculation

stream is a constructed or retrofitted stormwater conveyance channel that mimics the characteristics (morphology and vegetation) of natural streams (Department of Water 2016). The constructed wetland system will consist of a series of interlinked seasonal (ephemeral) and permanent open water bodies in the Helena River floodplain. The area of the constructed wetland site is about 5.71 ha (Fig. 10.8). The area of the living stream is approximately 1.7 ha.

To assess the benefits from the implementation of WSUD, we have followed a set of steps:

(1) Selection of benefits;
(2) Adjustment of existing estimates to the application site, and;
(3) Benefit-cost analysis.

We describe these steps below.

10.6.2.1 Selection of Benefits

Constructed wetlands and living streams could generate a range of nonmarket benefits, such as amenity and biodiversity protection in addition to pollution removal benefits. To identify the relevant set of benefits first, internal documents were reviewed (e.g., Landvision 2015; Coterra Environment 2017a, b; Shire of Mundaring 2017). Then, key stakeholders were consulted. Based on these activities, a list of potential services or benefits related to WSUD were identified:

- Amenity
- Recreation
- Connectivity (local access)
- Water quality (nutrient, heavy metal)
- Mental and physical health (active living and access to nature)
- Ecological/biodiversity/habitat
- Indigenous heritage

The second step in quantifying the monetary value of these benefits is to identify the set of studies that provide relevant estimates. Iftekhar et al. (2019) has carried out an extensive review of existing studies that have published estimates of the intangible benefits due to the use of water sensitive systems and practices. To estimate the total value of a benefit, we would need to understand the expected changes in the physical condition of the site (i.e., expected physical benefits) due to the implementation of WSUD. A site visit was conducted in June 2018 with representatives from the Eastern Metropolitan Regional Council (EMRC), Department of Biodiversity, Conservation and Attractions (DBCA) and University of Western Australia (UWA) to understand the local context better. Based on further follow-up discussions with the developers and key stakeholders, it was identified that the amenity and pollution benefits are likely to be the major benefits of implementing WSUD in this location. Therefore, in the following discussion and analysis, we focus on expected amenity and pollution benefits from living stream and constructed wetlands.

10.6.2.2 Adjustment of Existing Estimates to the Application Site

Estimation of Amenity Benefit

The benefits for the constructed wetlands are estimated using the estimates of values of urban lakes and wetlands from the

Table 10.1 Comparison of the main characteristics of the application site with the study site used

Context	Study site*	Application site
Location	Perth, Western Australia	Perth, Western Australia
Setting	Urban (established)	Urban (new)
Nature of wetlands	A mix of natural, man-made or extensively modified	Man-made or extensively modified
Area of wetlands	5.6% of the study area	5.7% of the study area
Average house price	$ 1,000,000 (2009)	$ 397,000 (2013–2018 in six suburbs area)

**Source* Pandit et al. (2014)

study by Pandit et al. (2014). The first step is to compare the characteristics of the study site and Belle View Estate (the application site). It can be seen from Table 10.1 that there are substantial variations between the two sites. Both sites are urban; however, the study site is established, while the application site is a new development, and the average house price was much higher in the study site.

To estimate the value of the benefits of constructed wetlands and living stream, we first need to know the values of homes without the influence of WSUD. We do this by using a hedonic model of home sale prices. Hedonic modelling assumes that the price of a good, such as home, traded on the market is a function of prices of its components. The empirical model can be written as:

$$\log(p) = F(\boldsymbol{X}, \boldsymbol{\beta}),$$

where $log(p)$ is the sale price of a home, $\boldsymbol{X}$ is a vector of home attributes, and $\boldsymbol{\beta}$ is a vector of parameters to be estimated.

In our model, the underlying attributes include the number of bedrooms, number of bathrooms, lot area, number of parking places, age. Besides, we control for spatial heterogeneity among suburbs by including suburb-specific binary variables (spatial fixed effects), as well as for the temporal changes in the real estate market by including year-quarter specific binary variables (temporal fixed effects). Once coefficients are estimated, we can predict home prices in a new development using expected values of home attributes.

Using regression results, we predict the values of new homes in the development in 2018 for a range of lot sizes and median values of key parameters such as the number of bedrooms, bathrooms, and car parking places in Bellevue suburb in the third quarter of 2018.

Locations and lot sizes for new homes were obtained from the developer (Strategic Planning Institute P/L). We assume that constructed wetlands will affect existing homes within 500 m of the site as beyond this distance the expected impact of constructed wetlands becomes negligible (less than 0.4%). Figure 10.9 shows the outline of the development, locations of the living stream and constructed wetlands, the location of existing homes affected by the constructed wetland, and locations of homes being constructed. The construction of homes within the development has been planned in two stages (Fig. 10.9). The first stage is expected to be completed within the next 2–3 years, and the second stage will start after that.

To estimate the potential impact of wetlands on house prices, we use the parameterised function from the original study (Pandit et al. 2014). To estimate the value of the environmental amenities such as wetlands, Pandit et al. 2014 used the gravity index constructed for each house following Powe et al. (1997). The gravity index captures the combined influence of the size and proximity of wetlands on property value and can be calculated as:

$$GI_i = \sum_{j=1}^{J} \frac{A_j}{(D_{ij})^2} \qquad (10.1)$$

where GI_i is the gravity index of wetlands for i-th home in the sample, J is the number of 100 m x 100 m grid cells within 3,000 m radius of the i-th home, A_j is the area of wetland site within j-th cell, and D_{ij} is the distance to the centre of the j-th cell from the i-th home.

The impact of constructed wetland on the property value is then calculated as:

$$\Delta p_i = \exp(\ln(GI_i + 1) \times \beta) - 1 \qquad (10.2)$$

where Δp_i is the relative change of i-th house price due to constructed wetlands, GI_i is the gravity index for the house i, and β is the regression coefficient obtained from Pandit et al. (2014). In addition to the point estimate (0.0438), we calculate upper and lower bounds by adding or subtracting the standard error of the regression coefficient (0.0221).[2]

Polyakov et al. (2017a) measured the impact of retrofitting a conventional drain into a living stream in an established suburb as the percentage change of property price within 200 m of the site. They also observed that there is not much amenity benefit of living stream projects on

[2]With a normal distribution assumption, it is expected that there is 68% chance that the true value is within one standard error range.

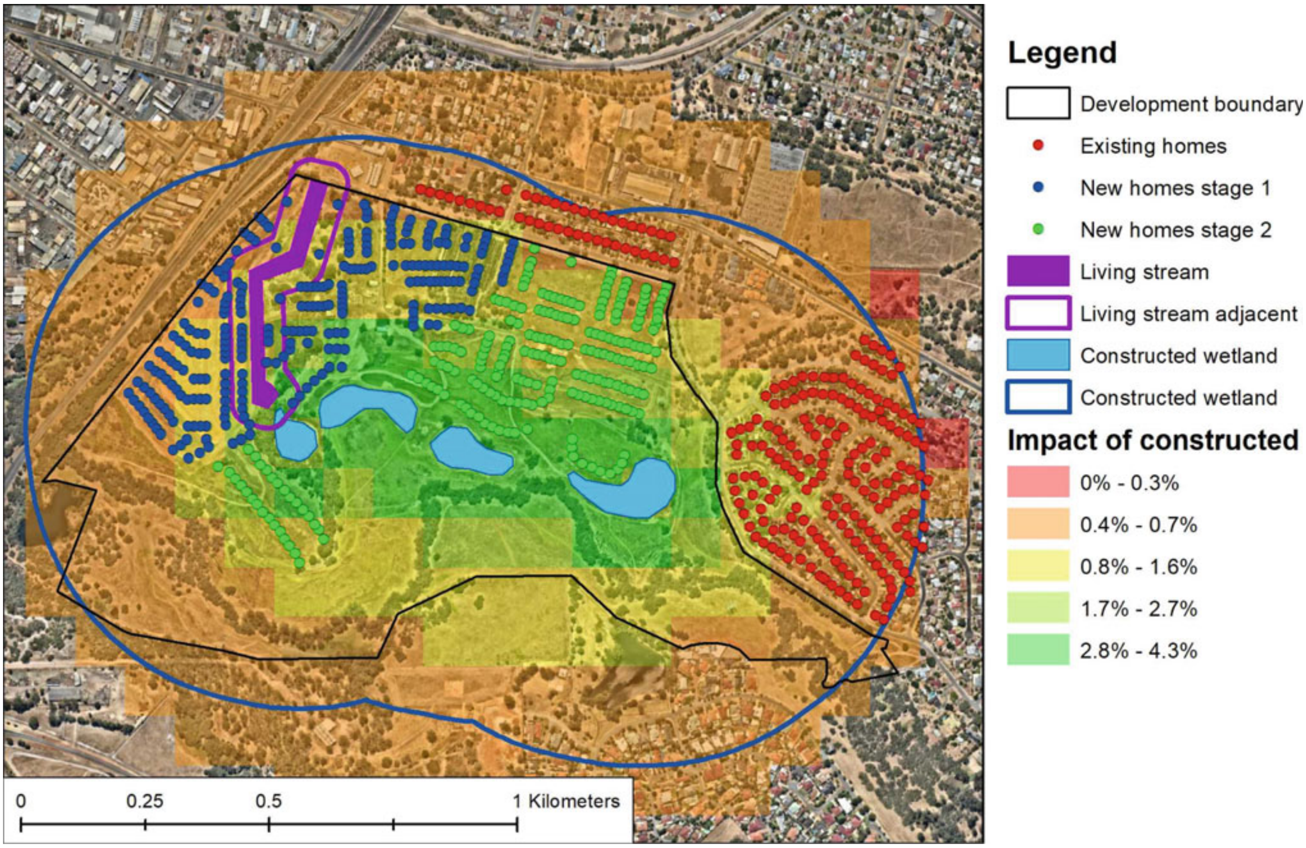

Fig. 10.9 Location of new homes, existing homes affected by constructed wetland, as well as buffers of the impact of the living stream and constructed wetland. *Source* Own calculation

houses located more than 200 m of the site.[3] It was estimated that within 200 m, the increase in house price due to the living stream could be between 2.9% and 6.5%. It should be noted that in the original study the positive impact of living stream on house prices was observed during the period 7–13 years from the start of the living stream construction. Whereas, the living stream in Belle view will be completed before or at the same time the houses are built. Therefore, it is reasonable to assume that the value increase will be observed immediately.

For both studies, we did not have to adjust estimates to income differences as house prices captured the income differences. Since the benefits were estimated as a percentage of house price, we did not adjust the values for inflation/time differences. However, the living stream proposed in the application site is smaller in size (30 m wide, 1.7 ha) than the living stream in the Polyakov et al. (2017a) study (50 m wide and 2.4 ha). The experts in the CRCWSC Regional Advisory Panel suggested that in a new development, the living stream will only impact the immediately adjacent properties. Therefore, we made the appropriate adjustment for the benefit transfer by applying the benefit of living stream only to the adjacent properties (i.e., within 50 m).[4] Because both features (wetlands and living stream) are in the same area, one feature can act as a substitute for the other. Therefore, we cannot add up both values. For homes that are affected by both the constructed wetland and the living stream, we selected the greater of the two values.

10.6.2.3 Estimation of Pollution Removal Benefit

Estimation of pollution benefit relies on information about the hydrological conditions, expected removal of pollutants by the living stream and estimation of monetary benefits. We use the Urban Nutrient Decision Outcomes (UNDO) tool developed by the Department of Water (Department of Water 2016) to generate the pollution scenarios. The model

[3]They compared specification with uniform 200 impact with two other specifications with diminishing impact, and the former had the best statistical fit.

[4]We are currently conducting a separate study of the value of living streams in greenfield developments in Perth metropolitan area. The initial results are consistent with the assumptions made in this section.

requires information on land use compositions and soil condition of the catchment. Based on the existing land use pattern, a catchment area for the living stream was considered. The total area of the catchment is 20 ha. The main land-use is residential (52%) followed by transportation (33%) and public open space (15%).[5] Drainage type was assumed as piped drainage as the control and soil type 'Pinjarra'.

Based on these land use parameters, the model generates loads of major pollutants (Total Nitrogen (TN) and Total Phosphorous (TP)) in the runoff. The relevant estimates are 51.30 kg per year for TN and 11.68 kg per year for TP. It has been further suggested in the model that if the living stream is fully functioning it can remove approximately 50% of TN and 20% of TP. This estimate is somewhat similar to the empirical observations made by Torre et al. (2006). Therefore, we use these values as the pollutant removal capacity.

Finally, we need to identify relevant monetary values of pollution removal. For this purpose, we use the estimates provided by Polyakov et al. (2017b). They estimated the cost of removing pollutants in Canning catchment for three scenarios under emission targets ranging from 20% to 100%: base case scenario where amenity values of the constructed wetlands are included, a scenario where banning regular fertiliser is a policy option, and a scenario where amenity values of the constructed wetlands are not included. In this paper, we use estimates from the base case scenario as it is the most relevant scenario for the Belle View Estate context.

To match with the base pollution removal capacity assumptions, we use the average estimates ($/kg) of 40% and 60% targets for TN. For TP, we use a relevant estimate for the 20% target. Using these values, it is possible to calculate the annual pollution benefit of a living stream. However, to avoid double-counting, we do not aggregate the values of removing nitrogen and phosphorous. The results of the calculations are presented in Table 10.2.

10.6.2.4 Benefit-Cost Analysis

The estimated benefits are incorporated in a benefit-cost analysis framework. Two different metrics are used in this framework: net present value and benefit-cost ratio to assess the performance of a project. The aggregate benefit function of the WSUD systems could be written as

$$PV = OV_A + \sum_{t=1}^{T} \frac{1}{(1+r)^t} AV_p \tag{10.3}$$

[5]Land use mix could change in the future. However, in the current analysis we do not consider this.

Here, PV = Present Value, OV_A = One-off amenity benefit, t = effective life year of the living stream, r = discount rate and AV_p = Annual Value of the pollutant removal benefit. The relevant values to populate this function has been described above.

The aggregate cost function has two main components, construction costs and maintenance costs, and takes the following form

$$TC = \sum_{s} CC_s + \sum_{s} \sum_{t=1}^{T} \frac{1}{(1+r)^t} MC_{st} \tag{10.4}$$

Here, TC = Total cost, CC_s = Construction cost of a system (s) and MC_{st} = Maintenance costs of a system s for period t. To obtain relevant cost estimates, we use the information contained in Polyakov et al. (2017a) for construction of the Bannister Creek living stream. They provided the following breakdown of construction costs (adjusted for 2018)—project personnel and overhead costs ($249,000 per year for five years), council costs ($49,800 per year for five years), approval time costs of the project ($8,300 per year for three years), contract design ($83,000), earthworks ($107,084 per hectare) and planting ($7,146 per hectare). Maintenance costs are assumed to be one percent of the total construction costs. Given that a private developer is the main implementer of the WSUDs which are part of the larger Belle View development project, we assume that project personnel and overhead costs and the council costs will be incurred for two years. We maintain the assumptions related to the other cost components the same as Polyakov et al. (2017a). The constructed wetlands proposed in the Belle View case study area is similar in nature of the Bannister Creek living stream. Therefore, we apply the same cost parameters for the living stream and constructed wetlands.

Finally, the net present value (NPV) and benefit-cost ratio (BCR) are calculated using the following formulas

$$NPV = \mathrm{PV} - \mathrm{TC} \tag{10.5}$$

$$BCR = \mathrm{PV}/\mathrm{TC} \tag{10.6}$$

A positive net present value indicates that the expected benefit outweighs the cost. Similarly, a benefit-cost ratio higher than one suggests that the expected benefit is likely to be greater than cost. For this exercise, we assume an effective life of 25 years of the living stream. As part of sensitivity analysis, we consider three discount rates: 3%, 5% and 7% following standard practice. We also consider three levels of pollution removal capacity: Low (20% lower), Medium (Base value) and High (20% higher) to reflect the situation when the actual pollution load could be different from the base values used in the study. Finally, we consider three levels of costs: Low (20% lower), Medium (Base value) and High (20% higher).

Table 10.2 Calculation of annual value of pollutant removal by a living stream

Parameters	TN	TP
Load (kg/year)	51.30	11.68
Removal capacity (%)	50.00	20.00
Removed Pollutant (kg/year)	25.65	2.34
Unit value of pollutants ($/kg)	1,223	2,058
Monetary value of removing pollutants ($/Year)	31,370	4,816

Source Own calculation

Table 10.3 Results of estimating a hedonic model of single-family home prices

Regression parameters	Coefficients	Significance	Standard errors
Intercept	10.831	***	(0.287)
Log (area)	0.174	***	(0.029)
Bedrooms	0.023		(0.021)
Bathrooms	0.192	***	(0.036)
Car Parks	0.042	**	(0.019)
Age	0.000		(0.001)
Suburb fixed effects	yes		
Year-quarter fixed effects	yes		
Number of observations	826		
R^2	0.38		

Source Own calculation. *Note* '***' and '**' indicate significance at 1% and 5% level respectively

10.6.3 Results

We present the results for amenity and pollution removal benefits separately, then follow with the total value estimates and benefit-cost analysis.

10.6.3.1 Amenity Benefit

To predict house prices in the development, we used 826 sales of single-family homes in Bellevue and five nearest suburbs (Greenmount, Helena Valley, Koongamia, Midland, and Midvale) from 2013 to 2018. We assumed that the sale value of a home is determined by its attributes, including the number of bedrooms, number of bathrooms, lot area, number of parking places and age. We estimated a linear regression model with the natural log of the sale price as the dependent variable. We also control for time and location using suburb and year-quarter fixed effects. The results of the estimation are presented in Table 10.3. The model explains 38% of the variation in house prices. While hedonic models usually have higher R^2 values, the values around 40% are not uncommon; for example, see Ma and Swinton (2011) and Tapsuwan et al. (2015). The relatively low R^2 of the current model is due to the small and relatively uniform sample and inclusion of only a few explanatory variables. The sample area is several neighbouring suburbs where house prices were relatively homogenous. Since the purpose of the regression model is to make predictions, we only included the variables for which we have relevant data/information. The regression analysis shows that the most important predictors are lot area and the number of bathrooms. The number of bedrooms is not statistically significant because it is highly correlated with the number of bathrooms. The age of the home is not statistically significant because of the limited range of ages in the sample.

Using the results of the regression, we predicted the value of homes in the development, as well as within 500 m of the constructed wetlands outside of the development using actual lot sizes and house characteristics in the study area. We assumed that homes would have three bedrooms, two bathrooms, and two parking spaces for lot sizes between 200 to 400 m^2. Lots greater than 400 m^2 will have four bedrooms, and lots less than 200 m2 will have one parking space.

These assumptions are based on the median values of numbers of bedrooms, bathrooms and parking spaces for homes built in the study area in the last five years. The predicted values of homes are presented in Table 10.4. It shows home values for homes of the 1st and 2nd stage of development separately, and for the existing homes that will be affected by the constructed wetlands. The predicted base values do not consider the amenity value of the living stream and constructed wetlands.

Amenity values of constructed wetlands and living stream (point estimates, as well as lower and upper bounds) were calculated for each house using methods described above.

Table 10.4 Predicted house values

Stage of development	Number of houses	Mean	SD
Development stage 1	334	$249,630	$15,688
Development stage 2	233	$255,396	$14,987
Existing homes	223	$286,630	$8,001

Source Own calculation

Table 10.5 Distribution of the benefits of WSUD measured as a calculated increase of home values due to the implementation of the living stream and constructed wetland

House types	Number of homes	Mean	Std Dev	Minimum	Median	Maximum
Development stage 1	334	$5,639	$4,760	$1,297	$3,035	$39,363
Development stage 2	233	$5,054	$3,922	$1,615	$3,940	$24,335
Existing homes	223	$1,612	$814	$783	$1,444	$4,987

Source Own calculation

We used predicted base values for each home separately. The amenity value of the living stream was calculated for each home adjacent to the living stream by multiplying the base value by percentage increase due to the living stream. Here we assume that the residents will start to enjoy amenity benefits earlier than what has been observed in Polyakov et al. (2017a). There are two reasons behind this assumption: (i) we assume that the living stream will be established before completion of the project; and (ii) it will take a shorter period of time for it to start generating amenity benefits as it would not have extensive vegetation that might require a long time to grow. Further, preliminary results from a separate study of ours on a new development suburb suggest that even planned living stream or public open space could uplift the value of adjacent properties. The percentage value increase due to constructed wetland was calculated for each home separately by using Eqs. (10.1) and (10.2). There are some houses which could be potentially impacted by both wetlands and living stream (approximately 5% of the houses). Because the amenity value of living stream and amenity value of constructed wetland are strong substitutes, we selected the higher of two values for those houses.

Distribution of point estimates of amenity values for houses in the first and second stages of the development as well as for the existing houses outside of the development is presented in Table 10.5. The predicted median amenity values are slightly higher for homes in the second stage of development than for homes in the first stage of development because homes in the second stage are on average closer to the constructed wetland. The lowest amenity values are for the homes outside of the development because they are not affected by the living stream and are located relatively far from the constructed wetlands.

Aggregate median estimates, as well as lower and upper bounds of amenity values of WSUD in Belle View Estate development, are presented in Table 10.6. Lower and upper bounds are calculated by subtracting or adding one standard error to/from the regression coefficient of the impact of the living stream or constructed wetland, respectively. According to our estimate, the amenity value of the proposed WSUD in the first stage of the development is valued between $1M and $2.7M, the amenity value of WSUD for the second stage of the development is between $0.6M and $1.8M, and the amenity value of WSUD for the houses outside of the development is between $0.2M and $0.5M. The total amenity value generated by WSUD is estimated between $1.8M and $5.0M (Table 10.6).

It can be seen from the median estimates in Table 10.6 that a substantial portion of the amenity benefits (11%) will be captured by the residents (existing houses). This could be considered as the public benefit generated by the project, in addition to the pollution removal benefits, which we describe below.

10.6.3.2 Pollution Removal Benefit

The present value of pollution removal over an estimated life of a living stream, under three levels of removal capacity and three discount rates, have been presented in Table 10.7. For Total Nitrogen (TN), the estimated benefit ranged from $0.16 million to $0.36 million. On the other hand, for Total Phosphorous (TP), the total benefit ranged from $0.06 million to $0.13 million. By comparing the values for TN and TP, it could be observed that the pollution benefit is likely to be mostly generated from the removal of total nitrogen.

10.6.3.3 Aggregate Benefits

We combine the amenity and pollution removal benefits of constructed wetlands and living stream (Fig. 10.10). It is possible to aggregate the amenity and pollution removal benefits as they are different types of benefits with limited

Table 10.6 Total amenity value (in AU$ millions) from wetlands and living stream

Stage of development	Number of homes	Home values	The amenity value of WSUD		
			Lower bound	Median	Upper bound
Development stage 1	334	83.38	1.04	1.88	2.74
Development stage 2	233	59.51	0.58	1.18	1.79
Existing homes	223	63.92	0.18	0.36	0.54
Total	790	206.81	1.80	3.42	5.07

Source Own calculation

Table 10.7 Pollution removal benefit (in AU$ millions)

Discount rate (%)	Removal capacity					
	Low		Medium		High	
	TN	TP	TN	TP	TN	TP
3	0.24	0.09	0.3	0.11	0.36	0.13
5	0.19	0.07	0.24	0.09	0.29	0.11
7	0.16	0.06	0.2	0.07	0.24	0.09

Source Own calculation

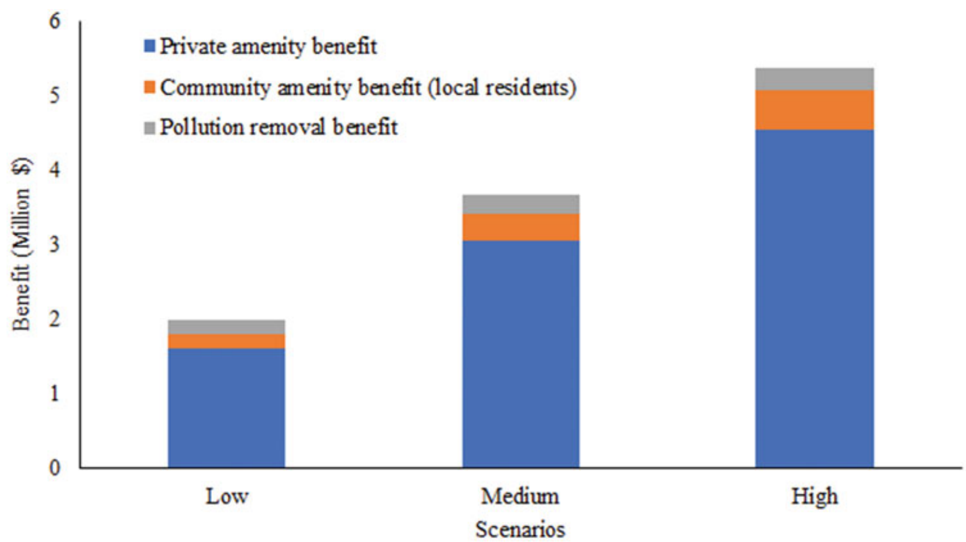

Fig. 10.10 Aggregate amenity and pollution benefits (in AU$ million) of constructed wetlands and living stream. Pollution removal benefit is based on TN removal benefit at a 5% discount rate at the base (medium) capacity. *Source* Own calculation and pollution benefits (in AU$ million) of constructed wetlands and living stream. Pollution removal benefit is based on TN removal benefit at a 5% discount rate at the base (medium) capacity. *Source* Own calculation

risk of overlaps. The aggregate value ranges from $2.0M to $5.4M. It could be noted that at a medium level, around 93% benefit is accrued due to amenity benefits and 7% due to pollution removal benefit. Further, almost 16% of the benefits are accrued to the residents (existing houses) and the community.

10.6.3.4 Benefit-Cost Analysis

For benefit-cost analysis, three levels of aggregate benefits are considered: $1.99 million (Low), $3.66 million (Medium) and $5.36 million (High) following Eq. 10.3. The aggregate cost is calculated to be $1.43 million (Low), $1.79 million (Medium) and $2.15 million (High), respectively following Eq. 10.4. Net present values and benefit-cost ratios are calculated for all nine combinations of benefit and cost levels which are presented in Table 10.8. It can be seen that except for the low benefit—high-cost combination, the net present value and benefit-cost ratios are favourable in other combinations. In the best-case scenario (i.e., high benefit-low cost), the net present value could be as high as AU$3.93 million. The benefit-cost ratio ranges from 0.93 to

Table 10.8 Distribution of net present values (NPVs) and benefit-cost ratios (BCRs)

Cost	Benefit		
	Low	Medium	High
	NPV (Million $)		
Low	0.56	2.23	3.93
Medium	0.20	1.87	3.57
High	−0.16	1.51	3.21
	BCR		
Low	1.39	2.56	3.74
Medium	1.11	2.04	2.99
High	0.93	1.70	2.50

3.74, which is similar to the range (1.6–4.2) estimated by Polyakov et al. (2017a) for the Bannister Creek living stream project. Usually, for small-scale WSUD projects, a conservative higher BCR threshold of 2 is suggested to assess whether the project is beneficial or not (Pannell 2019). In the base case (medium) scenario, the benefit-cost ratio is 2.04, which suggests that the WSUD project proposed in the case study area is likely to generate a net benefit to society.

10.6.4 Concluding Remarks

In this section, we make two contributions. First, we demonstrate the applicability of benefit transfer methods in estimating the nonmarket benefits of WSUD in a private residential development. We have observed that aggregate amenity and pollution benefit is substantial. As expected, private residents/owners are going to enjoy most of the benefits (84%) from the implementation of the project. However, it is interesting to note that the residents and a wider community are also going to reap amenity and pollution removal benefits from the implementation of the project.

Second, we incorporate non-market benefit estimates in a formal benefit-cost analysis to assess whether the implementation of WSUD in a private residential development is beneficial or not. The results show that the project is likely to generate net benefit. Such evidence might encourage other private developers to consider WSUD in residential development. For the Belle View case study site, even though the private developer is bearing the cost of the project, it would be beneficial to think about some sustainable long-term governance arrangement for the continuous management of the systems.

Given that the case study has relied on the benefit transfer method, the analysis was limited by the availability of data. It was not possible to consider all types of benefits due to a lack of data. For example, pollution removal benefits are based on avoided costs and may not capture the full non-market benefits of improving water quality. Site-specific cost data would also be useful. Future potential work would involve the collection of new information and updating the existing information when they become available. It will also be useful to conduct similar studies in other sites to understand the potential benefits of WSUDs in private residential development.

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Anik Bhaduri is an accomplished leader in the field of water economics, global water policy and water governance with over 20 years of experience. Dr. Bhaduri is the Director of the Sustainable Water Future Programme (Water Future) of Future Earth. Water Future is a global platform facilitating international scientific collaboration to drive solutions to the world's water problems.

Anik is also an Associate Professor within the Australian Rivers Institute, Griffith University. Previously, he served as Executive Officer of the Global Water System Project (GWSP). With a background in environment and natural resource economics, Anik has specialised in water resource management. He has worked on several topics and projects, ranging from transboundary water sharing to adaptive water management under climate change. Anik also serves as a senior fellow at the Centre of Development Research, University of Bonn, Germany.

C. Dionisio Pérez-Blanco is a Distinguished Research Fellow at Universidad de Salamanca, where he coordinates a group of 8 researchers (the Agricultural and Water Resources Economics Group—AWARE). Dr. Pérez-Blanco is PI and coordinator of the PRIMA/H2020 project TALANOA-WATER, the Program for the Attraction of Scientific Talent project SWAN and the Ministry for the Ecological Transition project ATACC. Dr. Pérez-Blanco is also a successful awardee of the Marie Sklodowska-Curie, the AXA Research Fund and Ikerbasque fellowships. Over the past eight years he has been working on topics related to water and agricultural economics in the context of national and EU research projects at Universidad de Salamanca, FEEM, CMCC, Universidad de Alcalá, IMDEA Water, and Spanish Research Council. He has also worked as a lecturer at UAH and Ca' Foscari University of Venice, and has been a visiting fellow at Middlesex University, University of Queensland and UAH.

Dolores Rey is lecturer in water policy and economics at Cranfield University. She is the Course Director for the Advanced Water Management M.Sc. She has over 10 years' research experience on water availability risks and water economics in the agricultural sector. She is the PI of the project "NEXus Thinking for sustainable Agricultural development in Andean countries (NEXT-AG)" working with partners in Chile, Ecuador, Peru and the UK on applying a Water-Energy-Food-Environment nexus approach to inform future irrigated agriculture development policies in Andean countries. She is Co-I of the STAR project (Strengthening Thailand's Agricultural Drought Resilience) looking at improving farmers' adaptive capacity and drought communications in Thailand. Her recent research under the UK Droughts and Water Scarcity research programme seeks to understand farmer decision-making processes regarding water management during drought events and the financial impacts of droughts on UK agriculture. Besides, she is involved in several research and consultancy projects related to sanitation, water availability risks, and irrigation in developed and developing contexts.

Sayed Iftekhar is an ARC DECRA Fellow and a Senior Lecturer at Griffith University. Sayed Iftekhar is an environmental economist with substantial experience in conducting research on mechanism design, natural resource management, environmental policies and water management. He uses various economic tools, such as, economic experiments, agent-based simulations, nonmarket valuation surveys and benefit-cost analysis.

Aditya Kaushik works as an Associate Director and as a Project Scientist of the Water Solutions Lab at Divecha Centre for Climate Change. Kaushik currently manages a team of 15 members with a goal to address water problems in India by bridging the gap between science and policy and between knowledge and practice through a combination of advance scientific knowledge, multi-stakeholder involvement, and digital information technology. He also serves as a Deputy Director of the Sustainable Water Future Program (SWFP), Future Earth where he helps in formulating strategic policy and implementation agenda for SWFP and assists in science-policy communication and outreach activities aimed at making scientific information and concepts useful for policy-making.

Kaushik is the founding member of an open, independent, and a collaborative platform called the Science Policy Forum (SPF).

Kaushik was instrumental in driving the science diplomacy initiative at the Fletcher School where co-founded the Fletcher Science Diplomacy club with an aim to highlight the role of science in policymaking, helped develop a Science Diplomacy field of study and was also a planning member of the Fletcher Science Diplomacy Center. Prior to joining the Fletcher School, Kaushik worked for a mathematical computing firm called The MathWorks based in Natick, Massachusetts. His research interests include exploring the use of emerging technologies such as blockchain in water governance and mapping the role science diplomacy in international relations.

Kaushik holds a Master of Science degree in Electrical Engineering from the University of Southern California and a Master of Arts degree in Law and Diplomacy from the Fletcher School at Tufts University.

Alvar Escriva-Bou is a research fellow at the PPIC Water Policy Center. Dr. Escriva-Bou's research explores integrated water, energy, and environmental resources management, including systems approaches, simulation and optimization of economic-engineering models, and climate change analysis. Previously, he worked as a civil engineer, managing and developing large infrastructure projects for local and regional governments and consulting firms in Spain. He holds a Ph.D. and M.S. in water and environmental engineering and a BS in civil engineering from the Polytechnic University of Valencia in Spain, as well as an MS in agricultural and resource economics from the University of California, Davis.

Javier Calatrava is Professor of Agricultural Economics and Policy and Rural Sociology at Universidad Politécnica de Cartagena, Spain (UPCT). He holds a Ph.D. in Agricultural Economics (Universidad Politécnica de Madrid, Spain, 2002) and an M.Sc. in Agricultural Engineering (Universidad de Córdoba, Spain, 1997). He has conducted extensive research for twenty years in the field of agricultural and resource economics, mainly focused on the economics and policy of water resources and of agricultural soil conservation, has participated in sixteen public research projects funded by the European Union or the Spanish Government (four as team leader) and supervised five doctoral dissertations. Dr. Calatrava has authored eighty academic references, including twenty-seven articles in peer-reviewed scientific journals and twenty-two chapters in international books, and conducted consultancy work on water resource economics and soil conservation policy for several Spanish agricultural and environmental administrations, the European Commission and the OECD.

David Adamson is currently a Senior Lecturer at The University of Adelaide, Australia where he specialises in risk, uncertainty, water resources and biosecurity, and he has an Honorary Senior Research Fellow position (One Health Economics) at The University of Liverpool, in the United Kingdom. David has been working on water issues since 2004 when he was employed at The University of Queensland by Professor John Quiggin to build an economic model of Australia's Murray-Darling Basin. He has been commissioned to work on The Garnaut Climate Change Review and the Murray-Darling Basin Plan. David moved to Adelaide, not long after winning his Australian Research Council's Discovery Early Career Award where he focused on optimising the gains from returning water to the environment.

Sara Palomo-Hierro is a lecturer at the Department of Applied Economics (Statistics and Econometrics) at the University of Malaga, Spain. She holds a Degree in Economics from the University of Malaga and a M.Sc. degree in Quantitative Economics from the University of the Basque Country, Spain. Her main research interests are in the fields of water resources economics, particularly the modelling and analysis of water markets as a tool for water reallocation and adaptation to climate change.

Kelly Jones is an Associate Professor in the Department of Human Dimensions of Natural Resources at Colorado State University (CSU). I apply microeconomic theory and methods to understand relationships between people and the environment. Specific topics of interest include payments for ecosystem services, impact evaluation, land tenure and property rights, and drivers of land cover change. Much of my scholarship has been devoted to interdisciplinary collaborations that combine physical, ecological, and social science theory and methods to advance knowledge. My work contributes broadly to the fields of land use science, evidence-based conservation, and ecosystem services science.

Heidi Asbjornsen is an Ecosystem Ecologist, with expertise in Ecohydrology, Plant Physiology, and Forestry. Heidi is an Associate Professor and program coordinator for forestry at the University of New Hampshire. Her research focuses on understanding the underlying ecological processes that determine the capacity of temperate and tropical ecosystems to sustainably provide diverse benefits to society while maintaining resilience to land use and climate change, and how to apply this knowledge to developing approaches for the sustainable management of watershed for hydrologic and other ecosystem services. Her work is inherently highly interdisciplinary and collaborative, and in recent years has focused on integrating biophysical and social science research with broad stakeholder engagement to enhance Payment for Hydrologic Service programs.

Mónica A. Altamirano, Ph.D., is Public-Private Partnerships specialist at Deltares and lead of Peru Valuing Water Journey. Committed to making water security financially viable for developing countries. Applying economics of infrastructure and systems engineering to analyze the institutional framework for infrastructure finance and facilitate complex multi-party financing. With 16 years of experience she has advised governments on how to catalyse private sector investments in water infrastructure and climate adaptation in Asia, Latin America and Europe. She has a Ph.D. on Economics of Infrastructures and MSc in Systems Engineering and Policy Analysis from TUDelft. Before joining Deltares she worked as scientific researcher at TUDelft and as technical assistant of the Nicaraguan Minister of Education. She has served as peer reviewer for the OECD Water Governance Review of Argentina, is secretary of the PIANC Permanent Task Force on Climate Change, member of the World Economic Forum Cities, Infrastructures and Urban Services Community, the UNECE Team of Specialists in PPP and the OECD-WWC-NL Roundtable on Financing Water. She has developed a collaborative investment planning approach called Financing Framework for Water Security, and within the H2020 project NAIAD (Nature Insurance value: Assessment and Demonstration) developed it further into project preparation guidelines for investable NBS and watershed conservation projects.

Elena Lopez-Gunn is Founder and Director of ICATALIST, a small innovation SME located in Spain. She is also a Cheney Fellow at the University of Leeds, UK and a collaborator with the Water Observatory, Botín Foundation. She was an Associate Professor at IE Business school and a Visiting Senior Fellow at the London School of Economics where she worked as an Alcoa Research Fellow. Dr. Elena Lopez-Gunn finished her Ph.D. at King's College. She also has a Masters from the University of Cambridge. Professionally, Elena has collaborated with a number of organizations including UNESCO, FAO, UNDP, EU DG Research and Innovation, the England and Wales Environment Agency, as well as the private sector like Repsol, public institutions and NGOs like for Transparency International-Spanish Chapter. She has published on a range of issues mainly related with innovation, water governance, climate change adaptation, partnership models, public policy and knowledge management.

Maksym Polyakov is an applied economist whose interests focus on the integration of ecology and economics to better understand the choices humans make regarding natural resources and the consequences of these choices for the environment. He is a Senior Economist in Manaaki Whenua —Landcare Research, New Zealand's Crown Research Institute for land and environment. He works on valuation of environmental assets to support informing policy and decision-making. Prior to coming to Manaaki Whenua, for more than a decade he worked at the Centre for Environmental Economics and Policy in the University of Western Australia.

Mahsa Motlagh is a research associate in the "Digitainable" Project at Bonn Alliance for Sustainability Research, Bonn, Germany. The focus of her research is on the cross-disciplinary interface of social and environmental aspects of digital transformation, sustainable development diplomacy, and capacity building for social and behavioural change. Her research addresses how digitalisation has contributed to the sustainable development to understand the requirement of the future digitalisation workflows, especially in the water sector. Holding a Ph.D. in transboundary water governance, and MSc. in natural resources economics, she has specialized in environmental diplomacy, conflict resolution and multi-stakeholder processes, human security, and social inclusion.

Maksud Bekchanov is a Research Associate at the Center for Earth System Research and Sustainability (CEN) of the University of Hamburg and a former Senior Researcher—Agricultural Economist at Center for Development Research (ZEF) in Bonn, Germany. His main research areas are water, land and energy resources management and economics. Dr. Bekchanov is interested in economic modeling analyses, system-wide economic-environmental assessments, and sustainable development futures. His research addressed various issues including irrigation versus hydropower, optimal irrigation efficiency improvements, water rights trading and pricing, wastewater recycling, water and soil ecosystem services, economic instruments along waste-to-asset value chain, deforestation prevention, and hunger eradication across Central and South Asia, South America, and Africa.

11 Drivers, Pressures and Stressors: The Societal Framework of Water Resources Management

Léna Salamé, Janos J. Bogardi, Zita Sebesvari, Klement Tockner, Burcu Yazici, Fatma Turan, Burcu Calli, Aslıhan Kerç, Olcay Ünver, and Yvonne Walz

Abstract

Every aspect of human activity and development indeed subjects water to a number of pressures at accelerated paces. Rapidly expanding populations, urbanisation, agricultural intensification, increasing energy demand, industrial production, land use changes, along with every infrastructure development works, among others, constitute a complex set of drivers who become source of pressure to the water bodies, and stress to their associated ecosystems. This chapter analyses a number of pressures and how they become sources of stress to water bodies but also on social systems. Thus three additional areas and interconnections (water and migration, water and food security and water and health) are presented to illustrate the associated drivers and pressures which ultimately yield stresses with unwelcome social and natural consequences. Each section ends with suggested actions to be taken in responding to threats and achieving realistic planning and efficient decision making for water management.

Keywords

DPSSIR • Integrated water resources management • IWRM • Pressures • Stressor • Drivers • States • Impacts • Responses • SDGs • Sustainable development goals • Population growth • Adaptation strategies • Freshwater ecosystems • Basin approach • Migration • Human mobility • Climate change • Climate resilience • Refugees • Food security • Nutrition • Agriculture • Marginalised groups • Diet • Waste • Water-related diseases • Human health • Freshwater-related pressures and stressors on human health • Water management • Drivers of migration • Low-regret solutions • Nature-based solutions • No-regret solutions • Stakeholder engagement

Abbreviations

CHF	Swiss Franc
COP	Conference of the Parties
CAF	Cancun Adaptation Framework
DALY	Disability adjusted live years
DO	Dissolved Oxygen
DPSIR	Drivers, Pressures, States, Impacts, Responses Model

L. Salamé (✉)
Paris, France
e-mail: lenasalame@gmail.com

J. J. Bogardi
University of Bonn, Institute of Advanced Studies Köszeg (iASK), Kőszeg, Hungary
e-mail: jbogardi@uni-bonn.de

Z. Sebesvari
Environmental Vulnerability and Ecosystem Services (EVES), United Nations University, Institute for Environment and Human Security, Bonn, Germany
e-mail: sebesvari@ehs.unu.edu

K. Tockner
Senckenberg Gesellschaft für Naturforschung and Goethe University, Frankfurt am Main, Germany
e-mail: klement.tockner@senckenberg.de

B. Yazici · F. Turan · B. Calli
Turkish Water Institute (SUEN), Istanbul, Turkey
e-mail: burcu.yazici@SUEN.GOV.TR

F. Turan
e-mail: fatma.turan@SUEN.GOV.TR

B. Calli
e-mail: burcu.calli@SUEN.GOV.TR

A. Kerç
Environmental Engineering Department, Marmara University, Istanbul, Turkey
e-mail: aslihan.kerc@SUEN.GOV.TR

O. Ünver
Polytechnic School, Environmental and Resource Management Program, Arizona State University, Mesa, AZ, USA
e-mail: olcay_unver@yahoo.com

Y. Walz
United Nations University Institute for Environment and Human Security (UNU-EHS), Bonn, Germany
e-mail: walz@ehs.unu.edu

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DPSSIR	Drivers, Pressures, Stressors, States, Impacts, Responses Model
ES	Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
LDCs	Least Developed Countries
NAPA	National Adaptation Programme of Action
OECD	Organisation for Economic Co-operation and Development
SDGs	Sustainable Development Goals
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
UNHCR	United Nations High Commissioner for Refugees
WASH	Water, Sanitation and Hygiene
WHO	World Health Organization

11.1 Introduction

The irrefutable and complex interlinkages between human activities and water make the management of this resource a delicate and multifaceted process. While developing, growing in numbers and improving their lifestyles, humans draw innumerable benefits from freshwater, its services and ecosystems; and while doing so in a voluntary or forced manner, they alter excessively and sometimes even irreversibly, the characteristics of the resource.

Every aspect of human activity and development indeed subjects water to a number of pressures at accelerated paces. Rapidly expanding populations, urbanisation, agricultural intensification, increasing energy demand, industrial production, land use changes, along with every infrastructure development works, to name only a few, constitute a complex set of drivers who become source of pressure to the water bodies, and stress to their associated ecosystems.

These pressures and stressors take on different faces and materialize in various manners such as the deterioration of water quality and ecosystems, water erosion, the decline in soil fertility and aquifer recharge, shortages of groundwater as well as flow alteration or biomass extraction.

Climate change and its consequences on the number of extreme events such as droughts and floods, add yet another layer of pressures and stress on the water and its ecosystems.

In the nature of things and their logical flow, these problematic manifestations of pressures and stressor on water resources and their ecosystems have in turn, a negative and considerable impact on human health and their movements. Water can indeed constitute at the same time the salvation resource as well as the source of deadly diseases and miseries. It can be the aim migrants pursue in their movements as well as, the root cause pushing them to flee. Water can also be a victim when people over-populate a region and impact its resources in terms quality and quantity.

This complex net of linkages among water, human activities and the mix of drivers, pressures and stressors, can be potentially perceived as a dangerous landscape if it is not well understood, anticipated and planned for.

A thorough and full image of this problematic picture is given in this chapter. The second section presents and analyses the modified Drivers, Pressures, States, Impacts, Responses (DPSIR) cycle with the additional "stressor" element (thus Drivers, Pressures, Stressors, States, Impacts, Responses (DPSSIR) model) to emphasize the interface between the anthropic and freshwater subsystems. The third section focuses on the challenges related to migration and water, and their complex interlinkages in the face of global and climate changes. The fourth section explores the links between water, food security, and nutrition, the complex mix of drivers, pressures, and stressors which determine future supply and demand for water for food, and agriculture's focus on producing more food with less water—"more crop per drop". The fifth section finally discusses potential impacts of freshwater related pressures and stressors on human health. It details the close interlinkages between water management and human health.

Each section provides policy options to support well anticipated, realistic and efficient responses to the complex web of linkages between anthropogenic and freshwater systems.

Given the multiple challenges, growing risks and uncertainties as well as the ever-changing socio-economic conditions our world is facing, suggested options imply a paradigm shift from prediction and control to management as learning approach, as recommended in Sect. 11.5.

11.2 The DPSSIR Framework Linking the Anthropic and Natural Water Resources Subsystems[1]

11.2.1 Distinctions and Interactions of Pressures and Stressors

Inland waters are among the most altered ecosystems globally. Indeed two third of all large rivers are fragmented due to water resources development activities, river training,

[1]Section 11.2 is based on and follows parts of Chap 2 of Volume 4 of UN Environment (2018) A Framework for Freshwater Ecosystem Management. www.unenvironment.org/resources/publication/framework-freshwater-ecosystem-management).

interbasin transfers and dam building. Reservoirs trap more than 25% of the total sediment load that formerly reached the oceans (Vörösmarty and Sahagian 2000). Out of the estimated 40,000 km^3 annual terrestrial water flux (aggregated stream flow and aquifer outflow to the oceans) as discussed in Sect. 2.2 (Trenberth et al. 2007) approximately 10% is withdrawn for human use and activities (Rockström et al. 2009). In average, around 70% of the water withdrawn globally is used for agricultural, mainly in irrigation (Wallace et al. 2003).

Riparian corridors are preferential human settlement areas. More than 50% of the global human population lives within 3 km of a water body; less than 10% of the population lives at a distance greater than 10 km from a water body (Kummu et al. 2011). River deltas have fertile soils and are, therefore, among the most populated areas globally. In total about 500 million people leaves on deltas (Ericson et al. 2006).

Life on Earth depends upon the integrity of ecosystems (Lindenmayer and Likens 2010). Aquatic ecosystems touch all parts of the natural environment and nearly all aspects of human life and culture. Freshwaters not only provide natural resources for humans such as fish and clean water, but they also provide water for industrial and agricultural production, transportation, energy, dilution of pollutants, and recreation (Naiman and Bilby 1998). As a result, complex inter-relationships between socio-economic factors and the hydrological and ecological conditions of freshwater bodies exist. Concurrently, these close relationships pose major challenges on the integrity of aquatic ecosystems (Bartram and Balance 1996; US EPA 2006). For achieving a sustainable, balanced coexistence of human aspirations and freshwater ecosystem requirements, freshwaters need to be considered as coupled social-ecological systems, and ecosystem health cannot be treated in isolation. The One-Health-approach encapsulates, since its launch in 2007 this concept.[2]

Humans benefit from the processes and services provided by freshwaters; concurrently, human activities have profoundly altered the physical, chemical and biological characteristics and dynamics of water bodies, locally to globally. Most ecosystems are exposed to multiple human-caused pressures, which has led to stresses including water pollution, flow modification, habitat degradation, overexploitation, and the introductions of alien species (Allan and Flecker 1993; Dudgeon et al. 2006; Malmqvist and Rundle 2002) (Fig. 11.1).

Pressures are the consequences of human activities seeking to satisfy human well-being. Without doubt, that the achievement of several goals formulated by the SDGs, like eliminating hunger (SDG No. 2) (increased agricultural production and potentially higher fertilizer and pesticide use), or improved health for all (SDG No. 3) (which may imply more pharmaceutical residues in wastewater), just to, mention two examples, could have negative consequences as far as pressures upon freshwater bodies are concerned (UNGA 2015). Pressures, however, may reach levels which cannot be compensated by the natural resilience of the respective ecosystems. Their functions are impacted and they deviate from their 'healthy state'. Thus, pressures become sources of stress. While implementing the SDGs special care is needed to avoid that potentially increasing pressures will not reach stress levels. Different, individually benign pressures may aggregate and can thus cause stress or contribute to different sort of stresses. Likewise, one type of high level pressure might cause a particular, or different kinds of stresses affecting freshwater bodies.

Thus, pressures are conceptualized in association with activities for human well-being, whereas stressors refer to the water bodies, epitomizing the negative impacts of potentially aggregated effects of pressures to the supporting freshwater ecosystems. This distinction is proposed to account for the "two sides of the coin" by benefiting from or exploiting of ecosystem service for (increasing) human well-being. The well-known Drivers, Pressures, States, Impacts, Responses (DPSIR) cycle is modified with the additional "stressor" element to form the Drivers, Pressures, Stressors, States, Impacts, Responses (DPSSIR) model. This addendum emphasizes the Pressures/Stressors interface between the anthropic and freshwater subsystems as shown in Fig. 11.1.

A matrix of relationships among different pressures and stressors is presented in Table 11.1. Pressures such as water withdrawals for domestic, industrial, mining, agricultural and energy generation (cooling water), purposes, and the subsequent discharge of used (waste) waters, but also fisheries, aquacultures as well as sand, gravel and other material removal from rivers and lakes constitute both extractive and potentially also discharge pressures. Hydropower generation and navigation are typically in situ pressures while transport infrastructure, traffic, terrestrial biomass production, urbanization and recreation, but also measures against water-related hazards, can be classified as riparian/basin scale pressures. Climate variability and climate change as well as aerosols and other atmospheric depositions constitute additional, global-scale pressures. The global connectivity of the atmosphere facilitates the geographical spread of this pressure.

Climate change (though unwantedly) is triggered by activities conceived to increase human well-being. Direct human impacts such as land use and land use change (see also in more details in Chap. 15), water pollution, and water

[2]https://www.onehealthcommission.org/en/why_one_health/what_is_one_health/.

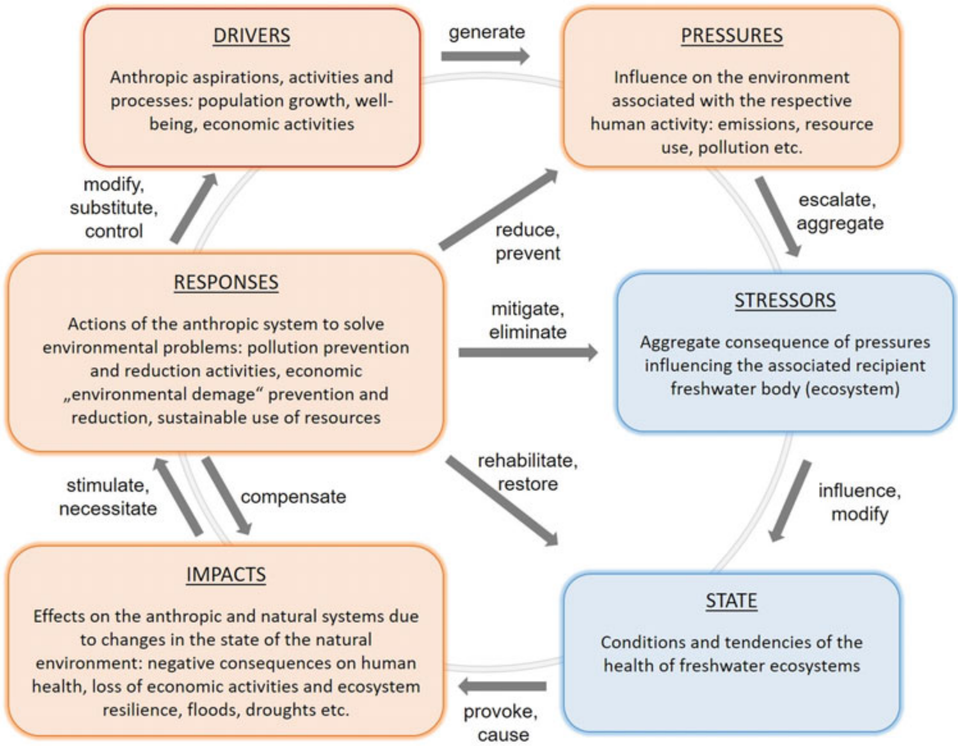

Fig. 11.1 Linking the anthropic and freshwater ecosystems and their causal chains of links. *Source* Modified based on ISTAT, C. Costantino, F. Falcitelli, A. Femia and A. Tuolini (OECD Workshop Paris, 14–16 May 2003)

resource development will remain major threats to most freshwater ecosystems over the next decades (Settele et al. 2014). However, climate change will exacerbate many of these pressures, thus showing how combinations of increasing pressures worsen the effect of individual stressors. For example, rising water temperatures are likely to lead to shifts in freshwater species distributions, support the spread of diseases, and further deteriorate water quality, especially in systems already exhibiting high anthropogenic nutrient loading (Settele et al. 2014).

Land use alteration and its inherent land cover change are consequences of (frequently unsustainable) human activities along shorelines or within the catchment of the respective water body. They may impede freshwater ecosystems through increased sedimentation, nutrient enrichment, contaminant pollution or hydrological alteration. Riparian clearing, the loss of forest cover and other human activities have shaped terrestrial and freshwater ecosystems for millennia. Agriculture and deforestation are the dominant land use changes globally. Urban land use, while increasing, covers a smaller percentage of catchments. However, urban areas disproportionately affect aquatic ecosystems. Land use patterns and human population density in the catchment are surrogate warning indicators of freshwater conditions, acting as an overall index of human disturbance.

Freshwater bodies occupy usually the deepest parts of their respective catchment: hence freshwater bodies mirror the human activities and related processes within the basin. As a corollary the proportions of cropland and urban area as well as the state of the riparian zones are probably the most effective proxies reflecting the environmental state of freshwater ecosystems (Bunn et al. 1999; Peterson et al. 2011).

Pressures influence water bodies through different, sometimes indirect links such as water withdrawal, discharge, seepage, atmospheric deposition, rainfall and radiation.

Stressors are understood as distinct and (potentially accumulated) negative manifestations of pressures on water bodies such as construction of water infrastructure (dams, barrages, sluices, ports, dykes, groins or other artificial obstacles), alteration of flow and water levels (through withdrawals, discharges, backwater effects, hydropower generation and the operation of water infrastructures), modification of aquatic habitats (dredging, mining, river training), overexploitation of aquatic resources, biological water pollution such as the emergence of invasive alien species and pathogens, genetic modification of freshwater organisms as well as chemical and thermal pollution (mainly through the discharge of wastewater and returning cooling water) (Table 11.1).

For example, the stressor 'overexploitation' depends on pressures emanating from various water uses (withdrawal, wastewater discharge), fishery and aquacultures, dense human population (settlements and recreation) and indirectly through climate change as an increasingly limiting factor of ecosystem resilience. Climate change "itself", however, is a

Table 11.1 Pressures and stressors relevant for inland surface waters. Pressures exert their influence on water bodies through hydraulic structures and river training, withdrawals, discharges, seepage through ground water bodies, atmospheric deposition, rainfall and radiation

Pressures \ Stressors	Water Infrastructure (artificial /physical obstacles)	Flow alteration	Modification of aquatic habitat	Overexploitation	Biological water pollution (invasive species, pathogens, etc.)	Chemical water pollution	Thermal water pollution
Water withdrawal/discharge (domestic use)	Strong	Strong	Indirect	Strong	Indirect	Strong	Strong
Water withdrawal/discharge (Industries incl. extractive ind.)	Strong	Strong	Indirect	Strong		Strong	Strong
Water withdrawal/discharge (agricultural use)	Strong	Strong	Strong	Strong		Strong	
Cooling water withdrawal/discharge	Strong	Strong	Indirect			Strong	Strong
Biomass extraction (e.g. fishery and aquaculture)				Strong	Strong	Strong	
Mineral extraction (sand, stones, gravel, gold, etc.)		Strong	Strong	Indirect		Strong	
Hydropower generation	Strong	Strong	Strong			Strong	Indirect
Navigation	Strong	Strong	Strong		Strong	Strong	
Transport infrastructure and traffic	Indirect	Strong	Strong			Strong	Strong
Terrestrial biomass production (food, timber, energy crops, animal husbandry & fish ponds, etc.)	Indirect	Strong	Strong		Indirect	Strong	
Hazard security (flood protection, etc)	Strong	Strong	Strong				
Human settlements (esp. in the proximity of water bodies)	Indirect	Strong	Indirect	Strong		Strong	Strong
Recreation			Strong	Strong	Indirect		
Climate variability and change, atmospheric deposition		Strong	Strong	Strong	Strong	Indirect	Strong

Extractive pressures, withdrawals, intruding discharges (rows: Water withdrawal/discharge … to Mineral extraction)
In situ pressures (rows: Hydropower generation, Navigation)
Riparian/basinwide pressures due to land use and landcover change (rows: Transport infrastructure … to Recreation)
Atmospheric pressures (row: Climate variability …)
Strong links
Indirect and secondary links

stressor too. The main stressors of freshwater ecosystems are described in the following sub-sections.

11.2.2 Water Infrastructure

Infrastructure development including dams, levees, port and harbour infrastructures, bridges and other engineering structures located in or constraining water bodies are usually stressors which modify flow and thermal regimes, lateral and longitudinal connectivity and hydromorphology with potentially harmful effects on freshwater species since they are not adapted to these changes (Allen et al. 2012; Smith et al. 2014). Water infrastructures can influence both upstream and downstream water uses as well. Impacts include:

- Alteration of the hydrology, temperature, and sediment dynamics. River flow, thermal and sediment regimes (e.g., seasonality, amplitude, frequency of events) may change;
- Decrease in biodiversity due to river regulation and dredging, shoreline development, and the inherent extensive habitat loss;
- Truncation of the longitudinal, lateral and vertical connectivity, which impedes the migration and dispersal of organisms, in particular of fish, and reduces sediment transport;
- Loss and degradation of wetlands, flood plains and fringing buffer zones from channel regulation, levee construction or inundation by impoundments.

Given the ongoing increase in human population, economic development and the rapid rise in energy demand, water infrastructure as stressor is most likely gaining in importance. Indeed, within the next 10–20 years, hydroelectricity production will almost double, thus further shaping and impacting the global river network, in particular the Amazon, the Congo, in South East Asia or in the Balkans (Fig. 11.2).

11.2.3 Flow Alteration

Hydrology is considered the "master variable" in inland waters (Jackson 2006; Poff et al. 1997). Flow alteration may be defined as "any anthropogenic disruption to the magnitude or timing of near-natural stream flows" (Rosenberg et al. 2000). Such changes in the magnitude and patterns of flow (or water level), caused by the storage, regulation, diversion and/or extraction of surface and groundwater by dams and other water resources infrastructure, are one of the primary contributors to the degradation in riverine (and lacustrine) ecosystems (Postel and Richter 2003). The physical (hard) and so-called soft (e.g. altered thermal regime) barriers created by water resources infrastructure fragment aquatic systems, blocking species movements between habitats, disconnecting rivers from their floodplains and associated wetlands, changing temperature, nutrient and sediment gradients, eroding deltas, and altering life cycle activities such as fish spawning. The water resources infrastructure involved is associated with the development, reliable delivery and use of water in communities and industries, for irrigated agriculture, energy production, and flood protection. In addition, water management, climate change, and its adaptation responses, such as increased water

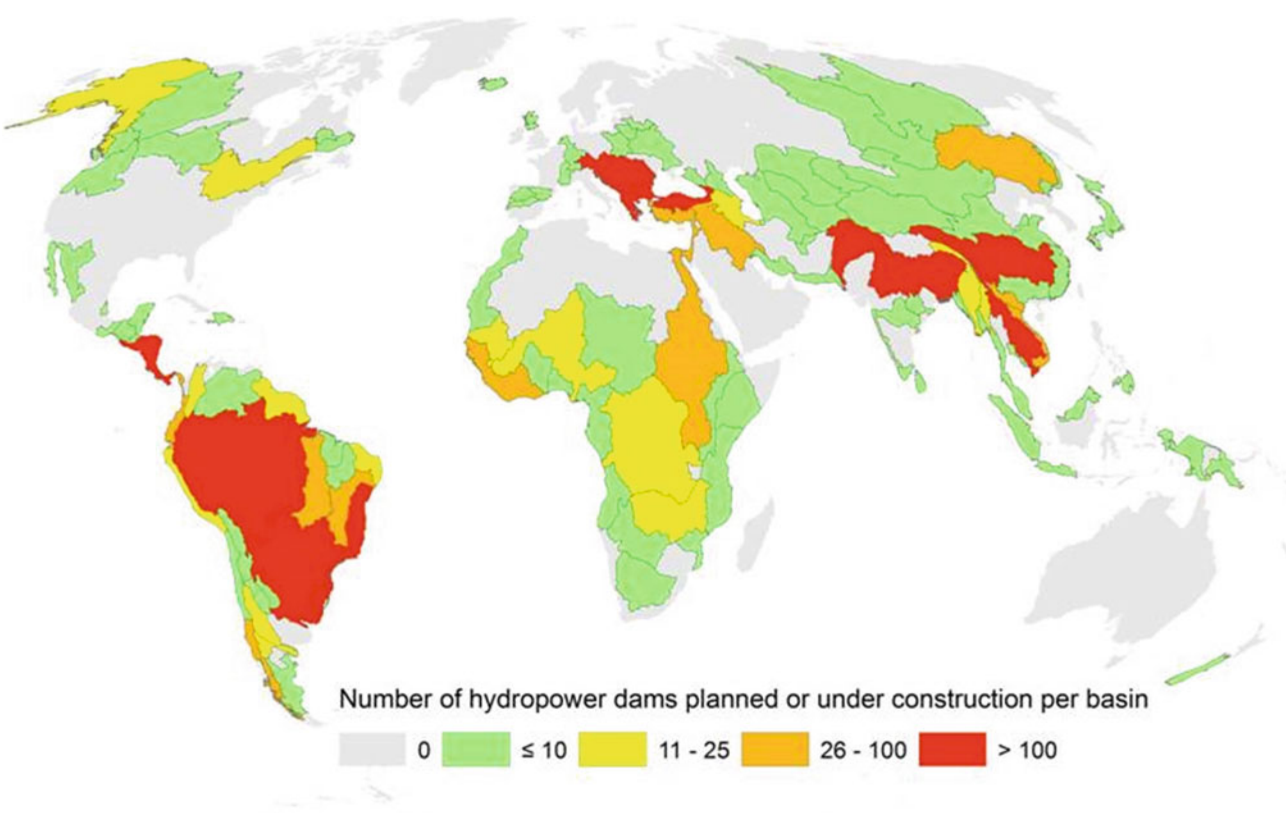

Fig. 11.2 Number of hydropower dams planned or under construction per basin. *Source* Zarfl et al. (2015)

storage, may impact the hydrological, thermal, nutrient and sediment regimes of water bodies.

The construction of dams has already profoundly altered the character and condition of rivers and other wetland ecosystems. By the end of the 20th Century, over 58,000 large dams (dam height: >15 m) had been constructed globally across more than 140 countries (WCD 2000).

About 20–25% of continental runoff and about 25–30% of the total global sediment flux in rivers are now stored in reservoirs (Vörösmarty et al. 2004; Vörösmarty et al. 2003). Global fragmentation of rivers by such hydrological alteration is well documented. Nilsson et al. (2005) showed that 59% of the world's large river systems (accounting for 60% of world runoff) were fragmented by flow regulation and channel fragmentation associated with dams. Lehner et al. (2011) report that 50% of the length of all rivers with discharge >1000 m^3 s^{-1} is impacted. They estimate that about 16.7 million reservoirs and impoundments larger than 0.01 ha surface area—with a combined storage capacity of 8070 km^3—may exist worldwide, increasing Earth's terrestrial surface water area by more than 305,000 km^2. Some 65% of continental discharge is considered under moderate to high threat in terms of human water security and biodiversity (Vörösmarty et al. 2010). Further major hydrological alteration, impacting wetland ecosystems, is on the horizon, as highlighted for the hydropower sector alone in Zarfl et al. (2015) and Opperman et al. (2015) as well as major interbasin water transfer projects (Shumilova et al. 2018).

Large dams in particular have severely disrupted the natural food production systems of rivers (e.g. fisheries, flood-recession agriculture), primarily by changing the natural flow regime and blocking the movement of fish and other biota. A diminished food security has placed downstream human populations and their livelihoods at considerable risk (Richter et al. 2010). Thus overstressed freshwater systems lack ecosystem services (ES) along their shores.

There are about 3,700 major hydropower dams either planned or under construction. These dams, if implemented, may almost double the total installed capacity from hydropower from currently 900 GW to more than 1600 GW (Zarfl et al. 2015). Hot spots of future dam construction include South America, Southeast Asia, including the Himalayas, Africa, the Balkans, Anatolia and the Caucasus regions. Many of the basins where such development is planned are also significant in terms of their conservation assets and ES values (Opperman et al. 2015).

More than half of all rivers globally are temporary, meaning that they fall dry at the surface for given periods of time; more permanent rivers are expected to turn into temporary rivers in the future due to climate change, over-exploitation and land-use alteration. The transformation of permanent to temporary waters fundamentally alters biodiversity and ecosystem processes. Flow intermittency per se is not necessarily a stressor along natural water courses (e.g. in semi-arid, Mediterranean, karstic or alpine areas); however, human-caused alteration of flow regimes is frequently associated with other stressors such as water pollution and species invasion (Acuna et al. 2014).

Climate change induced changes in precipitation will substantially alter important attributes of flow regimes in many rivers and wetlands, and increase impacts from human water use in developed river basins (Döll and Bunn 2014). Changes in flow regimes resulting from shifts in precipitation and evaporation patterns have already been documented locally, regionally and globally (Rosenzweig et al. 2008).

11.2.4 Modification (Degradation) of Aquatic Habitat

Habitat degradation is a universal stressor on all water bodies. For example, more than 50% of all wetlands have been lost worldwide (Finlayson and D'Cruz 2005). Large-scale losses of habitats are expected to continue, particularly in the Global South, as inland water systems are further modified to provide electricity, water for irrigation, drinking water, sanitation and other services.

Changes in land cover usually increase sedimentation, enrich nutrients, alter flow and lead to a decline of riparian areas (Allan 2004). Clearing of natural forests for agriculture and other land uses also impacts the hydrology, although interactions are complex and impacts are place-specific. In rivers, increased erosion following deforestation and other land use change may increase sediment, which again decrease light penetration, clog the river bed and disrupt the overall functioning of ecosystems. In small Amazonian streams, conversion of tropical forests into pasture has changed the biogeochemical and hydraulic characteristics of the system (Neill et al. 2006). In extreme cases whole mountaintops are removed for mining operations and the resulting dredge material is disposed in nearby valleys, burying entire streams (Palmer et al. 2010).

Subtle degradation of aquatic environments is common. For instance, removal of woody debris from rivers and lakeshores facilitates navigation and human recreation, but at the cost of habitat simplification. This can adversely affect populations of fish and other aquatic organisms.

11.2.5 Overexploitation

Overexploitation refers to both overstressing water bodies in their function to provide ES (such as fishing or absorption of water pollution), but also to excessive withdrawals and extraction of mineral resources. Overexploitation may affect ecological processes and biodiversity including evolutionary processes. Although it is difficult to determine the status of inland fisheries because of underreported catch data, there are strong indications that inland fisheries in most parts of the world are overexploited (Dugan et al. 2007; Kura et al. 2004). Overexploitation, for example, is the key driver for the global decline of freshwater megafauna including mega fishes (e.g., He et al. 2017).

11.2.6 Biological Water Pollution

Biological water pollution refers to invasive alien species and subspecies occurring outside of the range they occupy naturally or could not occupy without direct or indirect introduction, care, or even carelessness by humans. Although the majority of alien species cause no harm, some of them spread very rapidly and can harm biological diversity, human health, and/or economics and aesthetics.

Primary forms of biological pollution include deliberate introductions of species, aquaculture escapees, inter-basin water transfers, ballast water from vessels, canals, and releases from aquaria, gardens and bait buckets (Strayer 2010). Deliberate introductions occur for a variety of reasons—primary among these is the commercial or recreational harvest of the introduced species and biological control of other previously introduced species.

Species invasion may lead to faunal homogenization, alter ecosystem processes and, in some cases, cause the extinction of native species (Olden et al. 2008; Rahel 2000).

Beyond invasive species, the category of biological water pollution includes the occurrence of pathogens and parasites, threatening humans (Conn 2014) and aquatic species (Ashander et al. 2012; Meyer et al. 2015; Spikmans et al. 2013), and effects on the genetics of native species through escapees of captive bred stocks of e.g. fish (Baskett et al. 2013).

11.2.7 Chemical Water Pollution

Freshwater ecosystems suffer from the input of both nutrients and toxic chemicals due to human activities. Nutrient loading occurs as a consequence of transforming land cover from natural vegetation to highly productive farm fields, roads and cities. Moreover, both nutrients and other types of chemical pollution stems from human waste and untreated human wastewater. Most modern agriculture involves the application of large amounts of nitrogen and phosphorus. Emissions from cars, power plants and industry also contribute to nutrient loading. These emissions disperse in the atmosphere and long-distance atmospheric transport of nutrients has elevated inputs of nitrogen even in remote freshwater bodies that otherwise appear pristine. Near human population centres, phosphorus from wastewater requires societal investments in proper wastewater treatment technologies and control of inputs.

Harmful chemicals are also a widespread threat to human and natural uses of freshwaters. Contaminants such as pesticides, heavy metals, pharmaceuticals and organics can reduce water quality to the point where rivers and lakes can no longer support a full complement of species and can even become unsuitable as source for high quality water uses. For instance, acid rain arising from emissions of sulphur and nitrogen oxides was an acute problem in lakes and rivers of eastern North America and Europe until emissions controls became obligatory (Malmqvist and Rundle 2002). Highly acidic run-off continues to be problematic downstream of abandoned mine sites, making these streams uninhabitable for most species. A growing list of man-made chemicals used in industry and home products have been found in aquatic ecosystems, and scientists are still struggling to understand their prevalence and impact. Some of these disrupt the endocrine system of freshwater animals and people (Jobling et al. 1998; Mills and Chichester 2005); for instance, intersex fish possessing both male and female characteristics have been found in all nine of the large river basins sampled in the United States (Hinck et al. 2009). Much work remains to be done in order to be more certain about the consequences of even low concentrations of industrial chemicals that occur in many freshwaters.

Water quality is, moreover, expected to decline in some basins due to higher pollutant loads from heavy precipitation events, overflow of wastewater treatment plants during extreme rainfall and greater volume of withdrawal from low quality sources (Kundzewicz et al. 2008).

In recent decades, net-cage aquaculture has become one of the main patterns of the intensive fish culture in the lakes/reservoirs in several countries (i.e. Indonesia, China, Ethiopia and the Philippines). Net-cage aquaculture is considered one of the major stressors on lake water quality. Organic and nutrient loading from the excess feed and fish waste to the lakes has resulted in organic accumulation in the sediment and lake water quality deterioration and accelerated the process of lake eutrophication and toxic cyanobacterial bloom (Guo and Li 2003; Hallare et al. 2009).

11.2.8 Thermal Water Pollution

Temperature is a key environmental factor, as it influences the biology of every organism as well as all ecosystem processes. Most aquatic organisms are adapted to a specific temperature range. Beyond this range temperature becomes stressful and ultimately lethal. For example, the optimal temperature range for rainbow trout is between 13 and 15 °

C, with the lethal maximum of 24.3 °C (Bear et al. 2007). Climate change may exacerbate thermal pollution of freshwater bodies.

Thermal water pollution refers to an artificial increase or decrease in the temperature of a water body as a result of human activities (Kennedy 2004). Although enhanced water temperature can have beneficial aspects; altered water temperature and temperature regimes more often have a negative and long-lasting effect on freshwater ecosystems. Effects include lethal or sub-lethal effects of individual organisms and their development, adult migration, competition with non-native species (Riis et al. 2012), and the relative risk and severity of disease (Karvonen et al. 2010). Temperature also influences the capacity of water to hold dissolved oxygen (DO), which again affects aquatic organisms in various ways (Kennedy 2004). Specifically, in temperate lakes, thermal water pollution during winter was shown to be stored in the deep water column until the next winter. Accordingly, winter thermal water pollution can have a long-lasting negative effect on lake ecology (Kirillin et al. 2013). Moreover, increasing temperature may alter lake column circulation, thereby decreasing oxygen levels in the hypolimnic layer, stimulating the release of phosphorous and subsequent eutrophication.

Thermal water pollution is strongly associated with cooling water discharge, first and foremost from various types of power plants. Given the expected growth of energy demand on a global scale, thermal pollution will increasingly become a concern. As the temperature of water bodies should not exceed certain thresholds to remain supportive for aquatic life, it is frequently the case that power plants need to shut down or curtail their power generation during summer periods as well as in the light of the climate change driven increase in water temperature (van Vliet et al. 2012).

A less common form of thermal water pollution involves the release of cold water from reservoirs into warmer receiving water bodies. This occurs, for example, in Australia when cold water from reservoirs is released for irrigation purposes. If the water is released from the bottom of the reservoir, it can be considerably colder than the water in the receiving water body. The effects of cold-water pollution can be similar to that of warm-water pollution, but it has no negative impact on the water's DO holding capacity (Kennedy 2004).

Climate change induced air temperature shifts are altering surface water temperatures in many temperate lakes resulting in reduced periods of ice formation and the earlier onset and increased duration and stability of the thermocline during summer (Winder and Schindler 2004). These changes are projected to favour a shift in dominance to smaller phytoplankton and cyanobacteria (Settele et al. 2014). There is widespread evidence of rising temperatures (caused, at least partially by climate change) in streams and rivers over the past few decades, and this has been linked to shifts in invertebrate and fish community composition. These phenomena indicate how closely the different pressures and consequent stressors are intertwined.

11.2.9 Actions Needed to Revise the Trends of Deteriorating Freshwater Health

A sustained, global response is required to halt the ongoing loss of freshwater biodiversity and related ecosystem service and degradation of freshwater ecosystem health. In response, society must develop and implement strategies based on the best available scientific knowledge, to reduce threats in ways that both protect aquatic biodiversity and maintain human well-being within the coupled social-ecological systems (see Sect. 11.2.1).

The actions needed to counter these threats are in most cases obvious. For instance, providing adequate flow downstream of dams, or decommissioning (removal) of existing dams are relatively simple solutions to the suite of problems arising from damming rivers. However, resource limitations and conflicting human needs limit the range of feasible approaches, making it imperative to prioritize actions. Science-based, systematic approaches for conservation and restoration planning applied to freshwater ecosystems at national and regional levels have advanced greatly in recent years (Nel et al. 2009). However, further work is needed, particularly to guide prioritization at continental and global levels. Large-scale datasets on species, ecosystems, drivers and threats (i.e., Freshwater Ecoregions of the World,[3] DIVERSITAS,[4] Freshwater Information Platforms,[5] BioFresh,[6] GEOBON[7] and the IUCN Red List of Threatened Species[8]) are already supporting these goals. Concurrently these results can also contribute to minimize tradeoffs along the implementation of the SDGs.

Focusing on what has changed in the last few hundred years and simply trying to reverse these changes is unlikely to be productive or even possible. This is particularly pertinent in planning responses to climate change because it has the potential to completely alter the context within which near-natural systems will operate in the coming decades. Responding effectively to climate change in the context of freshwater conservation requires a shift in the human

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[3] http://www.worldwildlife.org/pages/freshwater-ecoregions-of-the-world–2.
[4] http://www.diversitas-international.org/.
[5] http://www.freshwaterplatform.eu/.
[6] http://project.freshwaterbiodiversity.eu/http://project.freshwaterbiodiversity.eu/.
[7] http://geobon.org/.
[8] http://www.iucnredlist.org/.

perception of natural systems and the actions that must be taken to conserve them. For example, as species' ranges shift due to a changing climate, it might be necessary for newly arriving species not to be classified as 'non-native and possibly invasive species', but as native species adjusting to a changing planet. New approaches to 'climate-aware' water management are required in many basins across the globe as are governance structures with sufficient capacity and authority to deliver that management (Matthews et al. 2009). Flexibility and adaptability, also in human endeavours, will be needed, as water managers will have to deal with ever greater climatic and eco-hydrological uncertainty (Matthews and Wickel 2009; Milly et al. 2008). There are several major approaches planned, beside the SDGs, such as the Green Deal and Nature-based Solutions (Pauleit et al. 2017), which must include a Blue Deal as well, the Rewildering Europe concept (Corlett 2016), or the One-Health approach (Dantas-Torres et al. 2012) to integrate human and ecosystem health, as actually manifested in the COVID-19 global crisis.

11.3 Water-Related Risks and Migration

11.3.1 Understanding the Interlinkages Between Water and Migration

Migration has historically been an important survival strategy adopted by people in response to water-related risks. Water scarcity and water related disasters have long been acknowledged as threats to livelihoods and prominent drivers for population movement throughout world history. However, addressing the relation between water and migration through the lens of climate change, mismanagement and conflicts is a recent perspective. Today's global environmental, economic and social challenges put pressure on livelihoods and intensify humanitarian needs worldwide. These emerging threats raise the number of people facing water risks, food insecurity and epidemics resulting in population mobility and forced displacement at national, regional and international levels. Dynamics of politics, economy, culture, and environment are deeply interconnected and it is this complexity that explains global migration today.

There has been a growing consensus on the complex but strong interlinkages between environmental challenges and human mobility, since the 1st Assessment Report of the Intergovernmental Panel on Climate Change (IPPC) in 1990, referred to migration as one of the most threatening short-term effects of climate change. IPCC listed loss of living resources like *water*, energy, food supply or employment affected by climate change among the major causes of migration (Tegart et al. 1990). Over the decades, there has been a growing concern in the international community about the need to understand, prevent and address climate change induced population movements. The first time that climate change induced displacement, migration and planned relocation were mentioned in an internationally negotiated document on climate change was in 2010 in the Cancun Adaptation Framework (CAF) as part of the Cancun COP 16. The CAF invited all parties to undertake *"measures to enhance understanding, coordination and cooperation with regard to climate change induced displacement, migration and planned relocation, where appropriate, at the national, regional and international levels."* (UNFCC 2010). The issue was highlighted in the 2015 Paris Agreement which calls upon parties to the Agreement to respect, promote and consider the rights of migrants and people in vulnerable situations (Paris Agreement et al. 2015). Moreover, a Task Force on displacement was initiated within the COP 21 to develop recommendations for integrated approaches to avert, minimize and address displacement related to the adverse impacts of climate change (Decision 1CP.21 2016).

The New York Declaration for Refugees and Migrants adopted by the UN General Assembly in 2016, addressed natural disasters and the adverse impacts of climate change among the various drivers that create and exacerbate migrant flows and cross-border displacement. A new dimension noted in the declaration was the necessity to support receiving countries to meet the immediate and ongoing needs including provision of assistance to protect the environment and strengthen infrastructure affected by large movements of refugees (UN General Assembly 2016).

The changing immigration patterns and the deepening interlinkages between environmental challenges including climate change and migration have led to the emergence of new concepts and descriptive terms. These concepts and terms are highly contested and subject of debate as migration, environment and climate terminology already have their own complexities. Migration is a broad term that encompasses a variety of human movements *"either across an international border or within a state whatever its length, composition and causes"* (IOM 2014). Migration generally refers to voluntary movements and migrants are assumed to have the ability to choose between options. Displacement, on the other hand, is the forced/involuntary removal of a person from his or her home region mainly for reasons such as armed conflict, civil unrest or natural catastrophes. Early conceptualizations of climate induced migration did not consider the differences between migration and displacement. Today with a more nuanced approach, these two concepts are distinguished in the context of slow-onset natural hazards, environmental degradation and the long-term impacts of climate change. Migration is now widely assumed as a conscious choice to *"avoid or adjust to* *deteriorating environmental conditions that could otherwise result in a humanitarian crisis and displacement in the future"* (The Nansen Initiative 2015).

Refugee status on the other hand, is a specific legal status for those forcibly displaced in the context of certain push factors (see Sect. 7.6). The 1951 Refugee Convention which is the main international legal instrument relating the status and rights of refugees defines refugee as someone "*who is outside the country of his nationality and is unable or unwilling to return to their country of origin owing to a well-founded fear of being persecuted for reasons of race, religion, nationality, membership of a particular social group, or political opinion"* (Convention relating to the Status of Refugees, Geneva, 28 July 1951). Environmental or climate change induced reasons however, do not fall within the criteria for refugee status according to the existing international refugee law. The term climate change refugee is avoided by the UNHCR. However, it is recognized by the UNHCR that, people displaced by a humanitarian crises linked to a mix of consequences of conflict, public disorder or climate change and seeking safety and assistance in another country, need to be ensured access to international protection (UNHCR 2017). In 2011, a new agenda for the international protection of cross-border displaced persons in the context of disasters and climate change who do not fall within the refugee category was developed through the Nansen Initiative. This state-led multi-stakeholder initiative built a knowledge base and created awareness on the topic. Instead of developing new legal instruments, the Nansen Initiative developed a set of recommendations and sought to address both the protection of people displaced across borders as well as the management of displacement risk in the context of disasters including those linked to water (The Nansen Initiative 2015).

The links between water and migration are also complex and not very well defined. Water-related challenges cannot be separated from general social, political, economic and environmental challenges causing migration, forced displacement or relocation. Influence of water-related changes on other drivers of human mobility should be addressed as it is difficult to identify water as the sole driver for migration (Black et al. 2011). As water-related challenges can induce internal and cross-border migration flows, mobility of people can also have impacts on water resources, water management practices and infrastructure in receiving regions and countries.

Between 2008 and 2014, an average of 22.5 million people were displaced each year by weather and climate-related hazards, some of whom crossed borders in order to reach protection and assistance in a new country (The Nansen Initiative 2015). Although there is available data on displacement due to natural hazards and weather extremes, there is a lack of quantitative data on movements associated with extreme climate events and slow on-set changes that happen on longer time scales (IDMC 2018). There is no universally accepted legal basis or specific definition for water-related migration. However, understanding the nature of migration from the specific perspective of water would help develop efficient adaptation strategies to manage risks and reduce water-related stress on both sending and receiving countries. The relation between water and migration needs to be addressed and treated as a matter of policy and operations including risk management, planning, humanitarian aid, and responsibility sharing and development cooperation at all levels (Warner et al. 2013).

11.3.2 Water-Related Drivers of Migration

In the general migration context, there are many economic, socio-political and environmental push and pull factors driving people to leave their area or country of origin (Table 11.2) (WEF 2017). Such drivers and their interconnectedness shape the nature of human mobility. Addressing drivers of migration including adverse effects of climate change and water-related challenges would help develop a sound understanding of the current global migration phenomenon, adaptation strategies and efficient policies in response to migration flows (Virupaksha et al. 2014).

These general drivers are deeply interconnected in complex ways in many of the migration flows (IOM Issue Brief 2017). Environmental drivers are the ones which have long been underestimated. However, it is no longer possible to neglect this fact, as climatic conditions and their impacts is expected to intensify in the future giving rise to sea levels, glacial melting, changes in rainfall patterns, droughts and floods that will affect four zones in particular: the Arctic, Africa, small islands, and Asian and African mega deltas (https://refugeesmigrants.un.org/sites/default/files/final_issue_brief_2.pdf; International Union for Conservation of Nature (IUCN) 2017; https://www.iucn.org/sites/dev/files/nbs_to_disasters_issues_brief_final.pdf; Klepp 2017; Brown 2008). Given the facts, migration may be the only option in certain parts of the world. Climate change affects availability and quality of water resources and these effects are directly and severely felt on society through challenges in critical sectors (e.g. agriculture, energy, etc.). Thus, environmental factors including water-related risks, which also trigger economic and social factors, are strong push factors, driving migration especially if communities or countries are not resilient to adverse effects of climate change. Another complexity is that, climate change and water challenges can trigger competition over the remaining resources or can indirectly increase risks of armed conflicts by *"amplifying well-documented drivers of these conflicts such as poverty, economic and political crisis"* (Wilk and Wittgren 2009).

Table 11.2 Drivers of migration

Push factors	Pull factors
Economic	
– Unemployment – Poverty – Unsustainable livelihood	– Employment opportunities – Better income
Socio-political	
– Political instability – Safety and security concerns – Conflicts or threats of a conflict – Slavery or forced labour – Inadequate services and infrastructure (health, education, water, energy etc.)	– Family reunification – Freedom – Integration and social cohesion – Food security – Accessible services
Environmental	
– Adverse effects of climate change (sudden-onset/slow-onset events) – Natural disasters	– Abundance of natural resources – Better climatic conditions

Water-related drivers of migration can be classified under 4 main groups (Table 11.3) (European Commission (EC) 2015).

Water-related challenges can be one driver among many and do not affect all members of the society equally. IPCC stresses in its 5th Report that *"rural areas are expected to experience major impacts on water availability and supply, food security, infrastructure and agricultural incomes, including shifts in the production areas of food and non-food crops around the world"* and this might lead to higher numbers of rural to urban migration or cross-border flows. Populations in developing countries with low income that lack resources for regular migration are also exposed to extreme weather events more than other populations according to the IPCC. Considering poor water, sanitation and health conditions in addition to human security threats due to the lack of resources for regular migration; women, children and elderly persons are the most vulnerable groups (Wilk and Wittgren 2009).

11.3.3 Migration and Its Water-Related Impacts in Sending and Receiving Communities/Countries

Scale, scope and duration of migration affects the needs of, and response by, sending and receiving communities and countries. In 2018, 18.8 million people were displaced by sudden-onset disasters within their country (IPCC 2014). Between 2008 and 2015, an average of 25.4 million per year were displaced by disasters within and across borders. The large majority (85%) of these were climate-related disasters (The Nansen Initiative 2015). Yet, displacement following sudden onset disasters are mostly temporary. As an example, in 2010, nine million people were displaced following the flood in Pakistan, but most returned home within a year (Naser 2012). On the other hand, at the end of 2017 there were 6.9 million refugees, whether it is climate-induced or not, in protracted situations between five and nine years, of which 5.4 million were Syrian refugees in Turkey, Jordan, Lebanon, Iraq and Egypt. Another fact is that, 95% of the total number of forcibly displaced people in the world are displaced in their respective region of origin (IDMC 2018). As an example, over 2.4 million people fleeing from war and famine in South Sudan sought asylum in the region, in neighboring countries like Uganda, Sudan, Ethiopia, Kenya and the Democratic Republic of the Congo which already face lack of access to water and sanitation (Wilkinson et al. 2016).

The rise in water demand induced by mass refugee influx threatens urban water infrastructures with disruption of services, reduced storage for potential emergencies, deteriorated water quality, and increased energy costs for operation and maintenance. Countries face significant and unequal responsibilities as the situation puts substantial pressure on water resources in host countries (UNHCR 2017). Investment requirements increase both for maintenance of the existing water infrastructure and construction of new infrastructure (Box 11.1). There is an increasing need for additional technical, financial, administrative and human capacity for better water planning and management in response to protracted refugee situations.

Box 11.1 Syrians under Temporary Protection in Turkey

The conflict in Syria resulted in one of the biggest humanitarian crises of the 21st century. Since the beginning of the conflict in 2011, there have been many papers arguing that growing poverty, mismanagement of natural resources, changing agriculture and irrigation policies including cancellation of state subsidies and the extreme drought experienced between 2006 and 2011 had a multiplier effect on social and economic instability in Syria (UNHCR). These factors had led to the failure of up to 75% of farms and forced migration of as many as 1.5 million Syrians from rural areas to urban centers where the civil unrest ignited in 2011 (Turkish Water Insitute (SUEN) 2017). Since then, millions of Syrians have fled their country. Turkey has been the primary receiver country worldwide by hosting over 3.5 million Syrian refugees (Châtel 2014). While only 5% of the Syrians are living in temporary shelter centers operated by state, the rest reside in cities, towns and villages throughout the country, concentrating in areas close to the Syrian border. Inevitably, smaller provinces have experienced sudden population booms that necessitated rapid response measures for enhancing water supply and sanitation services capacity. As a striking case, the population of the border province of Kilis doubled with over 120 000 refugees settled in the city center and surrounding villages. In several cities including Kilis demographic projections were updated and investment plans were modified to construct new water infrastructure such as dams, water and wastewater treatment plants, and water supply network. It is estimated that Turkey have spent nearly 31 billion USD in total for refugee needs, of which 5% was allocated for WASH related activities (https://www.washingtonpost.com/news/wonk/wp/2013/09/10/drought-helped-caused-syrias-war-will-climate-change-bring-more-likeit/?utm_term=.65e779e2c14e).

Human mobility can have two-sided effects on water related issues also in origin communities and countries. Lessened population in the country of origin may lead to diminishing payments for water services which may eventually result in less investments in the water sector. Besides, water management and projects may be disrupted in case water professionals leave their country of origin in times of conflict. Another adverse impact of out-migration is increasing water management burden for women, as male members of the family generally migrates first. On the other hand, returning migrants can put the knowledge and experience they gained, at the service of their home country. This is especially true when water professionals are provided with opportunities to work in the sector of their profession or when capacity building programmes on WASH are developed for migrants by the receiving country (UNHCR in Turkey).

11.3.4 Adaptation Strategies

No matter which key factors trigger displacement/migration, water resources management and governance are conducive both to stability and recovery, or else they act as risk multipliers, particularly in fragile systems. Unfortunately, water

Table 11.3 Water-related drivers of migration

Drivers		Results
Sudden-onset disasters (Weather extremes)	• Floods • Heat-waves • Storms	• Destroy settlements and infrastructure • Temporary local or cross-border population movement as a survival option
Slow-onset changes (Climate extremes)	• Changes in weather patterns: Rainfall variability • Longer-term drying trends and droughts • Desertification • Land degradation • Water shortages in response to increasing demand • Water stress and scarcity • Decrease in agricultural production • Food insecurity	• Negatively impacts sustainability of livelihoods, agricultural production, and economic life • Migration as a resilience strategy • Long term or permanent internal or cross-border migration/displacement
Conflicts triggered by depletion of water resources	• Competition over water resources, • Conflicts directly/indirectly triggered by water-related challenges	• Exacerbate challenges which contribute to conflicts • Damage water infrastructure • Waterborne epidemics • Forced displacement
Development projects	• Construction of dams, reservoirs, irrigation canals	• Planned relocation

challenges are distinctly intensifying in developing parts of the world due to poorly adapted governance structures that fail to address water-related problems, threatening environmental sustainability, even though technical solutions are readily available for implementation.

Effective water resources management and governance is not possible without incorporating short-term and long-term actions in planning. That said, short-term actions have the priority in ***fragile states*** to kick-off development and, in the case of conflicts, recovery. ***Least-developed and conflict countries*** are first and foremost vulnerable to waterborne diseases since water and sanitation facilities are either non-existent or have been destroyed. Therefore, disinfection should be given priority so people can have access to safe water in these areas. Subsequently, water supply and sewerage networks as well as treatment plants need to be constructed in order to ensure permanent potable water supply and sanitary conditions. The 2030 Agenda for Sustainable Development, in this regard, provides a robust framework to guide and monitor solutions for water-related challenges. The Sustainable Development Goals (SDGs) advocate starting the development/recovery by constructing/restoring basic water supply and sanitation services, and rehabilitation of irrigation schemes for agriculture, making sure that they are consistent with long-term strategies. In parallel, involving stakeholders from the outset is equally important, since information and knowledge exchange between citizens and state institutions enables trust building, and paves the way to equitable and sustainable water resources management (SUEN).

Refugee-hosting countries are fragile as well in terms of water risks, since most of them are developing countries. Mass migration causes a sudden increase in demand posing a major threat to the economic and environmental resilience of the countries. As in the case of Jordan, between 2011 and 2015, water demand rose 40% in Amman due to refugee influx from Syria, not to mention the pressure this situation created on sanitation services. Lebanon witnessed identical challenges following inflow of Syrian refugees, amplifying existing governance and infrastructure problems and forcing households to self-supply through private water services. Rise in water demand resulted in groundwater deterioration, depletion and salinization, while inadequate wastewater treatment worsened contamination of water bodies (UNHCR in Turkey).

As mentioned above, sudden population increase force many of the host cities to come up with fast solutions in order to meet the massive water demand that would perhaps be reached in a decade. In most cases, interprovincial and inter-institutional cooperation are required in addition to ithe mmense infrastructural investments undertaken by municipalities. UNHCR marks the ***importance of funds and financing***, and highlights the need for additional international funding as it will help states bolster adaptation, disaster preparedness and risk reduction as well as mitigate the impacts of climate change (World Economic Forum (WEF) 2017; UNHCR 2017; Jobbins et al. 2018).

Climate change is another factor exacerbating water related challenges not only in refugee sending/receiving countries, but also in various parts of the world vulnerable to extreme weather events. Even though climate change scenarios may have some uncertainties (w.r.t. timing, magnitude, etc.), decision makers should not abstain from taking necessary measures considering the extra burden climate change may bring to water resources management in near future. Development and adaptation policies need to focus on building resilience against climate change by incorporating strong strategies and capacity to manage its risks and impacts (World Economic Forum (WEF) 2017; https://refugeesmigrants.un.org/sites/default/files/final_issue_brief_2.pdf; International Union for Conservation of Nature (IUCN) 2017; UNHCR 2017; Food And Agriculture Organization Of The United Nations (FAO) 2018). To that end, effectiveness of ***no-regret and low-regret actions*** are asserted as they provide flexibility to future change. No-regret actions are defined as "measures/activities that bring net social and/or economic benefits, even if climate change does not occur (e.g. monitoring and early-warning systems for extreme weather events, water loss control, scaling back groundwater use to sustainable levels)". Low-regret actions, on the other hand, are relatively low-cost options (e.g. choosing wider dimensioned pipes in new drainage systems taking into account the impacts of climate change), but still effective in addressing the current adaptation deficit, building robustness and capacity (Jakobsson 2010; Intergovernmental Panel on Climate Change (IPCC) 2007).

Nature-based solutions can be listed as one of the coping mechanisms of no-/low-regret actions against climate change. Having emerged over the past decade, the aim of this concept is to "protect, sustainably manage, and restore natural or modified ecosystems, simultaneously providing human well-being and biodiversity benefits" by using nature itself. It offers functional options (e.g. restoring wetlands) to cope with the impacts of climate change that are cost-effective and complementary to conventional engineering measures (e.g. sea walls, storm channels) (Future Climate for Africa (NERC) 2015). Switzerland is one of the countries investing in nature-based solutions and spending around CHF 150 million per year in forest management. This figure is apparently 5–10 times less expensive if compared to engineered structures for reducing risks from landslides, rock falls and avalanches. The Government of Japan also invested in nature-based solutions and are specifically in the expansion of coastal forests as these proved to play a role in the reduction of tsunami impacts in

2011 (https://refugeesmigrants.un.org/sites/default/files/final_issue_brief_2.pdf). These examples accentuate the importance of ***adopting a proactive approach as it is cost-effective*** and efficient both in disaster risk prevention and for swift post-disaster recovery (Future Climate for Africa (NERC) 2015). It has also been reported that the least developed countries (LDCs) are in the process of preparing National Adaptation Programs for Action (NAPA) which is an initiative agreed under UNFCCC (Klepp 2017). Efficient execution of the above-mentioned solutions requires robust governance structures and financial possibilities, and a smooth way to adapt the strategies/options is their ***integration into existing policies*** instead of developing standalone adaptation plans (Jakobsson 2010).

Table 11.4, prepared by IPCC, points out a set of adaptation options/strategies against climate change including ways to support them with policies (Food And Agriculture Organization Of The United Nations (FAO 2018).

As shown in Table 11.4, the adaptation strategies/options ensuring resilience against disasters and climate change are, as a matter of fact, the main components of ***integrated water resources management (IWRM)***, advocating multi-layered integration and a holistic approach “to maximize the economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (SUEN; Intergovernmental Panel on Climate Change (IPCC) 2007; Future Climate for Africa (NERC) 2015). IWRM incorporates no-regret/low-regret solutions as well as participatory approach involving stakeholders such as users, service providers, planners, decision makers etc. at all levels.

One factor hindering desired results is top-down approach in management practices and policy development. In order to enhance the adaptation capacity of communities, tools need to be tailored according to local/regional vulnerabilities, making sure that stakeholders are engaged in the process, as they can better define the needs and monitor the results. ***Stakeholder engagement*** is strongly promoted also in IWRM, because it increases transparency and accountability in decision-making (Intergovernmental Panel on Climate Change (IPCC) 2007; United Nations Office for Disaster Risk Reduction (UNISDR): IWRM as a Tool for Adaptation to Climate Change, Training Course 2013).

Table 11.4 Adaptation strategies against climate change

Sector	Adaptation option/strategy	Underlying policy framework	Key constraints and opportunities to implementation (Normal font = constraints; italics = opportunities)
Water	Expanded rainwater harvesting; water storage and conservation techniques; water reuse; desalination; water-use and irrigation efficiency	National water policies and integrated water resources management; water-related hazards management	Financial, human resources and physical barriers *integrated water resources management synergies with other sectors*
Agriculture	Adjustment of planting dates and crop variety; crop relocation; improved land management, e.g. erosion control and soil protection through tree planting	R&D policies; institutional reform; land tenure and land reform; training; capacity building; crop insurance; financial incentives, e.g. subsidies and tax credits	Technological and financial constraints access to new varieties; markets *longer growing season in higher latitudes; revenues from ‘new’ products*
Infrastructure/settlement (including coastal zones)	Relocation; seawalls and storm surge barriers; dune reinforcement; land acquisition and creation of marshlands/wetlands as buffer against sea level rise and flooding; protection of existing natural barriers	Standards and regulations that integrate climate change considerations into design; land-use policies; building codes; insurance	Financial and technological barriers; availability of relocation space *integrated policies and management; synergies with sustainable development goals*

Nature-based solutions is one of the concepts that have emerged over the past decade and is one of the active components of IWRM. The aim of this concept is to "protect, sustainably manage, and restore natural or modified ecosystems, simultaneously providing human well-being and biodiversity benefits" by using nature itself. It offers functional options (e.g. restoring wetlands) to cope with the impacts of climate change that are cost-effective and complementary to conventional engineering measures (e.g. sea walls, storm channels) (Gumbo and Zaag 2001). Switzerland is one of the countries investing in nature-based solutions and spending around CHF 150 million per year in forest management. This figure is apparently 5–10 times less expensive if compared to engineered structures for reducing risks from landslides, rock falls and avalanches. The Government of Japan also invested in nature-based solutions and are specifically in the expansion of coastal forests as these proved to play a role in the reduction of tsunami impacts in 2011 (https://refugeesmigrants.un.org/sites/default/files/final_issue_brief_2.pdf). These examples accentuate the importance of adopting a ***proactive approach*** as it is cost-effective and efficient both in disaster risk prevention and for swift post-disaster recovery (Gumbo and Zaag 2001). Yet, efficient execution of the above-mentioned solutions requires robust governance structures and financial possibilities. A smooth way to adapt the strategies/options is their ***integration into existing policies*** instead of developing stand-alone adaptation plans (Jakobsson 2010). It has been reported that the least developed countries (LDCs) are in the process of preparing National Adaptation Programmes for Action (NAPA) which is an initiative agreed under UNFCCC (Klepp 2017). Nonetheless, the success of NAPAs depends on how well their content is linked with existing development plans of each country.

All in all, inclusiveness and viability of water resources management depend on how well infrastructural and institutional tools support each other. Hereof, the ***evidence-based approach*** offers a robust mechanism which is based on benchmarking, monitoring and evaluation, to identify the best measures to be implemented (SUEN; United Nations Office for Disaster Risk Reduction (UNISDR): IWRM as a Tool for Adaptation to Climate Change, Training Course 2013). Within this mechanism, the outcomes of chosen measures are monitored on a regular basis with the aim to identify the deficiencies so that final adjustments can be made.

11.3.5 Final Remarks

Challenges related to migration and water are interlinked in complex ways in the face of global climate change. As countries are continually being challenged to fulfill the expectations of growing populations, current management models may fall short in terms of cost effectiveness, technical performance, social equity and environmental sustainability, trying to respond to these challenges quickly. Migration and adverse effects of climate change including water-related risks may become an extra burden if these models are not flexible enough and fail to take necessary actions beforehand. These challenges may also trigger economic and social drivers of migration/displacement in different ways. There is an obvious need to understand these interlinkages to develop sufficient adaptation policies which will eventually benefit both sending and receiving communities/countries and migrants/refugees themselves. That said, the measures and tools needed to create resilient environment/societies and avoid conflicts are already available, yet there is still room for improvement in finding the best approaches to apply them in an effective way.

Urgent response capacity including technical knowledge and human capital is important to manage the impacts of the water-related migration. However, as countries face unequal responsibilities as a result of inflows of asylum seekers and migrants into their territories, the necessity of international burden-sharing, regional and global responsibilities arises. Thus, there is also a need to develop international capacity and global funding mechanisms on the basis of shared responsibilities in response to this global problem with many complexities.

11.4 Food Security, Nutrition, and Demographics

Food security, including nutrition (FSN) has been high on the agenda of nations, the international community, and the development community for many decades, though less so the water which is needed for food production. Drinking water and sanitation were rightly explicit priorities in the Millennium Development Goals (MDGs) at the turn of the century, whereas water for food was implicit in goals such as halving extreme poverty rates, reducing child mortality, halting the spread of HIV/AIDS and other diseases, and ensuring environmental sustainability.

Much has changed since the MDG period and lessons have been learned. Not least was the growing global concern over increasing demands for water in the face of rapidly expanding populations, agricultural intensification, urbanisation, increasing energy demand, industrial production, and the increasing number of extreme flood and drought events which are attributed to the changing climate. Water-related pollution has exacerbated the problem. Water uses create pollution and globally about 80% of the polluted water is still discharged into water bodies without treatment, reducing the availability of freshwater for others to use. It also contributes to the degradation of the water-related ecosystems on which future supplies depend. Together, over-exploitation and pollution now threaten to overwhelm and undermine nature's ability to provide key functions and services (United Nations 2018).

The 2030 Water Resources Group (2009) forecast that, "global water demand in 2030 will be close to double what it was in 2005—and 40 percent greater than the existing sustainable, reliable water supply" if the current practices in water-using sectors, particularly food value chain, urban water supply and energy, continue and the water demand by these sectors increase as projected. OECD (2012) estimated that global water demand could increase by 55% by 2050 if we continue using water at current rates. It was estimated (IFPRI nd) that if water demand continues to increase at current rates, by 2050 this will put at risk 45% of the global gross domestic product (GDP), 52% of the world's population and 40% of the global grain production. The World Economic Forum (WEF 2020) also put water among the top five greatest risks facing the world in terms of impact, for the twelfth consecutive year. The same report (WEF 2020) lists food crises also as a major global risk, and links it to water crises, biodiversity loss and ecosystem collapse, extreme weather events, and failure of climate change mitigation and adaptation.

The concerns over limited water resources are now well recognised in the United Nation's 2030 Agenda and particularly through Sustainable Development Goal 6, or SDG 6 ("Ensure availability and sustainable management of water and sanitation for all"). Known as the 'water goal'—this has focused attention beyond water supply and sanitation to include all aspects of the water cycle, including the important linkages between water and food production, eliminating hunger and poverty, improving peoples' nutrition and health, and in ensuring a healthy water-related environment which is so vital to sustaining all these activities.

For decades, water for producing food has been the 'proverbial elephant in the room'. Although globally, agriculture is the largest water consumer, this reality has been slow in rising-up the political agenda, largely because priority was, and still is, to secure water supply and sanitation services for everyone. Agriculture including irrigation, livestock, and aquaculture currently accounts for 69% of annual global water withdrawals, industry, including power generation, accounts for 19%, and households for 12% (FAO 2016).

At the level of the Sustainable Development Goals, SDG 6 links strongly to SDG 2 ("End hunger, achieve food security and improved nutrition and promote sustainable agriculture") and targets in other SDGs either directly or implicitly. A review of progress with SDG 6 (UN 2018) suggested that water for food, as the major consumer also offers opportunities for making significant water savings, thus making more water available for others to use. In this section we explore the links between water, food security, and nutrition, the complex mix of drivers, pressures, and stressors which determine future supply and demand for water for food, and agriculture's focus on producing more food with less water—"more crop per drop". We offer a number of policy options for achieving this. But we also explore changing attitudes from simply producing more food, towards making better use of the food we already produce, such as improving nutrition—"more nutrition per drop", changing diets, and avoiding the significant food waste and losses in the food supply chain from the farm to the markets and in the home that also wastes the resources used to produce the food.

11.4.1 Water for Producing Food

Agriculture consumes some 7,130 km^3 of freshwater annually. Some 20% of this is 'blue' water[9] withdrawn from rivers and groundwater and used mainly for irrigation and livestock farming, which accounts for over 40% of global food and fibre production (FAO 2016). Blue water has high opportunity costs and as such it is in demand for other purposes and is central to the debate over how best to use limited water resources. The bulk of water used for agriculture (80%) is 'green' water which supports rainfed farming and produces some 60% of the world's food and fibre (Falkenmark and Rockström 2004). Some farmers use blue water to supplement green water when rainfall is insufficient or unreliable as a means of ensuring a viable economic crop.

Across sub-Saharan Africa, south Asia and Latin America, agriculture, supported by millions of smallholder farmers, is often the mainstay of national economic growth. In sub-Saharan Africa most smallholders depend on the vagaries of sparse and unreliable seasonal rainfall. In Ethiopia and the United Republic of Tanzania, the rise and fall of annual GDP is closely correlated with rainfall, because their economies are strongly related to rainfed agriculture (WWAP 2009) Irrigation is an option for some, but most countries face a combination of high hydrological variability (which brings extremes of floods and droughts) and a lack of investment in water infrastructure and good water governance to exploit and effectively control and manage renewable water resources (UN 2018).

Most freshwater agricultural withdrawals are for irrigated farming, but this varies among regions depending on climate

[9]'Green' water comes from rainfall stored in the soil and transpired by crops. 'Blue' water is sourced from surface or groundwater and used for agriculture, industry and domestic purposes.

and the prominence of irrigated farming in the economy. Withdrawals vary regionally from more than 80% of total withdrawals in Africa and Asia to just over 20% in Europe (FAO 2016).

Although many farmers abstract water from rivers and lakes, the use of groundwater has grown significantly over the past 20 years. Currently, groundwater is the source for one third of water used for irrigation. It has become the main source of water for many millions of smallholder farmers, particularly across the poorest and driest regions of sub-Saharan Africa and south Asia. For many, shallow groundwater close to farmland, the availability of small affordable pumps, and local urban markets for fruit and vegetables has provided the ideal combination for sustaining rural livelihoods. But this success has come at a price, as groundwater in low-income countries is largely unregulated and often over-exploited which puts both resource and livelihoods at risk (GWP 2014).

Many water-stressed countries mitigate their food security risks by importing food from other countries. If food cannot be grown in-country because of insufficient water resources, it is imported from water-rich countries, and is known as 'virtual water trading'. However, this is an overly simplistic picture because many countries like to be self-sufficient in food and are reluctant to become dependent on imports. Some also grow high-value crops, such as Egypt (potatoes), Morocco (tomatoes and fruit), and Peru (asparagus) for international markets as a means of earning foreign exchange. Both issues can and do lead to over-exploitation of in-country water resources and unsustainable production.

Lundqvist and Unver (2018) estimated that average global per capita food supply increased by about 30% between 1961 and 2011 even though the global population doubled from approximately 3–7 billion people over the same period (Table 11.5). Consumptive use also increased and is expected to increase further by 2050. The figures indicate that more food is being produced with less water—'more crop per drop'. The production also includes more nutritious foods such as fruit and vegetables and meat products. But these are global estimates that may hide large variations among regions and countries.

However, global pressures to produce more food are changing. OECD-FAO (2018) in their agricultural outlook for 2018–2027 suggested that world agricultural markets are very different in 2018 than a decade ago with strong production growth and record levels for most commodities. Cereal stocks are at an all-time high as of 2018 with a marginal downward trend towards the end of the year (FAO 2019). But demand was slowing, particularly driven by China, and as such agricultural commodity prices were expected to remain low. Although weak demand growth was expected to persist up to 2027, pressures to produce 'more crop per drop' still remain as the demand for limited water resources continue to increase across all water using sectors. Lundqvist and Unver (2018) commented that food supply systems were shifting from insufficient production to issues that affect production such as water risks, global warming, and environmental consequences; and demand was concerned about food losses and waste and increasing nutrition and suggested that perhaps a focus on "more nutritious food consumed per drop" would be more apt.

11.4.2 Water and Food Security

Food insecurity[10] occurs when people lack secure access to enough safe and nutritious food for normal growth and development and an active and healthy life. World hunger is rising again, after a prolonged period of decline. Some 815 million people were undernourished in 2016, an increase from 777 million in 2015 (FAO 2017a, b). Most live in water scarce regions[11] where a lack of water availability for agriculture can slow down the achievement of SDG 2 which aims to end hunger, achieve food security and improve nutrition, and promote sustainable agriculture. Thus, water scarcity and food insecurity go hand in hand.

Sub-Saharan Africa experiences the highest level of food insecurity and also high levels of water scarcity, which affects almost 30% of the population. Other food-insecure regions include southern Asia (12.9%), northern Africa (12.2%) and western Asia (9.8%). Food insecurity has worsened in areas of conflict and fragility and is often compounded by extreme events of droughts or floods. In 2016, Yemen's economic crisis was further aggravated by natural hazards, including flooding caused by unusually high rains and tropical cyclones. Prolonged severe droughts in Aleppo, Idlib and Homs (in Syria) were drivers of conflict and migration. The El Niño phenomenon reinforced droughts in Burundi, Democratic Republic of the Congo, and Somalia (FAO 2017a, b).

Hunger and food security are intrinsically related. The global hunger index (GHI) (Fig. 11.3) describes the relative national progress on reducing hunger (increasing food security) over the 25 years from 1992 to 2017. Countries in green are high-achieving "frontier" countries. Countries in red are under-achieving and have made little progress on reducing hunger compared to other countries with similar levels in 1992.

[10]Defined as prevalence of moderate or severe food insecurity in the population, based on the food insecurity experience scale (United Nations, General Assembly 2017).

[11]Countries are considered water-stressed if they withdraw more than 25% of their renewable freshwater resources. They approach physical water scarcity when more than 60% is withdrawn, and face severe physical water scarcity when more than 75% is withdrawn (FAO 2016).

Table 11.5 Global trends in population growth, agricultural production, water use, and food supply. *Source* Lundqvist and Unver (2018)

Year	World population (billions)	Annual production (kg/person/year)	Consumptive water use* (litres/person/day)	Food supply (kcal/per person/day)
1961	3	1,002	2,280	2,194
2011	7.1	1,321	3,209	2,868
2050	9.8	1,450	3,760	3,000

11.4.3 Water and Nutrition

Malnutrition has traditionally been associated with developing countries with links to poverty and hunger, but it also affects wealthier countries as well. Lundqvist and Unver (2018) described the "triple burden of malnutrition" comprising undernutrition (access to too little food), overweight and obesity (excess food intake), and micro-nutrient deficiencies (unbalanced diets). Undernutrition is linked to hunger and poverty and mostly associated with developing countries. Globally the number of people affected has increased by 60 million as of 2019, following a steady decline through 2014 (Fig. 11.4). Preliminary projections suggest that the COVID-19 pandemic may have increased the global total by an additional 83 to 132 million people in 2020. Obesity is also increasing both among affluent and poor nations, with links to excess food intake, unbalanced diets, and social habits (WHO 2020). Nutrition and unbalanced diets now high on development agendas (FAO, 2017a, b; Pinstrup-Andersen, 2018). Malnutrition in all its facets, affects people's health and wellbeing, and puts a heavy burden on families, communities, and states (FAO et al. 2020). Globally, (Global Panel 2016) assessed the annual impact of malnutrition on public health and economic development at US$3.5 trillion. With the COVID-19 pandemic, malnutrition is increasing vulnerabilities and risk of dying, not only because of the increased susceptibility to the virus but also due to fact medical resources have to be directed towards caring for patients with COVID-19 (WHO 2020).

Lundqvist and Unver (2018) suggested a focus on "more nutrition per drop" that can complement the current drive towards producing "more crop per drop". Improving nutrition by eradicating hunger for some and encouraging sensible diets and reducing food intake for others are all key steps toward sustainable development (UN 2018).

11.4.4 Drivers and Pressures

Agriculture's share of global water withdrawals has decreased over past decades (Fig. 11.5) although overall consumption has increased. However, predicting future water demand at all levels, local, national and global, is fraught with difficulties. Planners face a complex and inter-connected mix of drivers and pressures. These include population growth; lifestyle changes and dietary preferences that are transforming our food and agricultural systems; and the challenges of expanding and intensifying irrigated and rainfed agriculture, livestock production, and aquaculture that bring new environmental externalities and impact water quality and quantity. The uncertainties of climate change will have major impacts on all aspects of the hydrological cycle and thus on our ability to produce food. Constraints to development and growth also come from thorny and persistent issues, such as weak human and institutional capacity and poor water governance in many developing countries and the challenges created by the 2030 agenda of leaving no-one behind.

11.4.4.1 Population Growth

Population will remain the main driver of consumption growth for most agricultural commodities, even though the rate of population growth is forecast to decline (OECD-FAO 2018). More people mean increased demand for food and more water needed across all sectors including agriculture. The global population has increased 4-fold over the last century, while water withdrawals increased 7-fold over the same period. Although world population was still growing linearly, and expected to reach over 9 billion by 2050, the rate of increase in water withdrawals has slowed down over the last few decades, particularly for agriculture (Fig. 11.5). Agriculture has intensified in recent years, and water productivity and crop production has increased to meet the food demands from a growing population with changing diets (Fig. 11.5).

Most population growth is expected in developing countries where water scarcity is greatest, and people are least able to cope. Populations are growing rapidly in Africa and Asia, and more people are migrating from rural areas into urban centres in search of better livelihoods. Africa's urban population is growing by approximately 4% annually and forecasts suggest that some 50% of the population or some 654 million people will be urban dwellers by 2030 (Jacobsen et al. 2013). This will impact food production among rural communities but may also benefit them as family members may have greater purchasing power to buy food and remit funds home.

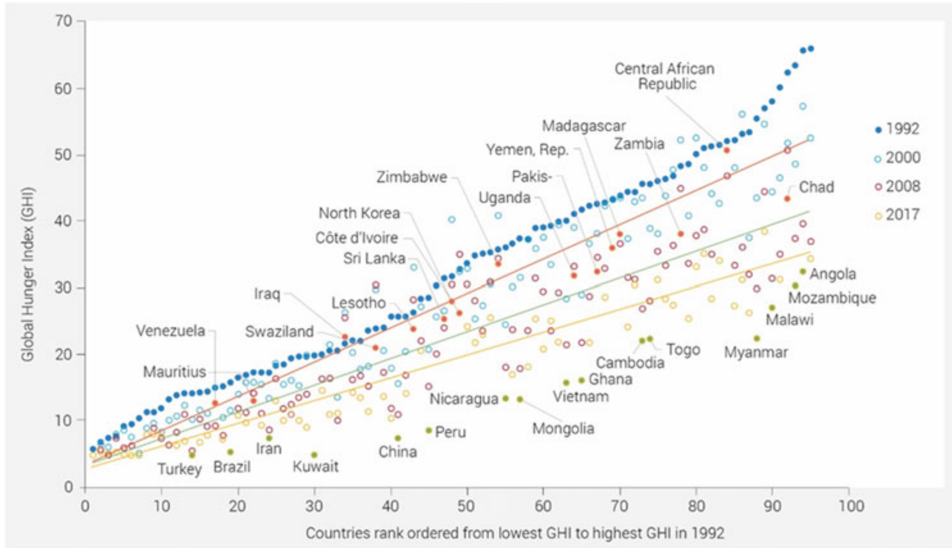


Fig. 11.3 Change in global hunger index (GHI) over time. *Source* UN, 2016 Data source: von Grebmer et al. (2015, 2017)

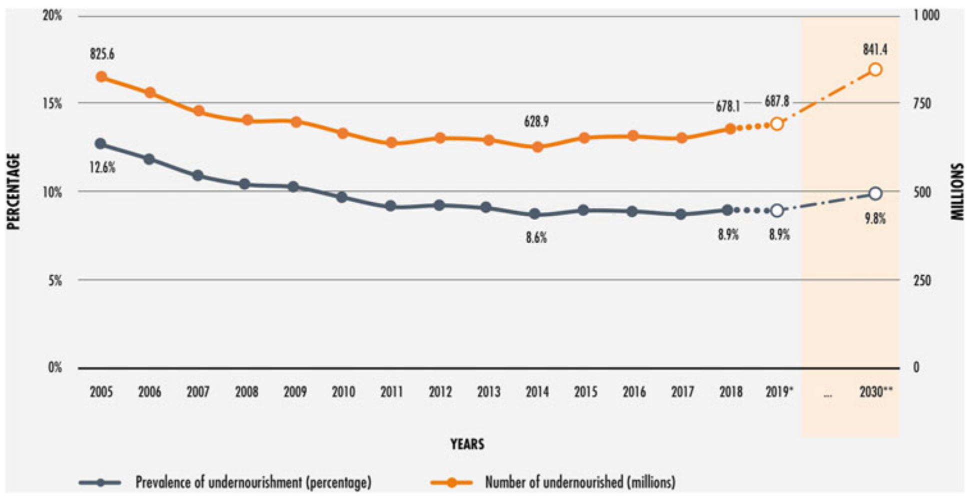


Fig. 11.4 Population undernourished and overweight/obese globally and in Ghana 1991–2012. *Source* trends of undernourished Population: FAO, IFAD And WFP (2015). Trends for obese and underweight population: IHME (2012)

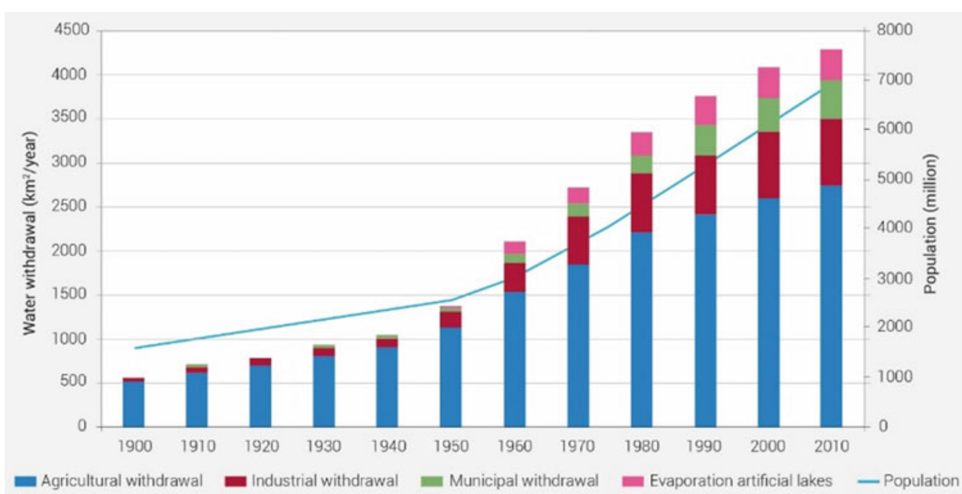


Fig. 11.5 Water withdrawal and global population over time in agriculture, industry and municipalities, 1900–2010. *Source* FAO (2016). Note: although all water withdrawals are aggregated, agriculture consumes water, whereas industry and municipalities only use water that is increasingly recycled for other purposes

Poverty remains highly concentrated in rural areas among people who earn meagre incomes mostly from agriculture. Population growth is expected to increase poverty and inequality among and within countries, between rich and poor, urban and rural populations, and among sociocultural environments. Gender inequality in agriculture stifles productivity growth and threatens food security. All influence access to food and water. Given persistent inequalities, current trends indicate that hunger will not be eradicated by 2030 (UN 2018).

11.4.4.2 Changing Diets

Over the past 40 years, nutrition has shifted from "traditional diets" (plant based, and high in cereal and fiber) towards "Western-style" diets (high-calorie foods, livestock products, processed foods, fast foods and bottled soft drinks), particularly in richer countries (UN 2018). All this has increased agricultural water consumption.

The average western style diet consumes about 3,600 litres per person per day, which is considerably more than most diets in developing countries, where the typical consumption is less than 1,000 litres per person per day.

FAO (2017a, b) reports that adult obesity is rising in all regions of the world at an accelerating rate, and North America and Europe far exceed other regions. People in these countries consume, per person, more meat, sugar, crop oils and animal fats, all of which have large water footprints. The suggested alternatives include eating more fruit and vegetables, which, in addition to the health benefits, consume less water.

11.4.4.3 Food Losses and Waste

Food losses and waste are also seen as wasting the water and other resources used in their production. Globally, around one-third of all food produced is lost or wasted along the food chain from production on the farm to consumption in the home (HLPE 2015) and accounts for an annual water wastage of 250km^3 (FAO 2013).

Annual estimates of food losses and waste are: 30% of cereals, 20% of dairy products, 35% of fish and seafood, 45% of fruits and vegetables, 20% of meat, 20% of oilseeds and pulses, and 45% of roots and tubers (FAO 2015a). Most food losses in developing countries occur on farms due to inadequate pest and disease control, and poor harvesting, storage, and transportation. Food waste occurs in rich countries along supply chains and rots in the bins of consumers and retailers (FAO n.d.b). All this is contradictory to both SDG 2 and SDG 12, which promote sustainable production and consumption. In the UK, 30% of food and drink are wasted representing about 243 litres of water per person per day (WRAP 2011).

Food losses highlight the inefficiencies in food chain systems, they constrain progress towards sustainable food systems, add to GHG emissions, increase economic losses for farmers and others along the food chain, and increase prices to consumers. Reducing food losses and waste can be an important part of climate change adaptation strategies.

11.4.4.4 Increasing Competition for Water

Agriculture must compete for water among many other demands. In many countries, demand for food is so great that agricultural systems are taking over water and land on such a scale that they are degrading and even destroying the natural water-related ecosystems on which future water resources depend (Fig. 11.6). In 2011, FAO reported that in some regions achievements in food production were associated with degrading land and water resources and causing related ecosystem goods and services to deteriorate. All this leads to a spiral of decline. Changes in land use reduce water availability and quality, and in turn water shortages and poor water quality affect our ability to produce more food from the land (Fig. 11.6).

11.4.4.5 Climate Change

Climate change will affect every aspect of food production in most regions, but particularly the low and middle-income countries, where millions depend on agriculture and are vulnerable to food insecurity. The main impacts of climate change will be experienced through changes in the hydrological cycle, such as overall water availability and water pollution, and the frequency of extreme weather events, like floods and droughts (Fig. 11.7), which drive food insecurity and malnutrition and can trigger or amplify conflict (Simmons 2013).

Declining and unpredictable rainfall is expected. Rising temperatures may adversely affect evapotranspiration, soil moisture, and crop yields and significantly expand land areas experiencing severe climate or soil constraints. Adopting sustainable agricultural and water management practices will be crucial to climate change adaptation efforts.

11.4.5 Policy Options and Concluding Remarks

Agriculture offers opportunities for significant water savings (UN 2018). Water consumed in producing food contributes to the challenges facing water resources planning and management, particularly in water stressed regions. But it is also increasingly viewed as part of the solution which can bring future demand and supply into line. Saving just a fraction of agricultural water withdrawals and making better use of rainfall could significantly alleviate water stress across

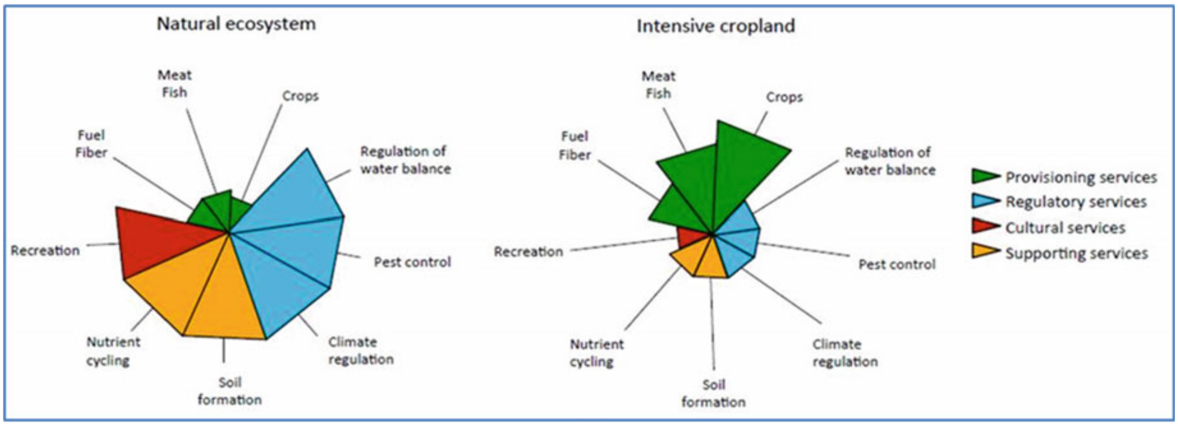


Fig. 11.6 Contrasting services provided by natural ecosystems and agricultural systems. *Source* Boelee (2011)

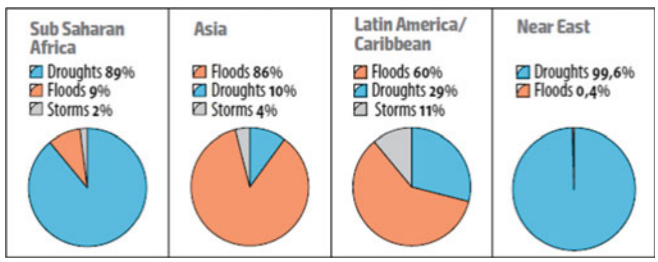


Fig. 11.7 Agricultural production losses following medium to large scale disasters in developing countries 2003–2013

all water and water-using sectors and improve both food and water security. In doing so it can strengthen economic development instead of constraining growth. Agricultural water savings can come in many forms, such as increasing productivity of food crops (more crop per drop), improving water management practices and technologies, implementing sustainable agricultural practices, growing fewer water-intensive crops in water-scarce regions, reducing food loss and waste, and importing food grown from water-rich countries (UN 2018).

Policy options include:

11.4.5.1 Improving Production and Productivity

Increasing water productivity is about growing 'more crop per drop'. For many countries, increasing productivity of rainfed farming is an important option before investing in irrigation. There are still significant differences in productivity between countries with high yields, such as in the European Union for example and the least developed countries (Fig. 11.8). Some 75% of anticipated additional food needs could be met by raising production in low-yielding agriculture (Molden 2007).

Irrigation has the potential to stabilize and substantially increase yields. Irrigation does have a reputation for inefficiency and wasting water. But in many cases, this is undeserved, and water that appears to be wasted by one farmer can either be captured and used by others, it can recharge groundwater, be used by trees and water-related ecosystems, or it can flow back into a water course to be used further downstream (FAO 2018).

Investing in irrigation can provide reliable water supplies for farmers where rainfall is sparse and unreliable. A 'twin-track' approach would make best use of available water resources and only then invest in developing new resources. Governments can provide incentives to promote the wise use of water and support technology uptake to improve water management practices.

The potential to increase the irrigated area is significant in most of humid and sub-humid sub-Saharan African, with the exception of Southern Africa, and Latin American countries, though less so in Asia and the Near East where most land suitable for irrigation is already being used.

11.4.5.2 Reducing Food Losses and Waste

SDG target 12.3 asks for 50% reduction in food losses and waste by 2030. This is an ambitious target with far reaching benefits for all. For smallholders in developing countries this can have a significant impact on their livelihoods given that they live on the margins of food insecurity (FAO 2011;

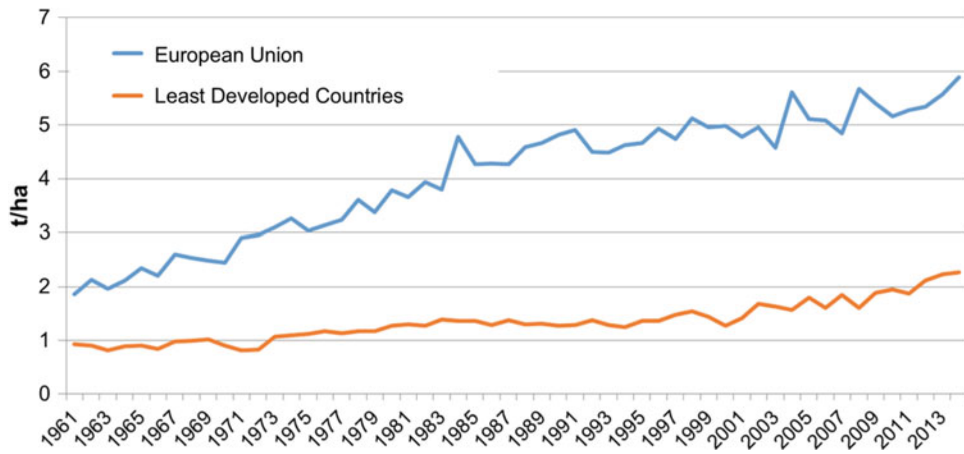


Fig. 11.8 Wheat yields in the EU and least developed countries. *Source* FAO stat

2015b). However, reducing food losses will require investment on farm, in 'last mile' infrastructure, storage, transport, and marketing facilities. For irrigated cropping significant water savings are possible.

11.4.5.3 Nutrition and Changing Life-Styles

Addressing the triple burden of malnutrition—undernourishment, obesity and overweight, and micronutrient deficiency—will be a major challenge for many countries in the decades ahead. A focus on "more nutrition per drop" should continue but so too should too should a focus on nutrition—"more calories per drop". This has important implications for human health and well-being as well as for food and water security. India for example is promoting millet in mid-day school meals to encourage farmers to grow it. Millet is known as "poor people's food" and as such there are few markets for this crop. But millet is high in nutrients compared to other staples, and thus brings benefits to child health and also improves the livelihoods of poor farmers. Thus, future strategies could focus on crops which have high nutritional value rather than on water productivity per se.

11.4.5.4 Protecting Marginalised Groups

In line with the 2030 Agenda of leaving no-one behind, it is essential to ensure that the poor and disadvantaged benefit from investment to provide access to water and affordable technologies that improve water productivity. The poor also need a voice in water management decision-making.

11.4.5.5 Taking a Basin Approach to Managing Water Resources

In water scarce areas, increasing water use in agriculture is likely to impact other water users both locally and downstream and so decisions must be taken on a catchment basis. This means taking an integrated water management approach (IWRM) to water planning management. This is in line with SDG 6.

11.4.5.6 Taking an Ecosystem-Based Approach to Agriculture and Water Management

Increasing agricultural productivity and yields, among other measures, is essential in order to meet the increasing food demand. Eco-system based or agroecological approaches that incorporate the ecosystems as an integral part of agriculture are fast becoming the new paradigm (FAO 2018). Through such approaches, intensification of agriculture can be materialized resulting in increased agricultural production to meet the demand for food, feed and fibre on the one hand and in enhanced resilience and sustainability of the landscapes, the biosphere, and the Earth system (Rockström et al. 2017), which, in turn, provides the framework for the management of land and water resources for sustainable intensification (FAO 2011).

Water is a critical resource for ensuring food security and adequate nutrition, particularly in water-scarce areas. At the turn of the century, concerns over having enough water resources to meet future demands were based on a 'business as usual' model and predicted significant short falls both water and food production in the future. But attitudes to water and food are now changing and opportunities for sustainable development exist if we are willing to change current paradigms, policies and lifestyles from the way we manage water resources to how much and what we eat.

11.5 Water and Health

Water and health is highly prominent in the global development agenda. Sustainable Development Goal (SDG) 3 aims at ensuring healthy lives and promoting well-being for all at all ages, and SDG 6 promotes to ensure that water and sanitation is available and managed sustainably for all (UN-ECOSOC 2017). The cross-cutting nature and high interdependency between water and health is depicted by the health-related targets 3.3 ("By 2030, end the epidemics of […] water-borne diseases and other communicable diseases") and 3.9 ("By 2030, substantially reduce the number of deaths and illnesses from […] water and soil pollution and contamination").

A safe, reliable, affordable, and easily accessible water supply is essential for good health. However, latest global statistics reveal that 2,1 billion people lack access to safe drinking water at home, and 4.5 billion people lack access to safely managed sanitation, with the largest share in sub-Saharan Africa (WHO and UNICEF 2017). It has been estimated that improvements in water resource management and the access to safe drinking water and sanitation could result in the reduction of almost 10% of the total burden of diseases worldwide (Prüss-Üstün et al. 2008).

The utilization of water for irrigation and for industry exerts pressure on water resources, which vary widely between countries and regions. In Europe, agriculture accounts for approximately 30% of total water abstraction and about 55% of consumptive water use (EEA and WHO 2002). Population distribution and density are key factors influencing the quantity of water resources, e.g. through increased local demand for water in areas of high population density and/or limited precipitation. Irrigation, drinking-water supply, industry, agriculture and leisure make competing demands on the quality and quantity of these resources, in addition to the need for water to maintain the aquatic ecosystem per se. It has been estimated that the most basic requirement for water is a minimum of 7.5 L per person per day for drinking, preparing food, and personal hygiene. In order to ensure also all personal hygiene, food hygiene, domestic cleaning, and laundry needs, at least 50 L per person per day is needed (Howard and Bartram 2003).

The key entry points to reduce health burden are linked to water availability and water quality. However, the management of water has become fragmented due of the existence of diverse stakeholders and regulatory frameworks (EEA and WHO 2002). This section elaborates the interlinkages between water and water-related human diseases classified according to different pathways of disease transmission, discusses the impact of pressures and stressors on freshwater ecosystems in the context of human health and provides entry points for ensuring health from the water management perspective.

11.5.1 Classification and Transmission of Water-Related Diseases

According to the World Health Organization (WHO) there are currently 26 water-related diseases listed (WHO 2018b), which are considered to be a diverse assemblage in terms of pathogens and transmission pathways: Hazards or pathogenic agents that cause water-related diseases include bacteria, viruses, protozoa, helminthes, chemicals and personal physical factors that may originate from human or animal excreta, industrial operations or be parts of natural or disturbed ecosystems (Bartram and Hunter 2015). The infection modes include ingestion, but also inhalation/aspiration, wounds and perforation of mucous membranes and even water contact with the intact skin (Bartram and Hunter 2015). Due to the fact that there are different routes of transmitting pathogens from water to humans and to become more precise in predicting effects of changes in water supply, water-related diseases have been originally classified by White et al. (1972, 2002) into (i) water-borne, (ii) water-washed, (iii) water-based, and (iv) water-related vector-borne diseases (Table 11.6). This so-called "Bradley Classification" is still the most popular classification of water-related diseases (Hunter et al. 2010). The understanding of how water is contaminated and how water-related pathogenic agents are transmitted and cause health impacts is essential to consider human health as part of an integrated water resources management (IWRM) and reduce the prevalence of and protect communities from water-related diseases. In addition to this more general classification along transmission routes, the disease life cycle and the exact role of water can be very specific for individual diseases and needs to be reflected in case of controlling specific water-related disease outbreaks. In the following paragraphs, the specificities of transmission routes and control measures with regard to water-related diseases will be explained in more detail in reflection of the most recent interpretation of this classification scheme by Bartram and Hunter (2015) (Table 11.6).

Water-borne diseases have been classified as "where water acts as passive vehicle for the infecting agent" (White et al. 1972: p. 162) and are transmitted following the faecal-oral route, where pathogens are contaminating water, which is consumed and ingested by humans. Thus, water-borne diseases are fundamentally concerned with water quality and safety (Bartram and Hunter 2015). Following the original classification, the source of water contamination originates from human and/or animal faeces containing pathogenic bacteria, viruses or protozoans.

Table 11.6 "Bradley classification" of water-related diseases with the description of the respective transmission routes from water to humans and example diseases of each category. *Sources* Adapted from White et al. (1972, 2002), Hunter et al. (2010) and Bartram and Hunter (2015)

Category of water-related disease	Description of transmission route	Example diseases	Entry points for water management and disease control
Water-borne diseases	Enteric infections spread through faecal contamination of drinking water	Diarrhea, Typhoid, Campylobacteriosis, Cholera, etc.	Improve water quality and avoid the contamination of drinking water with faeces
Water-washed diseases	Skin and eye infections that spread in communities with insufficient water for personal hygiene	Trachoma, Scabies, Shigella	Increase water accessibility and reliability Awareness raising to improve practices for personal hygiene
Water-based diseases	Infections transmitted through an aquatic invertebrate organism or eating insufficiently cooked aquatic species	Schistosomiasis, Dracunculiasis	Control snail populations, prevent unprotected water contact in case of parasite-infested water Reduce surface water contamination
Water-related vector-borne diseases	Diseases transmitted by insects that depend on water for their propagation	Malaria, Onchocerciasis, Trypanosomiasis	Destroy breeding sites Use of mosquito nets and protection
Additional classes			
Aerosol-transmitted diseases (Bradley 2009)	Diseases transmitted by inhaling aerosols	Legionallosis	Maintenance of building water systems
Engineered water system associated (Bartram and Hunter 2015)	Pathogens inhaled, ingested, contacted	Legionallosis, Mycobacterium avium complex (*MAC*), Pseudomonas infection	Maintenance of water infrastructure

However, since then increased attention has also been paid to chemical exposure as reflected in the consecutive editions of the WHO Guidelines for Drinking-Water Quality (WHO 1976, 1984, 1993, 2004, 2011). Most relevant from a global perspective is fluoride (Edmunds and Smedley 2013), arsenic (Ng et al. 2003) and possibly lead in drinking water, however, strongly depending on industrial processes, agricultural practices, geology, water treatment and distribution methods in the respective local or national context (Bartram and Hunter 2015). The most important water-borne disease with 4% of total deaths and 5% of disability adjusted live years (DALY) is diarrhea (WHO 2018c). Diarrhea is categorized as a disease per se (WHO 2018c), however, it is at the same time the key symptom of most other water-borne diseases, such as Cholera, Campylobacteriosis, and infections with other pathogens, such as E. coli, Norovirus, Cryptosporidium, etc.

Transmission of water-borne diseases can be prevented by assuring access to a sufficient quantity of safe and disinfected drinking water and access to improved sanitation. In this regards, the water, sanitation and hygiene (WASH) concept, which is a key element of public health programs within international development and the focus of SDG 6, provides guidelines for intervention measures to prevent water contamination and transmission of water-borne diseases (UNHCR 2018). An important effort to reduce water-borne disease prevalence is preventing open defecation through an increased coverage of safe sanitation (e.g. clean and fly-proof latrines considering minimum safe distances from drinking water reservoirs) and management of livestock excreta. However, the great majority of the pathogenic agents leading to water-borne diseases can also be transmitted by other means, all leading to ingestion. As such it overlaps very strongly with the class of water-washed diseases, where hygiene, and especially hand washing at critical times, is an important preventive measure as also reflected in the water-washed class of water-related diseases in the next section (Bartram and Hunter 2015).

Water-washed diseases are resulting from human exposure to pathogens due to poor personal or domestic hygiene with transmission following a person-to-person or fecal-oral mechanism. Originally classified as "infections whose incidence or severity can be reduced by augmenting the availability of water without improving its quality" (White et al. 1972: p. 162), the role of water is rather to prevent disease transmission than to serve as vehicle for the carriage of pathogens (Bartram and Hunter 2015). For the case of water-washed diseases, water serves both as a vehicle for the pathogenic agents but is necessary for adequate personal and food hygiene. Water-washed diseases are for example Trachoma (Chlamydia trachomatis), skin sepsis (diverse bacterial causes) and yaws (Treponema pertenue) (Bartram and Hunter 2015).

Water-washed diseases can be prevented by increasing the quantity of water available to populations and effectively promoting improved hygiene. Transmission has been reduced by increasing the availability and volume of water and providing soap in addition to facilities for bathing and laundering of bedding and clothes. Quality of water is relatively unimportant (Macy and Quick 2010). However, a meta analytical review of Freeman et al. (2014) resulted that only 19% of the world population washes their hands with soap after contact with excreta. However, it has been shown that the effect of handwashing with soap contributed highest with an average of 44% to the reduction of diarrheal disease morbidity compared to providing treated water alone without supporting hygiene promotion activities (UNHCR 2018). Despite water quantity is more relevant than water quality to reduced water-washed diseases, washing food with contaminated water and consuming this without further processing can result in (food- or) water-borne diseases, which illustrates once more the close overlap between water-borne and water-washed diseases (UNHCR 2018).

Water-based disease transmission is classified as such if a "necessary part of the life cycle of the infecting agent takes place in an aquatic animal" (White et al. 1972: p. 162). Human infection occurs if the pathogen is then either penetrating through the intact skin of a human in the water body (example: Schistosomiasis) or ingested by drinking infested water (example: Guinea Worm—Dracunculiasis). The example of Dracunculiasis highlights once more how difficult it is to classify water-related diseases and how complex individual disease transmission cycles are. The Guinea Worm larvae has its habitat in a water body, however, it can only be infective for humans, if the larvae has been ingested by species of crustacean, cyclops or water fleas, where they further develop to an infective larval stage. The human infection occurs, when water contaminated with larvae infested cyclops is ingested and the fully developed larvae released from the dissolved cyclops in the intestinal tract of the human. Thus, infection with Dracunculiasis therefore overlaps between the classes of water-based and water-borne diseases.

Water-based disease transmission can be prevented by eliminating contact with infested water, controlling the populations of the intermediate hosts in water, and reducing fecal contamination of surface waters by human waste for the example of Schistosomiasis. Some examples would be to apply protection measures (e.g. waterproof boots or gloves) to avoid contact with infested water (e.g. during rice harvest), to improve access to safe sanitation and avoid contamination of the water body, to treat surface waters with molluscicides, or drinking water in case of Dracunculiasis, and most importantly to educate the population concerning the risks of consuming or bathing in contaminated waters.

Water-related vector-borne diseases are infections that are "spread by insects that breed in water or bite near it" (White et al. 1972: p. 162). In contrast to water-based diseases, the pathogenic agent of water-related vector-borne diseases has itself no relationship with water, but it is rather determined by the insect vector. The disease is spread from person to person via biting mosquitoes, which have different habitat preferences, some preferring stagnant polluted waters and others preferring clean, fast moving waters. From a global perspective, Malaria is the most important water-related vector-borne disease, however, there are many more relevant diseases in this class (e.g. Yellow Fever, Dengue Fever, Zika). An example for a disease vector, which is found near rivers but does not breed in water is the Tsetse fly, which transmits the sleeping sickness (Trypanosomiasis).

Prevention strategies of water-related vector-borne diseases include (i) the reduction of the insect vector load through eliminating insect breeding sites, residual spraying or fogging with insecticide, and (ii) the reduction of human exposure to insects or pathogens through using insecticide treated bed nets, case treatment, and prophylaxis (including immunization).

As already suggested by Bradley (2009) and further complemented by Bartram and Hunter (2015), an additional class to accommodate **aerosol-transmitted diseases** is needed to complement the original classification of water-related diseases. The principal hazard of concern is the bacterium Legionella, which multiplies in biofilms within engineered water systems (e.g. plumbing, evaporative cooling), where nutrients and temperature conditions support their growth. The proposed class of Bartram and Hunter (2015) on **engineered water system** associated diseases highlights the endeavor to consider the entry points of water resource management for disease prevention directly in the classification scheme.

There have been several suggestions to improve the original "Bradley classification" of White et al. (1972), but none has gained as much recognition as the original system (Hunter et al. 2010). As partly addressed above, one perceived weakness of Bradley's classification is the non-exclusive nature of the individual classes, where many diseases can be both water-borne and water-washed or overlap between water-based and water-borne. Another example for water-related diseases that are not yet considered by the above classification are health impacts following transportation of heavy water containers over long distances, which is part of the every-day live of women and children in developing countries (Hunter et al. 2010). Nevertheless, this classification focuses mainly on the disease transmission routes, which needs to be in the center in order to highlight the entry points for health consideration from the water resource management perspective.

11.5.2 Impact of Water-Related Pressures and Stressors on Human Health

As outlined in Sect. 11.2 ("Pressures and stressors of freshwater ecosystems"), multiple pressures and stressors of freshwater ecosystems can be distinguished and their interrelation specified. The classification of water-related diseases (Sect. 11.5.1) already points out that some of these pressures and stressors are closely related to health impacts. In the following paragraph, the most essential health impacts from water-related pressures and stressors will be discussed.

There are several pressures and stressors that deteriorate the water quality of freshwater ecosystems and lead to severe impacts on human health (UNEP GEMS 2008). Water discharge can pollute freshwater ecosystems and cause health impacts depending on the pollutant source and type. Schwarzenbach et al. (2010) conducted a review on global water pollution and impacts on human health, where they summarize and discuss the main groups of aquatic contaminants, their effects on human health, and approaches to mitigate pollution of freshwater resources. The pressure of water discharge can then lead to several stressors impacting human health. One example for a stressor that leads to long-term health impacts are antibiotics, which are one of the most important groups of pharmaceuticals, but there is growing evidence that wastewater effluents and natural freshwater environments are enriched with antibiotics, antibiotic resistant bacteria, and antibiotic resistant genes, which could serve as a contributing factor to growing rates of antibiotic resistance to human infection (Allen et al. 2010; Martínez 2008; Pruden 2014). Release of residual antibiotics from e.g. aquaculture (Cabello 2006; Heuer et al. 2018) and many other sources (see Pruden 2014), is of particular concern as this elevates levels of resistance in native bacteria. Pruden et al. (2013) conducted a review and provides several management options to reduce the release of antibiotics and antibiotic-resistant bacteria from agricultural sources, aquaculture and domestic, hospital and industrial wastewater.

With regard to **biomass extraction**, declining numbers of fish is the cause of malnutrition especially in the low-latitudes developing nations, where human nutrition is most dependent on wild fish and where fisheries are most at risk from illegal fishing, weak governance, poor knowledge of stock status, population pressures or climate change impacts (Golden 2016). At the same time, intense fish production using aquaculture practices to satisfy the high demand of fish are causing health risks due to elevated levels of antibiotic residues, persistent organic pollutants, metals, parasites, and viruses in fish (Sapkota et al. 2015).

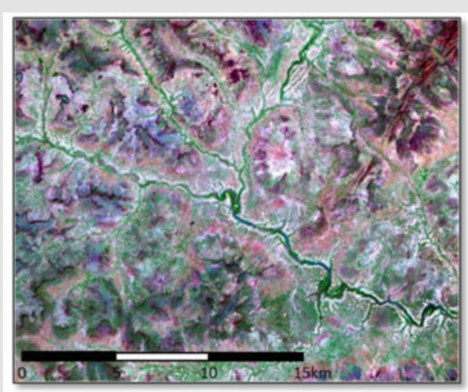
In the context of **mineral extraction**, mercury (Hg) is used in gold mining to extract gold from ore by forming "amalgam". Freshwater ecosystems are heavily affected by gold mining due to the heavy use of water when processing ore and due to water contamination with toxic discharged mining waste (see Fig. 11.9). The health impacts due to gold mining and exposure to mercury in the environment, mainly through contaminated water, resulted that gold-mining communities have to deal with kidney dysfunctions, cancers, neurological disorders and symptoms, as well as autoimmune dysfunctions (Emmanuel et al. 2018; Gibb and Leary 2014).

Direct health impacts due to **hydropower generation** and dam construction fall into three categories: population displacement, infectious disease risk, and disaster risk related to dam failures (Smith et al. 2013). A very prominent example is the construction of China's Three Gorges Dam, where at least 1.3 Million people were displaced (Hwang et al. 2011). Social and health impacts of dam construction and resulting displacement are impoverishment, collapse of social support networks, homelessness, unemployment, and direct health impacts such as depression and poor self-rated health (Hwang et al. 2007; Smith et al. 2013). The dam construction for generating hydropower is resulting in the alteration of the water flow and modifies the original aquatic habitat, both considered as stressors in this book. Many diseases classified as water-based or water-related vector-borne diseases are susceptible to such habitat modification and changes in water flow velocity. Besides multiple vector-borne diseases, one very prominent example is the water-based disease schistosomiasis, which is strongly related to the development of water resource projects (Steinmann et al. 2006). More details can be seen in Box 11.2.

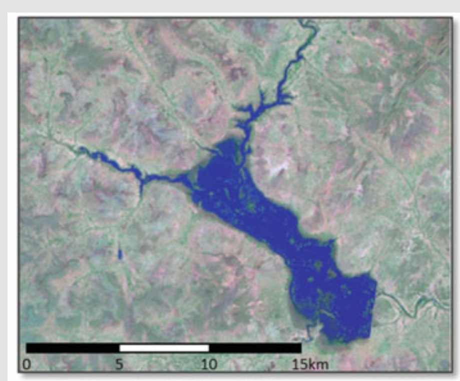
Fig. 11.9 Birim River in southern Ghana, which is heavily polluted from upstream gold mining activities. *Source* author

Box 11.2: Example of the modification of a natural river to a dam lake for hydropower generation in Burkina Faso

A: Remote sensing image from the Sourou region, Burkina Faso, taken in January 1986 showing the natural flow of the river



B: Remote sensing image from the Sourou region, Burkina Faso, taken in January 2010 showing the transformation of the natural river to a dam lake



Schistosomiasis is a parasitic disease in humans caused by blood flukes of the genus Schistosoma. The transmission cycle of the disease from human to human requires the parasite to meet specific snails as an intermediate host. These snails release the parasite in a development stage where it can infect humans within an aquatic environment. Schistosomiasis is a typical disease of poverty (WHO 2018a) that is widespread where access to clean water and basic sanitation is lacking, hygiene is at a sub-standard level and health infrastructure is weak or non-existent (Bruun and Aagaard-Hansen 2008; King 2010; Utzinger et al. 2009, 2011). In endemic parts of the world, the prevalence of schistosomiasis is intimately linked with water resources development projects and irrigated agriculture (Hunter et al. 1993; Steinmann et al. 2006). The modification of flowing hydrological regimes to stagnant water bodies enabled the spreading of the disease to previously non-endemic areas (Dianou et al. 2003; Fenwick 2006). The panel A shows the natural river flow in the Sourou region of Burkina Faso illustrated by a remote sensing Landsat image, and panel B illustrates the same region more than 20 years later and highlights very well the modification of the aquatic habitat due to the construction of a dam lake. The construction of this reservoir has caused an increase of schistosomiasis prevalence from 8% before the construction to 69% after the construction of the dam lake as a consequence of the reduction of water flow velocity, which turned the river into a suitable, large-scale habitat for parasites and snails to proliferate (Dianou et al. 2003). This is one example of a trend, which is expected to further exacerbate due to climate change and an increasing pressure of humans on environmental resources in the future (Utzinger et al. 2011; Zhou et al. 2008).

The pressure climate variability and change is impacting human health in a multifaceted way: Causal pathways of primary order are e.g. direct consequences from heat waves or extreme weather events, second order causal pathways are changes in biophysical and ecological processes such as water flows and consecutive impacts due to the emergence of infectious disease vectors, whereas effects considered as tertiary order are more diffuse, such as mental health problems due to displacement, yield losses or conflicts on limited water resources (McMichael 2013). Patz et al. (2005) assessed the impact of climate change on human health and attributed climate fluctuations to many prevalent human diseases, such as cardiovascular diseases, respiratory illnesses due to heatwaves, altered transmission of infectious diseases such as malaria or dengue fever, as well as diseases due to water scarcity (e.g. diarrhea) or crop failures (malnutrition).

The above mentioned examples of health impacts demonstrate that there is a very close interlinkage between pressures and stressors and how they impact human health. As the pressures result in stressors and then into health impacts, it is recommended to consider human health impacts in water management at the root-causes, the pressures. In the following section, general recommendations on how to consider human health in water management will be provided.

11.5.3 Entry Points for Water Management to Consider Human Health

The United Nations Economic Commission of Europe (UNECE) has negotiated the "Protocol on Water and Health" in 1999 to promote the protection of human health and well-being by better water management including the protection of water ecosystems, and by preventing, controlling and reducing water-related diseases (UNECE 1999). The Protocol is the first international agreement of its kind adopted specifically to attain an adequate supply of safe drinking water and adequate sanitation for everyone, and effectively protect water used as a source of drinking water. As a result of this protocol, Parties are required to establish targets to ensure quality of drinking water and discharges and to reduce outbreaks and the incidence of water-related diseases. To achieve this, guidelines are to be developed on country and/or catchment level.

The following six factors should summarize the key determinants of how water supply can maintain good health effectively (Hunter et al. 2010):

1. The quality of the water relates to pathogens and chemical constituents in water that can give rise to both diarrheal and non-diarrheal diseases.
2. The quantity of water available and used is largely determined by (a) the distance of carry involved, where water has to be transported (e.g. on the heads or backs of children and women), and (b) the wealth of the user.
3. Access to water may be primarily a matter of physical distance or climb, but it may have socio-economic and/or cultural dimensions if certain social groups are denied access to particular water sources through cost or culture.
4. The reliability of both unimproved and improved water supplies (e.g. supply only for a few hours per day or few days per week).
5. The cost of water to the user. This is represented by the cash tariff that is paid to a utility or provider or, in the case of unimproved water supplies, by the time and health penalty paid by the user.
6. The ease of management for the end user (e.g. paying tariff in urban utility-managed supplies versus

self-operation, maintenance and management in rural settings of developing countries).

Besides ensuring access to water and sanitation in general, the overall aim should be to leave no one behind and take into consideration that water and health is closely linked and the most vulnerable population is lacking access to safe water and sanitation and therefore at the same point highly exposed to water-related diseases. At the same time, water management is facing major challenges due to increasing uncertainties caused by global change and by fast changing socio-economic boundary conditions, which implies a paradigm shift from prediction and control to management as learning approach (Pahl-Wostl 2007).

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Léna Salamé graduated from the Sorbonne University in Paris as a lawyer in international public law. She specialized in conflict management and mediation, at a Harvard-MIT-Tufts joint programme and MWI, Boston, respectively. She served in the United Nations' system for 17 years as the strategic and operational coordinator of its programme on water conflict and cooperation.

Léna conceived around a 100 training courses and capacity building activities on international law, conflict management, confidence building and cooperation processes. She trained over 1500 persons on related topics. She also lectured in over 200 international events around the world. Her audiences encompass young, mid and high-level professionals, executive officers, as well as media professionals, decision-makers and the civil society from all continents (i.e. South East Asia, Arab States, Africa, Europe, Latin America, Central Asia). She published a number of scientific articles and scientifically edited over 5000 pages of research related to topics of her competence. Because of this, she is credited for having played a central role in the development and promotion of the modern concept of hydro-diplomacy.

Janos J. Bogardi is senior fellow of the Center for Development Research of the University Bonn. where he is also professor for water resources management. He is senior scientific advisor of the Institute of Advanced Studies Köszeg (iASK) in Hungary and fellow of the Stellenbosch Institute of Advanced Study (STIAS), South Africa. Since 2014 Distinguished Adjunct Professor of the Asian Institute of Technology (AIT, Bangkok). He was executive officer of the GWSP (2009–2012). He served till his retirement from the UN as director of the United Nations University (UNU) Institute for Environment and Human Security 2003–2009 and as Vice Rector a. i. in Europe 2007–2009. He was Chief of Section in the Division of Water Science in UNESCO, Paris (1995–2003) and chair professor of hydrology, hydraulics and quantitative water resources management at the Wageningen Agricultural University in the Netherlands 1989–1995. He was associate professor at AIT between 1985 and 1988. Between 1969 and 1985 he had research and consulting appointments in Europe and in Africa. He graduated in civil engineering at the University of Technology Budapest in 1969. He holds a doctorate in water resources engineering (Dr.-Ing.) from Karlsruhe University 1979 and three Dr. honoris causa distinctions from universities in Poland, Hungary and Russia.

Zita Sebesvari heads the Environmental Vulnerability and Ecosystem Services (EVES) Section at United Nations University, Institute for Environment and Human Security. Dr. Sebesvári is an environmental scientist with a research focus on ecosystem-based disaster risk reduction (Eco-DRR) and adaptation (EbA) guided by social-ecological vulnerability and risk assessments, and the interplay between soil and water degradation and disaster risk.

Klement Tockner received a Ph.D. in zoology and botany from the University of Vienna and a Titular Professorship at ETH Zurich. He is president of the Austrian Science Fund (FWF), professor for Aquatic Ecology at the Free University Berlin, and former director of the Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin. He is member of several international scientific committees and advisory boards, and elected member of the Germany National Academy of Sciences, Leopoldina and the Austrian Academy of Sciences.

Burcu Yazici is an environmental engineer and continues her studies in the same field as a Ph.D. candidate focusing on water pollution induced by agriculture. She is a project development and implementation expert at Turkish Water Institute (SUEN), working as a researcher and facilitator in several EU funded projects (H2020, PRIMA, ERA-NET) and international collaborations (WATER JPI, GW2I) since 2013. She also takes part in national projects on water quality and wastewater management, and modelling studies. Her main research areas include wastewater management and reuse, water quality management and pollution arising from agricultural activities.

Fatma Turan graduated as an environmental engineer from Istanbul Technical University (ITU) in 2004 and received her master's degree in Environmental Sciences and Engineering from the same university. She has been working at the Ministry of Agriculture and Forestry since 2006, specializing on marine and coastal management, solid waste management, environmental flows and hydroelectric power plants (2006–2016). She is currently employed at Turkish Water Institute (SUEN) as an expert, and is involved in national and international water management and governance projects, including transboundary waters.

Burcu Calli studied Political Science and International Relations at Marmara University and received her MSc degree in European Studies from the London School of Economics and Political Science. She works as an expert on water diplomacy and hydro-politics in the Turkish Water Institute (SUEN) and her research focuses on water and migration related issues. She was the thematic coordinator of the 4th Istanbul International Forum organised in 2017, which was the first international water event exclusively focused on the refugee issue under the main theme of "Water and Peace".

Aslıhan Kerç received her B.Sc. from Istanbul Technical University, M.Sc. from Marmara University and Ph.D. from Boğaziçi University in the field of Environmental Engineering. She is an associate professor at Marmara University and since 2012 she has been working as the Project Development and Implementation Coordinator at Turkish Water Institute (SUEN). Her research interests are water/wastewater treatment with chemical and advanced oxidation techniques, water reuse, micro pollutants, and water management. She represented The Scientific and Technical Research Council of Turkey (TUBITAK) in European Science Foundation (ESF) as a member of the Life, Earth and Environmental Sciences Standing Committee between 2005 and 2011. She is a board member of International Ozone Association (IO3A—EA3G). OECD Water Governance Initiative, Water JPI, Organization of Islamic Cooperation (OIC), World Water Council and UN-Environment are among the international platforms she is representing SUEN. She is the current chair of Global Wastewater Initiative (GW2I) of UN Environment.

Olcay Ünver is the UN-Water Vice-Chair since August 2018 and teaches Water and Food Security, since September 2020, as Professor of Practice, at the Polytechnic School, Environmental and Resource Management Program Arizona State University, Mesa, Arizona. He served as Deputy-Director of the Land and Water Division of the Food and Agriculture Organization of the United Nations (FAO) from September 2013 to February 2019. Between 2007 and 2013, he was the Coordinator of the United Nations World Water Assessment Programme and prior to that, he was a distinguished professor of water resources at Kent State University, Ohio, USA, and President of the GAP project in Turkey.

Mr Ünver holds a Ph.D. in Civil Engineering (water resources planning and management) from the University of Texas, Austin and a Masters (hydraulics) and Bachelor's degree in Civil Engineering, from the Middle East Technical University, Ankara, Turkey.

Yvonne Walz holds a Ph.D. in the interdisciplinary field of geographical remote sensing and spatial epidemiology from the University of Würzburg, Germany, which she conducted in close collaboration with the German Aerospace Center (DLR) and the Swiss Tropical and Public Health Institute (STP) in Basel. Thereby, she specialized in spatial risk profiling of human diseases, exemplified for the case of schistosomiasis in West Africa. Dr. Walz has gained several years of work experience in analyzing socio-ecological systems of environment and human health. Her research focus at UNU-EHS is on vulnerability and risk assessment, developing methodological approaches to support the monitoring of the Sendai Framework for Disaster Risk Reduction, multi-sectoral perspective on climate change adaptation, disaster risk reduction and public health.

12 Water Resources Management: Integrated and Adaptive Decision Making

Daniel Karthe, Janos J. Bogardi, and Dietrich Borchardt

Abstract

Over the past three decades, Integrated Water Resources Management (IWRM) has evolved into one of the leading water management paradigms. Revisiting the starting points and the development of the IWRM concept, this chapter critically analyzes the rationales and the major elements to be considered in the framework of IWRM. IWRM is then related to other recently emerging concepts such as adaptive water management and the Resource Nexus. Even though IWRM has been formally adopted almost worldwide for almost two decades, its implementation remains a challenge for many countries. IWRM also became a major research topic in water sciences and beyond, calling for a reflection of its role and impact. Based on theoretical and empirical analyses of contemporary IWRM research, this chapter provides best practice examples of science based implementation and synthesizes the lessons learnt.

Keywords

IWRM • Adaptive management • Sustainable development • Global change

D. Karthe (✉)
Engineering Faculty, German-Mongolian Institute for Resources and Technology, Nalaikh, Mongolia

United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany
e-mail: karthe@unu.edu

J. J. Bogardi
University of Bonn and Institute of Advanced Studies Kőszeg (iASK), Kőszeg, Hungary
e-mail: jbogardi@uni-bonn.de

D. Borchardt
Department Aquatic Ecosystems Analysis (ASAM), Helmholtz Centre for Environmental Research-UFZ, Leipzig, Germany
e-mail: dietrich.borchardt@ufz.de

12.1 Integrated Water Resources Management (IWRM): Concept and Development

Very few ideas and concepts have been embraced in the "water world" so quickly, so enthusiastically and universally as IWRM. Hardly any major international event with relevance to water and its management and their associated declarations have missed to endorse IWRM as the way to tackle and to solve water problems irrespective of their scales and scopes. Probably the most prominent among these events was the World Summit on Sustainable Development, held in Johannesburg in 2002. Its Johannesburg Plan of Implementation (JPoI) (United Nations 2002) stipulates that within five years all countries should have adopted IWRM and developed water efficiency plans. While this appeal triggered the compilation of national IWRM plans the implementation of this resolution was much less than universal. With this resolution the JPoI placed IWRM at the national level, but other models have been promoted subsequently. The European Water Framework Directive (EC 2000/60/EC) defines the basin and "water body" scale as the appropriate ones for water resources management while other sources promote small scale, stakeholder involved IWRM (Burton 2003; Zinzani 2014).

12.1.1 Origins of the Concept

The idea of IWRM is almost a century old (Giordano and Shah 2014): water resources management at the river basin level was incorporated into Spanish law as early as 1926, and IWRM was explicitly mentioned in water management directives of Hesse state in Germany in 1960 (Rahaman and Varis 2005). However, the concept was popularized by and after the World Summit in Rio de Janeiro in 1992 (Savenije and Van Der Zaag 2008):

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> During the 1990s, […] many more in the profession began to appreciate that the water problems had become multidimensional, multi-sectoral and multi-regional, and were enmeshed with multi-interests, multi-agendas and multi-causes, which could be resolved only through an appropriate multi-disciplinary, multi-institutional and multi-stakeholders coordination. (Biswas 2008:7).

Irrespective of these historical traces it is fair to identify the emergence of IWRM when it began to occur more commonly in laws, official government guidelines, or similar administrative documents as instructions for their administration and technical services to implement water resources management in a new "integrated" way. One comprehensive example of these guidelines is a water program called "Water vor nu en later" (Water for now and later) issued by the Dutch government (Rijkswaterstaat 1989). It is obvious that both the political will, but also the concept of IWRM predates the Dublin Conference of 1992, which is considered to be fundamental for the further development and popularization of IWRM (Ibisch et al. 2016a).

12.1.2 Development of the IWRM Concept

By reviewing the early definitions of IWRM the different aims and aspirations of the different protagonists can be analyzed. It is worth to juxtapose some of the most prominent definitions of IWRM to trace the dual nature of being considered as both a concept and a methodology and to highlight the diverging interpretations.

The Dutch water program (Rijkswaterstaat 1989) defined IWRM as

> Interrelated water resources policy making and management by government agencies responsible for the strategical and management tasks, executed on the basis of the systems concept under consideration of the internal functional relationships between quality and quantity aspects of both surface- and groundwater, as well as the external interactions between the water resources management and management of other fields like environmental protection, regional planning, nature conservation etc.

This definition is an example of a political/administrative guideline with clear limitations and degrees of consideration of what and how to be integrated. With the reference to systems concept even a hint of methodological prescription is given. Clearly this definition was formulated having IWRM as a practical tool in mind.

Even though the Dublin principles (the outcome of the Dublin Conference 1992) do not use explicitly the term "IWRM", principle 2 mentions the idea that

> Water development and management should be based on a participatory approach, involving users, planners and policy makers at all levels,

thus referring to a participatory approach involving all stakeholders at all levels by calling for a kind of vertical integration in the sociopolitical sphere rather than emphasizing the need for the topical (horizontal) integration. It is a substantial addendum (or difference) compared to the definition by Rijkswaterstaat (1989).

Along the promulgation of the new water law of the Republic of South Africa in the late 1990s the Department of Water Affairs and Forestry (DWAF) formulated the following definition (Görgens et al. 1998).

> IWRM is a philosophy, a process and a management strategy to achieve sustainable use of the resources by all stakeholders at catchment, regional, national and international levels, while maintaining the characteristics and integrity of water resources at the catchment scale within agreed limits.

This definition shows remarkable differences compared with the example from The Netherlands (Rijkswaterstaat 1989), irrespective that in both cases the definitions are formulated by a ministry of a national government. The South African definition gives different attributes to IWRM, thus implicitly acknowledging its duality. It rather emphasizes the "background" and philosophical characteristics and calls it a strategic approach instead of specifying how to implement it. One could see that the experience of the 1990s with attempted implementations of IWRM is already mirrored in this definition. It repeats the multistakeholder view of the Dublin principle and boasts the basin scale approach. The term "agreed limits" reflects the negotiations based decision making process involved. Compared to the definition given in the Dutch water program (Rijkswaterstaat 1989) the DWAF definition involves all levels of the jurisdictional hierarchy including the international one. It is a logical extension should the basin scale principle pursued consequently.

Most commonly used today is the definition of IWRM by Global Water Partnership (GWP 2000), which states that

> IWRM is a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in equitable manner without compromising the sustainability of vital ecosystems.

This definition calls IWRM a process and explicitly refers to the necessity of coordinated land and water management, a recommendation which has been repeatedly been called for (Bogardi et al. 2012). While this definition is much less prescriptive than that of the Dutch water program it links explicitly the elements of sustainable development to IWRM.

A more recent definition of IWRM was adapted specifically to the Central Asian context, considering IWRM as

> a management system supported by governance arrangements to consider all types of water resources (surface, ground and return waters) within hydrological units; which links the interests of different economic sectors and hierarchical levels of water use; involves stakeholders in decision-making; and promotes effective use of water, land and other natural resources in order to ensure sustainable water supply for the environmental and societal needs (Dukhovny et al. 2013:181).

While this definition almost completely reflects the one by GWP, it explicitly points out that IWRM needs to address different interests (which have diverged considerably after the dissolution of the Soviet Union) and water use efficiency (which is particularly relevant in a water-scarce region such as Central Asia).

It is needless to say that these four definitions are only examples which illustrate the broad spectrum of interpretations of IWRM. This "liberal" use of definitions was not and is not really conducive for the breakthrough of IWRM as a practical and often deployed tool.

Nevertheless, as the popularity of IWRM (at least as a slogan in the international water discourse) seems to be unabated, the calls for its implementation continue. Even in the final recommendations of the Sustainable Development Goals (SDGs) of the United Nations (13th session of the Open Working Group, 2014) appears the call to implement IWRM at all levels, including transboundary cooperative setups by 2030 (Smith and Jønch Clausen 2018). Compared to the "deadline" in the Johannesburg Plan of Implementation in 2002 (5 years) (United Nations 2002) at least the world gives itself 15 years to comply. Whether it means that the inherent obstacles are assessed adequately is yet to be seen. The UN-Agenda 2030 with the SDG 6 on clean water and sanitation for all, and the IWRM indicator under SDG 6.5.1 then sets a new hurdle and test for IWRM. After the unrealistic resolution in 2002 in Johannesburg the elevation of IWRM to be part of an SDG is an opportunity but not without risks. The credibility of the professional community, but also that of the concept is at stake. This forthcoming challenge, to be encapsulated in an intergovernmental binding resolution, underlines the importance of this book providing a broad review of the state-of-the-art of IWRM and its various components.

12.1.3 Conceptual Vagueness—A Barrier for IWRM Implementation?

If we assume that practical IWRM implementation was started in the late 1980s, this would enable us to look back to three decades of experience. Nevertheless, the implementation of the IWRM concept in the real world has been slow and unsatisfying and has not induced major transformations in the management of freshwater resources (Jeffrey and Gearey 2006; Mukhtarov 2008). A United Nations status report on IWRM prepared for the Rio+20 Conference documents progress in the inclusion of IWRM in national policies and legislation but also states that only half of the countries with IWRM plans report an "advanced state of implementation" (UN-Water 2012). Alike, at the 2011 Dresden International Conference on IWRM, experts concluded that "the actual implementation of IWRM is lagging behind". They urged that "the implementation of IWRM and the realization of the respective programs have to be accelerated" (Borchardt et al. 2013).

In this context it is worth to mention the critical evaluation of IWRM regarding its actual implementability (Biswas 2004, 2008; García 2008; Hering and Ingold 2012; Medema et al. 2008; Stålnacke and Gooch 2010), which is considered by some experts as the principal reason why practical progress considerably lags behind aspirations in many countries of the world.

Verbal enthusiasm for IWRM is accompanied by fairly broad interpretations (see above and review by Martínez-Santos et al. 2014). This might be acceptable as far as a concept or philosophy is concerned. However, this "plurality" could become a real handicap if IWRM were considered as a method to be encapsulated in practical guidelines and manuals to be implemented in practice.

The criticism by Biswas (2004)

> The definition of IWRM continues to be amorphous, and there is no agreement on fundamental issues like what aspect should be integrated, how, by whom, or even if such integration in a wider sense is possible. …in the real world, the concept will be exceedingly difficult to be made operational.

more or less refers to all definitions of IWRM and has therefore not lost any of its validity during the last decade.

This, basically unresolved duality of IWRM being interpreted either as a philosophy or a methodology (tool) can be seen as the main reason for its popularity and frequent endorsement whereas it simultaneously hampers to becoming a day to day tool of water related institutions.

One core dilemma, already highlighted by Bogardi (1990) is the question what is to be integrated. This question has ever since been reoccurring in the debate (Biswas 2004; Molle 2008; Hering and Ingold 2012). There is an inherent contradiction in the focus on integration in IWRM. On the one hand, the idea of integration is to holistically consider the full complexity of processes relevant for water management. On the other hand, however, too much complexity hinders real-world implementation of IWRM. Therefore, to this date, IWRM projects tend to break down water management into smaller components which can be solved by engineering, applied science and administrative or community actions. In the end, therefore, IWRM frequently needs to rely on simplifications rather than fully considering integration.

After a less than satisfactory almost 30 years with the implementation of IWRM the impression is emerging that stakeholder and other non-water professional interest groups attempt more and more to equate IWRM with the concept of multi-stakeholder involvement (thus integration mainly in the sociopolitical domain). While this is, not only for IWRM, a fundamental requirement of planning in a pluralistic society, it can by no means be equated with IWRM. Even though multi-stakeholder involvement has its merits to reach sustainable consensus solutions, reducing IWRM to a "simple" integration of various interest groups into the decision making process would not suffice the core idea of IWRM (Ibisch et al. 2016a).

12.1.4 IWRM Perspectives in the Context of Adaptive Management and the Nexus Approach

Recently, the concept of "adaptive management" has appeared as a response to increasing uncertainty und instability (Walters 1986; Pahl-Wostl 2007). The implications of climate change and the related uncertainties about its impacts at the regional scale have triggered a debate about how better to capture real-world water dynamics. The adaptive management approach to natural resource management emphasizes learning and is based on the assumptions that our knowledge is always incomplete (Allen and Gunderson 2011). The adaptive decision making process is well structured and includes careful consideration of goals, identification of alternative management objectives, and knowledge of causal connections, implementation, monitoring and evaluation followed by reiteration (see Fig. 12.1). Hence, although adaptive management can reduce uncertainty in decision making, it is primarily a means to enable decision making despite uncertainty (Allen and Gunderson 2011; Pahl-Wostl 2007). Adaptive management recognizes people and ecosystems as inherently complex, unpredictable and difficult to control, and encourages ongoing learning as the key to coping with complexity and uncertainty (Schoeman et al. 2014). The concept has been widely promoted as a solution to complex natural resource management problems and a supporting approach to integration. However, the concept runs the same risk of vagueness as IWRM and it remains more an ideal than a reality (Allen and Gunderson 2011).

The question remains whether IWRM and adaptive management are unrelated or parallel developments. A recent review by Schoeman et al. (2014) points out that each approach has its own strengths to contribute to improved water management. While IWRM in the range of hydrological boundaries provides a political platform for broad stakeholder participation and a process for consensus solutions, the adaptive management approach sets a norm for learning by application of experimentation and 'learning-by-doing' principles that can improve responsiveness to biophysical feedbacks. It is clear that the IWRM concept of the 1990s did not explicitly tackle the newly arising challenges of interconnected social-ecological systems and global environmental change. Water governance has to deal with the new risks and uncertainty and there is a strong call for the development of flexible institutions and policies that facilitate learning, adaptation and the ability to transform (Pahl-Wostl et al. 2011).

In many ways, the resource nexus resembles the IWRM concept. It was popularized much more recently, following the "The Water, Energy and Food Security Nexus" and "Water in the Anthropocene" conferences in Bonn, Germany in 2011 and 2013, respectively (Ibisch et al. 2016a). One major difference is that water management is not the main focus of the nexus but that multiple sectors are considered concurrently (De Strasser et al. 2016; Ibisch et al. 2016a); see Table 12.1. The reason to consider food, water and energy concomitantly are important links and similarities between these sectors, which are

- limited by resource constraints;
- deal with goods that traded globally but at the same time are produced in highly regulated markets;
- characterized by regional differences and temporal variations in availability and demand;
- fundamental to the function of society and thus regional (and global) security;
- strongly interdependent with the environment and climate change (Bazilian et al. 2011; Gerlak and Mukhtarov 2015).

"The term nexus has been used in a variety of contexts with the aim of advancing an understanding of how sectors are linked, and in turn to inform cross-sectoral governance coherence. [...] The nexus approach allows for a multi-sectoral dialogue that is in principle broader than the dialogue promoted with IWRM and that aims at discussing synergies out of the water management domain and beyond the river basin scale. [... Nevertheless] water holds in this context an undeniable importance over the other resources." (De Strasser et al. 2016:1).

Even though water is one (out of several) important sectors addressed in the nexus approach it is important to note that it considers different spatial scales and not only the river basin. Even though spatial mismatches between governance units and hydrological units have already been noted for the IWRM concept (Dombrowsky et al. 2014; Houdret et al. 2014; Moss and Newig 2010), this challenge is even greater for the nexus approach due to different governance structures of the energy, food and water sectors. Usually, the

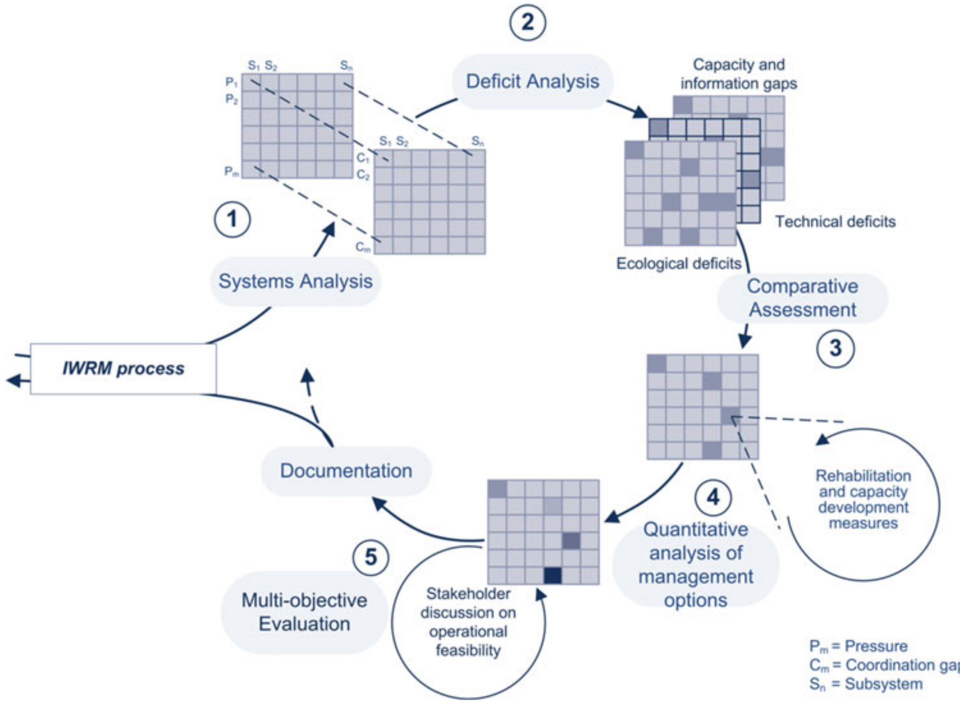

Fig. 12.1 The IWRM planning cycle takes into account the adaptive management concept. *Source* Leidel et al. (2014)

Table 12.1 Comparison of IWRM and the resource nexus. Modified from Benson et al. (2015)

	IWRM	Resource Nexus
Elements	• Primary focus: Water • Linkages considered: Land and related resources	Different constellations exist, e.g • water–food–energy (-ecosystems) • water–soil–waste nexus
Integration and objective	Integrating water with other policy objectives to maximize the resulting environmental, social and economic benefits	Integrating the management of several finite and renewable resources, thereby considering synergies and tradeoffs
Origin	Water management laws in Europe of the early/mid twentieth century; popularized by UN World Summit 1992 and by GWP around 2000	Based on other integrated approaches; defined and popularized as a concept after 2011 by the Bonn Nexus conference and various UN institutions
Governance and scale	Optimum scale: river basin. Usually implemented via national water policies/programs; increasing focus on transboundary perspectives	Multiple scales and governance via multiple sector-specific policies. Resource specific markets play a key role for governance, but with considerable differences between individual nexus elements

nexus approach is considered in situations in which water resources are stressed and when the environment no longer acts as a buffer which mitigates conflicts between different uses (Guillaume et al. 2015). Some authors, have, however suggested that the river basin is highly relevant in the context of the nexus discussion, and that "focusing on W-E-F Nexus issues could provide a basis for collaboration and data-sharing in basins where IWRM has proven difficult to implement" (Lawford et al. 2013:614). However, due to its greater complexity, the nexus approach may be considered even more challenging, particularly in the light that "very few people are expert in all areas" (Bazilian et al. 2011).

The Bonn 2011 Conference, The Water, Energy and Food Security Nexus: Solutions for the Green Economy triggered an unprecedented series of international conferences and events dedicated to explore this widened integrative framework of problem formulation and search for sustainable solutions. This integrative view on the linkages between water, energy, land and food has been promoted during the 2013 Bonn conference on *Water in the Anthropocene:*

Challenges for Science and Practice (Gupta et al. 2013; Ringler et al. 2013). Compared to the IWRM paradigm the nexus approach clearly steps "out of the water box" and focuses on the water's central role in linking the conceptual domains of energy systems, aquatic and terrestrial ecosystems and food production. While the nexus approach accentuates the interlinkages of different domains and economic sectors the IWRM concept has concentrated predominantly on the water sector; although the need for cross-sectoral views have already been addressed in the most widely used definitions of IWRM (e.g. GWP 2000). When translating IWRM into projects the connections easily become obvious (e.g. Bernhofer et al. 2016, Karthe et al. 2015a, b, 2016a, Liehr et al. 2016). The two concepts are thus not contradictory; through the nexus approach water management plans prepared for different sectors could be linked in an integrated way.

IWRM is obviously neither a unique, nor a lonely concept in the field of resource management. Its ultimate value could be proven by its documented contribution to solve multilevel, multi-sectoral, multiple stakeholder resource allocation and other problems. In this jigsaw puzzle IWRM, the nexus concept and adaptive management have their potential role. However, without fitting the pieces together all of these concepts and methods would lose credibility.

12.2 The Elements of Science-Based IWRM

Even though the core idea of IWRM is a holistic approach, the practical operationalization of the concept is usually based on its breakdown into constituting elements. In specific regional contexts, the relevance of individual elements can differ considerably, but the successful implementation of IWRM requires a holistic understanding of water in its environmental and anthropogenic context (GWP 2000; Ibisch et al. 2016a; Karthe et al. 2018). Therefore, empirical research on water resources and their natural and socio-economic context (see Fig. 12.2) is typically done in order to analyse the starting point for management measures. This typically includes:

- water quantity: availability of soil water, ground water, and surface water resources and their dependence on the regional hydrology and its drivers (e.g. climate or land cover change);
- water quality: physical, chemical and biological water properties and their relevance for aquatic ecosystems, irrigation and drinking water supply;
- water usage: consumption pattern and sectoral conflicts;
- water infrastructures: hydraulic modifications, irrigation techniques, water supply, sewerage, wastewater treatment technologies;
- water governance: institutional and socio-economic framework for water management, decision support tools;
- participation in water management: public information, capacity development, gender equality, role of marginalized groups.

12.2.1 Water Quantity

The precise knowledge on the amounts of available water resources within a region is an indispensable prerequisite for any attempt of its management. This includes an in-depth understanding of the components of the hydrological cycle and the variability over time and space within the individual region to be managed (Ibisch et al. 2016a).

Both at its global and its regional scale, hydrology and hydrogeology are influenced by physical and anthropogenic drivers. However, in the age of the Anthropocene (Crutzen 2002), the distinctions between 'natural' and 'anthropogenic' processes have become less clear, because human influences are now manifest in all parts of the natural environment. Global change "is marked by the interdependence of physical, biogeochemical, economic, social, cultural, demographic and political processes" (Germer et al. 2012:1). In this context, water plays a prominent role two ways: on the one hand, significant shifts in global and regional water distribution are expected; on the other hand, various earth systems (e.g. climates, soils, vegetation) are connected by oceanic currents and hydrological flows (Steffen et al. 2005). It is therefore not surprising that the International Association of Hydrological Sciences (IAHS) underlined the importance of interdisciplinary research efforts in the context of the scientific decade "Panta Rhei – Everything flows: changes in hydrology and society" (Montanari et al. 2013).

Despite some uncertainties regarding future scenarios, climate change is considered to be one of the major drivers of the change of water availability, acting both directly (via changes in precipitation) and indirectly (via changes in evapotranspiration and water demand). The effects of climate change can differ markedly among river basins (Bernhofer et al. 2016), and some parts of the world are likely to be affected more strongly than others. On the one hand, warming in some parts of the world, such as Central Asia, is much stronger than the global average (Karthe et al. 2017a). On the other hand, global climate change leads to both drying and wetting trends in different parts of the world,

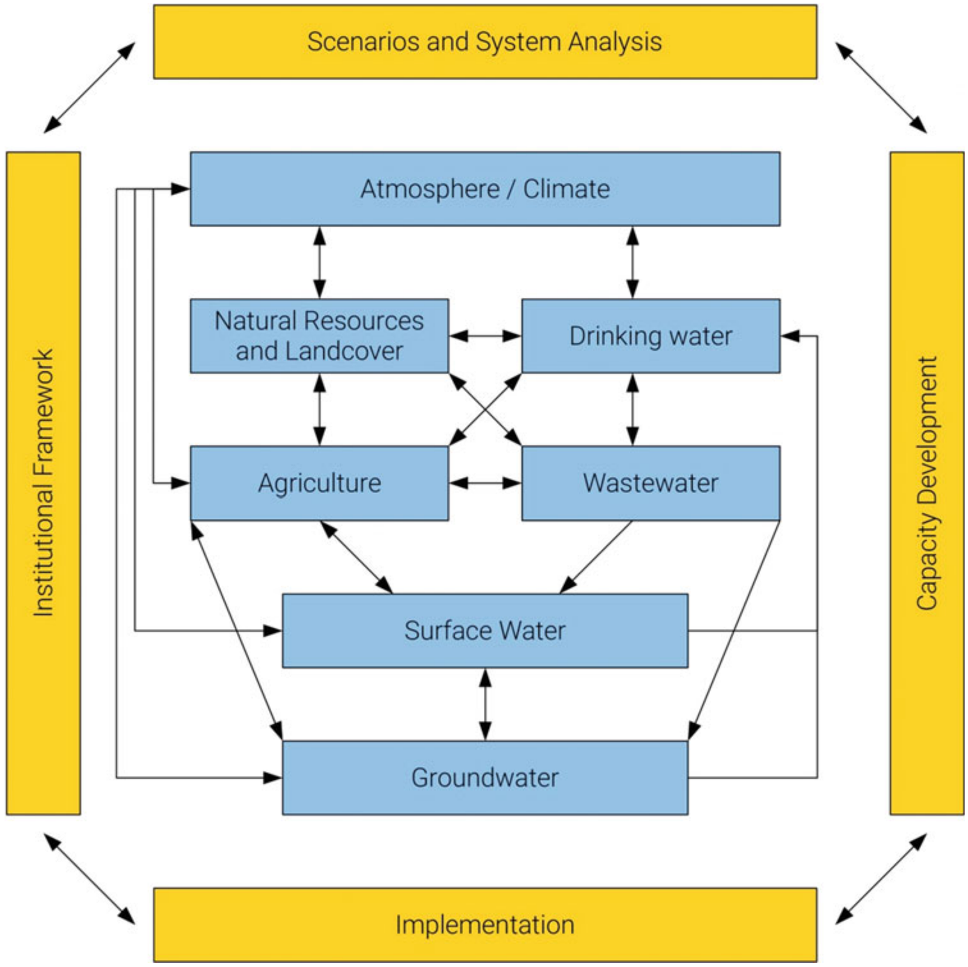

Fig. 12.2 Conceptual approach to a science-based IWRM, slightly modified from IWAS project (Kalbus 2012; Seegert et al. 2014)

resulting on both greater risks of drought and floods (Kappas 2009) and a greater unpredictability of changes in available water resources.

12.2.2 Water Quality and Aquatic Ecology

Water quality is a global concern as risks of deterioration translate directly into social and economic impacts including human health and food security. As the water quality situation on a global scale is poorly understood, an important step is to develop a world water quality assessment framework to reduce the information gap and support decision-making and management processes (UNEP 2016). As agriculture accounts for about 70% of global water use the potential risk of water quality impacts of agricultural return flows is significant (UNESCO 2012). Agricultural practices cause nutrient contamination, and the sector is the major driver of eutrophication, except in areas with high urban concentrations. Nutrient enrichment has become one of the planet's most widespread water quality problems (UNESCO 2009).

From a water management perspective, it is important to understand that hydrology, water quality and aquatic ecology are closely interlinked. For example, water quality in a river depends not only on the amount of pollutant influx, but also on its hydrology—i.e. its dilution capacity—and ecological state—i.e. the functioning of biogeochemical filtration mechanisms—(Chalov et al. 2016; Völker et al. 2013). Despite all progress in agricultural, mining, industrial and municipal water management, a good chemical status of rivers remains a challenge in many parts of the world (UNEP 2016), including economically advanced countries such as Germany (Karthe et al. 2017c; Völker et al. 2013). In mining regions throughout the world, water, sediment and soil pollution are often particularly problematic (Thorslund et al. 2012; Winde et al. 2004). One commonly observed problem in this context is the bioaccumulation of toxic substances such as heavy metals and metalloids (Kaus et al. 2017).

The ecological assessment of water bodies requires the monitoring not only of hydrological, hydro-morphological and physico-chemical water quality parameters, but also function-oriented biological indicators (Borchardt and Richter 2003). Because aquatic ecosystems depend on functioning riparian ecosystems, the ecological restoration of floodplains has received increasing attention in recent years (Aishan et al. 2015; Stammel et al. 2018), particularly regarding the provision of regulating ecosystem services (Tomscha et al. 2017).

12.2.3 Water Use

Even though the term 'water consumption' is frequently used in the context of water resources management, at the global scale water is withdrawn only temporarily from the hydrological cycle. However, water use leads to a spatiotemporal redistribution of water resources, and to water pollution which negatively affects aquatic ecosystems and subsequent water users. Mankind has significantly altered the natural water cycle by overlaying it with water abstractions as well as return flows from urban, agricultural and industrial sources (Anderson 2003). At the global scale, about 70% of all water withdrawals are due to agriculture, while 20% are for industry and mining and 10% for domestic use (Cosgrove and Rijsberman 2000).

Agriculture is not only the largest single water user in many parts of the world, but also one of the most important water polluters. Sufficient water availability is directly linked to crop productivity (Wagner et al. 2016). In fact, irrigation has existed for as long as humans have been cultivating plants, but more recently, the question of efficient resource usage has become more prominent (Karthe et al. 2017a). Moreover, agricultural production does not only use water directly (for irrigation), but also in indirect ways (e.g. for water use during the production of fertilizers, pesticides, food for livestock, equipment etc.; Bekchanov et al. 2016).

In the modern world, a significant amount of water use is concentrated in urban areas which, for their supply (and wastewater disposal) depend on vast areas around them. For this reason, integrated concepts for urban water management need to consider raw water withdrawals and wastewater discharge in the context of surrounding watersheds (Anthonj et al. 2014; Karthe et al. 2016a). Similarly, mining and industry have developed into major water users, which is particularly problematic in drylands (Winde et al. 2013). In water-limited regions, increased water use efficiency in these sectors is therefore as important as proper wastewater treatment (UNEP 2016).

Integrated concepts to reduce water demand and to use water more efficiently are especially needed in water scarce regions. Water scarcity threatens the livelihoods of about 4 billion people worldwide as well as the functioning of and valuable service provision by ecosystems. In this respect, drylands and densely populated regions face the most severe challenges (Rosengrant et al. 2002; Mekonnen and Hoekstra 2016). Nevertheless, recent progress in wastewater recycling and water use efficiency also nourishes the hope that in the future, even water-stressed regions can achieve both environmental and socioeconomic benefits through more sustainable water use (Anderson 2003).

12.2.4 Water Technologies and Infrastructures

In the modern world, water management often relies on technologies and manmade alterations of the environment, which may be both causes and solutions of water-related problems. Anthropogenic influences accelerated greatly during the industrial age and have completely changed the character of entire river landscapes (Blackbourn 2007). In Central Asia, large-scale irrigation projects implemented during the Soviet period massively changed the regional hydrology and led to one of the largest environmental disasters made by mankind, the massive shrinkage of the Aral Sea (Abdullaev and Rakhmatullaev 2015). While it is normally assumed that a water stress situation results in efforts to reduce water consumption, the example of Central Asia shows that (increasing) water scarcity has often been addressed by physical transfers of water and hydroengineering (Guillaume et al. 2015).

Even though water management is often considered more a political than a technical challenge (Allan 2003), the implementation of IWRM usually includes technical measures (Kalbus et al. 2012; Karthe et al. 2017a). However, IWRM considers water technologies as one solution among many, or as a specific part of a solution strategy. This requires holistic perspectives and prioritizing strategies (Rost et al. 2015; Yoo et al. 2014) and intelligent combinations of centralized and decentral technologies which optimally serve multiple purposes (Karthe et al. 2016a; Khurelbaatar et al. 2017; Liehr et al. 2016; Peter-Varbanets et al. 2009).

12.2.5 From Information to Decision Support

Decision making in IWRM is usually characterized by two challenges: the complexity of processes and interactions in and between the social and natural environment, and fragmentary knowledge with leads to considerable uncertainty (Pahl-Wostl 2007; Pahl-Wostl et al. 2012; Sigel et al. 2010). Data and information scarcity is a relatively common framework condition for water resources management (Ahlheim et al. 2015; Karthe et al. 2015b; Senent-Aparicio et al. 2015), which is highly problematic when related to the objective of truly integrated management planning (McDonnell 2008). On the one hand, modelling and the consideration of different scenarios can help to overcome such deficits (Asmael et al. 2015; Bekri et al. 2015; Ireson et al. 2006; Keilholz et al. 2015), but in case of such assumption-based approaches, it is important to quantify and openly communicate resulting uncertainties (Castagna et al. 2015). Despite some criticism (Allen and Gunderson 2011; Medema et al. 2008), adaptive approaches that reflect a continuous learning process are helpful to initiate water management in situations of a less-than-perfect information base (Pahl-Wostl et al. 2012; Schoeman et al. 2014). Neither modelling nor adaptive management can overcome the limitations of extreme data scarcity, though. In such circumstances, only new monitoring networks or campaigns can help (Kaden and Geiger 2016; Karthe et al. 2015a; Klinger et al. 2015). Chapter 13 deals with different aspects of observation, monitoring, data collection and management in more details.

Even if data is available, it needs to be comprehensible and accessible for water managers. Therefore, and because of the multitude of information to be considered for integrated approaches, information management systems are an important basis for water management planning (Braune et al. 2004; Flügel 2007; Hofmann et al. 2018; UNEP 2016). Because relevant planning data have a spatial and temporal dimension, Geographical Information Systems (GIS) have developed into important tools for data storage, visualization (Rink et al. 2012) and analysis (Batbayar et al. 2018; Udovik 2006). While open-source GIS systems are increasingly helping to close the technological gap between industrialized and developing countries (Chen et al. 2010), web-based GIS systems are increasingly used to facilitate access to data and information (Karthe et al. 2017b; Kulkarni et al. 2014).

Decision Support Systems (DSS) are computer-based tools which give structure and provide interactive support to the decision making process (Giupponi et al. 2004). One particular way in which they go beyond information systems is that they help decision makers to prioritize certain measures (Rost et al. 2015). Evidence has shown that that only those systems which have a clear client / user interface, problem-relevant and up-to-date information content, and a gradual but constant evolution of the software are likely to be successful in the long-term (Stärz et al. 2015; Kalbacher et al. 2012).

12.2.6 Water Governance and Participation

Integrated water resources management is inherently complex and since the early 2000s the topic of water governance came into the global water discourse as a key issue (Mollinga 2008). Governance, in a broad sense, can be understood as "the art of governing" and embraces the full complexity of regulatory processes and their interaction. This is reflected in the United Nations Development Programme (UNDP) definition of water governance: "The term water governance encompasses the political, economic and social processes and institutions by which governments, civil society, and the private sector make decisions about how best to use, develop and manage water resources" (UNDP 2009).

Effective and efficient water governance is a key prerequisite for the successful implementation of IWRM; conversely, deficits regarding water governance are the most common reason for the failure of IWRM (Pahl-Wostl et al. 2012; Hagemann and Kirschke 2017). A first key challenge for water governance is the complexity of its ecological, socioeconomic and (geo)-political context as well as the governance process itself (Pahl-Wostl et al. 2012; Kirschke and Newig 2017; Kirschke et al. 2017). Secondly, the question of the appropriate spatial scale for water resources management is rather difficult. Even though many authors have propagated watersheds are the primary units for water resources management, it cannot be ignored that in reality there is typically a spatial mismatch between administrative areas and hydrological basins (Dombrowsky et al. 2014; Houdret et al. 2014; Moss and Newig 2010). This challenge tends to be particularly great in transboundary basins where riparian countries may have fundamentally different interests (Boklan and Janusz-Pawletta 2017; Janusz-Pawletta 2015; Krengel et al. 2018). Thirdly, water governance is often complicated by institutions which lack the necessary capacities (in terms of budget, staff or equipment) or which have unclear or overlapping responsibilities (Dombrowsky 2007; Dombrowsky et al. 2014; Horlemann and Dombrowsky 2012; Houdret et al. 2014; Karthe et al. 2015a, b). According to Pahl-Wostl et al. (2012), "polycentric governance regimes characterized by a distribution of power but effective coordination structures have higher performance".

Participative approaches focus on the active involvement of all stakeholders. Participation comprises all forms of influence by individuals and organizations affected by (but not always routinely involved) in decisions and tasks related to water management planning and implementation (Renn 2006). There is evidence that an active involvement of multiple stakeholders leads to more comprehensive information inputs into IWRM planning (Ibisch et al. 2016a, b). At the same time, water management measures need to be communicated to the general public in a timely and transparent way in order to achieve public acceptance (Heldt et al. 2016). In some parts of the world, gender inequality still constitutes a major challenge for IWRM implementation (Kim and Hornidge 2016; Ahmed 2008). Even though in many developing countries, women play an important role for water supply at the household level, there is a different gender bias at the predominantly male decision making level (Kirschke et al. 2016).

12.2.7 Capacity Development

In recent years, there has been a growing recognition that the implementation of Integrated Water Resources Management is not so much constrained by technical shortcomings but by a lack of qualified staff in the water sector, a limited public awareness or understanding of water-related problems and ignoring the role of the civil society for their solution (Alaerts 2009; Borchardt et al. 2013; Ibisch et al. 2016b; Leidel et al. 2010). According to Leidel et al. (2012: 1415), “measures for solving existing water problems can only be sustainable and effective, if the knowledge generated about possible solutions is deeply rooted within the originating region”.

There are multiple definitions of capacity development. In the context of IWRM, the one proposed by UNDP is particularly suitable due to its comprehensive and inclusive approach. According to UNDP (2009), IWRM is an integral process for the mediation, strengthening, preservation and further development of individual, organizational and societal capabilities, in order to (i) realise functions, (ii) solve problems and (iii) set and achieve sustainable goals. In this light, it is clear that IWRM needs to consider multiple levels, including individuals, organizations and the general socio-political environment (Leidel et al. 2012). Nevertheless, for quite a long time the importance of a profound multilevel capacity development for sustainable water resources management has been neglected (Alaerts et al. 1991). Only recently, research and development projects aiming at the practical realization of IWRM more often involve capacity development components (Vincent-Lancrin 2009; Etgen et al. 2009).

Because the success of water resources management relies on many different stakeholders, capacity development has numerous target groups, including policy makers and water managers (Gallego-Ayali 2013; Ibisch et al. 2016b; van der Zaag 2005), technical staff (Karthe et al. 2016a; Leidel et al. 2012), and strategic representatives of a wider public such as school students or teachers (Ibisch et al. 2016b; Karthe et al. 2016b; Klinger et al. 2015) and specific water user groups (GWP-TAC 2000; Huamanchumo et al. 2008; Mkandavire and Mulwafu 2006; Ritzema et al. 2008).

In practice, capacity development activities do not always work as planned, for example due to changes in regulations and staff (both on the sides of trainers and trainees), due to a “brain drain” of qualified experts from public to private economic sectors especially in growing economies or through leaving their home countries to find better jobs and better living environments abroad. Moreover, capacity development in the context of development cooperation needs to consider intercultural differences, which may otherwise limit the effects of well-intentioned training programs (Ibisch et al. 2016a, b).

12.2.8 Economic Considerations

Even though there is a controversial discussion whether water should be considered as an economic good or a social resource that should be secured as a human right (Allan 2006), water management in reality is often linked to economic considerations. From the user perspective, there is the question of water affordability, which varies widely at the global scale, but also for different user groups within specific countries, regions and localities (Gawel et al. 2012; Fankhauser and Tepic 2007; Mack and Wrase 2017). Because water demand is to some degree elastic to price, water pricing is often considered as a management tool to limit water consumption (Hung and Chie 2013). At the same time, even moderate water pricing can limit the affordability of water for consumers with very low household incomes, which may lead to a serious underconsumption of water and thus personal and public health risks (Gawel et al. 2012). In many parts of the world, including the European Union, water pricing is predominantly seen as a tool for cost recovery and thus financial sustainability of water supply and wastewater infrastructures (Iglesias and Blanco 2008; Savenije and van der Zaag 2009).

Even though some (neoclassical and neoliberal) economists argue that economic water pricing leads to efficient water use and allocation to sectors with higher value generation, privatization of water supply has often had unwanted consequences such as high prices (Mack and Wrase 2017; Savenije and van der Zaag 2009) and underinvestment in water infrastructures in order to maximize short-time profit (Araral 2017). Moreover, privatization with a narrow economic motivation often failed to achieve the goal of direct competition and better efficiency of the private sector as compared to public utilities. One reason is that water companies often work in a highly government-regulated market (Araral 2017; Bakker 2004). Moreover, privatization in many cases implied the creation state-owned companies (Araral 2017) or public–private partnerships (Bakker 2003; Zhong et al. 2008). Today, the privatization of the water sector is often seen as negative, as is frequently addressed by anti-globalization and anti-privatization protests (Araral 2017; Bakker 2007). Opponents of water sector privatization even consider the resulting “corporate theft of water” (Barlow and Clarke 2017:1) as a violation of human rights. It is therefore not surprising that in some cases, there has even been a re-municipalization of water providers (Beveridge et al. 2014; McDonald et al. 2018).

12.3 Summary and Outlook

Even though considerable progress has been made to anchor IWRM in national policies, strategies and laws worldwide, the actual implementation of IWRM is lagging behind (Borchardt et al. 2013). Success factors for effective approaches and their implementations can be summarized as follows: (i) working horizontally across sectors such as economy, energy, agriculture, environment, science and vertically from international over national, regional, basin to local levels; (ii) working with an intense dialogue between governmental institutions, science, NGOs and society; (iii) targeted and coordinated capacity development on different levels (in particular academic, administrative, technical, stakeholder); (iv) addressing the key role of economics in effective water resources management with treating the water services as part of the economy to be paid for, while considering water as such in the human rights (United Nations resolution 64/292) and (v) implementing infrastructures that serve multi-purpose schemes (e.g. wastewater management for protecting the environment and human health, water storage schemes for producing energy or food and mitigation of extreme events such as floods and droughts).

The duality of the IWRM concept, being a philosophy and a methodological approach, bears both risk and opportunity. On the one side of the medal, there is a risk that IWRM may be captured by "traditionalists", which follow traditional and technocratic schemes, in particular by limiting problems to technical solutions, favouring end-of-pipe solutions with ex-post priorities rather than sets of measures derived from precautionary and adaptive management approaches. However, there is compelling evidence that the implementation of technical solutions can be effective only if embedded in an integrated systems approach recognizing the resource boundaries set by the natural environment and the social, cultural and institutional contexts. On the other side of the medal, the vagueness of the IWRM concept opens space for specific adaptation and integration of domains, disciplines and societal stakeholders across sectors and hierarchical levels. The term 'IWRM' might be seen as strategic anchor on a high abstraction level that can and needs to be filled with science based facts and practical management solutions on the ground. The procedural character of the IWRM concept (GWP 2000) gives room required for adaptation and refinement within the large variety of existing solution portfolios and pathways.

Priority fields for strengthening the IWRM concept includes (i) capacity development tailored towards effective IWRM implementation; (ii) the development of adequate governance structures; (iii) flexible participation models for different social and political systems; (iv) provision of data archives and metadata for IWRM from regional over national to global scales; (v) long term information services and update to support decisions; (vi) developing, implementing and operating tailored monitoring in order to close the crucial data and information gaps; (vii) implanting measures and technical solutions in a holistic manner and context and (viii) appropriately integrating economy at all relevant scales and especially on the prioritization of measures based on their cost-efficiency.

Major future research efforts should be directed to develop applicable and robust methodologies for IWRM implementation under different settings. The level of international acceptance of IWRM warrants a concerted effort to overcome barriers to its implementation. More pragmatic approaches that take into account a sound system knowledge of the natural resource base, the drivers of change and the specific social, cultural and institutional environment will support ways to sustainable water resources management. We propose a shift away from IWRM as a normative concept and argue for realism and action by giving attention to the critical needs of people and the environment as the core dimensions of integration.

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Daniel Karthe heads the research program "Resource Nexus for Regions in Transformation" at United Nations University's Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES) in Dresden, Germany. He currently still serves as Associate Professor for Environmental Engineering at the German-Mongolian Institute for Resources and Technology (GMIT) in Nalaikh, Mongolia, for which he previously worked as Vice Rector for Research. Between 2010 to 2017, he coordinated several water-related research projects at the Helmholtz-Centre for Environmental Research (UFZ) in Magdeburg, Germany. His expertise related to IWRM includes hydrological and water quality studies at the catchment scale, and the role of technical solutions, water governance and capacity development in the management context. He cochairs the Commission for Hydrology within German Geographical Society, and serves as one of the vice chairs of the Commission for Water Sustainability within International Geographical Union.

Janos J. Bogardi is senior fellow of the Center for Development Research of the University Bonn. Where he is also professor for water resources management. He is senior scientific advisor of the Institute of Advanced Studies Köszeg (iASK) in Hungary and fellow of the Stellenbosch Institute of Advanced Study (STIAS), South Africa. Since 2014 Distinguished Adjunct Professor of the Asian Institute of Technology (AIT, Bangkok). He was executive officer of the GWSP (2009–2012). He served till his retirement from the UN as director of the United Nations University (UNU) Institute for Environment and Human Security 2003–2009 and as Vice Rector a. i. in Europe 2007–2009. He was Chief of Section in the Division of Water Science in UNESCO, Paris (1995–2003) and chair professor of hydrology, hydraulics and quantitative water resources management at the Wageningen Agricultural University in the Netherlands 1989–1995. He was associate professor at AIT between 1985 and1988. Between 1969 and 1985 he had research and consulting appointments in Europe and in Africa. He graduated in civil engineering at the University of Technology Budapest in 1969. He holds a doctorate in water resources engineering (Dr.-Ing.) from Karlsruhe University 1979 and three Dr. honoris causa distinctions from universities in Poland, Hungary and Russia.

Dietrich Borchardt is a biologist by training, full Professor for Aquatic Ecosystem Analysis and Management at TU Dresden (Germany) and Head of Department at the Helmholtz-Centre for Environmental Research-UFZ (Germany). He is Research Director of the Unit "Water Resources and Environment" at UFZ which contributes to the Topic "Dynamics of the Terrestrial Environment and Freshwater Resources under Global and Climate Change within the "Earth and Environment" Research Program of the Helmholtz Association running from 2020 to 2027. His research focuses on the functional ecology of aquatic systems, innovative monitoring approaches and innovative modelling tools in order to mechanistically understand anthropogenic pressures and impacts in relation to trajectories of degradation and recovery of environmental systems. This work is complemented with concepts for hydro-ecological synthesis and the advancement of Integrated Water Resources Management. His research projects cover national, European and global contexts with a strong emphasis on the science-policy-interface.

Part III

Examples of Assessment of Water Resources, Their Protection and Use

13 Observations, Monitoring and Data Management

Balázs M. Fekete, Ana Andreu, Robert Argent, Tamara Avellán, Charon Birkett, Serena Caucci, Sagy Cohen, Timothy Dube, Sabrina Kirschke, and Ulrich Looser

Abstract

Water resources and their properties highly vary in both space and time and their observations have high uncertainties. The characterization of this variability requires long-term spatially distributed observations, that allow the recognition of spatio-temporal patterns and changes. Unlike other engineering activities that typically can be satisfied with a one-time surveying of the designated area prior to the development planning, water management requires continuous monitoring records capturing the historical variability of the hydrological conditions. The need for a sustained data collection often without the immediate use, places water resources management in a difficult position. The justification of operating monitoring networks in the absence of pressing objectives, particularly at long-time scales, is often challenging, but water managers need to convince policy makers that water management decisions require the knowledge of how the hydrological processes varied over time. Without sufficiently long and up-to-date data series, adequate water management planning, ecosystem monitoring, and early warning systems are severely limited.

Keywords

Groundwater • In situ monitoring • Observations • Satellite monitoring • Surface water • Variability • Water quality • Water quantity • Water resources • Water storage pools

List of Abbreviations

ADCP	Acoustic Doppler Current Profilers
AHG	At-a-station hydraulic geometry
AWEI	Automated Water Extraction Index

B. M. Fekete (✉)
Grove School of Engineering, The City College of New York, New York, USA

Environmental Sciences Initiative, Advanced Science Research Center at the Graduate Center, City University of New York, New York, NY, USA
e-mail: bfekete@gc.cuny.edu

A. Andreu
IFAPA Research Center, Córdoba, Spain
e-mail: anandreum@posteo.net

R. Argent
Bureau of Meteorology, Melbourne, Australia
e-mail: Robert.Argent@bom.gov.au

T. Avellán
Self-employed Expert in participatory water resource management, Dresden, Germany
e-mail: Tamara.avellan@posteo.de

C. Birkett
Earth System Science Interdisciplinary Center, University of Maryland, College Park, USA
e-mail: charon.m.birkett@nasa.gov

S. Caucci · S. Kirschke
United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany
e-mail: caucci@unu.edu

S. Kirschke
e-mail: kirschke@unu.edu

S. Cohen
University of Alabama, Tuscaloosa, AL, USA
e-mail: sagy.cohen@ua.edu

T. Dube
Department of Earth Sciences, University of Western Cape, Cape Town, South Africa
e-mail: tidube@uwc.ac.za

U. Looser
Global Runoff Data Centre, Federal Institute of Hydrology (BfG), Koblenz, Germany
e-mail: looser@bafg.de

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BREB	Bowen ratio energy balance
CGWB	Central Groundwater Board
DEM	Digital Elevation Model
DIODE	Détermination Immédiate d'Orbite par DORIS Embarqué
DST	Distributed Temperature Sensing
EC	Eddy covariance
ECMWF	European Center for Medium-range Weather Forecast
ECT	Eddy covariance tower
EO	Earth observation
EOS	Earth Observing System
ERTS	Earth Resources Technology Satellite
ESA	European Space Agency
ET	Evapotranspiration
EVI	Enhanced Vegetation Index
FAO	Food and Agricultural Organization of the United Nations
FLEX	Fluorescence Explorer mission
GCOS	Global Climate Observing System
GEMS	Global Environmental Monitoring System
GEOSS	Global Earth Observing System of Systems
GGIS	Global Groundwater Information System
GLAS	Geoscience Laser Altimeter System
GRACE	Gravity Recovery and Climate Experiment mission
GRACE-FO	Gravity Recovery and Climate Experiment Follow up mission
GRDC	Global Runoff Data Centre
GRDB	Global Runoff Database
GPR	Ground penetrating radar
GPS	Global Positioning System
GTN-H	Global Terrestrial Network for Hydrology
IGRAC	International Groundwater Resources Assessment Centre
HLPW	High Level Panel on Water
LAI	Leaf area index
LULC	Land covers and land uses
JAXA	Japanese Aerospace Exploration Agency
MNDWI	Modification of Normalized Difference Water Index
MODIS	Moderate Resolution Imaging Spectroradiometer
MOIST	Managing and Optimizing Irrigation by Satellite Tools
NASA	National Aeronautics and Space Administration
NCEP	National Center for Environmental Prediction
NESDIS	National Environmental Satellite Data and Information Services
NGWMN	National Ground Water Monitoring Network
NHS	National Hydrological Services
NOAA	National Oceanic and Atmospheric Administration
NOAA NMFS	NOAA National Marine Fisheries Service
NOAA-NOS	NOAA National Ocean Service
NOAA-OAR	NOAA Office of Oceanic and Atmospheric Research
NOAA-OMAO	NOAA Office of Marine and Aviation Operation
Nexrad	Next Generation Radar
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NWS	National Weather Service
OSCAR	Observing Systems Capability Analysis and Review Tool
PET	Potential evapotranspiration
SAVI	Soil Adjusted Vegetation Index
SMAP	Soil Moisture Active and Passive mission
SMOS	Soil Moisture and Ocean Salinity
SEBAL	Surface Energy Balance Algorithm for Land
SEBS	Surface Energy Balance System
SRTM	Shuttle Radar Topography Mission
SWAT	Soil Water Assessment Tool
SWOT	Surface Water and Ocean Topography
TEP	Thematic Exploitation Platforms
TOPC	Terrestrial Observation Panel on Climate Observations
TRMM	Tropical Rainfall Measuring Mission
TTS	Total Suspended Solids
UHF	Ultrahigh frequency
UNEP	United Nations Environmental Programme
UNESCO	United Nation's Education, Science and Cultural Organization
UNESCO-IHP	UNESCO International Hydrology Programme
USDA	US Department of Agriculture
USGS	US Geological Survey
VHF	Very high frequency
VI	Vegetation indices
WiMMed	Watershed Integrated Model in Mediterranean Environments
WOIS	Water Observation Information System
WMO	World Meteorological Organization

Fig. 13.1 Measuring shaft of the Nilometer on Rhoda Island, Cairo from AD 864

13.1 Introduction

Water resources are highly variable in both space and time, arising from the complex dynamics of interlinked and chaotic processes that are hard to predict, and their observations have high uncertainties. The characterization of this variability requires long-term spatially distributed observations, that allow the recognition of spatio-temporal patterns and changes. The traditional assumption was that variabilities in the hydrological processes oscillate around stationary average conditions. Limits to the "stationarity" assumption due to alterations of the watersheds (land use change, reservoir operation, river regulation, etc.) were always recognized (Fekete and Bogárdi 2015). The validity of the stationarity under a changing climate was questioned and the need to incorporate climate predictions from global circulation models in management planning was suggested by the authors (Milly et al. 2008). Accounting for non-stationarity only emerged recently as common practice. Several authors argued that under gradually changing conditions the stationarity assumption combined with regular updates of the "stationary" statistics, based on near-real time observations, allows for sufficient recognition of the changes (Fekete and Stakhiv 2013; Lins and Cohn 2011).

Regardless of whether the response to climate change will rely on information beyond data records, observations of past and current conditions are essential for water management and future planning. Unlike other engineering activities that typically can be satisfied with a one-time surveying of the designated area prior to the development planning, water management requires a continuous monitoring records capturing the historical variability of the hydrological conditions.

The need for observations was recognized long ago, and water monitoring dates back to the early civilizations of Babylonia and Egypt (Fig. 13.1). Based on the data from the Global Runoff Centre's archive (Koblenz, Germany), continuous record of "modern era" river discharge goes back to more than two centuries in a few European river basins, but half a century data series are quite common in many parts of the world (Fekete et al. 2012).

Traditionally, data collection was performed only at regional or basin scales, and the value of sharing data over larger domains was not recognized. The lack of data sharing still hinders water resources assessment at larger scales (continental or global) and severely limits the better understanding of the hydrological cycle (Famiglietti et al. 2015; Fekete 2012). Recent global efforts try to overcome these shortcomings, such the Hydrological Observing System web tool[1] of World Meteorological Organization (WMO) launched in 2016 to collect the links to open platforms of National Hydrological services that share their data online. UNESCO's International Hydrological Programme's Water Information Network System (UNESCO IHP WINS[2]) also presents data and information on various aspects of water resource management.

The introduction of remote sensing (both airborne and satellite based) allowing for spatially distributed observations was a major breakthrough since it brought

[1] http://www.wmo.int/pages/prog/hwrp/chy/whos/index.php.
[2] http://ihp-wins.unesco.org.

unprecedented capabilities to capture spatial variability (albeit at the limited temporal frequency). Remote sensing is still considered as a cutting edge approach (Famiglietti et al. 2015) despite its more than half a century history. An intrinsic difference between in situ and remote sensing observations is that most in situ sensors are in contact with the observed medium, making direct measurements of properties of interest, while remote sensing measures electromagnetic waves emitted or reflected by the studied surfaces (Famiglietti et al. 2015). One exception is the Gravity Recovery and Climate Experiment (GRACE) satellite that senses gravitational anomalies.

Traditional in situ monitoring (that only provides sparse point samples, but potentially at high temporal frequency and typically a direct measurement of the observation target) and remote sensing (that has limited temporal frequency and most sensors only provides indirect measurements but with large spatial coverage) clearly provides complementing capabilities (Fekete et al. 2015).

A new revolution is underway with the spectacular advancement in telecommunications, sensor technologies, computer and data sciences. Mobile telecommunication broke down the data transmission expense barrier to real-time telemetering. Cheap, low powered, smart and densely deployed sensors connected to fast communication networks offer in situ monitoring opportunities never seen before. The BOOT Project[3] at the Technische Universität Dresden is a good example, that monitors water quality parameters on a floating device to assess changes in the composition continuously along the stream blurring the differences in capabilities between point and remote sensing measurements.

13.2 Water Quantity

Freshwater resources, in the various surface and groundwater storage pools that can be tracked measuring water levels or extent, are of primary interest to water managers. Nevertheless, these metrics do not provide direct measurements of the volumetric water quantities or fluxes, but can be related after detailed surveying of the storage pools geometry (rivers, lakes or reservoirs). The combination of measuring water level or extent (tracking variables) (Bjerklie et al. 2005) and regular surveying of the corresponding water bodies are key for accurate observations.

[3]https://tu-dresden.de/bu/umwelt/hydro/isi/sww/forschung/forschungsprojekte?fis_type=forschungsprojekt&fis_id=16005&set_language=en.

13.2.1 In Situ Observations

Early in situ observations were limited to water levels (e.g. Nilometer on Fig. 13.1, and traditional water level rod Fig. 13.2) measured relative to some arbitrary datum, and recorded by human observers. River discharge measurements in the modern era date back to the 19th Century, when current meters (Fig. 13.3) became available to make accurate flow velocity measurements.

13.2.1.1 River Discharge

Direct measurement of discharge is only possible in very small creeks that can be diverted to buckets or tanks, while recording the time it takes to fill them up. In larger rivers discharge can be only estimated from the flow velocities measured along multiple vertical gradients across the river channel's cross-section. The mean flow velocity along the vertical is determined either by the more accurate a.) full curve method (taking flow velocity measurements at regular intervals) or b.) at a few selected locations, less precise but more efficient. US Geological Survey (USGS) recommends 0.6 depth below the surface (six tenth method), averaging

Fig. 13.2 Water level rod next to the Lánchíd (Chain bridge), Budapest, Hungary

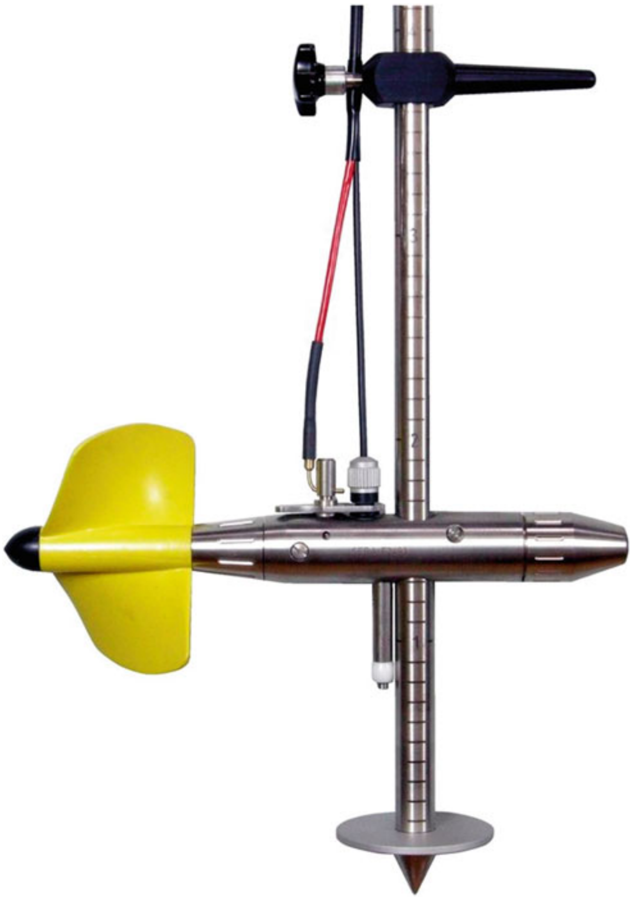


Fig. 13.3 Flow velocity meter

the velocity at 0.2 and 0.8 depth (two-point method) or at 0.2, 0.6 and 0.8 depth (three-point method) (Rantz 1982a). These locations are a good approximation of the average velocities along the vertical, as demonstrated both empirically and theoretically (based on the boundary layer theory of the flow profiles developed by Prandtl and von Karman) (Dingman 2009).

The river surveys are labor intensive even in wadable streams, but more so in large rivers where the hydrographer either needs to use boats, temporary cable ways, or to make the measurements from bridges. During high flows these measurements are potentially dangerous (Rantz 1982a, b).

Repeated field surveys under different flow conditions are essential for establishing rating curves that relate stage height (river surface elevation) to discharge. Stage height gauges are normally installed in control sections of the river channels where the cross-sections are either stable, or change less over time. The fields surveys need to be repeated periodically to adjust the rating curves for changes in the river channel.

Traditional current meters in field surveys can be replaced with Acoustic Doppler Current Profilers (ADCP) that measure the Doppler shift in the acoustic signals reflected from suspended material in the river flow. ADCPs make the flow velocity surveying more efficient, but still require human operators.

In the last few decades, the USGS invested heavily in "no touch" alternatives to discharge monitoring (Costa et al. 2006). Ground penetrating radar (GPR) pointing perpendicularly to the water surface and operating at very high (VHF) and ultra-high frequencies (UHF) can measure cross-section area with a ±3–4% compared to sonar sounding (Costa et al. 2006). GPRs can be operated above the water surface more safely from cable ways or bridges (unlike sonar sounders that needs to be submerged into the water), but it has limitations if the river banks are too steep or conductive. Conductivity above 300–400 µS (still within freshwater 0–1500 µS range) significantly reduces the return signal from depth over 2–5 m.

UHF and microwave frequency radar oriented towards the water surface at an angle can serve to measure flow velocities of the first few mm (depending on the frequency which determines the radio signal' penetration into the water). Bragg scattering of the radio signal produces radar echo, that has an intrinsic phase shift further amplified by the Doppler effect from the moving water. These radar instruments only work when the water surface has ripples moving away or toward the radar instrument.

The flow velocity measured near the water surface can be related to the mean velocity of the water column bellow by applying a 0.85 multiplier (Rantz 1982a) that arise from the same boundary layer considerations that supports the six-tenth, two- and three points methods discussed before. The surface velocity can be further impacted by the wind above the water surface. Based on empirical experiments, increases/decreases on wind speed (measured at 10 m above the water surface) can have effects on the surface water velocity of around 2% (e.g. 10 m s^{-1} wind speed could have 0.2 m s^{-1} effect on the flow velocity on the surface). While only the wind speed component parallel to the flow direction (where the radar instrument is pointing) affects the flow measurement, wind still can compromise the flow velocity measurements' accuracy that are often in the 0.5–2 m s^{-1} range.

The "no touch" techniques require more expensive equipment and can be justified only in rapidly changing river channels or when hysteresis is severe, where traditional riverbed surveying would almost require a permanent on site hydrographer. Hysteresis arises when the discharge varies for a given flow height in river channels (typically with shallow slope) as a result of the water surface slope changing significantly during the passing of flood waves. Steeper water slope during the rising limb of the flood wave leads to higher discharge, while the shallower slope when the flood is receding results in lower discharge passing through the same cross-sectional area under identical water surface elevation.

The stage-height/discharge rating curves normally follow power law relationships:

$$Y_s = \hat{a}Q^{\hat{b}} + Y_c \quad (13.1)$$

where Y_s is the stage height above some arbitrary datum point, Q is discharge, $\hat{a}$ and $\hat{b}$ are empirical constants and Y_c is the water level where the river ceases to flow. This equation when the datum of the stage height coincides with the "cease to flow" elevation leads to the classical at-a-station hydraulic geometry (AHG) (Leopold et al. 1964), for mean depth across the cross-section ($\bar{Y}$) flow width (W) and mean velocity ($\bar{U}$):

$$\bar{Y} = aQ^b \quad (13.2)$$

$$W = cQ^d \quad (13.3)$$

$$\bar{U} = kQ^f \quad (13.4)$$

The continuity equation ($Q = \bar{Y}W\bar{U}$) dictates that the product of the coefficients $ack = 1$ and the sum of the exponents $b + d + f = 1$. Recognizing that distance between the measured stage height (Y_s) and the water level where the river ceases to flow (Y_c) is the maximum river depth, the coefficients $\hat{a}$ and a only differ from each other by the ratio of the maximum depth and the mean depth $\left(\frac{\hat{a}}{a} = \frac{Y_s - Y_c}{\bar{Y}}\right)$ and $\hat{b} = b$.

Dingman (2007) demonstrated that the AHG relationships are consistent with theoretical derivation of these relationships by applying power law ($y = \alpha w^{\beta}$) functions to the idealized channel shape in the Manning or Chezy flow equations (Fig. 13.4). This finding suggests that channel geometry can be inferred from AHG relationships such as discharge stage height rating curves.

River discharge is regarded as the most accurately measured component of the hydrological cycle due to the extensive field surveys (Fekete 2012; Hannah et al. 2010). The USGS normally aims to maintain 5% accuracy (Rantz 1982a), but 10% is the widely accepted accuracy of most discharge gauges (Hannah et al. 2010).

Di Baldassarre and Montanari (2009) proposed a comprehensive evaluation framework applying HEC-RAS 1D (US Army Corps 1995) channel flow modeling software to assess the impact of uncertainties in the hydrographic field

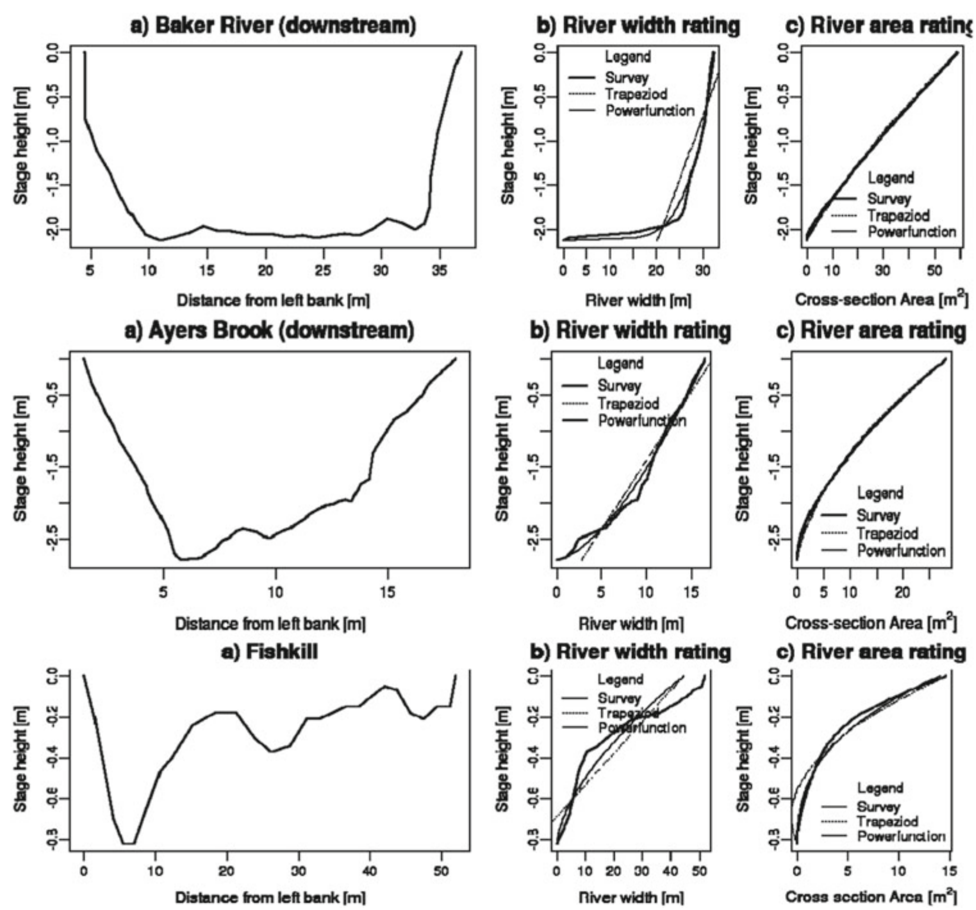


Fig. 13.4 River cross-sections and the corresponding depth/width (the symmetric equivalent of he real channel) and depth/cross-sectional area relationships

surveys in the Po river on the monitored discharge and concluded that the various uncertainties including hysteresis could lead to discharge measurement errors in a range between 6.5 and 42.8% with 25.6% average.

The challenge for hydrographers is to minimize those uncertainties and identify stable river cross-sections, where discharge can be measured more accurately. Undeniably, the discharge measurements accuracy deteriorates under extreme conditions such as unstable channels, ice coverage, braided streams, etc.

Alternative solutions that focus on substituting the relatively inexpensive stage height monitoring, without sufficiently addressing the river channel surveys, are likely to further degrade the accuracy of the discharge measurements (Fekete et al. 2012).

Advocates of developing remote sensing alternatives to traditional discharge monitoring like to point out that "In situ *methods essentially provide a one- spatial-dimension, point-based view of water surfaces that is appropriate in situations where a well-defined channel boundary confines the flow but not in more complex riverine environments*" (Alsdorf et al. 2007). Discharge changes gradually along the river (Fig. 13.5) since it is an integrated signal of the hydrological processes upstream, and a small change in the monitored area has little impact on the discharge itself, except at the confluences of major tributaries. Hydrographers have considerable flexibility in locating the best locations for in situ monitoring sites, while the complex riverine environments remain a challenge for both in situ and remote sensing solutions.

Given the ±5–10% accuracy of the discharge measurements, capturing the discharge changes along the river's main channel can be better accomplished by monitoring the incoming tributaries (that are easier to survey) instead of measuring discharge before and after the tributary confluence, where the difference could be below the measurement accuracy (Fekete et al. 2012).

Modern stage height recording instruments allow for continuous observations in time. This is important for rapidly changing discharges, even if longer term averages (e.g. weekly or monthly means) are sufficient for certain water management applications (Fig. 13.6).

13.2.1.2 Stage Heights in Lakes and Reservoirs

Similar to river channels, water levels in lakes and reservoirs have limited value for water managers without bathymetric information that relates water surface elevation to storage. The bathymetries of newly constructed reservoirs should exist from the planning stage, since topographic surveys are necessary for the design, but reservoir operators' willingness to share such information is limited. Lake bathymetries are more problematic since traditional lake surveying would require deploying boat(s) with sonar instruments to map the lake bottoms.

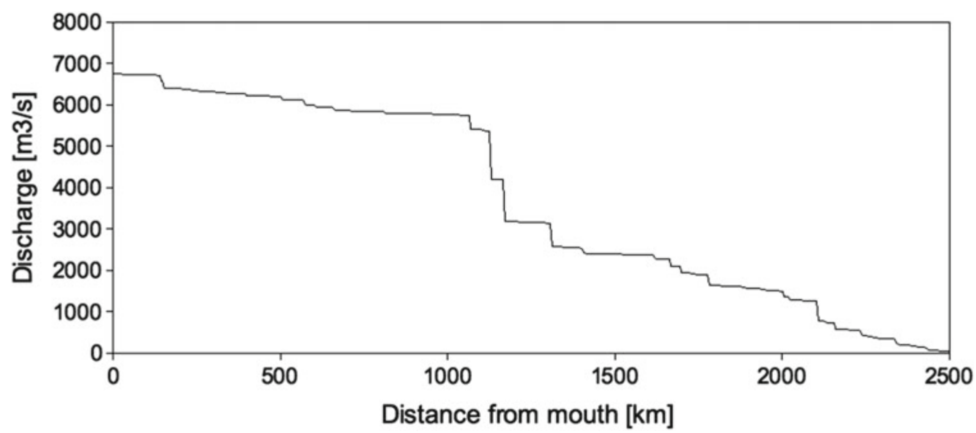


Fig. 13.5 Mean annual discharge profile of the Danube along its mainstem from headwater to river mouth

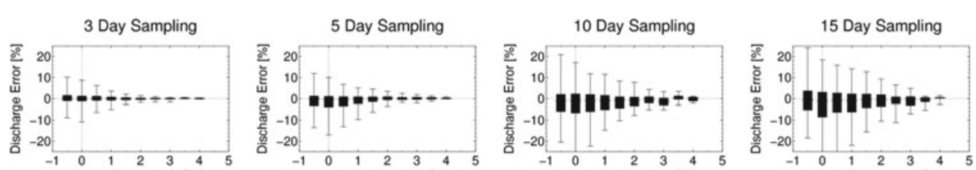


Fig. 13.6 The degradation of the mean annual discharge computed for a range of rivers of different sizes. The discharge error shows the difference between the mean annual discharge computed from daily values contrasted with 3, 5, 10 and 15 day sampling

The surrounding topography appears to be a good indicator of the lake/reservoir bathymetry. The hypsometric curves (depth/area relationships) in lakes and reservoirs follow similar power relations as riverbed geometries (Magome et al. 2002). The area encapsulated by the hypsometric contours around lakes, and their corresponding elevations above the water surface, can be used to estimate the depth/area relationship that can be applied below the water surface.

The large number of lakes, particularly at higher latitudes, that are the reminiscences of the last glaciation makes ground monitoring extremely difficult. Unlike river discharge that is better suited for in situ monitoring, lakes and reservoirs are better targets for remote sensing.

13.2.1.3 Groundwater Levels

Groundwater is the primary interest for many small scale hydrological analyses, therefore its monitoring is normally implemented on a somewhat “ad hoc” manner where groundwater resources are of elevated interest. IGRAC, the International Groundwater Resources Assessment Centre, a UNESCO center working under the auspices of WMO and supported by the Government of The Netherlands, hosts the Global Groundwater Information System (GGIS)[4]. Besides the collection of globally available data, it also contains more detailed national and regional modules, as well as a review of potential sites for Managed Aquifer Recharge.

Systematic regional groundwater monitoring is rare, even in well monitored countries such as the United States, where a National Ground Water Monitoring Network (NGWMN) was initiated only very recently (ACWI 2013). India appears to be more advanced in this respect and its Central Groundwater Board, within the Ministry of Water Resources, produced comprehensive assessments of the groundwater resources (Fig. 13.7) based on in situ groundwater monitoring data (CGWB 2006) with temporal updates (CGWB, 2011, 2014).

Perhaps the biggest obstacle in groundwater monitoring, beyond drilling monitoring wells and operating water level sensors, is the lack of detailed geological information about the aquifers (depth, porosity, water permeability, etc.), essential for the utilization of the groundwater level data. Aquifer maps are often only qualitative, offering general description and extents of major aquifers (e.g. Map of the Principal Aquifers of the United States (USGS 2003).

[4]https://www.un-igrac.org/global-groundwater-information-system-ggis.

13.2.1.4 Evapotranspiration

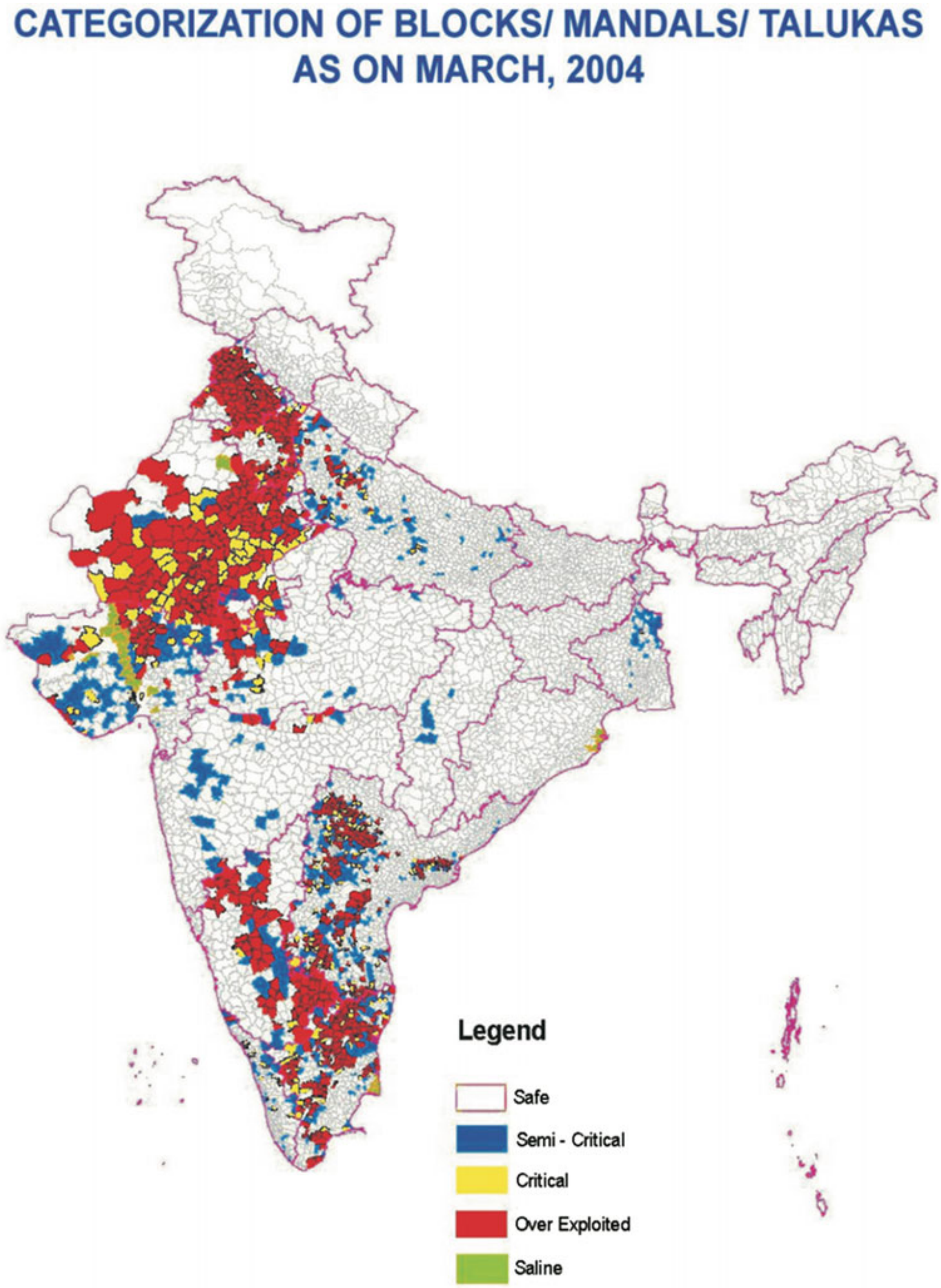
In water-controlled ecosystems there are complex interrelationships between climate, soil and vegetation, with evapotranspiration (*ET*) as a key variable connecting energy and water budgets. Evapotranspiration is essential for estimating water demands over rainfed and irrigated areas, determining moisture stress often quantified as the ratio between actual evapotranspiration and the potential value (*PET*) (Jackson et al. 1981), assessing drought conditions (Anderson et al. 2007; Bastiaanssen et al. 2002; Chandrapala and Wimalasuriya 2003), planning irrigation schedules (Garatuza-Payan and Watts 2005, 2005; González-Dugo et al. 2009; Rossi et al. 2010), analyzing the health status of the ecosystem (Andreu et al. 2019, 2018) and analyzing irrigation productivity and performance (Akbari et al. 2007; Bastiaanssen et al. 1999; González-Dugo et al. 2009).

Given the high variability of soil moisture in space and time, and the heterogeneity of terrestrial ecosystems (e.g. semiarid savannas or mosaic crop landscapes), direct evapotranspiration measurement techniques (such as lysimeters or pan evaporation devices) are often not representative for large areas. The integration of earth observation (EO) data into process-based land models enables the spatial mapping of evapotranspiration (*ET*) and the temporal tracking of environmental conditions (Andreu et al. 2018). Remote sensing data allows better representation of vegetation and soil heterogeneity, while capturing local conditions. The resulting data products, ranging from field scale studies to regional and continental areas, are more useful for management purposes. The representativity and footprint of the in situ measurements, the resolution of the remote sensors, and the up-/down-scaling of the ecosystem parameters, will be crucial for the precision of the results. The integration of remote sensing information into evapotranspiration (*ET*) estimation techniques is discussed in Sect. 13.2.2.

From the physical perspective, evapotranspiration can be divided into evaporation and transpiration (Fig. 13.8). Evaporation is the vaporization of water from surfaces or from the soil to the atmosphere, while the water evaporated through the plant stomata is the transpiration. In practice it is often difficult to separate them, as both are affected by the canopy structures. Nevertheless, regarding agricultural management, water losses supporting plants’ growth must be isolated from other surface evaporation.

Evaporation and transpiration take place simultaneously, and their relative proportions vary according to the growth state of the canopy and soil-water status. For example, evaporation dominates in the first phase of an annual grass growth, due to the exposure of bare soil. As the canopy is developing, the grass will gradually cover most of the soil surfaces and water losses will be mostly due to transpiration.

Fig. 13.7 Groundwater resources of India according a government study



The evapotranspiration process requires energy, called latent heat flux (L_{ET}), that is dominantly provided by incoming shortwave solar radiation and to a lesser extent by longwave radiation from the soil surface and the surrounding air. Vaporization is controlled by the vapor pressure deficit of the air above the surface (that determines its capacity to hold more vapor, depending on the air temperature), and the turbulent exchanges that enable eddies to take wet air away while bringing drier air, greatly depending on wind speed) (Penman 1947).

Transpiration adds additional constraints, since plants can control the opening of their stomata (pores on the leaf surface and sometimes over stems) through which water vapor, carbon dioxide needed for photosynthesis, and oxygen from respiration, can circulate (Brutsaert 2010). The vapor pressure gradient between the intercellular space air and the atmosphere is the force that drives the water vapor through the stomata. Plants can also close or open their stomata to control the water exchange and, regulate their temperature. Some vegetation used to water stress. For example, oaks over Mediterranean climates such as evergreen oak (Quercus Ilex) or blue oak (Quercus douglasii) will close stomata at dry conditions and high temperatures even with high vapor pressure

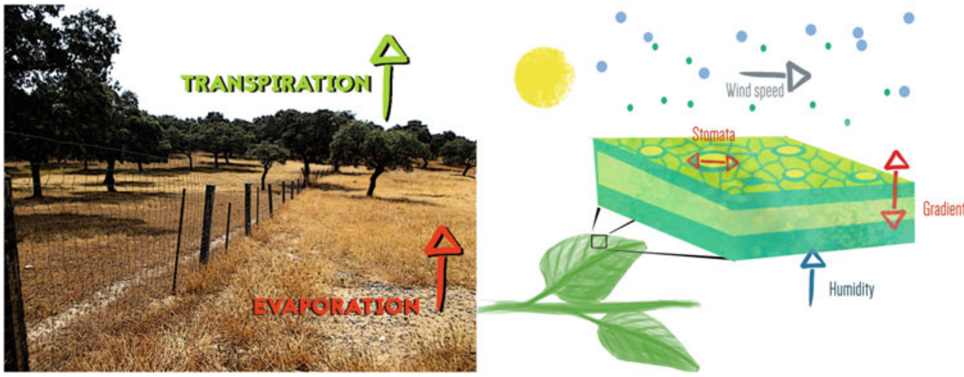


Fig. 13.8 **a** Evapotranspiration process. **b** Factors determining transpiration. *Source* Andreu et al. (2017). TIGER Savanna Tool Handbook: On Remote Sensing of Water Use and Water Stress in African Savanna Ecosystems from Local to Regional Scale

deficit (higher atmospheric water demand), as a water conservation strategy.

It is not easy to measure evapotranspiration directly, but it is possible tracking the water fluxes in a heavily controlled environment (evaporation pan or lysimeter) and computing the water losses. Indirect methods consider the relationships between evapotranspiration and various physical parameters that can be measured directly. Both methods are dependent on meteorological and/or surface factors that affect the water vapor exchanges (Rana and Katerji 2000). The meteorological factors include solar radiation, wind speed, and thermodynamic characteristics of the air above the vaporizing surface (Rana and Katerji 2000). The surface dependent factors are water content of the soil and surface characteristics such as albedo (amount of incoming shortwave solar radiation reflected by a surface), canopy density and height, surface roughness etc.

The evapotranspiration measuring approaches for field surveys can be grouped into three categories, (i) water balance methods, (ii) micrometeorological flux measurement methods and energy balance and (iii) plant physiology methods (Rose and Sharma 1984).

Water Balance Methods

The Soil-Water Balance method is an indirect measurement, where evapotranspiration (ET) is obtained as a residual term by measuring the remaining balance components, determined in the root zone of the soil at regular intervals. The water inputs are precipitation (P), irrigation (I) in the case of irrigated crops, and the upward contribution from the water table (W); while the output fluxes are surface runoff (R), and deep percolation (D). Subsurface fluxes are usually neglected; however, they should be considered in areas with high gradients. Runoff term in arid and semiarid areas with low slopes can also be neglected (Holmes 1984). The factors influencing the water exchange at the soil are the soil physical properties, vegetation characteristics, and climate patterns.

Lysimeters are isolated soil tanks (Fig. 13.9) located in the field, with a canopy structure (fractional cover, height, etc.) and management (irrigation schedule, cover crop, etc.) similar to the surrounding area, in order to be representative of the natural conditions (Aboukhaled et al. 1986). Conceptually lysimetry is a direct method based on conducting a water balance over a controlled system, where all the components are measured and evapotranspiration is calculated as the water weight gain or loss at the instrument, the mass exchange obtained as a continuous monitoring of the tank weight (Sharma 1985). Lateral fluxes, percolation and capillary are negligible due to the isolation of the root.

Energy Balance Methods and Micrometeorological Techniques

In contrast with the water balance, this method tracks the energy available for evaporation (latent heat flux) in a system comprising the vegetation, the soil surface and the atmosphere. Conservation of energy dictates that the amount of energy reaching a surface must be the same as the energy leaving the surface in a given period of time (Fig. 13.10). Taking into account only the vertical fluxes and neglecting horizontal heat advection, the simplified energy balance can be expressed as:

$$R_n - G - L_{ET} - H - F - \frac{dS}{dt} = 0 \qquad (13.5)$$

where $R_n\left[\mathrm{Wm}^{-2}\right]$ is the net short-wave and longwave radiation reaching the surface; $G\left[\mathrm{Wm}^{-2}\right]$ is the soil heat flux exchange by conduction into the soil; $L_{ET}\left[\mathrm{Wm}^{-2}\right]$ is the latent heat of evapotranspiration, $H\left[\mathrm{Wm}^{-2}\right]$ is the sensible heat flux, the heat exchange by convection from the surface and the air above, photosynthesis $F\left[\mathrm{Wm}^{-2}\right]$ representing 2–

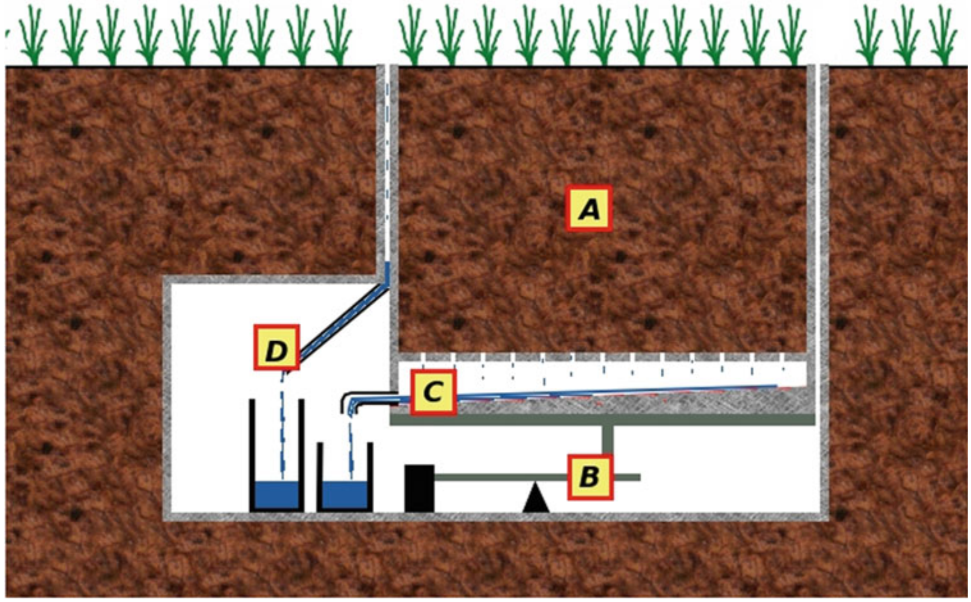


Fig. 13.9 Schematic representation of a weighing lysimeter. **a** is controlled soil column with canopy. **b** is scale measuring the soil column, both the solid material in the soil and the canopy and the water percolating through the soil column. **c** is the water outflow from the soil column. **d** is water input (precipitation and/or irrigation) reaching the lysimeter's tank

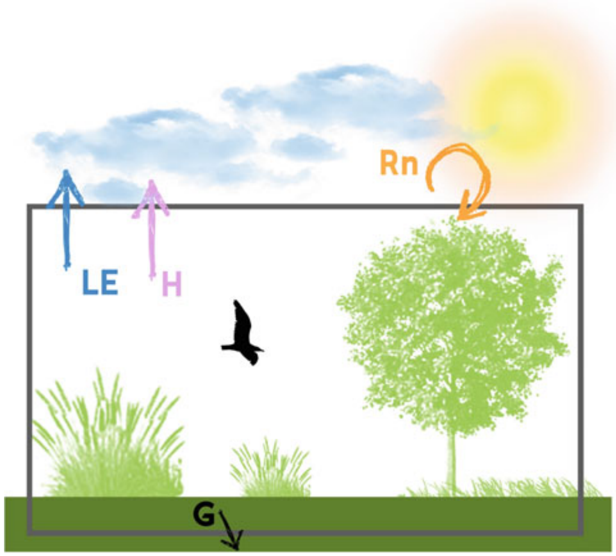


Fig. 13.10 Surface energy balance fluxes scheme. *Source* Andreu et al. (2017). TIGER Savanna Tool Handbook: On Remote Sensing of Water Use and Water Stress in African Savanna Ecosystems from Local to Regional Scale

3% of the net radiation is often neglected, and the energy storage change ($\frac{ds}{dt}$) within the system S is usually just considered in forest ecosystems with tall vegetation (Foken et al. 2006; Hillel 1985; Meyers 2004; Wilson et al. 2002). These energy balance components are measured over the field using a range of sensors: radiometers to measure the radiation budget, soil heat flux plates to account for the soil heat flux, etc. These flux measurements are relatively simple and inexpensive. Direct measurements of H (sensible heat) and/or L_{ET} (turbulent fluxes) are more complex and require high frequency data. Different techniques are described below, being the most widely used the eddy covariance technique.

The latent heat of evapotranspiration L_{ET} $\left[\mathrm{Wm^{-2} \equiv Js^{-1}m^{-2}}\right]$ is related to the rate of evapotranspiration $ET\left[\mathrm{lm^{-2}s^{-1} \equiv mms^{-1}}\right]$ as $L_{ET} = \lambda\rho E_T$, $\lambda_v\left[\mathrm{Jkg^{-1}}\right]$ is the latent heat of vaporization where $\rho[\mathrm{kg\ m^{-3}}]$ is the density of water. The amount of energy needed for phase change from liquid to vapor is dictated by the latent heat of vaporization/condensation ($\lambda_v\left[\mathrm{Jkg^{-1}}\right]$, where vaporization takes energy and condensation releases the same amount) that follows the following empirical relationship for liquid water as a function of the evaporating surface's temperature ($T[°\mathrm{C}]$ in between $-25\,°\mathrm{C}$ and $40\,°\mathrm{C}$):

$$\lambda_v = 2.5008 \times 10^6 - 2.36 \times 10^3 T + 1.6T^2 \qquad (13.6)$$

For sublimation and deposition ($\lambda_{ice}\left[\mathrm{Jkg^{-1}}\right]$, when solid ice directly turns into vapor and vice versa) the following empirical equation is more appropriate for evaporating surface' temperatures ($T[°\mathrm{C}]$) between $-40\,°\mathrm{C}$ and $0\,°\mathrm{C}$:

$$\lambda_{ice} = 2.8341 \times 10^6 - 0.29 \times 10^3 T + 0.4T^2 \qquad (13.7)$$

Direct sublimation is typically negligible and solid water normally warms up to freezing temperature dictated by the heat capacity of the ice ($c_{ice} = 2.108 \times 10^3[\mathrm{Jkg^{-1}\,°C}]]$) before the melting starts. The latent heat of fusion $\lambda_f = 0.334 \times 10^6\left[\mathrm{Jkg^{-1}}\right]$ is a constant (independent of temperature since fusion takes place at freezing temperature ($T = 0\,°\mathrm{C}$). At freezing temperature $\lambda_{ice} \approx \lambda_v + \lambda_f$ (Eqs. 6–7).

For measuring turbulent fluxes (just H, or both L_{ET} and H) the following systems are available:

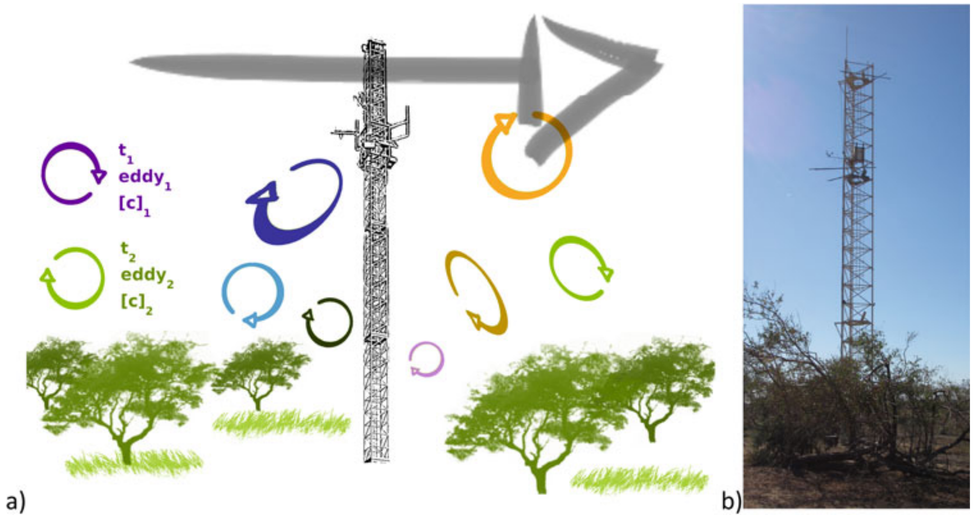


Fig. 13.11 **a** eddy covariance tower system scheme. *Source* Andreu et al. (2017). TIGER Savanna Tool Handbook: On Remote Sensing of Water Use and Water Stress in African Savanna Ecosystems from Local to Regional Scale. **b** an eddy covariance tower (ECT) system located in Skukuza, South Africa (*Source* Ana Andreu, field campaign experimental areas of CSIR, SA)

1. *Eddy covariance systems (EC)*: (Fig. 13.11) measure latent (L_{ET}) and sensible (H) heat fluxes, and CO_2 or other gases depending on their configuration. EC technique has become standard for direct *ET* measuring. The methodology is highly reliable (Burba and Anderson 2010), but the instrumentation is relatively fragile, expensive, and complex to operate, it requires regular maintenance, and the post-processing of the data is intensive.
   The method is based on the covariance between the fluctuations of the speed of the vertical air movement, the upward and downward eddies, and the concentration of interest (temperature, gas and water vapor concentration, etc.) (Figure 13.11a). The turbulent eddies carry water vapor (and the corresponding latent heat content) and sensible heat upward, and bring down dryer and colder air from upper atmospheric layers. Measuring differences in humidity and temperature of the upward versus downward moving air masses or any other constituents allows the estimation of the vertical fluxes. Since the turbulent fluctuations are very fast, temperature, wind velocity, and humidity changes have to be measured at high sampling rates ranging between 5 and 20 Hz frequency. The high frequency wind speed and sonic temperature is measured with three-dimensional sonic anemometers, water vapor can be measured by means of a quick response hygrometer or, together with carbon dioxide and/or methane, N_20 or other gases, using gas analyzers.
   The major assumptions made by this method are that: (a) the measurements at one point represent an upwind area and are assumed to be made within the boundary layer of interest, (b) the fluxes are measured only in the area of interest, (c) the flux is fully turbulent, and (d) the terrain is horizontal and uniform, which means that the average fluctuation is zero. This implies that field sites need to meet a number of conditions such as gentle slopes, sufficient undisturbed, homogeneous surrounding (fetch) area (maintaining uniform wind conditions) around the instruments, etc. The height at which the sensors must be placed depends on the height of the vegetation, the extent of the fetch and footprint, and the frequency response of the instruments. Most of the contribution usually comes from the area located between the underneath of the tower and the end of the fetch, and a number of models to evaluate the footprint contribution are available (Hsieh et al. 2000; Kormann and Meixner 2001; Schuepp et al. 1990; Soegaard et al. 2003).
   Eddy towers often underestimate the turbulent latent and sensible heat fluxes ($L_{ET} + H$) compared to the available energy (net radiation minus the heat flux into the soil $R_n - G$), with average closure errors around 20–30% (Foken 2008; Franssen et al. 2010; Twine et al. 2000; Wilson et al. 2002). Possible reasons are the influence of the horizontal advection, heat storage in the canopy, flux divergences, photosynthesis, errors in the measurement of the incoming and outgoing radiations and heat conduction into the soil, frequency response of the sensors, measurement errors on turbulent fluxes, and separation of the instruments. FluxNet, a network of networks for CO_2, water vapor and energy flux data, was created as a worldwide database of individual and regional networks (Baldocchi et al. 2001), with more than 500 long-term micrometeorological tower sites covering various types of canopy covers.
2. *The Bowen ratio (B)* energy balance (BREB): measures the ratio between sensible heat and latent flux. It is an indirect micrometeorological method (Bowen 1926) that solves the energy balance equation by measuring air temperature and vapor pressure gradients in the

near-surface layer above the evaporating surface. The Bowen ratio has proved to be an accurate method in semi-arid environments and tall crops (Cellier and Brunet 1992; Dugas et al. 1991; Frangi et al. 1996). It does not require information about the aerodynamic characteristics of the canopies, but it may result in evapotranspiration values without physical meaning when BREB $\sim(-1)$.

3. *Scintillometry*: uses an optical device, called scintillometer, that measures small fluctuations of the air refractive index caused by temperature, humidity, and pressure-induced variations in density. Current scintillometers measure sensible heat flux and obtain evapotranspiration as a residual, being measurements of the net radiation (R_n), and soil heat (G) fluxes also required (De Bruin 2008; Hartogensis et al. 2003; Meijninger et al. 2002; Meijninger and de Bruin 2000).
4. *Surface renewal*: is a less expensive scalar based agrometeorological method, where the sensible heat flux density is obtained by means of fine wire thermocouples that measure high frequency air temperatures at the surface-atmosphere interface. The method requires a calibration with a sonic anemometer (Kyaw Tha Paw et al. 1995; McElrone et al. 2013; Shapland et al. 2012).

Plant Physiology Approaches

The chamber system (Reicosky and Peters 1977; Wagner and Reicosky 1996) and sap flow (Cohen et al. 1988) are the most widely used plant physiology methods (Rana and Katerji 2000). Both are based on analyzing water behavior of individual plants, attending to their physiology. Chamber systems consist of a plastic chamber where air is mixed continuously and vapor density is measured with infrared analyzers. The chambers are suitable for research studies on herbaceous crops, but also on orchard crops such as vines and olive trees (Katerji et al. 1994; Pérez-Priego et al. 2014). The sap flow method assumes that this flow is directly related to the transpiration rate, requiring individual measurements to be extrapolated to the scale of interest. Because the effect of evaporation from the soil is not assessed with this measurement, additional measurements are required in combination with sap flow to estimate total evapotranspiration if the canopy fractional cover is not full.

13.2.1.5 Soil Moisture

Soil moisture or volumetric water content (θ) is the ratio of the water volume with respect to the volume of the soil, that determines the pressure head or specific tension ($\psi(\theta)$ [kPa]) in the soil. The maximum amount of water that the soil can hold after excess water has drained due to is the field capacity (θ_{fc}), at which the change in pressure head balances out the gravitational force ($d\psi(\theta) = \rho_w dz$, ρ_w is the density of water) (Dingman 2015). Drainage never stops entirely from wet soil therefore, field capacity ($\theta_{fc} = \theta(\psi_{fc})$) is often defined by a critical specific tension or pressure head ($\psi_{fc} = -33$ [kPa]) at which the drainage is negligible. The relationships between specific tension and soil moisture ($\psi(\theta)$ [kPa]), and its inverse relating soil moisture to specific tension ($\theta(\psi)$), are intrinsic properties of the soil that depend on the grain size distribution (that is normally characterized by the clay, silt and sand fractions), the compactness of the soil, and to a lesser degree its chemical composition.

A plant can only access the water content of the soil if the specific tension does exceed a critical negative pressure (suction that the plant would need to exert). While this threshold varies by plants for hydrological purposes the $\psi_{pwp} = -1460$ [kPa] is the accepted constant and $\theta_{pwp} = \theta(\psi_{pwp})$ is called the permanent wilting point. From plant physiology perspective the water content between field capacity and the permanent wilting point $\theta_a = \theta_{fc} - \theta_{pwp}$, called available water capacity, is an important characteristic of the soil that determines the amount of water that the soil column can hold, to support the canopy during dry periods.

The most accurate measurement of soil moisture requires sampling the soil and measuring the sample volume and the wet, oven dry, and fully saturated weights of the sample. The difference between the saturated and oven dry weights, divided by the density of water, allows the measurement of the pore spaces (V_s) in the soil sample. The difference between the wet and the oven dry weights, divided by the density of water, provides the water volume (V_w) in the sample. The volumetric water content can be computed as $\theta = \frac{V_w}{V_s}$.

Collecting samples and performing laboratory measurements are impractical for soil moisture monitoring, therefore a number of indirect measuring techniques were developed, applicable to field scale observation. Perhaps the most obvious choice is the installation of tensiometers that can measure the specific tension in the soil, that can be related to the soil water content. Since specific tension expresses the force the plants need to exert in order to extract water from the soil, the specific tension is more relevant for plant physiology than the volumetric soil moisture.

Electrical resistance block uses the inverse relationship between electrical resistance and water content. The electrical resistance is measured in a porous material (gypsum, nylon or fiberglass) placed in the soil, so its water content equilibrates with the surrounding soil. Similarly to the electrical resistance, the electrical capacity or electromagnetic inductivity can also serve as an indicator to the soil wetness. Electromagnetic induction instruments are particularly useful in field measurements, particularly when they are linked to global positioning systems, as they can cover large areas. Heat pulse sensors measure the heat conductivity of the soil, producing heat pulses and measuring the propagation of the heat from the heater to the head sensor (Dingman 2015).

The main challenge collecting soil moisture data is the representativeness of the measurements for larger domains, that requires the deployment of a great number of sensors, distributed both spatially and vertically in a soil column, since soil moisture can vary significantly in both horizontal and vertical dimensions.

Fiber-optic cables of 10,000 m can be used as temperature sensors down to 1 m spatial intervals due to the Raman scattering. Raman Stokes and anti-Stokes photons that arise from collisions with electrons in the core glass fiber have different thermal sensitivity, therefore the ratio of the backscattered Raman Stokes and anti-Stokes is an indicator of the temperature at the location where the collision happened. The travel time of the returning signal pulse allows to determine the positioning of the collision within the optical cable, which is the basis of the fiber optic Distributed Temperature Sensing (DTS) (Dingman 2015; Sayde et al. 2010).

Ground penetrating radar transmits pulses of radio (1 Mz–1 GHz) signals and relates the reflected electromagnetic waves to volumetric water content in the soil columns up to tens of meters. The elapsed time between the emitted radio signal and the returning echo allows to position where the reflection of the radio signal occurred.

13.2.2 Remote Sensing of Water Quantity

Remote observation techniques of Earth's surface are essential tools for monitoring ecosystems and evaluating management strategies in many sectors, such as agriculture, forestry, weather forecasting, or land-use policy (Alcaraz-Segura 2014). Satellite-based earth observations are particularly attractive since they provide continuous observations over large domains, with various temporal, spatial and spectral resolutions. The immediate transmission, digital format, and the open accessibility of some of these data (e.g. Sentinels missions from the European Space Agency, or Landsat series and Earth Observing System (EOS) from NASA), make them essential to evaluate ecosystems functioning. In countries with compromised access to observational records—due to scarce and unreliable monitoring infrastructure as result of lacking expertise and financial resources to operate them—remote sensing offers alternative means to assess water resources (Sheffield et al. 2014). However, the existence of these data sources has not necessarily resulted in benefits for the civil society. They have to be processed and analyzed, using complex statistical approaches and modeling techniques, in order to derive information that can be used by stakeholders. Thus, the linkages between the public and private sectors, and the end users must be reliable and robust, and the characteristics of the new missions and final products must be determined by the society needs.

The first Earth orbiting satellite (the Vanguard II) was launched in 1959, partly driven by the space race between the United States and the Soviet Union, followed by the first low Earth orbital weather satellite (TIROS-1), since meteorology was deemed to benefit the most from satellite observations. The first Earth Resources Technology Satellite (ERTS I) was launched in 1972, which was renamed to Landsat missions in 1975. The Landsat program is the longest running satellite acquisition system, which is still operational with its latest satellite Landsat 8, launched in 2013.

Despite more than half a century history, some practitioner still advocates satellite remote sensing as an emerging new technology, while a large portion of the satellite assets are still operated as experimental missions. For instance, considering the United States spending on satellite missions, the National Oceanic and Atmospheric Administration (NOAA) has only 50% more budget for its largely operational satellite program than the National Aeronautics and Space Administration (NASA) that mostly launches experimental satellites, therefore there is an approximately 60–40% split between investment in operational versus experimental satellites.

Given the long records of satellite remote sensing, it is time to approach them with maturity. Remote sensing has a proven record of providing high quality spatially specific data that are highly relevant to water managers, but experimental satellites are inappropriate for mission critical applications. Ensuring that a set of widely used satellite sensors are guaranteed to operate and replacement sensor are either already in place or rapidly deployed leaving minimal gap in the observational records is a must. Successful programs, like the Landsat or EOS satellites need continuation. The Landsat program faced potential cancelation ten years ago and the Aqua and Terra satellites of the EOS program has no replacement or the satellites that are meant to replace them are far less capable than the currently operating ones. Without guarantee that essential satellites and sensors are continuously operated, water managers need a precise assessment of the uncertainties and errors of the final products derived from Earth Observation data.

The vast majority of the remote sensing sensors rely on detecting emitted or reflected electromagnetic waves (Fig. 13.12) from the monitored object. The distinct spectral properties of water at various wavelengths in terms of absorption, emission, and reflectance, makes water surfaces

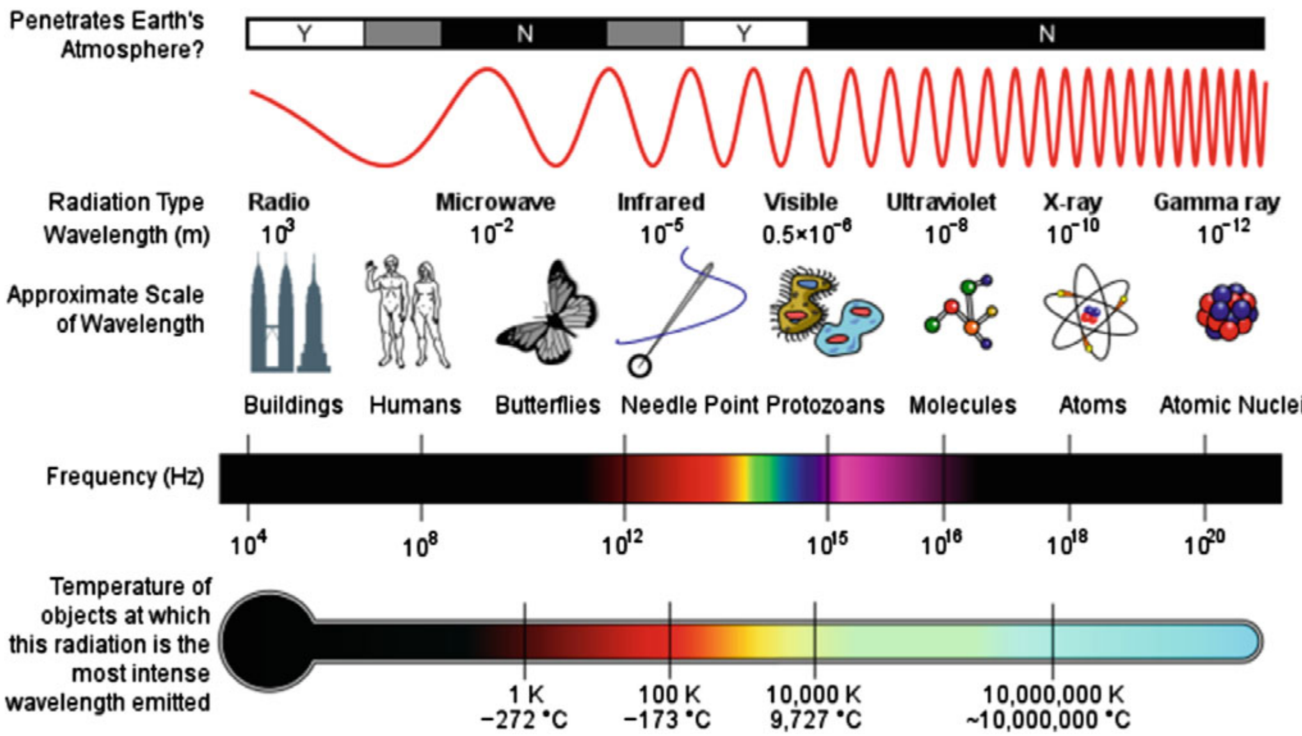


Fig. 13.12 The electromagnetic spectrum and their wave properties as a function of wave length

(and ice) good targets for remote sensing, allowing for example to quantify water masses or snow cover. Water cycle components such as soil moisture or evapotranspiration are more challenging, since remote sensing does not measure them directly, but they are inferred from other variables sensed by the sensor (surface temperature, reflectance in the near infrared, etc.).

13.2.2.1 Satellite Orbit Configurations

Satellites' orbits are dictated by the necessary balance between the centripetal forces, due to the circular motion of the satellite, and the gravitational pull between the satellite and the planet (Fig. 13.13). As a result, the angular velocity of the satellites is determined by their altitudes. The higher the orbit, the slower the satellite. For instance, a satellite that completes one orbit around the Earth in 24 h has to fly at 35,786 km (22,236 mi) of altitude, while a satellite at 705 km (438 mi) completes an orbit in approx. 99 min. High Earth orbit satellites placed over the equator in the same plane (0° inclination) will rotate at the Earth's angular velocity so they will stay over the same area, hence, they are called geostationary.

Geostationary satellites were first proposed by Herman Potočnik, and Arthur C. Clark (famous science fiction author) developed the idea further, demonstrating that three radio signal relaying satellites placed in geostationary orbits enable telecommunication between any two locations on our planet (Clark 1945). The high altitude of their orbits limits the acquisition of high resolution Earth observations, therefore they are primarily used for telecommunication and meteorological purposes, where the ability of continuously monitoring is more critical than the spatial resolution of the retrieved imagery. The new generation of geostationary satellites from NOAA, the GOES-R series, which entered service in 2017, allows image retrieving at resolutions never seen before.

Manned satellites, such as the International Space Station or NASA's Space Shuttle, orbit with steep inclination relative to the Earth's rotational axis, at 200–300 km altitude (where the Earth's atmosphere still provides the astronauts some protection against cosmic rays). Unmanned satellites normally fly at 500–700 km above the Earth's surface, where the atmosphere imposes less drag, often on near polar orbits (inclination around 90°).

The inclination of the satellites determines the highest latitude that the satellite can monitor. For instance, the Shuttle Radar Topography Mission (SRTM) that was carried out from the Space Shuttle only covers the Globe between 60°N and 60°S latitudes[5]. Satellites fly on near polar orbit to provide full global coverage.

[5]https://www2.jpl.nasa.gov/srtm.

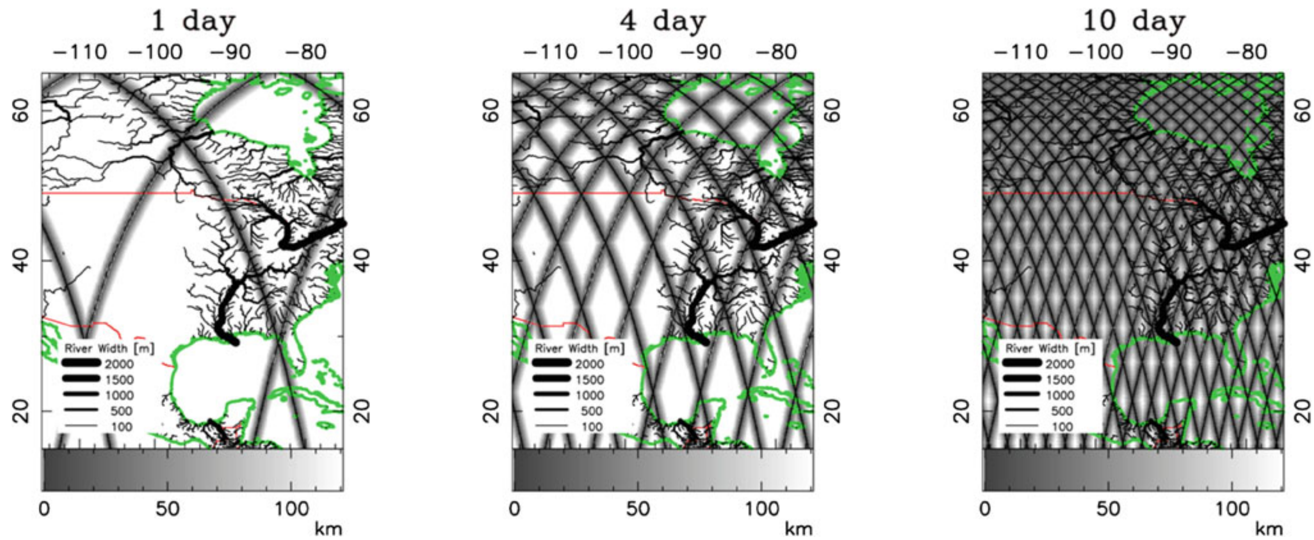


Fig. 13.13 Synthetic orbit configurations with different return frequencies and corresponding ground track distances

The satellite altitude dictates the number of orbits that the satellite can complete in 24 h. Satellites flying at 500–700 km altitudes can take 10–17 orbits per day. The number of orbits per day dictates the distance between ground tracks. For example, the Landsat 7 and 8 satellites that flies at 705 km altitude perform approx. 14.0625 orbits per day, so the distance between consecutive ground tracks at the equator is ∼2860 km.

The fractional part of the number of orbits per day results in a slight offset between the tracks on consecutive days, and the satellite returns to the same track only after several day orbits (Fig. 13.13). In the case of Landsat 7 and 8, this return period is 16 days. As a result, the satellite orbit produces $14.0625 \times 16 = 225$ tracks that are ∼178 km apart at the equator (so the satellite sensor, spanning that distance to produce full global coverage, has a viewing angle equivalent to a 140 mm telephoto lens of a 36 mm film camera). The Landsat 7 and 8 satellites cross the equator at the same time (sun-synchronous orbit) as a result of their 98.2° inclination, which is critical for reflected wavelengths to ensure that adjacent images taken on consecutive days have the same illumination from the Sun.

Low Earth orbiting satellites need to find a compromise between return frequency and track distance. Large ground track distance needs to use wide angle viewing sensors, that can be highly distorted at the edges. As an example, the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors flown on NASA's TERRA and AQUA satellites have a 2330 km swath (which is the equivalent of an 11 mm wide angle lens for 36 mm camera, known as fisheye lens in photography) with severe bow tie distortions[6].

The only way, to ensure smaller ground track distances while maintaining high return frequency, is the use of a constellation of satellites. In the case of the Landsat mission, the Landsat 7 and 8 satellites have an 8 day offset in their orbit, which halves the 16-day return period of the individual satellites. Sentinel missions from the European Space Agency (ESA) are designed as a two-constellation identical satellites, to increase the temporal resolution of their acquisitions, for example Sentinel-1 A and B, Sentinel-2 A and B, or Sentinel 3 A and B.

13.2.2.2 Imaging Sensors

Remote sensing sensors detecting emitted or reflected electromagnetic radiation could operate in a profiler mode (detecting only a transect of the electromagnetic radiation along the ground track of the satellite) or imaging mode (when the sensor scans a swath of area on either side of the sensor's nadir). Depending on the source of the detected electromagnetic radiation, the sensors can be active or passive. Active sensors such as radar and LIDAR emit radio or laser light signals, and detect the returning radiation. Passive sensors either detect the emitted electromagnetic radiation (typically thermal or radio wavelengths), or the reflected signals (visible, near infrared) from other sources (typically from the Sun).

LIDAR (as an active sensor) illuminates the target with a laser (light amplification by stimulated emission of radiation, accomplished by limiting the radiation to single wavelength and polarization, resulting in spatial and temporal coherent) pulses, and measures the time of the returning echo and the changes in wavelengths, allowing to build 3D-representations of the target.

[6]http://eoweb.dlr.de:8080/short_guide/D-MODIS.html.

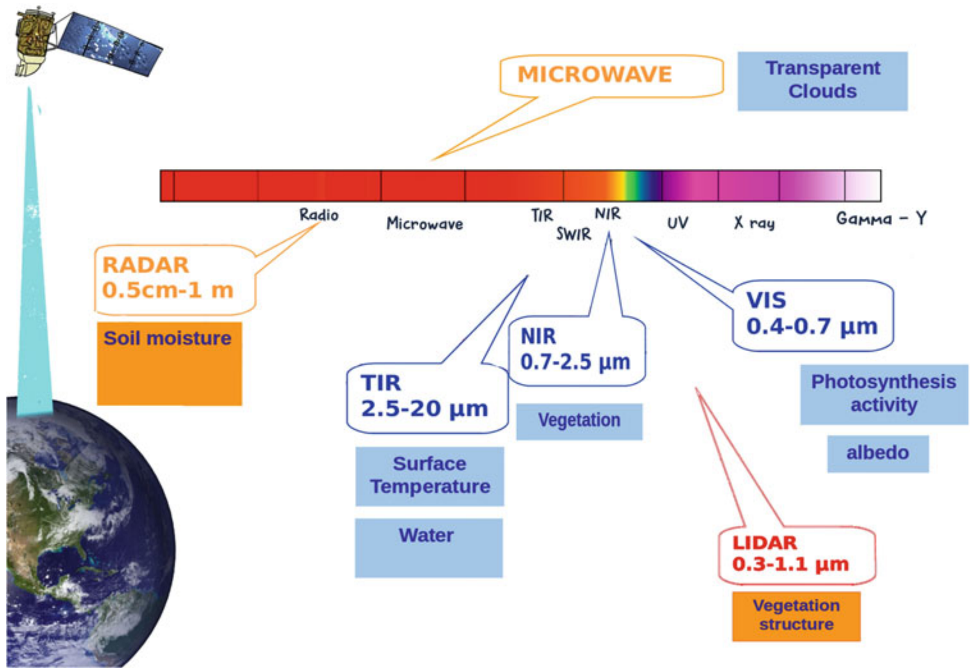


Fig. 13.14 Main applications of each spectral region. *Source* Andreu et al. (2017). TIGER Savanna Tool Handbook: On Remote Sensing of Water Use and Water Stress in African Savanna Ecosystems from Local to Regional Scale

Although the electromagnetic spectrum (defined by either wavelength or frequency, where the product of the wavelength and frequency is constant and equal to the speed of light) is continuous, remote sensing sensors only operate in specific ranges called bands, within which the radiation shows similar behavior. The most frequent regions of interest for water monitoring are the visible part of the spectrum (VIS, 0.4–0.7 µm) and the near-infrared (NIR, 0.7–1.3 µm) that are useful for discriminating canopy and detecting water surfaces; medium-infrared (SWIR, 1.3–3 µm), where reflectance of solar energy and emissivity from the surface are shown together; thermal (TIR, 3– 00 µm), which includes the emissivity portion of the spectrum in terms of ground cover temperature; and microwave bands (1 mm–1 m), radiation that can penetrate clouds. The different regions/bands have different applications, determined by their capabilities (Fig. 13.14).

The reflectance (the proportion of the incident energy reflected) as a function of wavelength gives the spectral signature, which is characteristic of each surface and state, enabling land uses, materials, canopy growth status, etc., to be discriminated and classified (Richards and Jia 2006). The spectral resolution of a sensor is the number, wavelength center, and width of spectral bands, that the sensor can discriminate and register, depending on the optical filter installed. The radiometric resolution is defined as the minimum quantity of energy that is needed to increase the pixel value by one digital number, and it is referred to as the sensor sensitivity.

Using simple numerical combinations of spectral information measured at different wavelengths, mostly the visible and near infrared regions of the spectrum, it is possible to extract information about the ecosystem, minimizing the perturbation caused by soil and atmospheric conditions (Huete 1988) and derive biophysical parameters describing the soil and canopy state, and dynamics, such as albedo, surface radiometric temperature, fractional cover (fc) and leaf area index (LAI) (Chuvieco and Huete 2010; Glenn et al. 2008; Moran et al. 1997). These combinations of spectral information that monitor vegetation status are called Vegetation Indices (VI), being the more widely used the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), or the Soil Adjusted Vegetation Index (SAVI). For water bodies monitoring, Water Indices has also been developed (as well as for fire or desertification monitoring), taking advantage of the regions of the spectrum useful to infer water characteristics, like the Normalized Difference Water Index (NDWI), the Modification of Normalized Difference Water Index (MNDWI) or the Automated Water Extraction Index (AWEI) (Feyisa et al. 2014; Gao 1996; McFeeters 1996). Early and late stages of plant water stress can also be detected by means of the thermal portion of the spectrum, due to the direct link between the transpiration process and the vegetation thermal response (Idso and Baker 1967).

The electromagnetic radiation that travels through the atmosphere is attenuated by absorption and dispersion processes. The absorption is defined as the transformation that the energy undergoes when it passes through a medium. A fraction of the energy is absorbed by the atmospheric components (O_2, CO_2, O_3 and water vapor) and emitted at different wavelengths. Sensors used in remote sensing are designed to operate outside the regions where absorption effects are the highest, in what are called atmospheric windows. The dispersion process produces a change in the direction of a portion of the incident radiation in relation to the original one, due to the interaction between the energy and the suspended atmospheric particles. To avoid the effects of these processes in the analysis it is necessary to correct the original data acquired by the sensor using various methods, according to the part of the spectrum of interest (Asrar et al. 1985; Gordon and Morel 1983; Kaufman and Sendra 1988; Lenoble 1993; Saunders and Kriebel 1988).

The World Meteorological Organization developed the Observing Systems Capability Analysis and Review Tool (OSCAR), which among other capabilities provides detailed information on Earth observing satellites, instruments, and a list of past, current, and future missions and satellites for earth observation and meteorological purposes[7]. Table 13.1. compiles and describes some of the principal satellites useful for Earth Observation purposes.

The satellite data volume produced daily (e.g. Sentinel 1 produces 1 TB of daily data, Sentinel 2 produces 1.3 TB of daily data) makes it difficult for the user to perform post-processing, as well as conduct processing chains that requires large computing capabilities. To overcome these limitations, several providers pre-process and offer these data in different platforms (Google Earth Engine, remote servers). European Space Agency (ESA) Thematic Exploitation Platforms (TEPs) are shared virtual environments to integrate diverse Earth Observation datasets (Copernicus and other sets), tools and simple functionalities, with the possibility to share the algorithms, products, findings and processing chains, creating long-term monitoring and mapping capabilities. They allowed the use of Big Data (high volume of data, different formats and sources, etc.) without the need of a deep computing knowledge, in a scientific community-based space matching the area of interest (e.g. hydrology, coastal zones, food security or forestry).

13.2.2.3 Altimeter Sensors

Satellite altimeters measure surface elevation, and with repeated overpasses at a given temporal resolution, variations in surface water levels can be monitored. The majority of these altimeters have been pulse-limited, operating at Ku- or Ka-band frequencies. Such instruments transmit a series of microwave pulses and record the two-way timing between pulse emission and echo reception. This enables the altimetric "Range" (distance between the antenna and ground) to be determined, from which the surface water level can be deduced with respect to a given datum. The early satellite-based LIDAR mission (ICESat) (Zwally et al. 2002), operated at 1065 and 532 nm (red and green) wavelengths, and also provided surface elevation measurements. The three onboard lasers however, proved problematic though and operations were restricted to certain months of each year over the lifetime of the mission (Table 13.1). Although the utilization of altimeters for recording surface water levels in rivers and lakes/reservoirs is being increasingly recognized, the primary objectives of each of the missions has focused on the monitoring of ocean surface levels, ice sheets and sea ice. As of 2017 there has been no mission dedicated to the recording of inland water levels, but the future multi-agency Surface Water and Ocean Topography (SWOT) mission has primary objectives to collect simultaneous inland water level and extent measurements, with the ultimate goal of creating river discharge and water storage variation products.

The current radar altimeter missions operate in a defined fixed (reference) orbit that results in a network of ground tracks across the Earth's surface. The instruments interpret the echoes along these ground tracks and the result are averaged elevation measurements within the instrument footprint, the effective diameter of which could be several hundred meters to several kilometers wide. The radar altimeter instruments are restricted to measuring surface levels at nadir, which is a severe limitation compared to imaging instruments and their designated spatial swaths. However, there are some advantages.

The instruments do operate continuously, providing water levels at a set spatial resolution along the ground track (typically every 290–670 m). They are also "all-weather" and day/night sensors, and have the ability to measure water surfaces under canopy or vegetation. Although surfaces can be complex and rapidly varying, each instrument employs its own set of surface tracking logic to quickly acquire and keep the "lock" on the surface. For example, the use of look-up Digital Elevation Models (DEM), and Détermination Immédiate d'Orbite par DORIS Embarqué (DIODE) functionality (Birkett and Beckley 2010), can greatly assist with the capture process. Post processing of the radar echoes to uniquely identify the inland water surface can also support water body identification, and water level extraction (Berry et al. 2005; Dubey et al. 2015; Sulistioadi et al. 2015; Troitskaya et al. 2012). Although, in some extreme cases, both on-board logic and post-processing fails to acquire the surface, and a set of factors (footprint size, data posting rate, terrain complexity) create higher uncertainties on what final water body size/width is achievable. Surface water level measurements derived

[7]https://www.wmo-sat.info/oscar/satellites.

Table 13.1 Principal satellites useful for Earth Observation purposes

Mission	Agency	Main purpose and Payload	Spatial resolution	Temporal resolution or/and repeat cycle	Time period
Meteorological					
GOES	NOAA NASA	Imager (NIR/VIS), Sounder (Atmospheric T° and moisture profiles, surface-cloud T°, O_3 distribution)	0.5–2 km		3rd G and R: 2006–present
MSG (8-11)	EUMETSAT, ESA	GERB (Earth Radiation Budget), SEVIRI (Spinning Enhanced VIS-IR)	1–3 km	15-min full disk	2002–present
NOAA (5th G)	NOAA	AMSU (Advanced Microwave Sounding Unit), AVHRR (Advanced Very High Resolution Radiometer), HIRS/3 (High resolution Infra Red Souncer)	AMSU: 48 km, AVHRR: 1.1 km, HIRS/3: 18 km	Near or global coverage once or twice/day	1998–2017
Resources satellites					
SPOT	CNES, Spot Image	High-resolution land and vegetation observation. HRV/HRVIR/HRG (VIS, NIR, SWIR, MS and PAN channels)	From 5 m (PAN) to 10–20 m (VNIR, SWIR)	26 days. Strategic pointing: 3 days.	1986–2015
MODIS AQUA, TERRA	NASA	Multi-purpose: Cloud, Ocean, Ice, Land. Moderate resolution optical imagery (VIS, NIR, SWIR, MWIR, TIR channels)	From 0.25 km (2 channels) to 1.0 km (29 channels)	Twice (long-wave) or once a day (short-wave)	2000–present
Landsat 4/5 TM	NASA	High resolution land and vegetation observation. TM (Thematic Mapper, VIS, NIR, SWIR, TIR)	TM: 30 m VNIR 120 m TIR	16 days	1982–2013
Landsat 7 +ETM	NASA	ETM+ (Enhanced Thematic Mapper + PAN,VIS,NIR,SWIR, TIR)	ETM+ : 30 m VNIR, 15 m PAN, 60 m TIR	16 days	1999–present
Landsat 8 OLI	NASA	OLI (Operational Land Imager, PAN,VIS, NIR,SWIR) TIRS (Thermal Infra-Red Sensor, TIR)	OLI: 30 m VNIR, 15 m PAN, TIRS 100 m	16 days	2013–present
Sentinel-1 (A,B) *	ESA	Land and Ocean monitoring. C-SAR (C-band Synthetic Aperture Radar)	5 × 5 m to 25 × 100 m (mode)	175 orbits in 12 days	A2014, B2016
Sentinel-2 (A,B)	ESA	High-resolution land vegetation. Hazards mitigation MSI: Multi-Spectral Imager (VIS/NIR/SWIR)	10 m, 20 m, 60 m, depending on channel	10 days (5 days with the 2 satellites)	A2015, B2017
Sentinel-3 (A,B) *	ESA	Ocean and land mission. DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite), LRR (Laser Retro-Reflector), MWR (Micro-Wave Radiometer), SRAL (Synthetic aperture Radar Altimeter), OLCI (Ocean and Land Colour Imager), SLSTR (Sea and Land Surface Temperature Radiometer)	MWR (20 km), OLCI (300 m), SLSTR: 0.5 km for short-wave channels and 1 km for long-wave SAR mode: 300 m × 1000	27 days OLCI and SLSTR, 2 days	A2016, B2018
ENVISAT *	ESA	Atmospheric chemistry, climatology, ocean, and ice. Land and vegetation observation. AATSR (Advanced Along-Track Scanning Radiometer), ASAR (Advanced Synthetic Aperture Radar C-band SAR), DORIS, GOMOS (Global Ozone Monitoring by Occultation of Stars), LRR (Laser Retro-Reflector), MERIS (Medium Resolution Imaging Spectrometer), MIPAS (Michelson Interferometer for ESA Passive Atmospheric Sounding Chemistry of the high atmosphere), MWR (Micro-Wave Radiometer), RA-2 (Radar Altimeter), SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography)	AATSR 1 km, MERIS 300 m MWR, RA-2 20 km	Within 1–3 days MWR, RA-2, 35 days	2002–2012

(continued)

Table 13.1 (continued)

Mission	Agency	Main purpose and Payload	Spatial resolution	Temporal resolution or/and repeat cycle	Time period
Radar and lidar altimeter missions: Enhanced instruments offer Delay-Doppler (DD) SAR and SARIn, or Radar Interferometry functionality. The spatial resolutions are a combination of conventional altimeter along-track data posting rates (e.g., 20, 40 Hz), SAR resolution cells, and the distance over which a set of pixels or laser shots are averaged (#)					
Mission	Agency	Main frequency/mode	Spatial resolution (m)	Temporal resolution (days)	Time period
TOPEX/Poseidon	NASA, CNES	Ku	580	10	1992–2002
Jason-1	NASA, CNES	Ku	290	10	2002–2008
Jason-2	multi	Ku	290	10	2008–2016
Jason-3	multi	Ku	290	10	2016–present
Sentinel-6 Michael Freilich	multi	Ku, DD/SAR	300 × 1000	10	2020–present
HY-2A	CNSA	Ku	290	14	2011–2016
Geosat	NRL	Ku	670	17	1986–1990
GFO	NRL	Ku	670	17	2000–2008
SWOT	NASA, CNES, CSA	Ka, Interferom.	<100#	~22	launch 2021
Sentinel-3A	ESA	Ku, DD/SAR	300 × 1000	27	2016–present
Sentinel-3B	ESA	Ku, DD/SAR	300 × 1000	27	2018–present
ERS-1	ESA	Ku	350	35	1992–1995
ERS-2	ESA	Ku	350	35	1995–2002
SARAL	ISRO/CNES	Ka	175	35	2013–2016
ICESat-1	NASA	laser 1064 nm	170	91	2003–2009
ICESat-2	NASA	multi-beam laser 532 nm	0.7–3.0#	91	2018–present
GEDI	NASA	multi-beam laser 1064 nm	TBD	TBD	2019–present
CryoSat-2	ESA	Ku, DD/SAR, SARIn	300 × 1000	369	2010–present

during winter ice/snow-covered periods can also be erroneous due to penetration of the radar pulses.

For the majority of the mission lifetime, the ICESat laser altimeter (the Geoscience Laser Altimeter System or "GLAS") operated at nadir, following a set of reference ground tracks though, unlike the radar altimeters there was some off-pointing capability. It also operated with a much smaller footprint (~70 m) allowing the acquisition of smaller reaches and lakes (Srivastava et al. 2013; Wang et al. 2013; Zhang et al. 2011). Echo saturation effects and dense clouds did hamper performance and restricted full continental coverage. Overall, both radar and lidar instruments have recorded water level variations with root mean square (rms) accuracies (when compared to co-incident in situ measurements) ranging from a few centimeters to several decimeters (Birkett 1998, 1995; Birkett et al. 2005).

In general, measurements have been obtained on river reaches several hundred meters wide, and on lakes/reservoirs in the >50 km^2 size range. However, the accuracy can be instrument dependent, and echoes post-processing is improving the range at these scales. With altimetric data sets spanning several decades, and temporal resolutions on the order of 10–35 days, these instruments have enabled the monitoring of seasonal and inter-annual water level variations, supplementing the in situ networks, and proving information where gauge deployment is difficult, or gauge data access delayed or denied.

It is important to stress that the requirements of the basic and applied science communities ensure continuity of the altimeter missions. The radar instrument-suites offer a set of 10 day or (approximately) monthly resolution measurements from 1992 or from 1994. The application of satellite radar altimetry in particular is a well-validated technique with mature data processing chains and data products. Several organizations are producing river reach and lake/reservoir surface water level products either in archive form (e.g., within the NASA PO. DAAC, Fig. 13.15), or within an operational service (e.g. within the NASA/USDA funded G-REALM program, Fig. 13.16). It is also worthy to note that the 25 year surface water level products for lakes/reservoirs has been recognized as a new Climatic Index, acting as a proxy measurement for precipitation (Birkett and Cretaux 2012).

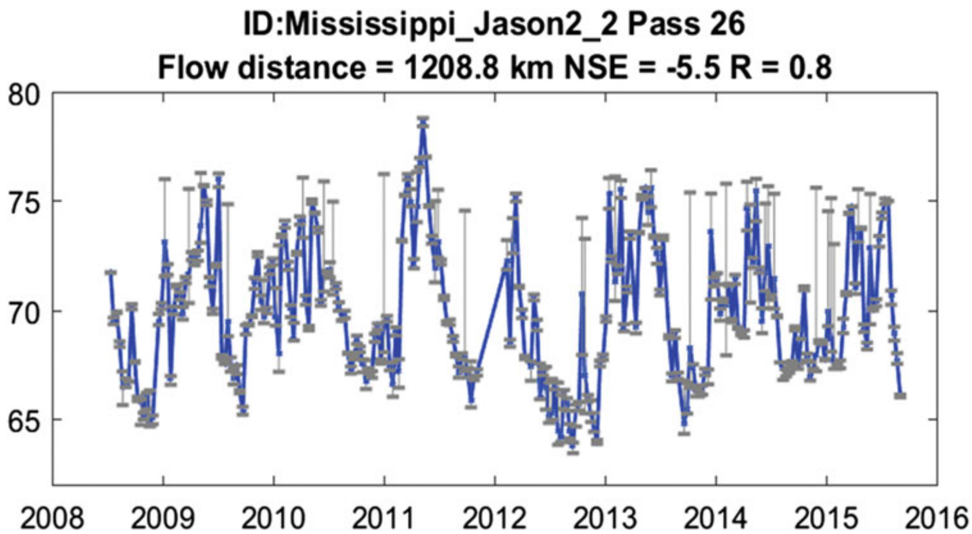


Fig. 13.15 Altimetric surface water level variations for a section of the Mississippi River as observed by the NASA/CNES Jason-2 satellite mission at 10-day temporal resolution. Figure courtesy of M. Durand personal communication and the NASA MEaSUREs Earth Science Data Records program. The products can be found archived at the NASA Jet Propulsion Laboratory: [8]

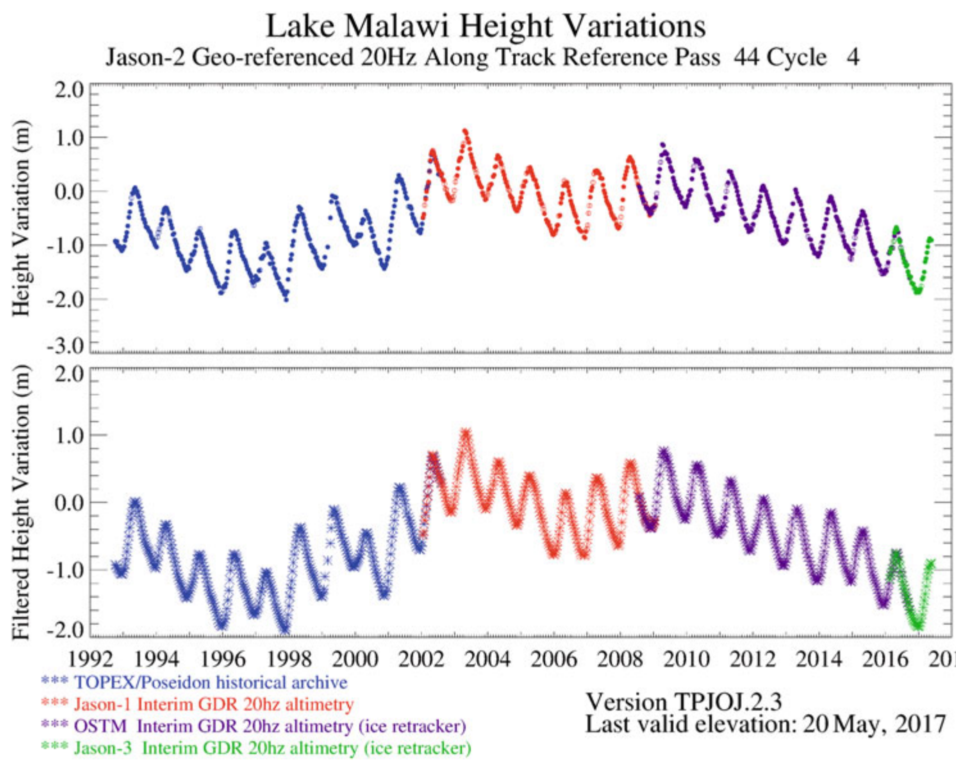


Fig. 13.16 Altimeter-derived surface water level variations for Lake Malawi, Africa. The time series shows measurements from 1992 to 2017 as observed by the NASA/CNES Topex/Jason series of satellite radar altimeters. The temporal resolution is 10 days, and the variations are relative, with respect to an arbitrary datum. The top plot shows minimally processed results, the bottom plot after routine filtering procedures. These variations can be accurate to 3-10 cm rms for such large lakes Graphic product is courtesy of the USDA/NASA funded G-REALM program [9]

While the hydrologic remote sensing communities await the launch of SWOT, a Ka-Band Synthetic Aperture Radar (SAR) interferometer with swath capability, the use of conventional pulse-limited radar altimeters is transitioning across to the use of Delay Doppler radars (Raney 1998). This enhanced technology was first employed on the CryoSat-2 (Wingham et al. 2006), and then Sentinel-3A,-3B (Donlon et al. 2012) missions, and will now be employed on the future Sentinel-6/Jason-CS mission. Although still restricted to reference ground tracks, their advantage lies in improved along-track spatial resolution, achieved via the coherent processing of the groups of transmitted Ku-band pulses, essentially creating a type of unfocused SAR. The ability of CryoSat-2 to retrieve high-resolution elevation measurements is already being exploited for lake and river monitoring (Villadsen et al. 2013, 2016). Unlike CryoSat-2 the future Jason-CS/Sentinel-6 altimeter will be able to

[8] https://podaac.jpl.nasa.gov/dataset/PRESWOT_HYDRO_GRRATS_L2_VIRTUAL_STATION_HEIGHTS_V1
[9] https://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/

operate conventional and SAR altimeter modes simultaneously.

While technology advances are being made with radar altimeters, a new generation of lidar altimeters has recently been launched. Although temporal resolutions are long (being mapping rather than monitoring missions) they are nevertheless recording surface water levels across river reaches and lakes/reservoirs. The ICESat-2 mission, for example, (Abdalati et al. 2010) uses six high/low energy beams for enhanced spatial coverage, and employs photon-counting technology to enable along-track spatial resolutions on the order of meters. The GEDI forest mapping mission also utilizes several laser beams, split to provide multiple ground tracks with 60 m along track sampling. The conventional and Delay Doppler radars, and the ICESat-2 mission, aim for centimeter to decimeter accuracy for surface water levels.

13.2.2.4 Gravity Recovery and Climate Experiment (GRACE)

The Gravity Recovery and Climate Experiment (GRACE) mission launched in March 2002 opened a new era in remote sensing exploration of our planet. The twin GRACE satellites flew in tandem, $\sim 2^{\circ}$ apart at with at an altitude oscillating between approx. 480–500 km on a non-repeat orbit. The approximately 61-cycle, 4-day orbit pattern (Zenner et al. 2010) is equivalent to ~ 657 km ground track distance at the equator. The first GRACE satellite was decommissioned in 2017 and its follow up (GRACE-FO) was launched in January 2019 with similar orbit configuration.

GRACE is the first remote sensing instrument in space where the primary observation does not utilize the electromagnetic spectrum. Instead, the GRACE satellites (which are the sensors themselves) respond to changes in gravitational forces as they fly over gravity (mass) anomalies. Precisely tracking the motions of the two satellites (with on-board accelerometers), the distance between them (using K-band ranging sensors), and their exact locations (via GPS) allows the mapping of the Earth's gravity field at the equivalent of a few kg m^{-2} on the Earth's surface (Rodell and Famiglietti 1999). This accuracy can be contrasted with the mass of the 1 m^{-2} Earth cone, 1.17×10^{10} kg m^{-2} (WMO 2009), to fully appreciate the engineering achievements.

While the accuracy of GRACE is impressive, the spatial and temporal resolutions severely limit the range of potential hydrological applications. The sparse "ground track" distance, the altitude, and the distance between the satellites dictate the spatial resolution that GRACE can provide, which is about 400 km on the ground, equivalent of $\sim 160{,}000$ km^2 area at the Earth's surface, determining the smallest basin size that GRACE can monitor (Rodell and Famiglietti 1999). Future missions might improve with alternative orbit configurations (e.g. operating constellations) to allow a more detailed depiction of the time varying gravity fields.

While the orbit configuration remained the same for the GRACE-FO mission, but it employs additional laser ranging interferometry (LRI) allowing 20 times more accurate measuring of the distance between the two satellites compared to the first GRACE mission. Furthermore, via wave front sensing it can measure the angle between the two satellites.

The primary challenge in utilizing GRACE and GRACE-FO in hydrological applications is separating the different storage components affecting the dynamic variations of the mass distributions. The original GRACE mission plan assumed that mass variation due to atmospheric moisture fluxes, tidal movements in the oceans and postglacial rebound are known from NCEP (Kalnay et al. 1996; Kistler et al. 2001) or ECMWF reanalysis products, and various ocean tide models (Han et al. 2004). The majority of the remaining mass variations are expected to reflect changes in soil moisture, snow pack, ice cover, surface and groundwater storage. Since GRACE can only observe the integrated signal of all these storage terms combined, the accuracy of any particular storage retrieval will depend on the accuracy of the storage terms that are assumed to be known from independent sources.

Additional difficulties in processing GRACE data arise from the aliasing effects of the interference between the GRACE non-repeat orbit and the monitored mass fluctuations (Schmidt et al. 2006; Velicogna et al. 2001). The approximately four-day sampling of the integrated gravity signal from multiple storage terms, each with their own temporal signal, results in a complex superposition of aliased signals. High frequency storage terms (e.g. atmospheric vapor, surface water, soil) have to be known at observational frequencies higher than GRACE's four-day repeat, to facilitate not only the decomposition of the mass dynamics but the de-aliasing of the GRACE signal as well. So far, GRACE has not been able to achieve the accuracy predicted before launch, primarily due to the higher uncertainties in the "known" storage terms than was anticipated (Zenner et al. 2010).

The studies testing GRACE's potential were dominantly carried out at continental scales (Rodell et al. 2009; Seo et al. 2009; Syed et al. 2009). Early works confirmed GRACE's ability to depict gravity changes due to hydrological processes (Rodell et al. 2004; Schmidt et al. 2006; Syed et al. 2009). These studies presented the first global estimates of continental monthly and annual water fluxes to oceans using GRACE data in combination with both NCEP and ECMWF reanalysis. Syed et al. (2009) estimated the mean annual discharge $30{,}354 \pm 1212$ km^3 yr^{-1}, based on averaging results from using GRACE with NCEP and ECMWF reanalysis (otherwise yielding different values, 32,851 ± 1744 and 28,590 ± 1685 $km^3\ yr^{-1}$ respectively), that are well outside of the majority of previous estimates, ranging between 38,800–42,700 $km^3\ yr^{-1}$ (Fekete et al. 2002).

This deviation from previous estimates is not surprising, as the NCEP reanalysis products alone are known to have significant biases representing precipitation (Fekete et al. 2004). The marked differences between the NCEP versus ECMWF reanalysis-driven estimates demonstrate the need for highly accurate values for the storage components that are assumed to be known. The necessity of incorporating reanalysis data, representing mass variations in the atmosphere, limits severely the accuracy of the remaining storage terms derived from GRACE.

Rodell et al. (2009) demonstrated the utility of GRACE to track groundwater depletion due to irrigation groundwater uptake. Since the inter-annual storage variations in most of the other storage terms (atmosphere, surface waters, soil moisture) are typically negligible, this minimizes the uncertainties of separating out those terms in the processing of GRACE data.

While this study cited the CGWB (2006) report (discussed in Sect. 13.2), but made no attempt to compare the extent of groundwater depletion according to GRACE versus these in-situ data, instead they used an "unscaled, dimensionless averaging function" that happened to coincide with the greatest groundwater depletions according to the CGWB (2006) report, but missed major depletions in the southern part of the country. More recently Famiglietti and Rodell (2013) estimated water storage changes over the conterminous United States from GRACE data (Fig. 13.17) that offers some insights to GRACE's capabilities.

Due to spatial resolution (even if the GRACE-FO mission shows major improvements), temporal frequency (since the orbit configuration of GRACE-FO remained unchanged), accuracy, and uncertainty in decomposing the aggregated signal of change in mass into changes in the different hydrological storage pools, one could safely state that GRACE has a long way to go before it can be used by water managers at local and regional scales.

13.2.2.5 Evapotranspiration Monitoring

Due to the difficulties of ground evapotranspiration measurements, along with the cost, maintenance of instrumentation and the non-distributed nature of the data, significant research efforts have been put into estimating evapotranspiration by using models with different physical foundations. Remote sensing time series can assist the monitoring of the energy and water balance components, with special attention to the evapotranspiration and vegetation water stress over large areas. Long-term data analysis may improve our understanding of the functioning of the system, helping to assess the ecosystem impacts and leading to reduce the economic and environmental vulnerability. Different models for estimating evapotranspiration at medium-large spatial scales have been developed, based on both soil water balance and surface energy balance (Calera et al. 2017).

The first approach (soil water balance) includes models such as VIC (Variable Infiltration Capacity) (Liang et al.

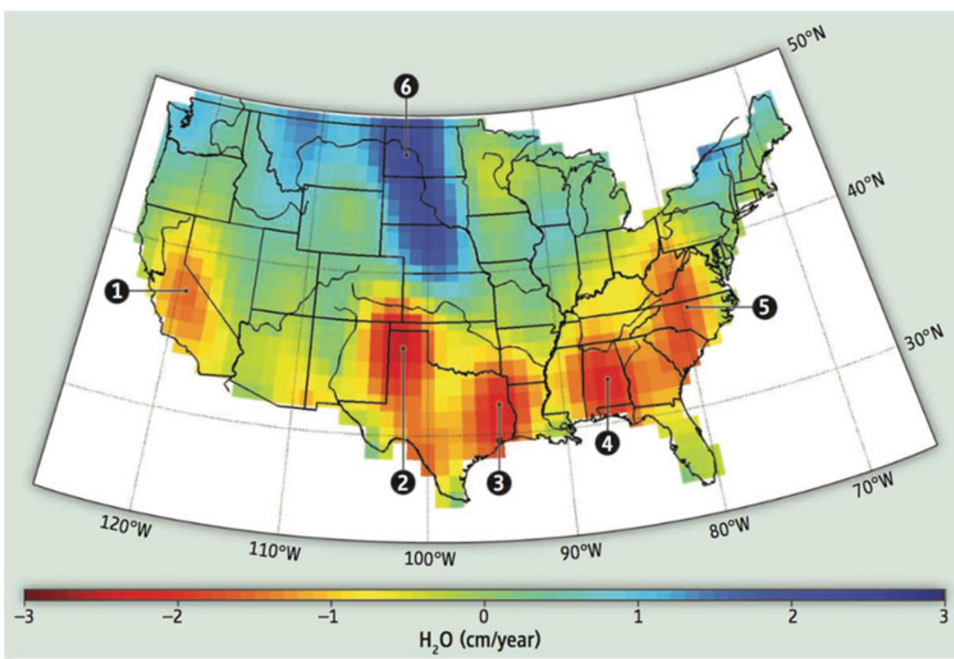


Fig. 13.17 Water storage change between 2003 and 2012 within the conterminous United States from GRACE data

1996; Wood et al. 1997), or evapotranspiration formulations being incorporated in the hydrological calculations (as a fraction of potential evapotranspiration regulated from some control state variables) that perform in a semi-distributed or distributed way, such as SWAT (Soil Water Assessment Tool) (Arnold et al. 1998) or WiMMed (Watershed Integrated Model in Mediterranean Environments) (Polo et al. 2009) among a wide group of models. They require spatially distributed inputs that can be derived from remote sensing, such as maps of land use, vegetation/crops and soil characteristics (e.g. texture, soil depth, hydraulic conductivity); topographic information (from digital elevation models) and superficial network indicators of the river basin; precipitation and irrigation information; and meteorological variables.

These evapotranspiration models are regulated by the soil water content, which is dependent on the precipitation input data (and irrigation) and on hydraulic soil properties, which are difficult to determine on a regional or continental scale (Beljaars et al. 1996). They usually produce continuous estimates that allow for water use monitoring on different time-scales. However, cumulative errors may develop in the absence of regular corrections being implemented (Betts et al. 1997; Schaake et al. 2004).

More common research lines for evapotranspiration estimation based on remotely sensed information include: (1) Using vegetation indexes (VI), derived from airborne or satellite measured surface reflectance, to determine crop/vegetation growth to estimate the basal crop coefficient (K_{cb}) (Bausch and Neale 1990). Together with data coming from meteorological stations to compute the reference evapotranspiration (ET_0), that accounts for the atmospheric demand, they can be used to determine the crop actual evapotranspiration (Allen et al. 1998) together with a water balance to account for the water stress. The most widely used vegetation indices (e.g. Normalized Difference Vegetation Index- NDVI, Soil-adjusted Vegetation Index-SAVI) are derived from the visible and near infrared part of the spectrum, with spatial resolutions usually of meters, with potential gaps due to cloud coverage. Nevertheless, composites using multiple days can improve the final quality of the product (e.g. MODIS 8-day composite surface reflectance or the 16-days composite VI).

(2) Using the surface radiometric temperature derived from the thermal bands of remote sensors to estimate evapotranspiration as latent heat flux, that enable updated diagnosis of the actual surface water condition.

Latent heat (L_{ET}) is computed in these methods as the residual of the energy balance (Bastiaanssen et al. 1998a, 1998b; Gillies et al. 1997; Kustas and Norman 1996; Moran et al. 1994). In general, these models do not require precipitation or soil properties inputs and are mostly conditioned by surface radiometric temperature (T_{RAD}) observations. Other information required is a characterization of the canopy coverage, along with common meteorological data such as air temperature, humidity and wind speed. Some examples of these models in current use are: Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al. 1998a) Surface Energy Balance System (SEBS) (Su 1999), the triangulation method for temperature/NDVI (Normalized Difference Vegetation Index) (Gillies et al. 1997) the Two-Source Energy Balance model (Kustas and Norman 1999; Norman et al. 1995) and the ALEXI model (Atmosphere—Land Exchange Inverse model) (Anderson et al. 1997). One of the main disadvantages of these approaches is, besides the complexity of the formulation, the potential input gaps caused by the availability of thermal data due to the cloud coverage, which may distort the final images, and the medium-low spatial resolution of the acquisitions (e.g. Sentinel 3 and MODIS 1 km of spatial resolution, Landsat 8 with 100 m).

13.2.2.6 Soil Moisture Monitoring

The distinct spectral and dielectric properties of water make wet surfaces distinguishable from dry surfaces in almost all spectral domains used in remote sensing (optical, thermal infrared and microwave) (Wang and Qu 2009).

In the optical wavelengths (0.4 nm–2.5 μm) the presence of water leads to a darkening of the soil (by reducing its reflectance). The main challenge using optical wavelengths is that the reflectance at a particular wavelength varies not only due to the water content, but also due to other soil properties. Therefore, the water content can be inferred only if the factors affecting the reflectance are known, or site empirical specific relationships between the reflectance and moisture content are developed.

While the optical spectrum offers high spatial resolution, it has severe limitations, such as cloud contamination and limited surface penetration (Wang and Qu 2009). Normalized multiband drought index (Wang and Qu 2007) isolates the differences due to the soil and the vegetation spectral signatures from the impact of soil wetness by considering two water absorption bands (1.64 and 2.13 μm) in contrast with the 0.86 μm as reference, which is insensitive to water content.

An alternative to optical spectrum is the thermal infrared (3.5–14 μm), corresponding to the electromagnetic spectrum emitted by the Earth's surface as a function of its temperature. The high heat capacity of the water leads to higher thermal inertia. When the soil is wet the increased thermal inertial leads to a reduction of the diurnal temperature fluctuation (Veroustraete et al. 2012; Verstraeten et al. 2006). Thermal infrared sensors can provide high resolution soil moisture mapping capabilities, but it requires pairs of daytime and nighttime remote sensing imageries. Just like optical sensors, these thermal images are also contaminated by clouds and meteorological conditions, and vegetation could lead to severe perturbations.

Perhaps, microwave (between 0.5 and 100 cm wavelengths) spectrum has the greatest potential for regular soil moisture monitoring. The high contrast in relative permittivity (the ratio between the capacitance of a particular material versus vacuum as a capacitor, traditionally called dielectric constant) between water ($\sim$80) and soil particles (<4), leads to distinct differences in both emitted and reflected microwave signals.

Passive microwave sensors measure the intensity of the microwave emission, which is proportional to its brightness temperature, a product of surface temperature and emissivity. A number of mathematical models relating land surface properties including soil moisture to microwave emission have been developed, with different parameterization as a function of the applied microwave frequency range. From remote sensing perspective, these radiative transfer models are inverse models, since they are designed to approximate the microwave signal that the microwave sensors are expected to detect.

Forward models are derived from the radiative transfer models by inverting them, in a way that minimizes the residual error between the model simulated and the measured microwave brightness temperature. Since these models rely on a number of surface parameters other than soil moisture, the determination of the missing parameters normally requires statistical regression analysis.

Alternatively, statistical approaches could be applied to relate measured brightness temperatures to soil moisture directly. Since, these statistical approaches need site and method specific calibration their application is limited, since their application to altered conditions requires a new calibration (Wang and Qu 2009).

Active microwave sensors measure the return signal from a microwave pulse sent out by the sensor to determine the backscattering of the surface. Both theoretical and empirical models were developed to relate the observed backscattering to soil moisture. The theoretical approaches predict the backscattering responses to changes in surface roughness and soil moisture content, but complex terrains and intensive vegetation limit their application, as the parameterization of the roughness and attenuation microwave signal through canopy becomes increasingly challenging.

Empirical approaches bypass the need for complex parameterization and can be applied under conditions where theoretical models are no longer applicable. However, they require calibration/validation data, normally from ground observations, that needs to be acquired again when the surface conditions change, like in the case of passive microwave sensors.

Passive sensors tend to provide wider swath width so they offer larger area coverage, but only at moderate scales (several km spatial resolution). Active sensors provide higher spatial resolutions, in the order of tens of meters, that requires large antenna for narrower swath (50–500 km).

The SMOS (Soil Moisture and Ocean Salinity) mission from the European Space Agency was launched in November 2009, and their goals were to provide soil moisture over continental surfaces (with a space resolution of $\sim$40 km and an accuracy goal of 0.04 m^3/m^3), vegetation water content over land, and ocean salinity (to improve climate predictions). SMOS deliver systematic passive L-band measurements, like SMAP, but the coarse resolution of the data hinders local within-field applications. The combined use of C-Band synthetic aperture radar systems (SAR), such as the Copernicus Sentinel 1, and/or optical sensors, offering high spatial and temporal resolution, may overcome this limitation (Balenzano et al. 2011, 2013; Gao et al. 2017; Notarnicola et al. 2017; Paloscia et al. 2013) as well as the combination of different radar sensors (Escorihuela et al. 2018; Eweys et al. 2017; Li et al. 2018; Lievens et al. 2017; Rodríguez-Fernández et al. 2015; Tomer et al. 2015, 2016). Radar C-Band SAR, combined with other Earth Observation data or/and field measurements, has other important applications regarding water monitoring, such as flood assessment for risk management (Amitrano et al. 2018; Chini et al. 2018; Cian et al. 2018; Clement et al. 2018; Giustarini et al. 2013; Landuyt et al. 2019; Mason et al. 2012).

NASA's Soil Moisture Active and Passive (SMAP) mission (Fig. 13.18) launched in January 2015 was anticipated to combine the advantages of active and passive soil moisture monitoring, by carrying both a high-resolution radar along with a coarser resolution radiometer.

The expectation of the SMAP science team was: "*The baseline science mission shall provide estimates of soil moisture in the top 5 cm of soil with an error of no greater than 0.04 cm3/cm3 (one sigma)* ***at 10 km spatial resolution*** *and 3-day average intervals over the global land area* ***excluding*** *regions of snow and ice, frozen ground, mountainous topography, open water, urban areas, and* ***vegetation with water content greater than 5*** *kg* $\boldsymbol{m^{-2}}$ *(averaged over the spatial resolution scale)*"[10], which by itself gives important guidance about the role that satellite derived soil moisture estimates can play in local water management.

Unfortunately, the radar sensor on SMAP halted transmission after six months of operation, that greatly reduced the mission's anticipated capabilities.

[10]https://smap.jpl.nasa.gov/science/objectives.

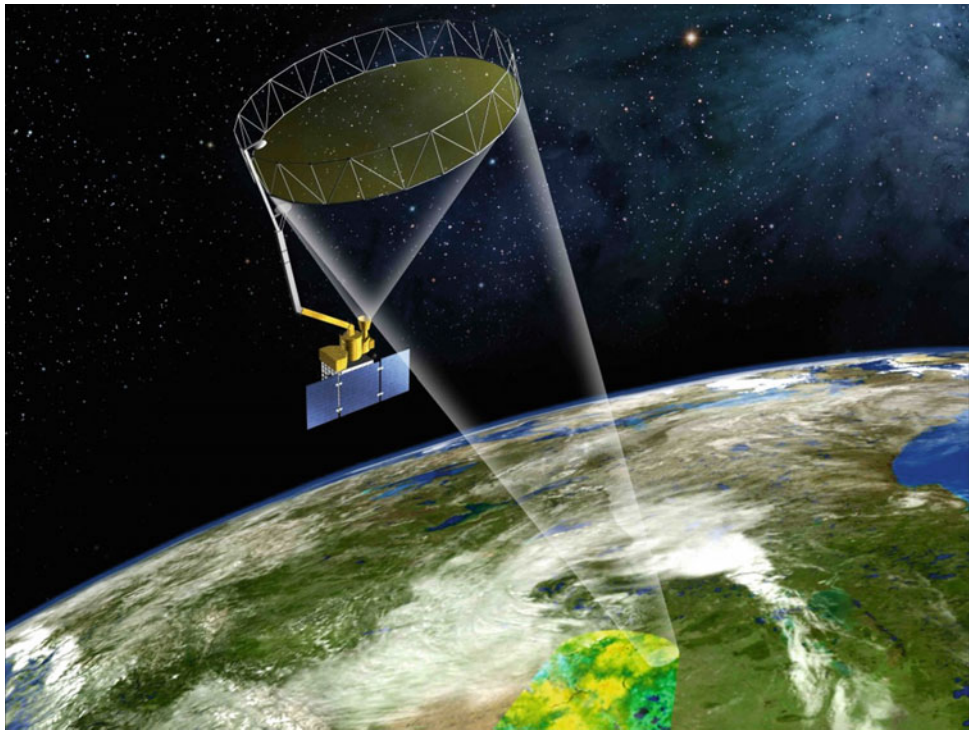


Fig. 13.18 NASA Soil Moisture Active and Passive (SMAP) mission

13.2.2.7 Monitoring of Water Using Multiple Data Sources

As shown in the previous sections, each sensor has its own capabilities and limitations. The assessing of the hydrological water balance components through the combination of multiple satellite data (e.g. altimeter, radar, optical, thermal data, etc.), along with other data sources (e.g. meteorological ground and reanalysis data, bathymetries, ground monitoring, etc.), can overcome the limitations of a single sensor: data gaps due to cloud coverage, coarse spatial and temporal resolutions that hinder within-field applications, etc.

Multiple applications make use of a constellation of satellites, or diverse data sources, along with data fusion techniques, disaggregation/aggregation (Anderson et al. 1997; Guzinski et al. 2014), and sharpening methods (Gao et al. 2006), enabling water managers to develop monitoring plans, such us: TIR imagery from geostationary platforms and meteorological data to develop US monthly Evaporative Stress Index (Anderson et al. 1997) (https://hrsl.ba.ars.usda.gov/drought/index.php) or downscale evapotranspiration estimations using a combination of VIS/NIR and TIR images (Gao et al. 2006; Knipper et al. 2019); combination of radar, optical and thermal data to assess water consumption by the vegetation (Andreu et al. 2019); like the SEN-ET Sentinels for Evapotranspiration project funded by ESA (Guzinski and Nieto 2019), or the multi-band remote sensing data project MOIST, Managing and Optimizing Irrigation by Satellite Tools, (Sandholt et al. 2018) funded by the Innovation Fund Denmark or the MOSES project, Managing crOp water Saving with Enterprise Services (Felice et al. 2017) funded by the European Horizon 2020; radar and optical data for crop classification (Skakun et al. 2016); reservoirs monitoring and mapping using remote sensed data along with field reservoir bathymetry or radar altimetry observations, or high-resolution optical images and SAR (Markert et al. 2018); as a small example of the potentialities of combining different data-sources.

The reliance on multiple data sources is particularly critical when applications incorporate *experimental* satellites. The early hardware failure of the SMAP mission, losing its most important radar sensor, along with the first ICEsat mission that was designed to operate for 3–5 years but its Geoscience Laser Altimeter System (GLAS) wore out far quicker than expected, should serve water managers as a reminder that experimental satellites should not be the single data source in critical applications (Fekete et al. 2015). Thus, the experimental nature of some satellites has to be emphasized, since they are not meant to support mission critical applications, even though some of them (e.g. the Tropical Rainfall Measuring Mission (TRMM) which was in operation for 17 years despite its 3–5 years anticipated life span) outlived their design lifetime. The NASA Terra and Aqua satellites, carrying the popular MODIS imaging sensors along a number of others, are in orbit since 1999 and 2002 respectively, and expected to operate well into 2020.

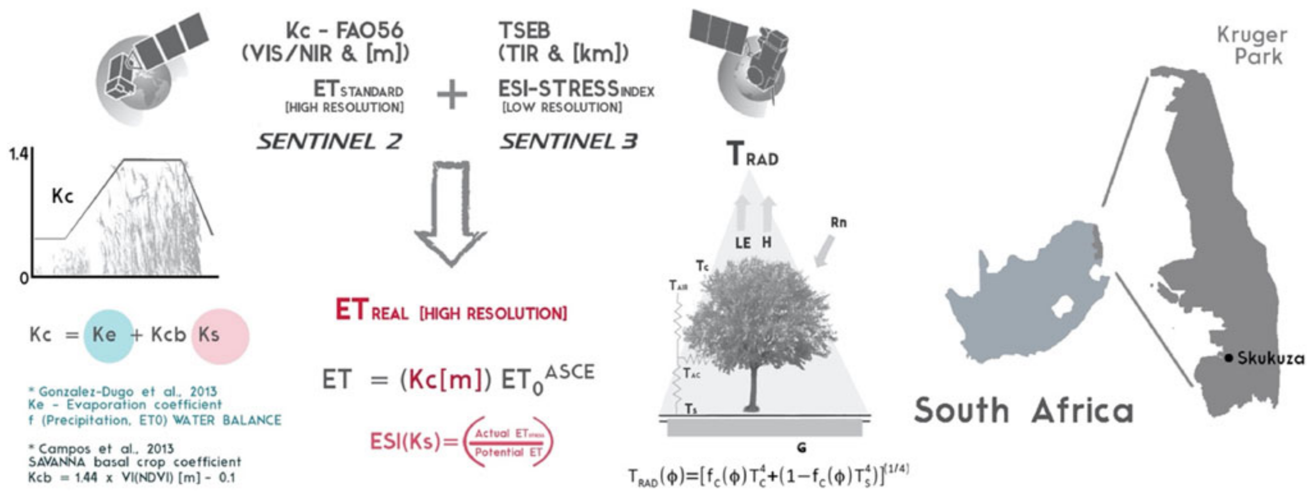


Fig. 13.19 Conceptual approach of TIGER project 401 and a pilot area in South African Kruger National Park

13.2.2.8 Case Study: Water Fluxes Over Savanna Ecosystem: Evapotranspiration Assessment via Earth Observation and Modeling Tools

Semiarid savannas are among Africa's most productive multifunctional landscapes—supporting wildlife, livestock, crops, and livelihoods (Mbatha and Ward 2010)—but experience frequent droughts. These are made worse by climate change and other human-induced changes. To maintain ecosystem productivity, there is a need to develop mechanisms for monitoring water availability and vegetation dynamics. Due to the interlinkages between resources, and between resources and society, their sustainable management requires a holistic perspective, taking a Nexus Approach. This necessitates the integration of tools that are capable of addressing and reducing uncertainties associated with resources management, with the use of timely and precise information on ecosystem dynamics. One way is to make use of Earth Observation data and technologies. Especially in developing countries where ground data are often scarce, monitoring networks are unreliable, and data accesses are restricted therefore open data sources are essential for monitoring ecosystems. Open-source software, like the Water Observation Information System (WOIS) developed by the TIGER Initiative, or the Sentinel Application Platform (SNAP) from the European Space Agency (ESA), are valuable in this regard.

In December 2015 UNU-FLORES, together with the University of Limpopo and the University of Western Cape (South Africa), were selected as one of the ten TIGER Water for Agriculture teams for conducting joint research for integrated water management, within the project "Remote Sensing of Water Use and Water Stress in African Savanna Ecosystem from Local to Regional Scale: Implications for Land Productivity" (Andreu et al. 2019, 2017). The TIGER initiative, launched by ESA in 2002, promotes the use of Earth Observation data to improve Integrated Water Resources Management in Africa, while strengthening the scientific collaboration between African and European partners.

Understanding the spatio-temporal variations of water use and water stress across savannas plays an important role, not only for rangelands management, but also for the global land-surface processes analysis (Sibanda et al. 2016). To model semiarid savanna water use, we need to understand how the endemic dry seasons (high air temperatures and no rainfall), along with the vegetation structure (dispersed trees transpiring during part of the dry season, with an annual herbaceous layer) interact with the land-atmospheric processes. Besides, we need to develop robust methodologies to derive and upscale/downscale the ecosystem parameters from remote sensing, distinguishing between the canopy layers at different scales and seasons.

The EO data provided by the new European Satellites Sentinel S2 and S3 allow us to map the water use and water stress, as well as the vegetation distribution, across the African savannas, monitoring seasonal and long term temporal variations. To monitor savanna ecosystem in a semi-continuous spatio-temporal way, this project integrates two different evapotranspiration-ET-estimation approaches, with different conceptual and operational capabilities and limitations (Fig. 13.19). The high spatial and temporal resolution visible/near infrared (VIS/NIR) data, provided by S2, allow a continuous monitoring of vegetation cover (from each layer) and unstressed evapotranspiration (Allen et al. 1998). Meanwhile thermal data (TIR), provided by S3, at lower spatial resolution, will help to assess ecosystem water stress (Norman et al. 1995) (Fig. 13.20).

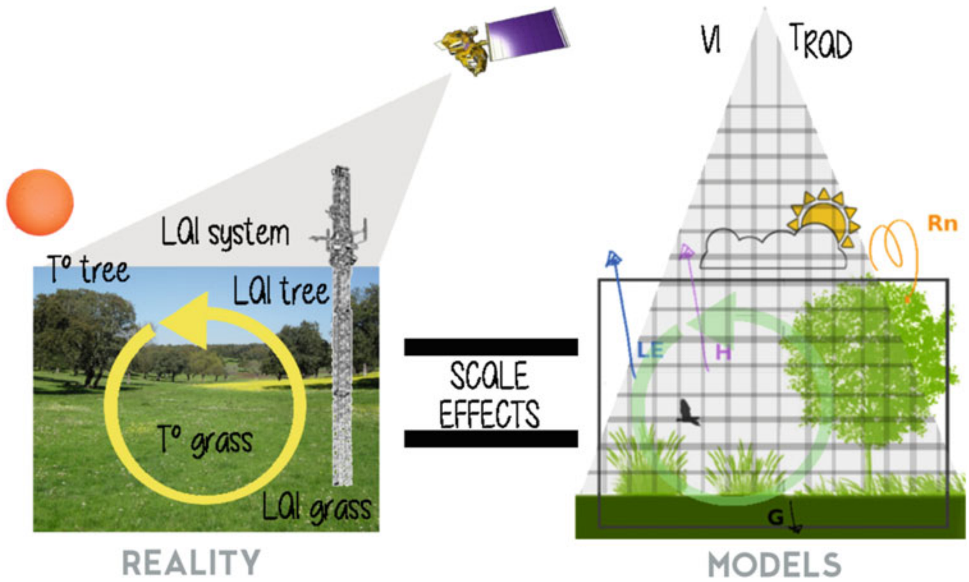


Fig. 13.20 Conceptual approach of TIGER project 401. *Source* Andreu et al. (2017). TIGER Savanna Tool Handbook: On Remote Sensing of Water Use and Water Stress in African Savanna Ecosystems from Local to Regional Scale

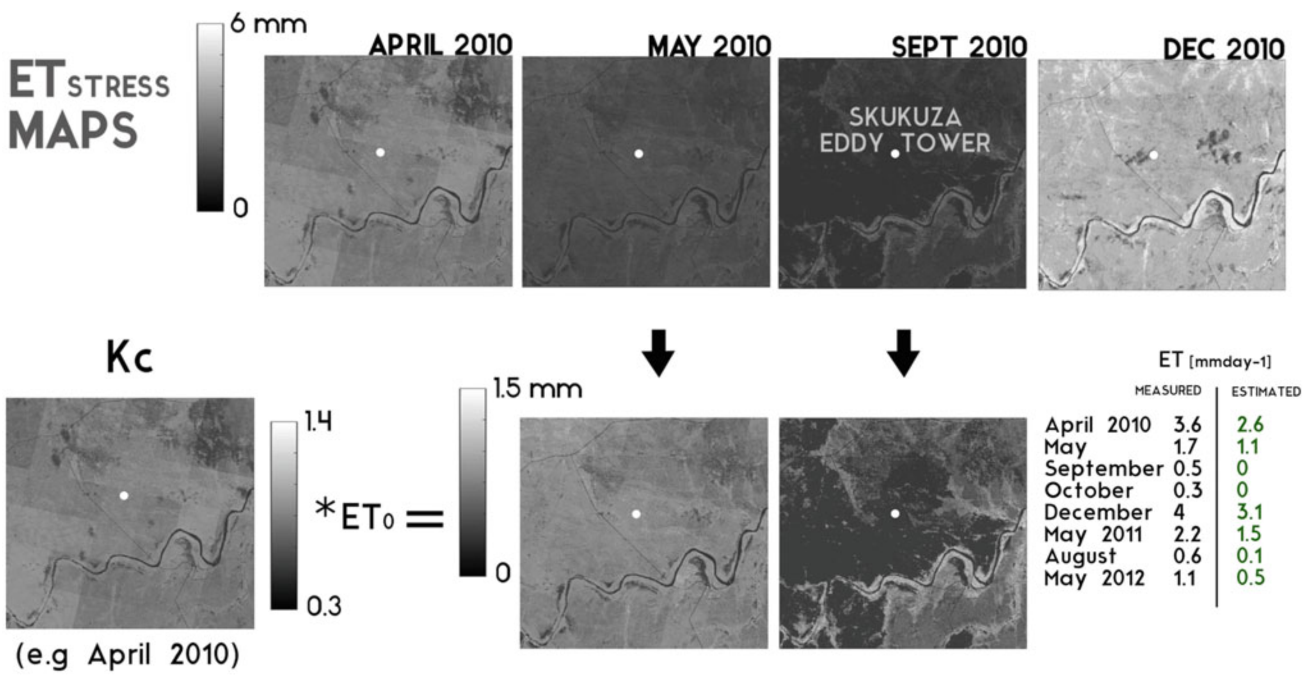


Fig. 13.21 ET estimation over savanna ecosystem using a combine method (Crop coefficient—Kc and TSEB for stress index) resulting in the modeling of canopy water stress during the dry season months

The choice of the two approaches is based on their proven ability to estimate ET over partially vegetated heterogeneous landscapes (Cammalleri et al. 2010; González-Dugo et al. 2009), and savanna-type ecosystems (Andreu et al. 2018, 2013; Campos et al. 2013; Campos 2013). This procedure was tested over eddy covariance experimental site (Skukuza) in South African Kruger National Park, using different satellite datasets (SPOT 5 MS and AATSR) with good performance (Fig. 13.21). The high spatial resolution of VIS/NIR data was used to precisely map water use and stress over the savanna (Fig. 13.21), enabling to monitor the ecosystem changes over the different seasons during the study period. The data indicate that the ecosystem water losses through evapotranspiration were maximum during April and December (wet season), reaching the minimum during September (dry season), where potential evapotranspiration requirements cannot be covered by the ecosystem, and the vegetation enters water stressed conditions. Nevertheless, semiarid woody vegetation has developed a mechanism to face water stress during naturally occurring droughts.

13.3 Water Quality

Water quality monitoring is a more challenging task than measuring water quantities. The plethora of constituents that water can carry, compared to the few water quantity metrics of interest, explains the difference. Measuring various chemical compounds present in the water requires widely different sensors or laboratory analyses, ranging from handheld instruments, to sophisticated collection of highly volatile and easily contaminated samples, which require skilled professionals following strict protocols.

Exact measurements of the water's chemical contamination and compounds of interest can only be accomplished by in situ sensors, in touch with the sampled water body, or by taking water samples into properly equipped laboratories. Nevertheless, some compounds or water quality properties have distinct optical properties, allowing their detection and characterization via remote sensing.

13.3.1 In Situ Monitoring

Besides the large number of chemical constituents that can be of interest to water managers, the constituent themselves can be measured with multiple methods with distinct accuracy and error, relevant for the evaluation of the measured values and the manager's needs.

13.3.1.1 Most Commonly Monitored Water Quality Parameters

Systematic water quality monitoring that spans beyond national boundaries is rare, and even where water quality data are available, often significant differences exist in the monitored constituents, the sampling and processing methods or the monitored data over time. Regional or county boundaries also often hinder the continuity and homogeneity of a policy application on a hydrological unit. The European Water Framework Directive provides a start in this direction, marking the steps and requirements that European countries need to comply to.

The United Nations Environmental Programme's (UNEP) GEMS/Water[11] Database assembled a large collection of water quality data from all over the world. This database is probably the most comprehensive compilation of water quality information, and a good start to list the typical constituents that are usually monitored. The GEMS/Water database contains records for ∼3700 stations globally, with more than 600 unique parameter codes for different water quality constituents.

The unique parameter code does not necessary mean completely different constituents. After grouping comparable parameters, only differing by the methods of collection or/and the laboratory processing, the number of parameters drops to a few hundred. Further grouping by compounds of the same elements (e.g. various nitrogen and phosphorous species) the parameter count still remains over one hundred.

The most frequently measured parameters are the various nitrogen and phosphorous species and suspended solids, but the number of sampling locations and collected samples vary significantly by regions (Table 13.2).

Table 13.2 lists the number of stations, number of observations, and observations by station for the top twenty parameter groups. The number of stations and observations drop rapidly from frequently measured parameters (various forms of Nitrogen and Phosphorus) to the more esoteric ones (e.g. Lignosulphonates, that is not listed in the table, was measured at two locations in Canada, providing nine samples). Such rarely observed water quality parameters do not qualify as monitoring since they are not collected regularly over time.

The large number of parameter codes arise from the various reporting combinations of certain constituent groups. For instance, various forms of Nitrogen species, combined with the measurements method, represents 56 distinct indicators in the GEMS/Water database. These distinct indicators also arise from the different possible representation of the nitrogen compounds (NH_4, NO_2, NO_3), such us total N, NH_4, NOx separated, etc. In some cases, the missing combinations can be inferred from the remaining constituents, but some samples only provide the lumped compound combinations without any information on their partitioning (Table 13.3).

13.3.1.2 Water Quality Indices

Water Quality Indices combine a number of water quality indicators to determine the overall quality level of a water body. They usually categorize the water masses into different levels such as 'excellent', 'good' or 'poor'.

Of the eighteen water quality indices reviewed, such as the British Columbia Water Quality Index, the Canadian

[11] http://www.gemswater.org.

Council of Ministers of the Environment Water Quality Index, or the Global Water Quality Index, a number of the high ranking parameters listed previously are used. When developing a global index, parameters included need to be meaningful for all sites. Turbidity, or the level of suspended/dissolved solids, which is usually included is in fact a poor one, as many tropical rivers are naturally turbid, whereas high latitude streams are rather clear. The Global Water Quality Index serves as one of the indicators of the Sustainable Development Goals target 6.3.2 (*Proportion of bodies of water with good ambient water quality*). To allow for sufficient flexibility, it is designed in a way that countries can choose in between 171 indicators to build their index from (including pathogens), complying with the following criteria: (1) adequate global and regional coverage, each parameter must be measured in 20% of the countries within each region; (2) consistency following the Four by Four Rule: each parameter must be measured at least four times per year at stations that measure at least four parameters, (3) Non-detects and Zeros: values below the detection limit and zeros are removed (except for fecal coliform bacteria).

In an analysis of the 18 Water Quality Indices and 9 most commonly used water quality standards such as APHA, EPA and ISO, more than 450 different water quality indicators were listed. The top 20 indicators are listed in Table 13.4. These standards use different methodologies for sampling, handling and analyzing the samples. For example, a common indicator as Dissolved Oxygen content can be assessed by at least four different methods. Therefore, choosing the right method can be challenging. Each method also can make use of different tools, that can be as simple, such as hand-held devices, or sophisticated ones, like in situ sondes. For a majority of parameters complex laboratory systems are needed, that require collecting and transporting the water samples. Many compounds carried by the water are volatile, thus the water samples may require proper handling in order to preserve the samples original chemical compositions. To fully assess the water quality level, surface or groundwater, capacities at various levels are needed. Skills to develop a monitoring plan as well as for sampling, analyzing and interpreting the water quality indicators are required.

13.3.1.3 Planning Water Quality Monitoring

Monitoring plans at catchment or national level are challenging. Developing and implementing them requires a set of capacities by water managers, especially public authorities. Water research generally differentiates here three levels of capacities: individual, organizational and societal (Alaerts 2009), all of relevance in developing and implementing monitoring plans. The organizational level seems particularly important, providing the adequate human and financial resources for monitoring. However, these capacities are not always present, resulting in deficient plans, characterized by a lack of water quality indicators, measurement stations, or a wrong application of measurement methods (Ibisch et al. 2016).

13.3.1.4 Sediments

Sediment particles are transported in rivers by two main modes, suspension and bedload. Suspended sediment transport tends to be the dominant mechanism in large rivers, while bedload is the dominant mechanisms in steep mountainous streams (Meade et al. 1990). The ratio between suspended sediment and bedload can be highly dynamic in space and time, as a function of the flow magnitude, and basin and fluvial characteristics (e.g. slope, lithology). Monitoring sediment fluxes in rivers, in both suspended and bedload forms, is important as the mass/volume, attributes and fluctuations in transported sediment are directly linked to water quality, hydrological and geomorphic dynamics, and fluvial and coastal ecosystem sustainability. Sediment particles are conduit for nutrients, heavy metals and pollutants (Wang et al. 2017) adversely effecting water quality along riverine systems and coastal regions (Boening 2000; Shahidul Islam and Tanaka 2004). Influx of sediment into reservoirs and lakes reduce their water holding capacity, considerably diminishing water availability to many

Table 13.2 The number of stations, observations and observations by station for the most frequently measured constituents in the GEMS-Water database

Group	# of Stns	# of Obs.	Obs./ Stn
Nitrogen	2243	317641	142
Phosphorus	2180	161867	74
pH	1375	167481	122
Conductance	1306	158206	121
Temperature	1045	128793	123
Oxygen	1037	301304	291
Chloride	988	102031	103
Sulphate	884	80343	91
Magnesium	837	71245	85
Solids	819	67727	83
Alkalinity	816	80622	99
Calcium	802	71719	89
Potassium	763	51530	68
Sodium	744	61804	83
Iron	705	51737	73
Bacteria	689	59023	86
Zinc	545	39421	72
Coliform	540	35203	65
Copper	532	42190	79

Table 13.3 Number of stations and observations by continents from the GEMSWater database reporting with Chlorophyll A, various forms of Nitrogen and Phosphorus constituents, solids and water temperature

Parameter	Africa		Americas		Asia		Europe		Oceania	
	Stations	Obs.	Stations	Obs.	Stations	Obs.	Stations	Obs.	Stations	Obs.
Chlorophyll A	16	3865	13	1349	26	2371	104	10130	9	258
Ammonia	172	17484	1151	7053	519	26529	266	31029	90	19460
Nitrate	77	3174	1252	6419	260	7184	123	22172	10	188
Nitrate + Nitrite	177	16628	224	12069	435	33689	188	23147	21	1720
Nitrite			1053	3223	67	125			78	18550
Nitrogen—Dissolved			2	55						
Nitrogen—Particulate			34	206						
Nitrogen Organic—Dissolved	8	246	12	113	13	817	33	4380		
Nitrogen Organic—Particulate			1	3	7	373				
Nitrogen Total Kjeldahl	48	8009	104	6097	222	16426	94	11372	89	19701
Orthophosphate—Dissolved	84	16017	51	1522	36	1669	29	9044	77	19453
Orthophosphate—Reactive					67	125				
Orthophosphate—Soluble Reactive	18	241	63	3342	145	10833	26	2990	5	963
Orthophosphate—Total	16	188	14	325	81	5050	17	1309	4	323
Phosphate—Dissolved			1126	1353						
Phosphate—Inorganic Dissolved			14	212						
Phosphate—Total	43	554	1197	2892	106	8409	67	4399	84	19757
Phosphate—Total Inorganic							1	11		
Phosphorus—Dissolved	17	269	50	1505	73	3026	83	4842	3	142
Phosphorus—Particulate	7	197	8	325	5	521	7	298		
Phosphorus—Total	21	866	89	5262	179	13421	142	18933	13	1095
Phosphorus—Total Dissolved Reactive					2	184				
Fixed Suspended Solids	45	2078	34	467						
Suspended Solids	51	1264	174	8033	306	22080	178	30845		
Total Dissolved Solids	10	40			69	282				
Volatile Dissolved Solids			19	273	3	44				
Volatile Suspended Solids			17	566	17	541	2	250		
Water Temperature	85	2526	243	16280	398	36264	312	51886	93	21837

communities worldwide (Wisser et al. 2013). Sediment dynamics affect the river morphology, either gradually over time, or swiftly during extreme events (e.g. floods, landslides). Changing river morphology affect the accuracy of water quantity measurements, as these are based on measured or derived channel geometries (see above).

Gray and Landers (2014) and Hicks and Gomez (2005) offer a detailed description of sediment measurement approaches and their limitations. Below we provide a short overview of commonly used approaches.

Suspended Sediment Measurement

At its core, suspended sediment flux measurement is based on the development of a rating curve between suspended sediment concentration, and water discharge at a site. Sediment concentration is measured by filtering a water sample at a known volume, and weighing its dry mass. This procedure provides the Total Suspended Solids (TSS) concentration. TSS incorporates all waterborne solids (minerals and organic material). To distinguish between the minerals and

Table 13.4 The top 20 indicators used across 18 Water Quality Indices and 9 Water Quality Standards and guidelines

No.	Name of indicators	Number of use
Most-used		
1	pH	14
2	Dissolved Oxygen	12
3	Biochemical Oxygen Demand	10
4	Ammonia	7
5	Chloride	7
6	Fluoride	7
7	Turbidity	7
8	Arsenic	6
9	Nitrate	6
10	Temperature	6
11	Colour	5
12	Copper	5
13	E. coli	5
14	Faecal Coliform	5
15	Total coliform	5
16	Zinc	5
17	Aluminium	4
18	Boron	4
19	Cadmium	4
20	Cyanide	4

organic matter, the filtered mass is burned at high temperature, which incinerates the organic matter, leaving behind the mineral component. TSS analysis is sensitive to human and instrumentation errors, as the amount of filtered material is often very small, and multiple samples are needed in order to reliably represent actual conditions. Suspended sediment concentration can vary considerably with depth and along channel width. Depth-discrete or depth-averaged sampling are commonly taken along a cross section at the gauging site. The density and frequency of such sampling, as well as uncertainties in the sampling instrument, can considerably misrepresent actual sediment concentration at a site.

Converting sediment concentration to sediment flux is done by multiplying averaged concentration by water discharge. For example, a 1 mg/L TSS concentration during a 1000 m^3/s water discharge (1 m^3 of water equals 1000 L) will be equal to a sediment flux of 1×10^6 mg/s or 1 kg/s. Rating curves between sediment flux (or concentration) and water discharge are developed by analyzing sediment flux at multiple discharge conditions. Similar to rating curves between water stage and discharge, sediment flux rating curves often do not include observations from extremely high flow conditions. In addition, the relationship between suspended sediment flux and discharge during a high flow event typically show a hysteresis effect, in which sediment concentration on the falling limb of the hydrograph is lower than that of the rising limb (Bogen 1980). Statistical approaches can be employed to account for such temporal dynamics, but these introduce additional uncertainty.

In recent decades, multiple indirect (proxy) measurement approaches of suspended sediment have been developed. Most widely used are those based on optical and acoustic sensors. Water turbidity can be used as proxy to TSS concentration by developing a rating curve between the two, with a large number of water samples from different turbidity conditions. Turbidity sensors are relatively cheap and reliable but require, as for most sensors, routine maintenance and calibration. They are increasingly used in gauging stations and are also widely used in field surveys and lab analysis. Disadvantages of turbidity-based sensing is its sensitivity to dissolved materials in the water column (Hicks and Gomez 2005). Acoustic sensors can also be used to approximate TSS concentration by developing a rating curve between backscatter signal and TSS (Gray and Landers 2014). Advantages of sonar-based sensing of TSS is the ability to quickly survey large stretches of river, providing spatially explicit information. Disadvantages are the relatively large signal to noise ratio associated with this technique. Other indirect TSS measurement technique developed in recent decades include laser diffraction and pressure difference (Gray and Landers 2014).

Bedload Measurement

Monitoring bedload fluxes is challenging due to high uncertainty in in situ measurements, and its high spatial and temporal variability, even for constant water flow conditions (Hicks and Gomez 2005). As a result, compared to suspended sediment, bedload flux data is acutely sparse. There are a number of bedload measurement techniques, their utility depending on the bed material (gravel, sand or mud), river size and intended purpose. The two most common bedload measurement techniques are based on trapping sediment particles as they move along the river bed. Bedload samplers (e.g. Helley-Smith; Fig. 13.22), are typically bucket-like devices with particular dimensions and shape (intended to minimize pressure differences), which are lowered to the river bed with a pole or cable, collecting near-bed particles that pass through their opening, during a specified time interval. Given that bedload fluxes can vary significantly over a channel cross section, large numbers of samples are typically warranted for a given location (Hicks and Gomez 2005). Bedload sampling is a time consuming and error-prone process, which limits the availability and reliability of measurements. Bedload traps are reinforced dugouts, at the bottom of a river, which trap bedload sediment for a given section of the channel cross section (for small rivers they may cover the entire width of the channel). Weighting the sediment accumulated in a trap at a known time interval provides information on bedload flux for a given proportion of the channel cross section, which can then be interpolated to provide in-station estimate. Pressure gauges and automatic trap clearing design can provide time-continuous bedload flux data. While traps offer more accurate estimate of bedload flux, they are expensive to install and maintain, and are therefore not common.

Analysis of time-varying river morphology is increasingly used to estimate bedload flux. Most prominent is the use of multi-beam acoustic sensors to map sand dune formations at the bottom of large rivers. By analyzing the movement and size of the sand dunes from one bathymetry survey to another, the volume (and thus mass) and transport rate can be estimated (e.g. Nittrouer et al. 2008). A major advantage of this technique is its ability to provide information on large swaths of a river sections. It is, however, a relatively expensive and time-consuming procedure, which is prone to errors associated with noise in the acoustic data and calculation of dune volumes and migration rates.

Similar to suspended sediment monitoring, rating curves between measured bedload fluxes and discharge can be developed, allowing for time-continuous site estimations. It has been estimated, however, that the ability to reliably represent flow-varying bedload fluxes using regression based rating curves is limited, due to high variability in bedload dynamics, even during constant flow conditions.

Fig. 13.22 Helley-Smith bedload sampler (*source* Erskine et al. (2011)

13.3.2 Remote Sensing for Water Quality Monitoring

The European Water Framework Directive, established to ensure the protection and sustainable use of the fresh, ground and coastal waters, provides the baseline requirements for water monitoring, compelling European countries to assess water ecological status by means of spatially distributed (often transboundary), comparable, and repeated data.

Earth Observation data can complement water quality in situ measurements, to support the monitoring of the physical, chemical, and biological status of water bodies (Gholizadeh et al. 2016). Nevertheless, the accuracy and uncertainties of the data (including the atmospheric corrections, cloud masking, and accurate georeferencing) and the retrieval algorithms to assess the optical, physical, and biogeochemical parameters at the scales needed present several challenges (Mouw et al. 2015; Wang et al. 2017). In water quality assessments remote sensing techniques have been in use since 1970 (Gholizadeh et al. 2016), even preceding terrestrial uses of some observations, like fluorescence (Blondeau-Patissier et al. 2014; Gower 2016).

UNESCO-IHP International Initiative on Water Quality (IIWQ) also recognizes the importance of satellite data to improve the monitoring at the global level of freshwater quality, to support the SDGs implementation and monitoring, developing the UNESCO World Water Quality Portal[12].

Particles and substances present in the (near surface of) water can change water spectral signature, and backscattering or absorption properties, and these changes can be measured by remote sensing techniques. These depend on the substance measured, its concentration, the concentration of other substances, and the sensor characteristics (hyperspectral and multispectral images; satellites or airborne sensors; covering the visible, near infrared, thermal, parts of the spectrum or microwave; field radiometry and spectroscopy, etc.). Depending on the scale of analysis and measurement, suspended sediments, chlorophyll-a concentration, turbidity, total phosphorus, dissolved organic matter, salinity and thermal changes of water bodies can be assessed by means of Earth observation data (Ritchie et al. 2003). Pathogens, chemicals or acidity do not change the spectral properties of the energy, and cannot be directly detected, but may be inferred. It is necessary to remark again that field surveys and ground measurements are required in order to calibrate and validate the models and remote sensed indicators.

In general, it is possible to distinguish two bio-optical algorithm approaches. One is based on site-dependent empirical statistical relationships between the remotely

[12]http://www.worldwaterquality.org.

sensed signal and the water quality parameters; and the other uses semi-analytical radiative transfer inversion models. However, the differentiation between them is sometimes not clear (review by (Mouw et al. 2015).

13.3.2.1 Remote Sensing Estimation of Chlorophyll and Other Ecological Parameters

Gholizadeh et al. (2016) reviewed different qualitative parameters than can be determined by means of remote sensing, with strong spectral characteristics and a low signal noise ratio. In between them, chlorophyll-a (ocean and in-land waters), temperature, water clarity, colored dissolved organic matter, total suspended matter. As mentioned in previous sections, sea ocean surface salinity is also provided by satellites as SMOS, requiring extensive procedures for internal and external calibration.

Satellite retrievals of chlorophyll-a (chl-a), a pigment essential for photosynthesis, serve as a proxy for algae and cyanobacteria presence, as an indicator of water eutrophication (case study 2) and quality. Standard chlorophyll-a algorithms developed for global scale studies, for example the ones based on MODIS Aqua data, showed poor accuracy on a basin level, and need to be regionalized (Abbas et al. 2019; Darecki and Stramski 2004; Tzortziou et al. 2007). Using broad wavelength spectral data (e.g. Landsat, SPOT) for discriminating chlorophyll-a in waters with high suspended sediments is hindered by the dominance of the spectral signal from the sediments (Ritchie et al. 1994), and narrow bands in the "red edge" are needed (Gitelson et al. 1994).

Sun-induced fluorescence (SIF) has a good correlation with chlorophyll-a concentration, and can be remotely retrieved. However, SIF detection is complex, due to the weak signal and therefore high spectral resolution needed to sense the emission, and to the presence of other substances in the water. Nevertheless, the upcoming Fluorescence Explorer (FLEX) mission from ESA, that will be launched in 2022, will monitor globally the chlorophyll fluorescence, and can potentially identify phytoplankton and cyanobacteria (Blondeau-Patissier et al. 2014; Gower 2016).

Water temperature, that regulates biological, physical and chemical water processes, can be mapped using thermal-infrared region of the spectrum (e.g. Landsat, MODIS, AATSR, Sentinel 3 satellites), although the spatial resolution of the available satellite data often hinders the assessment of river and stream temperatures (Gholizadeh et al. 2016). Airborne or handhold sensors may be considered for small water bodies.

13.3.2.2 Sediment Monitoring

The use of multispectral satellite and airborne sensors for estimating suspended sediment concentration has been well documented, though mostly for large water bodies (Gilvear and Bryant 2005). Some spectral bands (particularly the red and near-infrared) are strongly reactive to changes in sediment concentration near the water surface. Imagery-based estimation of suspended sediment has the advantage of providing spatially distributed information and, especially for satellite imagery, relatively frequent data.

Once the relationship between suspended sediment concentration and a sensor's spectral signature is established, large scale mapping can be readily produced in near-real-time and, depending on the sensor's image archive, in hind cast. Disadvantages of imagery-based estimation of suspended sediment is its reliance on site-specific calibration (Gilvear and Bryant 2005) its sensitivity to atmospheric conditions and non-sediment constitutes in the water column (e.g. algae), and the relatively coarse resolution of most available sensors (meters).

Relatively many sediment concentration observations are needed in order to 'train' the remote sensing algorithm. The density of observation, both spatial and temporal, depends on the complexity of the water body and sensor resolution. Lakes and coastal areas require low density of observation, given their size and relative homogeneity. Rivers, on the other hand, tend to include varying water depths which can considerably complicate the remote sensing algorithm, especially for shallow sections of a river reach, where the river bed is visible. A potential remedy to this problem is to develop more sophisticated algorithms based on samples strategically taken at river sections with distinct spectral signature (Mertes et al. 1993; Volpe et al. 2011). Naturally such an approach will increase uncertainty, and may have difficulty accounting for temporal changes in flow and river morphology.

13.3.2.3 Case Study: Water Quality Assessment in Sub-Saharan Africa

Sub-Saharan Africa is facing the largest wave of Rural-Urban migration in history; it is estimated that by 2035, half of the population will live in cities. Despite progress, urban sprawl is leading to unsustainable living standards. The unplanned growth has translated to an increase in demand of resources (water), degradation of ecosystems, and pressure on public health systems due to inadequate water and sanitation infrastructure, as well as climate change. As a consequence, water bodies near cities

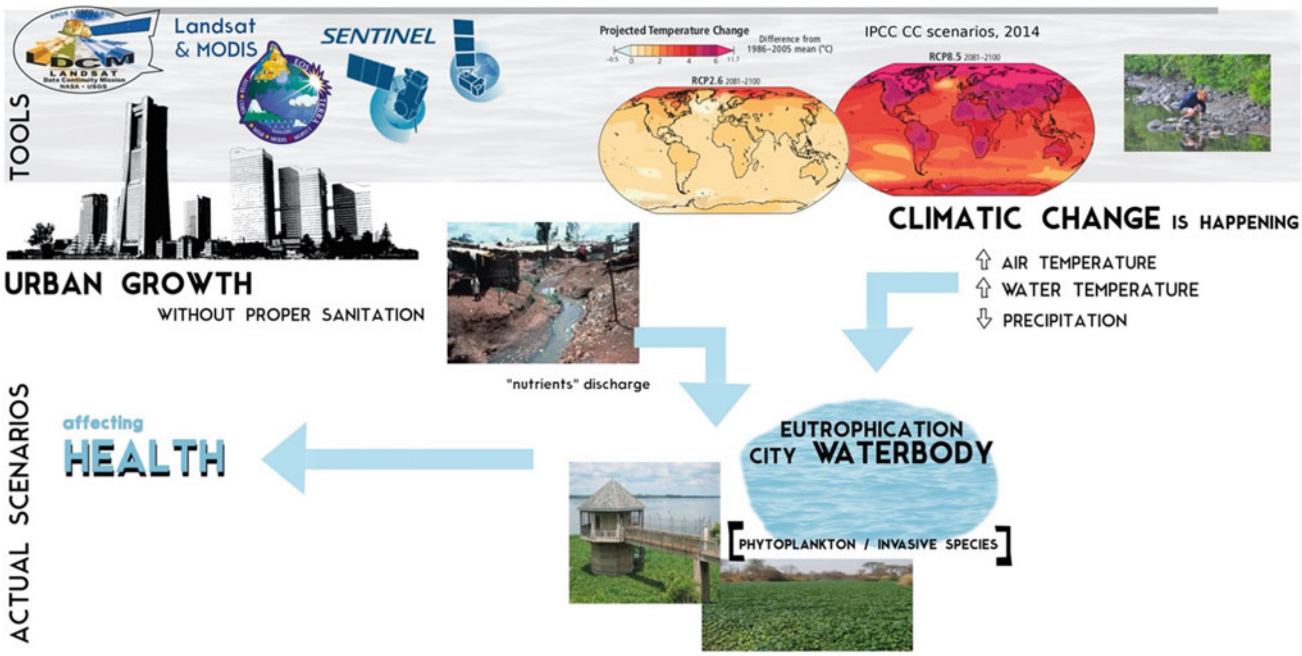


Fig. 13.23 Interlinkages between anthropogenic impacts in urban areas and consequent repercussions on Water and Health

experience microbial contamination and phytoplankton/invasive species (P/IS) blooms. To improve the urban poor's resilience and their ability to cope with climatic variability, urban planning should include a management plan that considers water-health interaction as well as the effects of climate change. In order to analyze how urban growth dynamics contribute to freshwater pollution and its impact on human health, remote sensing techniques related with P/IS—water quality levels will be essential. Equal engagement of academics, non-academics and local communities will ensure a policy relevant impact on the urban water-health management (Fig. 13.23).

The fast urban-growth, together with the Rural-to-Urban migration, generates continuous expansion of slums, which cannot cope with the development of sanitation infrastructures. Recent reports indicate that approximately 60% of African urban dwellers are living in such areas (Brown 2015), whose population is highly vulnerable to environmental stresses and health risks (Brown 2015; Un-Habitat 2012). Nowadays, many African cities are failing to deliver basic services like housing, health, energy, water, and sanitation to their urban population (Un-Habitat 2012; UNICEF 2009; United Nations, Department of Economic and Social Affairs 2014). Rural-to-Urban migration and uncontrolled city growth has led to heavy urban water pollution (microbial and nutrient) via the discharge of poorly treated municipal wastewater into freshwater ecosystem (Chawira et al. 2013). Microbial and chemical freshwater pollution are responsible for both waterborne disease outbreaks and water eutrophication processes, often interlinked (Munamati et al. 2015). The predicted effects of climate change will further aggravate the already unstable situation of African freshwater and will make cities more vulnerable to natural disasters. Indeed, water and health sectors are closely linked and dependent on hydro-climatic conditions and temperatures (IPCC 2007; Russo et al. 2016). In Africa, the lower precipitation will reduce the ability of water-bodies to mix, and will foster the concentration of phytoplankton and invasive species (P/IS) in waterways and infrastructures. Moreover, the increase of toxic P/IS and opportunistic pathogens near cities' aquatic ecosystems will affect public health (Michalak 2016).

Particularly in Sub-Saharan Africa (SbSA), climate change projections show that the ratio of temperatures/precipitation portrays a progressive increase (Park et al. 2016). Scientific reports show how SbSA water bodies across cities are increasingly becoming eutrophic (Dlamini et al. 2016) and infested by toxic P/IS and microbial pathogens (Michalak 2016). The lakes Chivero and Mutirikwi in Harare, Zimbabwe are one of the best exemplifications of such synergistic effects. The algae/pathogen pollution of lakes and rivers is the direct effect of poor wastewater sanitation coupled with the temperature increase. The already low water quality of many freshwater ecosystems across African cities will thus worsen (Dube et al. 2015; Makoni et al. 2016). Unfortunately, the management and control of freshwater quality in SbSA cities are often hindered by the economic instability of the region, as evidenced in highly populated areas like Harare (Zimbabwe). In these areas, the delivery of a regular water and health services is not guaranteed and the poor water management has caused cholera outbreaks in 2008 and 2009 that have killed thousands (approx. 4000 death) of Harare inhabitants (Ahmed et al. 2011; WHO 2009). As the Médecins Sans Frontières (2009) report showed, there was direct nexus between large-scale diseases outbreak and severity and the limited access to health care, poor sanitation and water.

In order to improve urban poor communities' resilience and their ability to cope with climatic variability and health risks, urban growth should therefore include integrated urban water management, built on a precise assessment of the current situation. The interactions between Water and Health (W-H) sectors, future projections of W-H demand and climate change impacts should be integrated into routine cities management plans and initiatives. To achieve that, city vulnerability and freshwater pollution thematic maps have to be developed. These maps will help the financially challenged SbSA cities to adapt progressively to the predicted future scenarios via the identification of priority areas of intervention.

Zimbabwe as one of the African low income countries, faced an economic meltdown which started during 2000 (Chagonda 2016; Clemens and Moss 2005; IRIN 2008). The Capital of Zimbabwe, Harare, is experiencing continuous rapid unplanned urban growth, rising poverty levels and lack of proper water and sanitation infrastructure. This is causing water and sanitary problems to the urban vulnerable communities, especially women and children (Hoko and Makado 2011). The water distribution system of Harare was built during the colonial period (before 1980) to initially serve a population of 367.000 people (Morton Jaffray Water Treatment Plant with three treatment units; Unit 1 the oldest unit built in 1954, Units 2 constructed in 1976), (IRIN 2008) and now serving over three million inhabitants. Few actions have already been taken to improve the provision of quality water (e.g. the construction of the Jaffray and Morton water treatment plant).

Unfortunately, this is not enough. Still the authorities face the uncontrolled fast urban growth, which derives in poor water sanitation, and many communities are not connected to the municipal water supply system. A report from the Harare Residents Trusts published in 2008 revealed that the Harare main wastewater treatment plant has the capacity to treat only fifty percent of the total flux received (Morton Jaffray WTP Unit 1) as the city fails to supply enough water, resulting in reduced sewage inflows. The other 50% remains and is discharged in the neighboring water-bodies. Consequently, freshwater bodies near the city are experiencing P/IS species blooms (Dube et al. 2014, 2017).

To determine water vegetation dynamics over the affected water-bodies and to monitor the land-use changes in the surrounding communities and seasonal and long-term temporal variations, Dube et al. 2014, used time-series satellite images from different sources (Landsat 5TM, 7TM and MODIS archives and Landsat 8 OLI from NASA,) over a time period (1984–2011). All images were atmospherically corrected using the FLAASH model, to minimize non-target effects and to extract accurate spectral signatures for different land uses and land covers (LULC) and P/IS. LULC information for the area was derived from the different earth observation datasets sources (spatial resolution in m) using computer-based classification algorithms, such as random forests and support vector classification ensembles.

Figure 13.24 shows the land cover and land cover classification maps for 1984 and 2011 around Lake Mutirikwi, derived from bands 3, 4 and 5 of Landsat imagery. It is possible to observe how the cultivation and grassland areas increase, while forests and shrubland decrease. These changes will affect waste discharge into the Lake Mutiriki and P/IS dynamics.

Different vegetation indices (NDVI, EVI, SAVI) derived from the Earth Observation data were used, after validation, as a proxy for lake aquatic vegetation concentrations. The

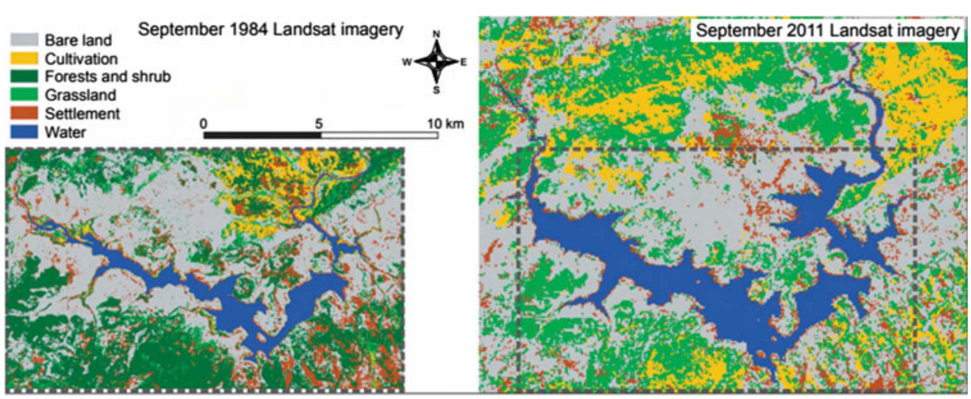


Fig. 13.24 LULC classification maps for 1984 and 2011 in and around Lake Mutiriki near

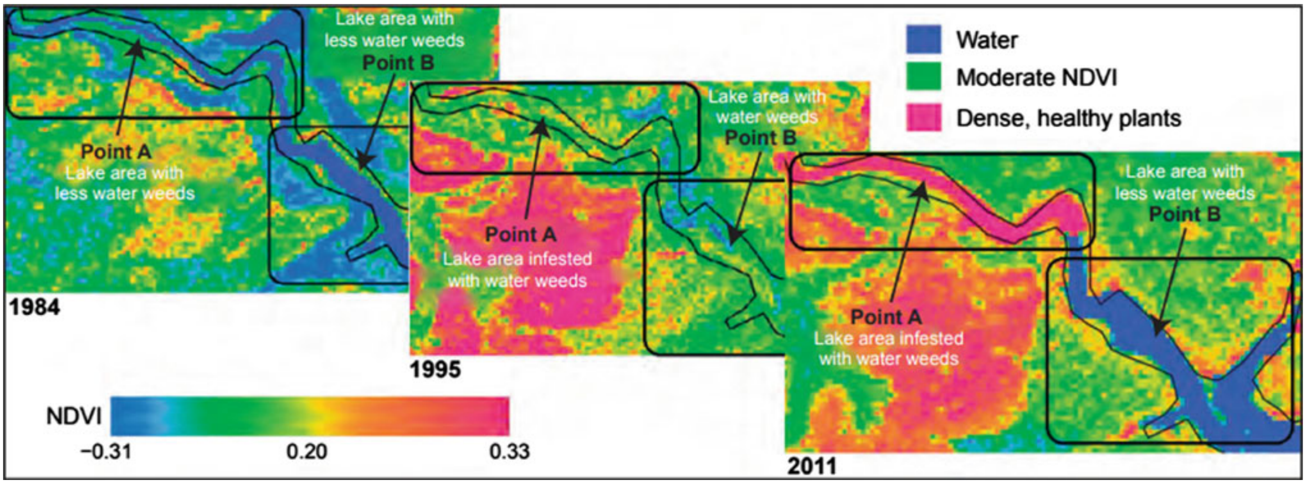


Fig. 13.25 Enlarged NDVI maps of the upper weed-infested section of Lake Mutirikwi near Harare in 1984, 1995 and 2011, indicating areas covered with surface floating aquatic weeds. *Source* Dube et al. (2014)

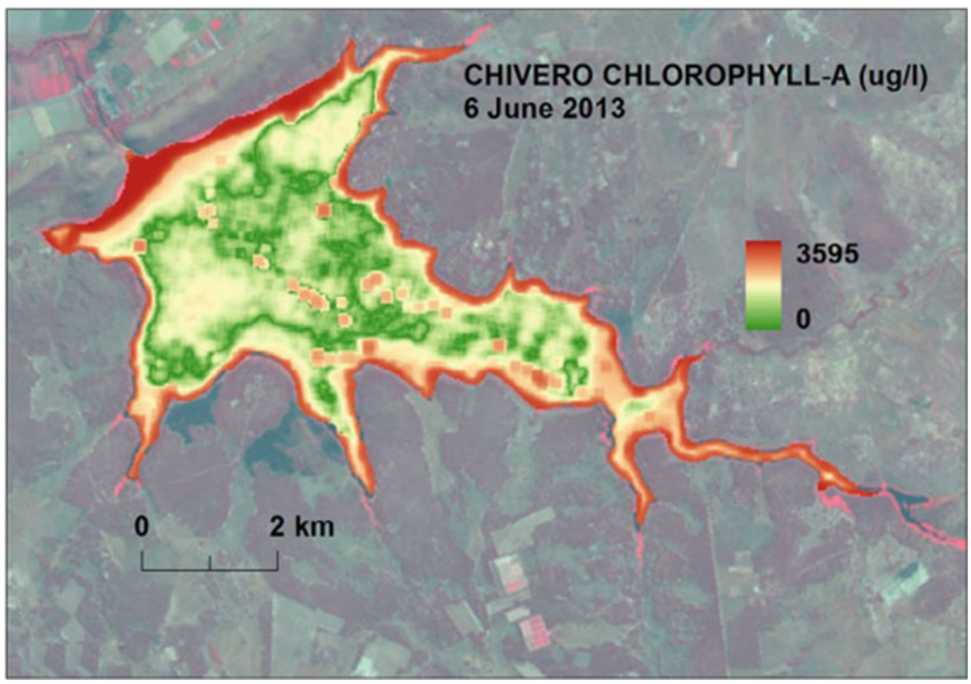


Fig. 13.26 Maps of chlorophyll-a concentrations for Lake Chivero near Harare. The maps are overlaid on top of a false colour composite consisting of Landsat bands 5, 4 and 2. *Source* Dube et al. (2014)

current P/IS proliferation levels at lake scales were derived using the high-resolution Landsat images (Fig. 13.25). The high spatial resolution data from Sentinel 2, launched in June 2015, will allow for further future characterization of P/IS proliferation levels given its 5-day temporal resolution.

Maps of chlorophyll were also determined (Fig. 13.26) using linear regression models developed from Landsat 8 satellite, calibrated with ground-measurements.

Harare municipal statistics and the Multiple Indicator Cluster Survey indicate that approximately 29% of the city residents have access to clean- piped water (Munamati et al. 2015; Zimbabwe National Statistics Agency 2014). Therefore, some residents have to use polluted water sources (rivers, boreholes and shallow wells) as main drinking/domestic water (Zimbabwe National Statistics Agency 2014). The impacts of this situation have largely been felt by the low-income communities living in high-density areas, which are not connected to the city's main water supply system, such as Mabvuku-Tafara and Mufakose.

13.3.3 The Role of Citizen Science

Water quality monitoring is a set goal of the international community. One important example is Sustainable

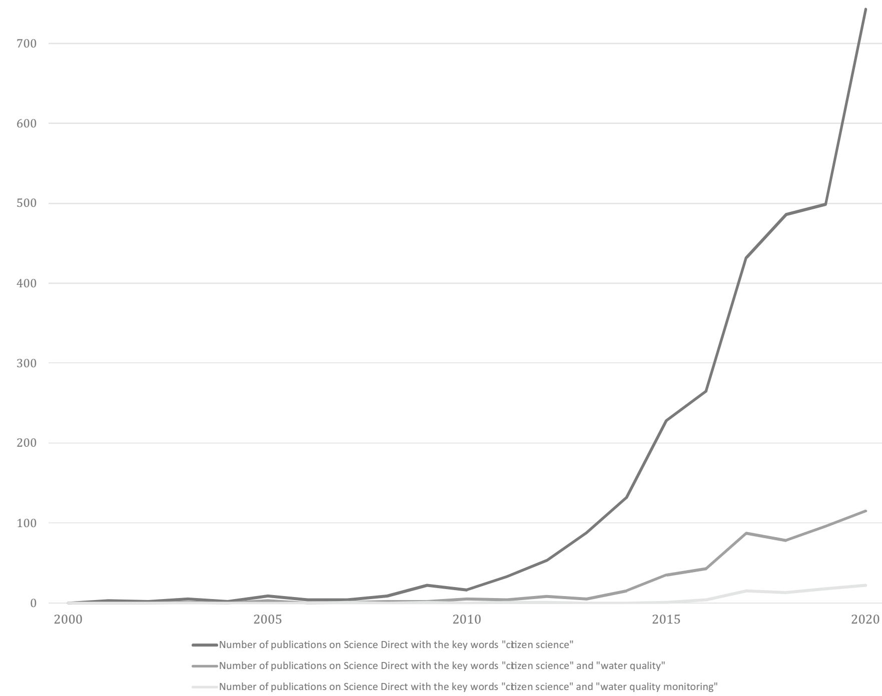


Fig. 13.27 Number of publications related to 'citizen science' in general as well as on 'citizen science' in the field of 'water quality' and 'water quality monitoring'. *Source* Own compilation and representation

Development Goal (SDGs) indicator 6.3.2 on good ambient water quality, aiming at the measurement of the commonly used parameter groups of oxygen (dissolved oxygen, biological oxygen demand, chemical oxygen demand), salinity (electrical conductivity, salinity, total dissolved solids), nitrogen (total oxidized nitrogen, total nitrogen, nitrite, ammonia, nitrogen, nitrate), phosphorus (orthophosphate, total phosphorous), and acidity (pH) (UN Water 2018).

Global monitoring data related to those parameter groups are however patchy, as the recent data drive on SDG indicator 6.3.2 has shown (UN Water 2018). This lack of data can be related to various capacity challenges in water quality monitoring, amongst them (i) challenges in creating an enabling environment (e.g., creating and enforcing obligatory rules, monitoring strategies, and institutional capacities), (ii) challenges in prioritizing the right set of parameters, and (iii) challenges with the actual measurement of parameters through monitoring, analytics, and data handling and analysis (Kirschke et al. 2020). The lack of technical equipment, human skills and financial means seems to be particularly important here. Recent analyses have also shown that human development affects the extent to which the lack of resources and equipment affect public authorities in water quality monitoring (Kirschke et al. 2020).

To address the water quality data lack, research and practice increasingly call for new data sources, including remote sensing, modeling, and citizen science. The Oxford Dictionary defines citizen science[13] as "the collection and analysis of data relating to the natural world by members of the general public, typically as part of collaborative projects with professional scientists". Citizen science has gained huge momentum in the recent past.

A preliminary research of water quality-related citizen science projects reveals a diversity of citizen science projects across the globe. Based on a screening of about 80 research articles and various online sources (project libraries, citizen science networks, further internet searches), a total number of 188 mostly ongoing projects in thirty-eight (38) countries was identified. A screening of the geographical location of these projects revealed an uneven distribution of projects between regions, with most of the projects located in North America (115 projects), and much fewer projects located in Europe (17 projects), Asia (13 projects), Australia (11 projects), Central America (5 projects), South America (4 projects), and Africa (3 projects), and 20 of the projects identified operating across several countries. While such data demonstrate a larger diversity of citizen science activities globally, it is reasonable to expect that the geographical spread of citizen science projects is even larger, since the search approach of the researchers—e.g., peer-reviewed journal articles in English—most likely led to an overrepresentation of developed countries rather than the actual distribution of citizen science in less developed countries (see Bennett and Ghazani 2020).

In addition, the number of Science Direct listed publications on 'citizen science' in general as well as on 'citizen science' in the field of 'water quality' and 'water quality

[13] https://en.oxforddictionaries.com/definition/citizen_science.

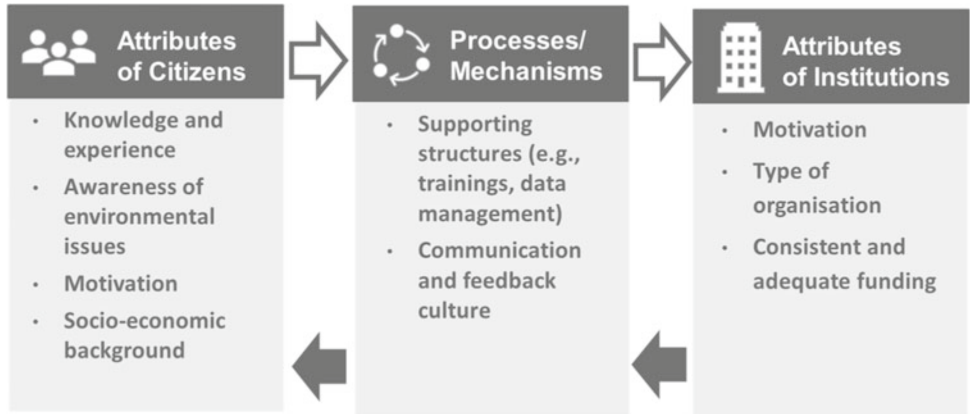


Fig. 13.28 Three sets of success factors for citizens science projects in water quality monitoring. *Source* San Llorente Capdevila et al. (2020)

Table 13.5 Criteria to differentiate citizen science projects in water quality monitoring. Source: Adapted from San Llorente Capdevila et al. 2020

No.	Characteristics	Description
1	Knowledge and/ or experience of citizens regarding data collection	Scientific knowledge of citizens and/or previous experience of citizens in water quality monitoring projects
2	Awareness of citizens regarding environmental problems	Existing awareness of citizens regarding environmental problems, e.g. with respect to water quality problems and their impacts
3	Motivation of citizens	Intrinsic motivation of citizens (e.g., environmental change, social interaction) and extrinsic motivation of citizens (e.g., financial incentives)
4	Socio-economic characteristics of citizens	Various socio-economic characteristics such as the age, education, profession, and gender
5	Motivation of institutions	Increased number of water quality data, scientific publications, cost effectiveness, impacts on political problem-solving, awareness-raising
6	Type of organization	Different types of organizations, such as research entities, non-governmental organizations, and public authorities
7	Funding of citizen science activities	Consistent and adequate funding of citizen science activities, e.g., for data collection, subsequent analysis, financial incentives for involving citizens
8	Supporting structures	Trainings for citizens on collecting water quality data, tools for data collection and management, including applications for uploading scientific data
9	Communication and feedback	Communication between all actors involved (institutions and citizens), feedback from institutions to citizens (e.g., regarding data quality)

monitoring' has increased tremendously since the turn of this millennium (Fig. 13.27), and since 2010 most particularly (UN Water 2018). The number of publications per year on citizen science and water quality monitoring has increased here slightly in the past 20 years, from zero publications in 2000 to 22 publications in 2020. The increase of citizen science publications in general from zero publications per year in 2000 to 743 per year in 2020 shows that water-quality related citizen science publications follow here a general research trend in the field of citizen science.

While citizen science has become increasingly important both in science and practice, doubts remain with respect to the best design of citizen science projects for high quality data. A systematic review of literature in the field of citizen science and water quality monitoring by San Llorente Capdevila et al. (2020) has revealed here various characteristics of citizens and institutions, as well as different ways of interactions between citizens and institutions, contributing to the success of citizen science projects (Fig. 13.28 and Table 13.5).

In terms of the attributes of citizens, researchers consider their knowledge and experience (e.g., on how to collect data), environmental awareness (e.g., reasons and effects of water quality problems), motivation (e.g., intrinsic and extrinsic motivational factors), and socio-economic background (e.g., age, gender, education, and profession). These attributes of citizens likely influence the success of citizen science projects across the globe, meaning that a certain knowledge, awareness, motivation, and socio-economic background of citizens most likely effects the willingness of citizens to participate in water quality monitoring activities and to collect good quality data. However, research also shows much diversity of citizen scientists across the globe. This becomes particularly apparent with respect to gender, with some projects having an equal share of male and female citizen scientists and other projects showing a clear predominance of one gender.

In terms of attributes of institutions, the researchers differentiate various motivations of citizens (e.g., increase of good water quality data and subsequent publications of research outputs, awareness raising, and political change), various types of organizations (e.g., research entities, non-governmental organizations, and public authorities), as well as funding for citizen science activities (e.g., consistent and adequate funding). Such attributes likely shape the design and effects of citizen science projects, particularly when it comes to the funding of citizen science activities. For while citizen science has often been promoted as a cost-effective means of data gathering, such activities do need funding for tool kits for data collection, platforms for data exchange, as well as adequate trainings, communication, and feedback mechanisms.

Finally, in terms of processes and mechanisms, research highlights both supporting structures (e.g., trainings for tools of citizens for data collection and management) and communication and feedback activities (e.g., providing feedback to citizens with respect to data quality). Such supporting structures are particularly important for improving the quality of data. Through initial trainings, for instance, citizens receive important basic knowledge to collect data; subsequent interaction with and feedback from scientists then increases learning throughout the process. Such feedback may also motivate citizens to participate in projects in the long run. Future research will show the relative importance of face-to-face interactions and digitalized processes for learning and motivation in such communication and feedback cultures.

Considering these success criteria, citizen science most likely can have a positive effect on addressing the water quality data lack related to SDG 6.3.2 on good ambient water quality. This is also in line with current research, highlighting the important role of citizen-derived data for (i) several SDG 6.3.2-related parameters (Quinlivan et al. 2020), (ii) for environmental assessments (Turbé et al. 2019), and (iii) the Sustainable Development Goals more generally (Fritz et al. 2019).

13.4 Data Availability

The need for the historical records of the evolution of the hydrological regimes preferably well into the past makes satisfying the data needs for water management and infrastructure investments uniquely challenging. As discussed in the introduction, water managers are in a difficult position, since they need to provide policy makers with a convincing rationale to steadily fund often expensive monitoring systems without clear immediate benefits.

13.4.1 In Situ Observations

Meteorologists, were able to demonstrate the value of monitoring shortly after the invention of telegraph, when the instantaneous exchange of weather information became possible and meteorologists realized that weather conditions in nearby regions propagated to other places over time. Shortly after this realization the International Meteorological Organization was formed (in 1873), that the World Meteorological Organization regards as its predecessor[14]. The immediate value of meteorological information and a steadily improving forecasting capabilities provided strong arguments to operate meteorological monitoring networks.

While, modern hydrological monitoring emerged around the same time as meteorological observations (Fig. 13.29), systematic data collection did not happen before UNESCO's International Decade of Hydrology was launched in 1965 (Nace 1969). This led to the first comprehensive compilation of river discharge data around the world, which ultimately was the starting point of the Global Runoff Database (GRDB) maintained by the Global Runoff Data Centre (discussed in Sect. 13.4.4.2).

The start dates of the observation records in GRDB allow the assessment of the evolution of discharge monitoring over time. The earliest entries date back to 1807 from Sweden followed by the next site operated in Lithuania with 1812 start year. By the mid-19th Century a number of discharge gauges operated on the Rhine and the Danube (Fig. 13.29). By the time of the International Decade of Hydrology the entire planet was already reasonably well monitored.

A little bit over 50% of the continental mass is monitored (Fekete et al. 2002), but considering that more than 30% of the continents are too dry for having organized river

[14] https://public.wmo.int/en/about-us/who-we-are/history-of-wmo.

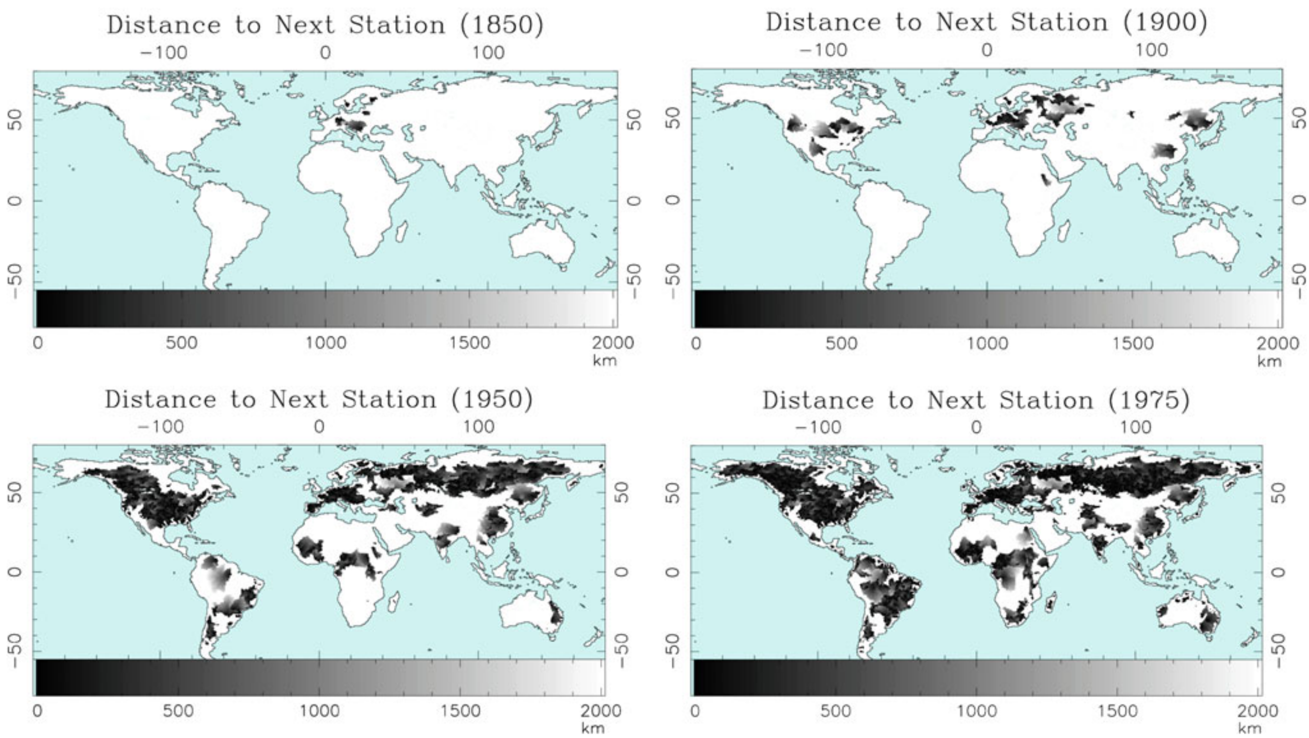


Fig. 13.29 Distance to the next discharge gauge downstream as a metric representing the monitoring station coverage and density. The darker shade corresponds to shorter distance that fades into the non-monitored white areas with lighter shades of grey

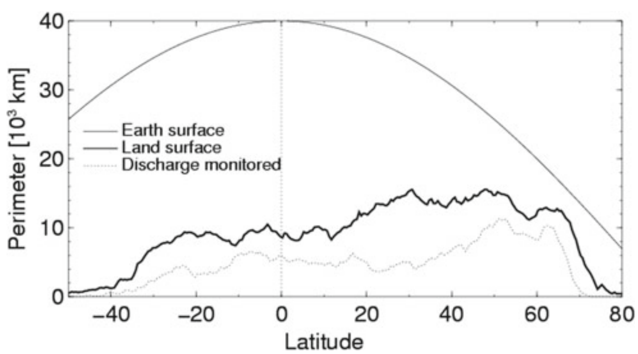


Fig. 13.30 Monitored land mass by latitude. The figure shows the circumference of the Earth including oceans (in thin grey line), the distance that can be traveled on land (thick black line) and the portion of the land that is within monitored basins by latitude (thin dotted line)

networks therefore the 50% monitored land mass is actually 72% of the 70% land mass with organized river systems. The monitoring network actually covers the continental land mass by latitude quite evenly (Fig. 13.30) albeit with very different density as the dark colors reflecting the short distances to the nearest discharge gauge reveal on Fig. 13.29 unlike some of the large river basins in Africa and South America with large sections in light colors (representing long distances to the nearest discharge gauge) fading into the unmonitored regions (in white).

Systematic water quality monitoring is either absent or the collected data are largely outside of the public domain even in developed countries. International efforts to assemble water quality data only lead to a hodge-podge of "ad hoc" recorded values of a plethora of water quality variables without much consistency in space or time. The small team UNESCO/GEMS-Water (Global Environmental Monitoring System) from Department of the Environment of Canada that was charged with this giant task went through a major set back when after 36 years of successful operation the Canadian government decided to discontinue its support[15]. The GEMS-Water database itself found a new home at the Federal Institute of Hydrology, Koblenz, Germany that hosts the Global Runoff Data Centre, but reduced commitments to expand the GEMS-Water data holding.

A World Bank report (Rogers and Tsirkunov 2013) focusing on National Meteorological and Hydrological Services attempted to assess the state of the existing monitoring network. They found that the observing infrastructure deteriorated in many parts of the world in the previous two decades. This is particularly disturbing given that the decline of the monitoring capabilities coincided with elevated interest in climate change. Climate change alone could

[15]http://www.gemswater.org.

justify serious investment in improving monitoring to provide detailed record of its progression (Fekete et al. 2012, 2015).

The World Bank report makes a strong case that cost of improved monitoring capabilities are only a fraction of the costs of weather related disasters that could be prevented or reduced by better forecasting capabilities resulting from up-to-date and more accurate hydrometeorological observations (Rogers and Tsirkunov 2013).

The shrinking national budgets to maintain hydrometeorological monitoring services not only resulted in a decline of the monitoring infrastructure but lead to a rise of commercialization of the observational data. NMHSs are often forced to secure supplemental revenues by selling data (Rogers and Tsirkunov 2013). Such arrangements, inevitably can be seen as a corruption of the operation of monitoring infrastructures. Data that was partially paid by public funding sources are sold as commercial products.

Agencies in the United States were among the first that were mandated to freely distribute their data because lawmakers recognized that these data were already paid for by taxpayers. For several decades the World Meteorological Organization attempted to promote free access to hydrological monitoring data (WMO 1999, 1995) with limited success.

Recently, the tide is changing and a growing number of national hydrometeorological agencies joined the organization sharing their data freely. WMO's Hydrological Observing System[16] (WHOS) is a portal dedicated to direct those who need hydrological data to the organization providing such data freely via the internet. Although, WHOS is still a long way from the ease on-line commerce, but it is undoubtedly a significant step in the right direction. The tremendous benefits in sharing observational data is becoming increasingly clear and growing number of national and international directives are dedicated to promote data sharing such as European Union's Digital Agenda for Europe (European Commission 2010) to facilitate the wider and more effective use of digital technologies.

13.4.2 Remote Sensing Observations

Remote sensing observations have a merely half century of history, but had more success in wide distribution of the recorded data. For decades, remote sensing was considered as the only viable means of collecting data over large areas since the telecommunication to telemeter in situ monitoring networks was prohibitively expensive.

Since the first Earth resource satellites were launched by the United States (see Sect. 13.2.2) they were made available at the cost of delivering the data to customers. In the case of geostationary satellites, the satellite images are typically directly available to customers who have their own receiving antennas. Since these satellites stay at the same location above the earth, their data broadcast is accessible to anyone with the right equipment. As a result, most meteorological organizations around the world have their own satellite data receivers even today.

Low orbit Earth resource satellites like Landsat, SPOT, etc. are different because as they orbit around the Earth their broadcast is only available in the proximity of the area over which they are flying. To gather the steady stream of satellite data from the satellites, NASA and other space agencies rely on a series of communication satellites or relaying stations on the ground. As a result, customers rarely can tap into the raw satellite data stream directly, but receive processed data from the space agencies. These data were distributed on magnetic tapes or as high quality analog images in the early days, but the internet changed the data delivery drastically and most data today are accessible from on-line sources.

Congress made an misguided attempt to privatize the Landsat program in 1984[17], but it failed and as a result Landsat and other satellite data from NASA are distributed freely. Other space agencies like ESA (the European Space Agency) or JAXA (Japanese Aerospace Exploration Agency) have mixed record of producing freely available data and commercial products, but the general trend that public agencies follow is to distribute their data freely and use their level of utilization to justify their satellite programs. Most space agencies are visibly very keen on making sure that their products are widely used.

Besides public space agencies, a number of private organizations entered in the remote sensing data market by providing high resolution satellite data (e.g. QuickBird and IKONOS). Since both of them already stopped operation and DigitalGlobe [18], their former distributor does not list any successors suggests that the commercialization of remote sensing products is still difficult and maintaining satellite programs remains the task of public space agencies.

While the internet solved the challenges of delivering large amount of satellite data and following Moore's law (Moore 1975) processing power of modern computers increased dramatically, remote sensing became available for a wide array of users. The primary challenge today is data storage, but the new trend of processing remote sensing data is to utilize cloud computing. The computer cloud removed any limits on computational resources and data storage.

[16]http://www.wmo.int/pages/prog/hwrp/chy/whos/index.php.

[17]https://landsat.gsfc.nasa.gov/landsat-5.

[18]https://www.digitalglobe.com.

Google Earth Engine[19] not only provides access to almost all freely available remote sensing data, but allows users to freely carry out the processing of remote sensing data using a comprehensive library of processing modules optimized for Google's High Performance Computing facilities. Google is not the only cloud computing provider in this market. The National Aeronautics and Space Agency (NASA) of the United States is partnering with Amazon to use Amazon Web Services[20] platform. Microsoft is partnering with ESRI (the producer of ArcGIS, the most popular commercial geographical information system on the market) to provide geospatial analysis capabilities including image processing on Microsoft's Azure platform[21].

13.4.3 Operation Costs of Monitoring Networks

Operating monitoring networks is undoubtedly a costly investment that does not always pays off immediately, but the lack of critical information could turn out far costlier. A presenter at the Integrated Global Water Cycle Observation[22] meeting many years ago mentioned a story without providing the name of the company involved, when a hydropower operator neglected to fix in the winter a discharge gauge upstream to their reservoir that would have costed approx. \$10 k due to the harsh weather. As a consequence of the missing information about the flow entering their reservoir the company committed to generate more power than what they were actually able to produce and had to compensate their customers by buying them the electricity from other sources leading to multimillion losses in US\$.

In the United States, the average cost of operating over 5200 real-time reporting (with up to 15 min frequency) discharge gauges (Afshari et al. 2017) is approximately 20,000 USD yr^{-1} per station (personal communication with David Bjerklie, US Geological Survey, Connecticut Office, Hartford, CN, USA). This cost includes the deployment and maintenance of telemetered discharge gauges that report real-time, carrying out river surveys (described in Sect. 13.2.1) and making the reported data available on USGS Water Information System[23].

Considering the data archive of the Global Runoff Data Centre (GRDC, discussed later in Sect. 13.4.4.2) that holds discharge observational records for more than 10,000 discharge gauges Worldwide (many of them no longer in operation), the total cost of their operation at the USGS costs would be 200×10^6 USD yr^{-1}. In contrast, building and launching remote sensing satellites designed with 3 + years operation normally cost somewhere between 200×10^6 and 500×10^6 USD.

Similar picture emerges by looking at the annual budgets of the agencies that are responsible to operate various monitoring networks in the United States. The National Oceanic and Atmospheric Administration (NOAA) has an annual budget around 5.3×10^9 USD yr^{-1} out of which 1.5×10^9 USD yr^{-1} is allocated for the National Environmental Satellite Data and Information Services (NESDIS).

The National Weather Service (NWS) has a 1.1×10^9 USD yr^{-1} annual budget that includes the operation of the Next Generation Radar (Nexrad) network of high resolution Doppler weather radars, high performance computing facilities for weather forecasts, etc. Only a small fraction of NWS budget is allocated for in situ monitoring. The rest of NOAA's budget goes to the National Marine Fisheries Service (NMFS), National Ocean Service (NOS), Office of Oceanic and Atmospheric Research (OAR) and Office of Marine and Aviation Operation (OMAO)[24].

In addition to NOAA's satellite programs, the National Aeronautic and Space Administration (NASA) spends 1.5×10^9 USD yr^{-1} from the 21×10^9 US\$ yr^{-1} budget on Earth Sciences that includes launching and operating low earth orbit satellites[25].

The US Geological Survey has a 1.5×10^9 US\$ yr^{-1} budget[26] out of which it spends 179×10^6 US\$ yr^{-1} on water resources to collect and deliver hydrologic data and model and analyze hydrological systems. USGS also spends 105×10^6 US\$ yr^{-1} on maintaining Water Observation System for water quality monitoring and the analyses of water.

It is probably safe to estimate that the ratio of satellite versus in situ monitoring in the United States is around to 4:1 in favor of satellite monitoring. This ratio is probably similar for the European Union and Japan with substantial satellite programs, but the BRIC countries (Brazil, Russia, India and China) also have considerable satellite programs.

The countries that don't have sizeable investments in satellite remote sensing are unlikely to have substantial in situ monitoring budgets to reverse the afore mentioned 4:1 ratio since most of those countries tend to lack in situ monitoring as well.

A renaissance of in situ monitoring is long overdue given the rapid decline in the cost of telecommunication and the availability of cheap sensors (Fekete et al. 2015). Citizen science is already taking advantage of these developments

[19]https://earthengine.google.com.
[20]https://aws.amazon.com.
[21]https://azure.microsoft.com.
[22]https://www.earthobservations.org/wa_igwco.shtml.
[23]https://waterdata.usgs.gov/nwis.
[24]https://crsreports.congress.gov/product/pdf/IF/IF11185.
[25]https://www.nasa.gov/sites/default/files/atoms/files/fy2020_summary_budget_brief.pdf.
[26]https://www.doi.gov/sites/doi.gov/files/uploads/fy2020_bib_bh051.pdf.

and empowering ordinary people to participate on operating monitoring networks, but more targeted investments in operating both in situ and remote sensing monitoring are much needed.

13.4.4 Data Centers

The agencies of the United Nations (e.g. Food and Agricultural Organization of the United Nations—FAO; United Nations Environmental Programme—UNEP; United Nations Education Scientific and Cultural Organization—UNESCO; World Meteorological Organization—WMO) pursued collecting monitoring data for a wide range of disciplines and promoted the sustained maintenance of global data archives by establishing data centers dedicated to specific observational records. Since none of the afore mentioned agencies have financial resources to operate these data centers, institutions within the member countries have to step up the plate and host these data centers under the auspices of relevant UN organizations.

The coordination of the activities at the different data centers lies in the hands of collaborative efforts in the form of expert panels under a number of coordinating programs such as the Global Earth Observing System of Systems—GEOSS, Global Climate Observing System—GCOS, Terrestrial Observation Panel on Climate Observations (TOPC). Arguably, the most relevant panel for water managers is the Global Terrestrial Network for Hydrology.

13.4.4.1 Global Terrestrial Network for Hydrology

The Global Terrestrial Network for Hydrology[27] was established two decades ago and predates many of the broader programs (e.g. the Global Observing System of Systems—GEOSS) under which currently it operates. GTN-H is a steadily expanding effort to coordinate the water related activities between data centers dedicated to various aspects of water resources.

Initially, GTN-H included the Global Runoff Data Centre, Koblenz Germany; the Global Precipitation Climate Center; Offenbach, Germany, the National Snow and Ice Data Center; Colorado, USA; Global Environmental Monitoring/Water—GEMS-Water, International Groundwater Resources Assessment Centre, Delft, The Netherlands. Over the course of the two decades GTN-H established connections to a number of water related monitoring programs depicted on Fig. 13.31 showing the GTN-H configuration as of its last triannual meeting held in Koblenz, Germany in 2017.

[27]https://www.gtn-h.info.

The different programs have different levels of activity and success in assembling comprehensive monitoring records. The Global Runoff Data Centre, Koblenz, Germany is not only the most relevant for water managers, but one of the most successful in expanding its database of river discharge records.

13.4.4.2 Global Runoff Data Centre—GRDC

The most substantive quality assured global runoff dataset is available at the Global Runoff Data Centre (GRDC) which was established at the Federal Institute of Hydrology (BfG) in 1988. It is a contribution of the Federal Republic of Germany to the World Climate Programme of the World Meteorological Organization (WMO). Under the auspices of WMO the GRDC has proven to be a reliable data supplier and partner in the field of climate change and trans-boundary water resources studies.

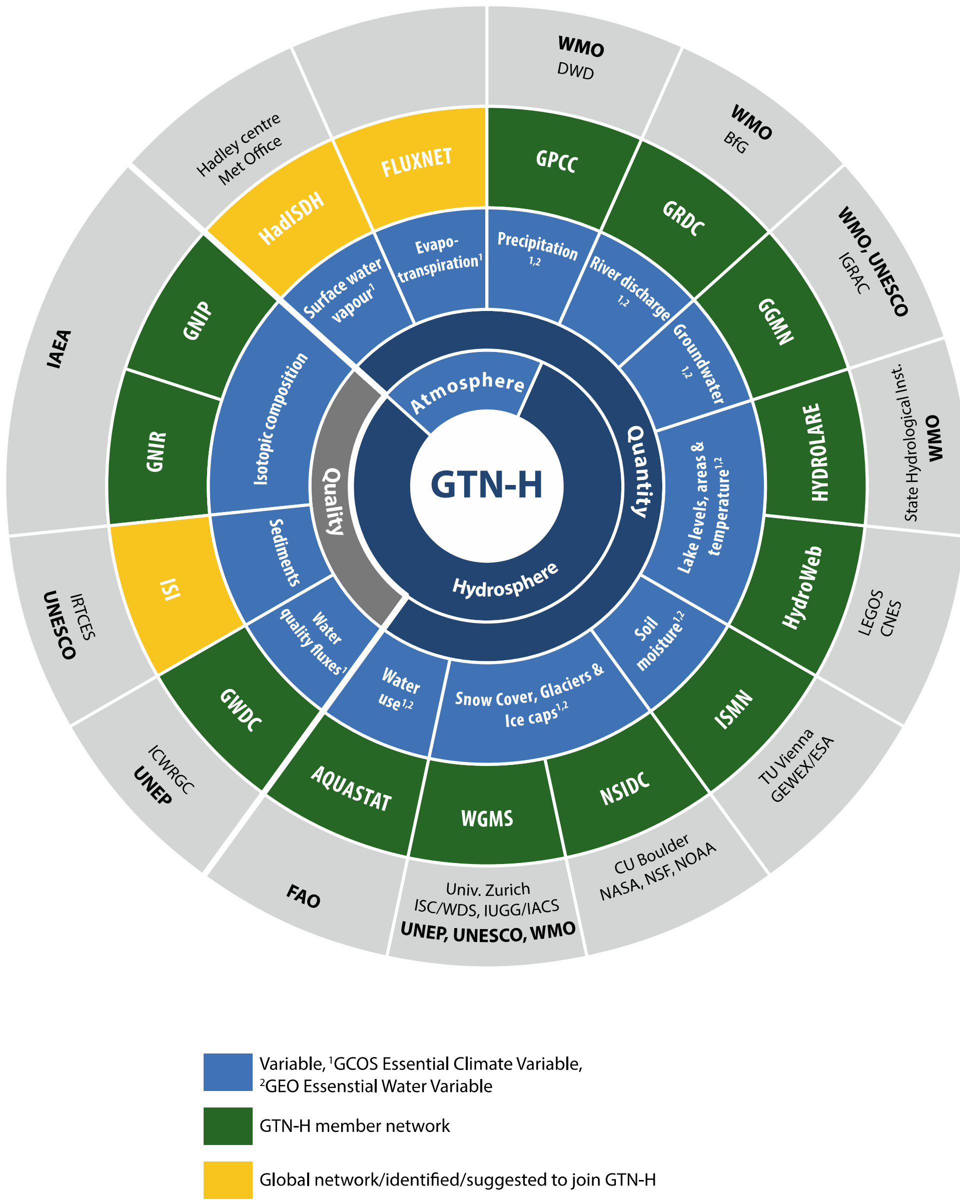
Central tasks of GRDC are the world-wide acquisition, harmonisation and storage of quality assured historical river discharge data and supporting station metadata. GRDC obtains daily and/or monthly discharge data mainly from National Hydrological Services (NHSs) around the world. As no legal mechanisms exist to regulate river discharge data provisioning to GRDC, NHSs are acting on a voluntary basis to concur with WMO resolutions on free and unrestricted distribution of hydrological data and information. Often lengthy negotiations are needed to convince NHSs to entrust their discharge data to GRDC and over time many countries became regular suppliers of discharge data and station metadata.

The Global Runoff Database (GRDB) maintained by GRDC is a unique collection of river discharge data from 159 countries around the world. It has been endorsed in 2019 by WMO Congress as one of initial 18 global datasets that were successfully assessed with the WMO Stewardship Maturity Matrix for Climate Data for inclusion in the WMO Catalogue for Climate Data. https://climatedata-catalogue.wmo.int.

Currently it contains daily and monthly time series of river discharge data from more than 10,000 stations. This adds up to around 450,000 station-years with an average record length of 45 years. The longest discharge time series date back more than 200 years. Datasets and stations metadata are continuously updated.

The collected datasets are focussing on three areas of interest. Stations representing the hydrological regime of the respective basins resemble the basis of the GRDB. Furthermore those stations upstream of tidal influences on major rivers are relevant to calculate total freshwater fluxes to the world oceans. Lastly stations with minimal anthropogenic impact and long time-series valuable for climate change studies, referred to as “climate sensitive stations”, complement the GRDB.

Fig. 13.31 The configuration of the Global Terrestrial Network for Hydrology (GTN-H)



For station selection purposes GRDC provides station catalogues on its website in addition to KMZ files (compressed Keyhole Markup Language—KML files containing geographic data) which can be utilised to visualise station locations using Google Earth. Stations of interest can be requested from the GRDC data portal https://portal.grdc.bafg.de. Users will have to accept GRDC data policy before data are made available. This ensures that WMO Resolutions are not violated and that data policy conditions of data providers are met.

Apart from the daily and/or monthly discharge time series, GRDC provides products such as "Long-Term Statistics and Annual Characteristics of GRDC Time series Data" listing primary hydrological values and "Global Freshwater Fluxes into the World Oceans".

Several spatial products are available at GRDC. Shape files with a global coverage are "Major River Basins of the World" and "WMO Regions and Subregions". Watershed boundary shape files for more than 7000 stations can be requested as well.

GRDC aims to provide quality assured and up-to-date daily and/or monthly river discharge data collected from reliable providers to the scientific, research and teaching communities. For further information please visit http://grdc.bafg.de or contact grdc@bafg.de.

13.5 Data for Decisions: Overcoming Barriers

Sustainable water management needs good water data to support evidence-based decisions. Getting water data right requires high quality planning, wise and ongoing investment, and assiduous implementation of strategy across seven key elements of good water data practice.

Adaptive management of water resources (Allan and Stankey 2009) identifies management as a considered and structured learning process. In this the evidence used to inform a decision is known, including risks and uncertainty, and the outcomes of a management intervention form part of the data used to support the next intervention. This creates a compelling case for good management of water data and increasing data sharing, as well as for making the effort needed to overcome the political, institutional and technical barriers to data access, sharing and use.

The range of decisions and problem situations in water management is broad. In the *Good practice guidelines for water data management policy* the Australian Bureau of Meteorology (2017) and the World Meteorological Organization identify seven basic uses of water data in management:

- **Water operations**—real-time monitoring of water data parameters for the purposes of operating water infrastructure
- **Water assessment**—how, where and when water resources are changing
- **Water foresighting**—how water resources are likely to change in the future
- **Water design**—determining design parameters for water infrastructure
- **Water evaluation**—judging the efficacy of water management interventions
- **Water accountability**—water managers building trust with customers, investors, regulators, the community and other stakeholders
- **Water education**—enabling communities to understand where our water comes from, how it is managed and how it is used.

Although all of these require the support of data, the data needed and the sources of those data, vary considerably. There are four basic sources for water data used to support decisions (Bureau of Meteorology 2017)—direct measurements, inference from remote sensing, estimation from models, and administrative data collection, such as via household or industry surveys.

Managers trying to access and use these types of data face a range of barriers, and overcoming these barriers requires both good policy and good data practice. The seven key elements of good practice in water data management (Fig. 13.32) contain two broad scale approaches to overcoming data barriers, along with a set of five practical aspects for sustainable data management and sharing. By embracing these good practices, countries, agencies and managers will establish sustainable approaches to supporting water management decisions with a solid evidence base.

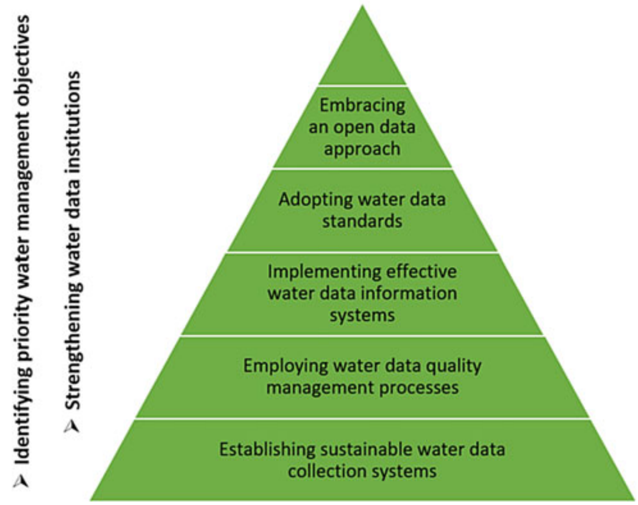


Fig. 13.32 Seven elements of good water data practice (adapted from Bureau of Meteorology 2017)

This section explores these elements from the perspective of integrated water resources management, and how the implementation of good policy and good practice overcomes the political, institutional and technical barriers to good use of water data in decisions.

13.5.1 The Case for Good Data and Data Sharing

Globally, government and trans-boundary water agencies are finding that water data and information arrangements are not meeting their needs for timely and sustained evidence-based decision making. There are many similarities seen in cases across the world. Data holdings and monitoring systems have many gaps and discontinuities. Data are gathered by many groups, but are not able to be accessed by others. Data quality varies significantly and is often poor. Where data are accessible, they are difficult to interpret and use.

There are four high-level challenges or ‘perils’ that arise from inadequate water data (Bureau of Meteorology 2017), and which, together, provide a compelling case for getting water data right.

The first of these is “blindness”. Good water information allows an agency or government to see where they have come from and where they are going. In the situation where water data is inadequate, water shocks such as urban "day zero" water supply scenarios come as a surprise rather than being foreseen and avoided through strong, timely and informed government action.

The second challenge is 'ignorance', or the lack of facts within the policy debate. With low quality or no data, poor and good policy ideas are often considered equally weighted, and policy makers are more likely to make unwise choices.

'Mistrust' is the third peril, including mistrust within and between agencies and government, or between government and community. As pressure builds around times and places of water scarcity, the lack of trust that arises through information vacuums is exacerbated. Sharing of data and information is a great diffuser of tension, as people turn attention from arguing to determining what can be done by applying data to decisions.

The final one is "wastage", where the potential benefits of significant investments in water infrastructure are not realized due to lacks in application of good quality data to water allocation and system operation.

Overcoming the barriers allows agencies to work their way up the data value ladder. Governments make considerable investment in data collection, and the return on this investment increases considerably when the data is shared and used. Additionally, good foresight, good decision making, and trust all arise through reducing the cost and complexity of accessing and exchanging fit-for-purpose water data.

This impetus for data openness was emphasized by the United Nations and World Bank High Level Panel on Water (High Level Panel on Water 2018) which had as a first recommendation that we should all *"commit to making evidence-based decisions about water, and cooperate to strengthen water data, such as through the HLPW World Water Data Initiative."*

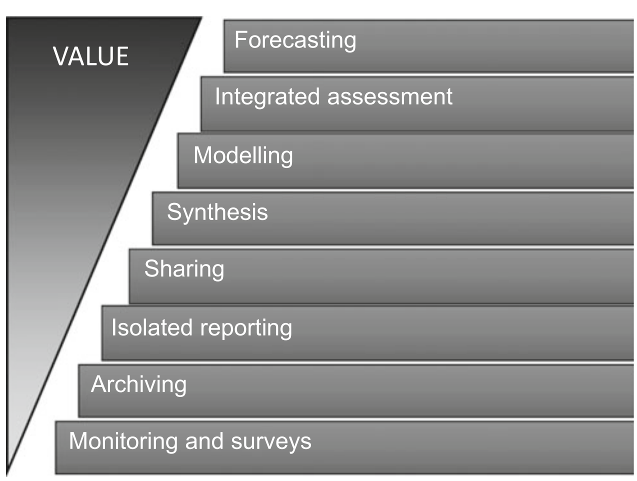


Fig. 13.33 The water data value ladder (adapted from Commonwealth of Australia 2016)

13.5.2 The Data Value Ladder

The data value ladder (Fig. 13.33) identifies the growth in value that arises as we move from processes of gathering basic data, such as from on-ground sensors, models, remote sensing or administrative data, through to delivering value-added products that best support to decision maker needs.

The lower rungs of the ladder cover the functions that are done commonly across much of the world—gathering or generating, storing and managing data. Many agencies focus on this as their primary function, and deliver isolated reporting on particular aspects of water that support specific management needs.

Moving up the value ladder takes us to the first steps of value-adding for broader needs of customers and managers, synthesizing and sharing data. As noted previously, water resources management problems are many and varied and solving most of these requires integration and use of multiple data sources. Thus, good decision making relies heavily on open access to data, particularly data that is 'integration ready' with sufficient metadata and standardization that enables integration and direct application to management problems.

This brings us to the higher rungs on the ladder, where the highest value lies. On these rungs the gap between **data** and **decision** is narrowest, with the resulting assessment and forecasting products being those most directly applicable to supporting common high-value water management questions.

13.5.3 Overcoming Barriers Across the Value Ladder

The following guidance steps through approaches to overcoming the barriers to climbing the data value ladder, built on the seven elements of good data practice (Fig. 13.32).

In most situations action will be required for some, if not all, of the seven elements. In an example situation, monitoring and data systems may not be maintained, data may not be shared, and there might be multiple competing and overlapping jurisdictional responsibilities around water. This sets the scene for a 'call to action' to develop a compelling case for water data reform, through which the situation will move to a more sustainable footing that continues to deliver high value data and information for current and future decision making.

As is often the case in policy and reform development, the willingness of government to act on reform is driven by a crisis. It is sensible therefore to prepare and propose a comprehensive and feasible case for reform, including multiple viable options, that details (Bureau of Meteorology 2017):

- The water management challenges being addressed
- Effective solutions for identified institutional problems
- A lead agency responsibility for reform
- Who will be affected by the proposed reforms and how
- Full costs and benefits of the reform options
- Realistic timelines for the reform implementation
- Sequencing of reforms and any vital dependencies
- Risks and risk mitigations for each of the proposed reforms
- Reform project governance arrangements.

A well-founded package of reforms that is feasible and politically attractive in the face of a crisis will give the impetus and support required to take action to improve data access and use by decision makers across all the elements shown in Fig. 13.32.

13.5.3.1 Strengthening Water Data Institutions

The first element (Fig. 13.32) is that of strengthening institutions, where 'strengthen' is not taken to mean "make larger" but rather to clarify and simplify purposes and roles. An almost universal situation appears in the context of water-related institutions due to the natural cycling of government concerns and agency responsibilities. This is where, either within an area or across regions, countries or in trans-boundary situations, there are multiple agencies with similar, if not overlapping, responsibilities.

A situational assessment is required here, which identifies the involved institutions, relevant legislation, costs and functions, deficiencies in monitoring and data sharing, technology and capability gaps, and the opportunity cost of failing to reform, in the context of any current crises as well as into the future.

The outcomes from this analysis are included in the package of reforms, with clear recommendations for changes to strengthen the institutions. Although this can be challenging for some institutions due to perceived risk of loss of role, the reality is that all institutions participating in water data reform benefit from the increased capacity, capability and relevance across the whole water sector.

Noting that institutional strengthening is an activity that cuts across many of the elements, it is important that the full package of reforms is shared and publicized at the highest level possible, ideally by highly respected, seniors figures who are trusted as advocates of better water resources decision making.

13.5.3.2 Identifying priority management objectives

Managing water data to support decisions will be most effective when it is done to support those that decision makers agree address their highest priority concerns. The converse also applies, that data management efforts that fail to support critical decisions will not be considered of value and will lose support and resourcing. Thus, developing a water data management strategy to operate within a strengthened institutional framework requires identification and attention to those high priorities.

Example management objectives range across areas such as flood risk, potable water supply, effective sanitation services, water supply and drainage infrastructure, or water security for agriculture, aquatic ecosystems or power generation. Most integrated water resources management is multi-objective, so the nature, timing, key features and priorities of multiple objectives must also be considered.

Including and prioritizing these objectives within strategy development can be done by considering a number of questions (Bureau of Meteorology 2017), such as:

- Which of our many water management problems are the most important to solve?
- What kind of water data is needed to diagnose problems and develop solutions?
- Who will use this water data and what decisions will they need to make?
- What form must the water data be in, to be useful in decision making?

Identification of objectives also provides an indication of the type of data required, as not all data supports all types of decisions. Data collection considerations include the variables (e.g. water use, rainfall, river flow, groundwater chemistry), spatial distribution and density of sampling sites, frequency and focus of sampling (e.g. regular sampling v. focusing on low flows or events), precision, and length of monitoring period (e.g. months, years or ongoing).

Finally, arrangements for water data management need to be reviewed periodically as hydrologic, ecological and societal conditions change, and as new or different objectives occur.

13.5.3.3 Sustainable Data Collection Systems

Data collection includes on-ground (in situ) collection of observations and administrative data as well as collation or management of data generated from models and via processing of earth observations from space. Three fundamental elements are required to establish a sustainable monitoring system (Bureau of Meteorology 2017): (i) identifying user needs, (ii) specifying operating requirements and (iii) implementing a sustainable funding regime.

The previous section noted the importance of identifying priority management objectives. These, in turn, identify the types and nature of the information required from a data collection or monitoring system and therefore inform the system requirements (such as variables and sampling regime). In addition to the management objectives, user needs also include data formats, data exchange and sharing requirements, data system compatibility, and the metadata required to support use of the data for decision making.

Once user needs are clear, the next step is to work out how to get the required water data. For administrative data such as household water use, the survey and survey collection methods need to be well designed, whereas for river flow there is a need for exact specification of how the measurement should be done. This includes selecting monitoring equipment and associated communications systems, along with siting, installation, calibration, operation and servicing. When using earth observation from space, choices will include the satellite platform, the channels and the signal post-processing algorithms to deliver the required variables.

A common strategic mistake in water data management is failing to secure ongoing and sufficient capital and operating funding to provide enduring high value to water decision makers. There are many examples where isolated grants have been used to establish monitoring sites or a network, with these then falling into disrepair due to lack of support for operations, including routine calibration and maintenance, and future upgrades. Plans for capital funding should account for acquisition, installation, repair and replacement of monitoring equipment, while operating resources must include servicing, calibration, telecommunications charges, software licenses, data quality processes, training of technical staff, and, finally, periodic review of the goals, processes and realized benefits of the data collection investment.

13.5.3.4 Employ Water Data Quality Processes

In managing and sharing data for decisions, key quality aspects include data validity, accuracy, completeness, timeliness, consistency and availability. Quality processes for these aspects include certification, quality assurance, quality control, quality management, and quality management systems, where best practice procedures and systems for quality lie under the ISO (International Organization for Standardization) 9000/9001 'Quality Management Systems' family of standards.

In respect of quality management for hydrological monitoring systems, the World Meteorological Organization (WMO 2013) outlines a suggested approach to implement a Quality Management System at a national scale, focusing on attaining ISO 9000/9001 certification. Key benefits arising from quality management of water data and data management include a culture of continuous improvement, a consistent approach to understanding and meeting customer needs, standardized and understood procedures and processes, maintenance and building of skills and internal resources to support quality processes, and reduction in wastage of time and resources spent of resolving recurring problems around data quality.

Overall, applying quality management processes through the water data value chain returns significant benefits, particularly in the quality and trust related to the decisions made using data of a relevant and appropriate level of quality.

13.5.3.5 Effective Water Data Information Systems

Water data information systems are the essential software elements used throughout the data value chain, from data collection through quality management to publishing, sharing, integration and reporting. The capability and performance of such systems are, therefore, a major component of effective and efficient water data management.

There are four key attributes of effective water data management systems (Bureau of Meteorology 2017). These are:

- Functionality—readily supporting both internal quality and processing needs, along with external access and sharing requirements to enable the use of data in decisions.
- Maintainability—good design, easy maintenance and upgrading, and high use of technical and data standards.
- Spatial enablement—enabling and ensuring that relevant and comprehensive spatial information is associated with all data.
- Dependability—ensuring that systems are available with minimal disruptions to services, that outages are well-planned and managed, and that upgrades and changes occur through managed development, test and deployment processes.

13.5.3.6 Adopting Water Data Standards

The value of water data in decision making, and savings in cost and efficiency of data handling, are significantly increased through adoption of data standards. These standards include those used for both acquiring data, such as

Table 13.6 Characteristics of open data (adapted from Australian National Data Service)

Characteristics of open data	Meaning
Freely available to download	• There is no cost to access the data • Access is via an internet accessible download • Data is in a form that can be readily downloaded
Licensed	• An open license is applied
Well described	• Standards based metadata is used with details of data elements and inclusion of data dictionaries • Describe the purpose of the collection, the characteristics of the sample and the method of data collection
Provided in an open format	• The data is in a convenient, modifiable and open format that can be readily retrieved, downloaded, indexed and searched • Where possible, formats should be machine-readable and non-proprietary formats are preferred
Well managed	• The data is managed on an ongoing basis with a point of contact designated to assist with data use

field observation and laboratory analysis of water samples, and for storing, sharing and transferring data.

Standards for data acquisition have been produced, for example, by the World Meteorological Organization, the United States Geological Survey, the International Organization for Standardization, the American Public Health Association and the Australian and New Zealand Environment and Conservation Council. These include a broad suite of standard approaches that include measurement and monitoring of hydrological and water quality variables.

The definitive water data exchange standard is WaterML2.0, published by the Open Geospatial Consortium. WaterML2.0 is a five-part standard, with individual information models for the encoding and exchange of:

- Hydrologic time series (WaterML2.0 Part 1).
- Streamflow ratings, gauging and sections (WaterML2.0 Part 2).
- Surface hydrology features (WaterML2.0 Part 3).
- Groundwater data (WaterML2.0 Part 4).
- Water quality data (WaterML2.0 Part 5).

These standards are based on a series of eXtensible Markup Language (XML) schemas. As these standards are widely available to the public and are supported by many organization and data systems, the primary barriers for adopting these relate to resourcing and staff training, both discussed previously.

13.5.3.7 An Open Data Approach

The final challenge in supporting data for decisions is to adopt and embrace an open approach to data sharing. Table 13.6. identifies some of the characteristics of open data. There are many experiences internationally to show that economic and social benefits arise from open data, as the initial significant investments in data collection, quality processes, data systems and data standards are returned many times over. Making water data open makes it easy to discover, download and use, and supporting re-use through open licensing makes it easier for those supporting decision makers to share, remix and apply the data directly to urgent decisions. Open licenses examples are publicly available and, with policy support, can be implemented with minimal effort and cost. The Creative Commons and the Open Data Commons license groups are a good starting point when seeking to adopt open licensing.

Many countries around the world have enforced open data and data sharing though national policy, and many data systems support these open data policies 'out of the box' through data publication via standards-based web services. Overall, the technological barriers to open access have been falling rapidly in recent years, and momentum is building to help overcome the primary policy barriers.

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Balázs M. Fekete earned his M.Sc. in civil engineering with specialization on water resource at the Technical University of Budapest and Ph.D. in Earth Sciences at the University of New Hampshire. He worked as research scientists in various ranks at the Water Resources Research Center, ISTER Environmental Research, University of New Hampshire and City College of New York. He joined the faculty of the Department of Civil Engineering at the City College of New York of the City University of New York in 2012 and he has affiliated faculty status in the Advanced Science Research Center at the Graduate Center, CUNY.

Dr. Fekete's primary scientific interest is hydrological modeling and data assimilation at various scales for water resources assessments and the integration of modern spatial data management with modeling frameworks to integrate the available data into hydrological analyses.

Ana Andreu is a Marie Curie Fellow with IFAPA Research Center (Spain) as her core institution, modelling savanna and Mediterranean ecosystem water and carbon fluxes, integrating multiple source-scale Earth Observation data. For more information about Dr Andreu's previous work, you can visit her website https://savannahwatch.cc/.

Robert Argent led the Bureau of Meteorology's Water Program, delivering a suite of national water data and information services that include past, present and future assessments of surface and groundwater resources. Over 2017–2018 he led the World Water Data Initiative under Australia's membership of the UN and World Bank High Level Panel on Water. He previously directed Australia's Water Information Research and Development Alliance, a research partnership delivering operations-ready research outputs across water data, assessment and forecasting. Prior work includes research and consulting in hydrological analysis and catchment modelling.

Tamara Avellán's research focuses on the overarching understanding of the bio-physical interlinkages between the natural resources with a particular focus on water, and on the interlinkages of these resources with social, economic and institutional spaces. Dr. Avellán's career has shown her the world of academic research and its implementation in the service to member states through the United Nations in Latin America and the Caribbean, Small Island Developing States and West Africa. Working at this interface, learning and applying inter- and transdisciplinary methods have been crucial.

Charon M. Birkett earned her Ph.D. in Astronomy at the University of Leicester U.K. but switched to Earth Sciences and satellite remote sensing at the University College London. She later became a senior research scientist at the Earth System Science Interdisciplinary Center, University of Maryland, but now resides within the Geodesy and Geophysics branch at the NASA Goddard Space Flight Center.

Dr. Birkett's primary area of research is continental water and the exploration of satellite-based altimetry datasets for both the sciences and the applied sciences. Specifically, focus is on lakes, reservoirs, wetlands and river reaches regarding dynamics, long-term variability, water resources, water storage contributions to mean sea level rise, and natural hazards.

Serena Caucci is an Associate Programme Officer at the United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES).

Prior to joining UNU-FLORES, Serena served as a researcher and scientific project manager at the Technische Universität Dresden and at the Helmholtz-Centre for Environmental Research—UFZ in Leipzig, Germany where she elaborated and coordinated efforts on water sanitation and the impact of contaminants of emerging concern in anthropogenic-driven environments. Serena has also worked as consultant for the EIT Climate KIC where she developed curricula for innovation trainings and knowledge transition in bioeconomy. She began her career as Environmental Science Fellow at the University of Florence, Italy where her work on carbon storage mechanism by microbial community in soils was part of a LIFE project Natura 2000.

Dr Caucci's current research is geared towards sustainable development with a special interest in the impact that anthropogenic activities have on natural resources. Focusing on the sustainable management of wastewater and organic waste, Serena is working towards the development of a transdisciplinary framework that could make use of socioeconomic and environmental interlinkages to enhance sustainable natural resource management. The final goal of her activities leads to knowledge translation for evidence-based decision-making processes and its implementation at various scales.

Sagy Cohen earned his Ph.D. in Environmental Sciences at the University of Newcastle, Australia. He held a two-years post-doctoral appointment at the Community Surface Dynamics Modeling System (CSDMS) group within the Institute of Arctic and Alpine Research (INSTAAR) at the University of Colorado. He joined the faculty of the Department of Geography at the University of Alabama in 2012, establishing the Surface Dynamics Modeling Lab (SDML) shortly after. In 2017 he was promoted to Associate Professor.

Dr. Cohen's primary scientific interest is modeling and analysis of hydro-geomorphic processes and dynamics in large global rivers. He is also leading research and development efforts focusing on flood remote sensing, analysis and modeling. He serves on the Global Flood Partnership (GFP) steering committee and was a research theme leader in several National Water Center Summer Institutes (organized by the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI)).

Timothy Dube is a rated NRF researcher and academic currently affiliated with the Department of Earth Sciences, at the University of Western Cape. Prof Dube's research focuses on GIScience and Earth Observation application riparian ecosystems and water resources (quality and quantity), land-use change, invasive species modelling and terrestrial carbon accounting as well as precision agriculture. He has expertise in geospatial analytics and satellite remote sensing and sensor networks for terrestrial ecosystems, inland waters, and wetlands.

Sabrina Kirschke is a Senior Research Associate at United Nations University - Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), in Dresden, Germany. As a political scientist, she contributes to the research, academic, and capacity development activities in water resources management within the resource nexus.

Ulrich Looser has been head of the Global Runoff Data Centre (GRDC), operated under the auspices of WMO, at the German Federal Institute of Hydrology since 2007. He grew up in Namibia, obtained his masters from Giessen University and was working for 22 years at the Hydrological Research Institute of the South African Department of Water Affairs.

14 Assessment of Water Quantity

András Bárdossy and Abbas El Hachem

Abstract

Freshwater is distributed in a very non-uniform manner on the surface of the earth. Both spatial and temporal variability have a strong influence on water management. In this chapter both mean values and spatial and temporal variability measures of the main hydrological variables, precipitation (rain and snow), discharge, groundwater availability are mapped in order to enable specific evaluation of the regional water management requirements. Besides the natural variables socio-economic factors are also investigated, water availability is presented for the different countries of the world.

Keywords

Water availability • Water variability • Precipitation temporal • Spatial distribution

14.1 Introduction

Freshwater is an indispensable natural resource for any human society. In Fig. 14.1, the world's water resources, as present in the different compartments of the water cycle, are displayed. From the total global water volume, only 2.5% is freshwater. An estimated 1.2% is present in easily accessible compartments with short residence time, such as rivers, lakes, soil moisture, and the atmosphere. The remainder is in inaccessible compartments with long retention time, such as glaciers, ice caps, and deep groundwater.

In 2020 natural water resources would be enough to cover all demands but the high spatial variability of the water supply in the form of precipitation and river flow, combined with the high variability of water demand resulting from population distribution and economic activities, makes water management necessary. The continuous increase in the global population, changing climate and human activities has led to a continuous increase in the water demand. In some regions this means overstressed supply systems and deteriorating water quality. Freshwater needs to be well managed. Much of the world's population relies on surface water and groundwater for their freshwater supply. Many of the available resources have been affected by pollution resulting, for instance, from the discharge of untreated domestic and industrial wastewater. This puts additional stress on the already stressed resources. Many competing sectors are interacting together and sharing available resources. It is therefore necessary to protect and manage freshwater in a sustainable manner to ensure the survival and development of societies.

In the following sections, an analysis of the different resources not only in terms of quantity, but also in terms of spatial and temporal variability, is presented. In the second section, the management strategies and use of different resources to satisfy human needs in the current global water availability situation are described. In the final section, a case study of the Nile river basin is given.

14.2 Fluxes

All the water on Earth today, every drop, is all the water there has ever been on the planet. Freshwater is actually millions of years old. The same water goes round in a continuous loop, falling as rain and snow from clouds to the Earth surface, running in rivers, cooling in ponds, irrigating crops, traveling through plants, generating power, eventually evaporating into the air, and condensing into clouds again.

A. Bárdossy · A. El Hachem (✉)
Institut für Wasser- und Umweltsystemmodellierung, Universität Stuttgart, Stuttgart, Germany
e-mail: abbas.el-hachem@iws.uni-stuttgart.de

A. Bárdossy
e-mail: Andras.Bardossy@iws.uni-stuttgart.de

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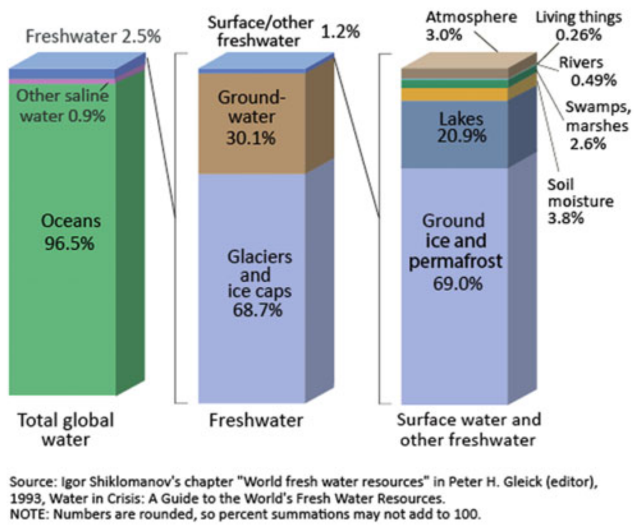


Fig. 14.1 World fresh water resources

Flows and stores summarize the water cycle. The water cycle is a series of flows of water between various water stores or storages. The global hydrological cycle in qualitative terms is illustrated in Fig. 14.2, starting with precipitation, which is the process of water falling onto the surface of the Earth. There is always water in the atmosphere, either on a dry or a humid day. Most of the water, around 70%, is found in the oceans. In the ice sheets and glaciers, two-thirds of all freshwater on Earth is present. The remaining one-third exists in snow packs atop mountains, in lakes, in rivers and streams, in reservoirs and watersheds, in wetlands, in the soil, in and on plants and trees rooted in the soil, and beneath the soil, in water tables and underground aquifers. All of this storage is temporary, but for the volume to remain constant, a balance between influxes and outfluxes is needed. Water, in all its forms, is always in flux and continuously moving.

Precipitation comes in many forms; the most common are rain, snow, and hail. Rain is falling water in liquid form. Snow, ice hail and sleet are falling water in solid or frozen form. Fog and mist are falling water in vapor form. Precipitation that falls directly into the oceans becomes part of the surface layer of the ocean and can be churned by wave and wind action into ocean currents. Rain and snow that fall directly on rivers and streams immediately join the stream flow. The rain that falls onto land takes a longer path to the river as do the snow and ice that fall and collect on mountaintops. When the snow melts, some of it runs through the snow pack, and goes into small streams, tributaries that feed into large rivers. Some of the precipitation that falls over land is intercepted by vegetation, plants and trees. The precipitation reaching the ground can run off if the ground is very compacted, covered with asphalt or concrete, or if the soil is too wet or saturated to accept more water like an over soaked sponge. Otherwise, precipitation infiltrates the soil surface, percolates into the ground and is pulled downwards by gravity, through the topsoil into spaces between soil and rock particles down to bedrock, and further into fractures to deep underground aquifers. Even groundwater is moving sideways or laterally, discharging toward a river, lake or the sea; generally the deeper the flow the slower it is. Water returns to the atmosphere through evaporation.

As water evaporates, it is turned from a liquid into a vapor by the heat of the sun. Water evaporates from every wet surface and even from wet air. Some rain and snow evaporate into the air while falling. Water evaporates through animal respiration and perspiration and through transpiration from plants. Plant roots draw up groundwater, and this water is pulled upwards through their stems into their leaves and then released through transpiration. The process of evapotranspiration is defined as evaporation from soil and water surfaces plus transpiration from plants. Evaporated water molecules are tiny enough to flow into the air, mix with other fine particles such as smoke and dirt in the atmosphere, and cool, condense into visible masses of water vapor or clouds. Wind moves clouds into colder air; water droplets collide and merge, grow bigger and heavier until they are so heavy that they fall again as rain or snow, sleet or hail. Precipitation, collection, runoff, interception, infiltration, percolation, discharge, transpiration, evaporation, and condensation define the water cycle (National Science Foundation (NSF) 2013). The water cycle can also be described in terms of residence time, defined as the average amount of time that water remains in a given reservoir. The residence time can be derived from the ratio between the average volume of the reservoir and mean total influxes or outfluxes (Fig. 14.3).

The residence time for the different components of the water cycle varies considerably. For rivers, the mean residence time is estimated to be around two weeks. On the other hand, for some groundwater aquifers, the recharge is minimal, and the residence time can reach thousands of years. Understanding how the water on Earth moves, and how the different processes vary in space and time is essential for analyzing the global water availability.

14.3 Temporal and Spatial Availability and Variability of Precipitation

In order to assess the global temporal and spatial availability and variability of water resources, long term records of globally gridded precipitation data sets were evaluated. The data-set used in this study is the Global Precipitation Climatology Centre (GPCC) product with a cell size of 0.25°. GPCC is operated by the German Weather Service (DWD) and provides global daily and monthly land-surface rainfall values based on data from national meteorological

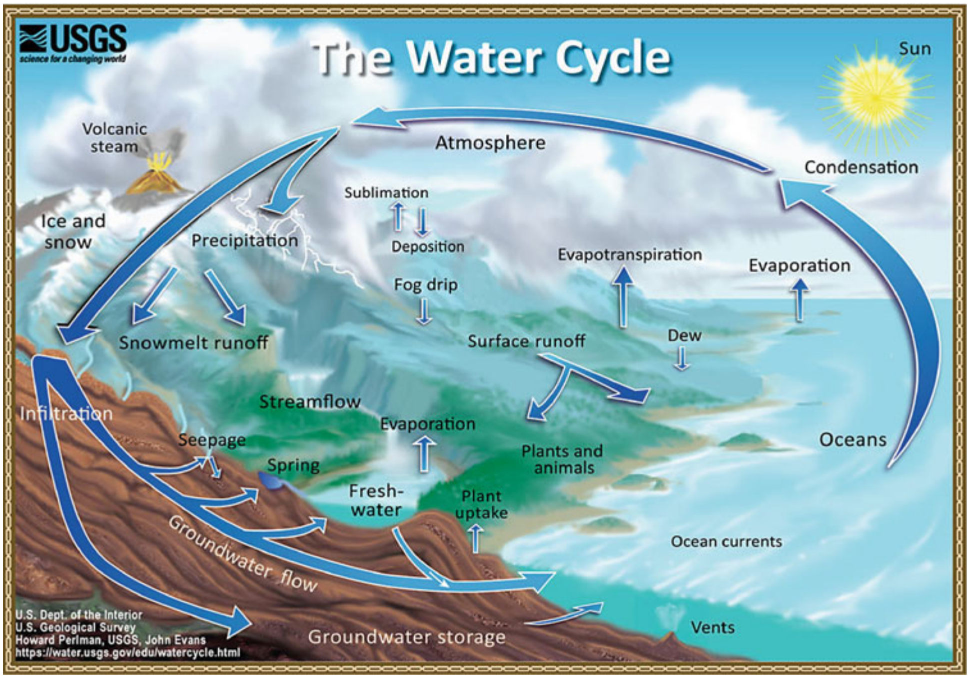


Fig. 14.2 Illustration of the global hydrological cycle in qualitative terms. *Credit* USGS Water Science School (2017)

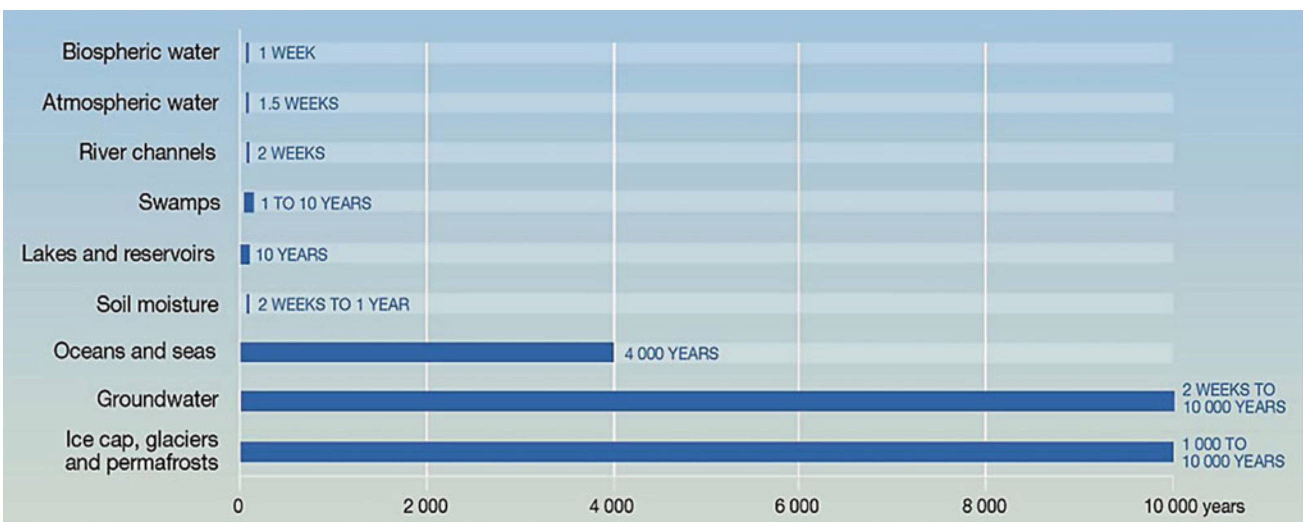


Fig. 14.3 Residence time of water within the different water cycle components. *Credit* Philippe Rekacewicz, Delphine Digout, UNEP/GRID-Arenda (2005)

and hydrological services, regional and global data collections as well as the World Meteorological Organization (WMO) Global Telecommunication System (GTS) data (Schneider et al. 2018).

Understanding precipitation variability in space and time is essential for adapting to the changes in water resources accessibility occurring due to climate change and urbanization. Informations regarding patterns, frequency, volumes, and spatial variation is needed for understanding the local and regional precipitation distribution. Changes in the spatial or temporal structure of rainfall fields have a direct impact on different consumer groups such as agriculture and hydropower.

In Table 14.1 the average yearly rainfall values for every continent are displayed. This is a rough estimate of the values since precipitation is highly spatially and temporally variable.

Table 14.1 Yearly average rainfall per continent

Region	Rainfall (mm/year)
Antarctica	160
Australia	420
Asia	720
Africa	800
Europe	650
North America	760
South America	1400

14.3.1 Spatial Distribution

The data have a monthly resolution and spans from the year 1950 until 2016. The average yearly rainfall value was calculated for every cell in the grid. The result is displayed in Fig. 14.4. This gives an idea of the spatial distribution of precipitation. The global rainfall values have a high spatial deviation. At local and at a global scale, large variations from one region to another are present. The major locations with low yearly values are identifiable, mainly the north of Africa and the Middle East. Part of the west coast of Peru, Chile, Namibia, and South Africa are also regions with low average yearly rainfall values. On the other hand, areas around the equator, parts of Europe and the east coast of the United States are characterized by high annual rainfall averages. The spatial distribution of precipitation shows unequal water availability worldwide. In some regions of the world, the local fluctuations between the rainfall values are very high. This is due in part to the local micro-climates and in part to the interpolation technique used to derive estimates of the data. Since precipitation is the driving agent for replenishing water resources, freshwater availability is a location specific issue.

14.3.2 Spatial Deviation

To investigate the spatial deviation between each location and its neighbors based on the yearly cycle for every one of the more than one million (1,032,484) cells, the standard deviation between the average rainfall value and the mean of the surrounding eight cells was calculated. The result is displayed in Fig. 14.5. For some regions, local differences between the neighboring rainfall values are high. This might be partly due to local extreme events and partly to the influence of topography. In mountainous regions where topography greatly influences local rainfall events, the standard deviation between the neighboring cells is the highest. This is in accordance with the physical process related to rainfall formation and altitude. The mountain slopes and their orientation influence the precipitation amounts; slopes with aspects facing the prevailing weather patterns will obtain more rainfall than their opposites (Davie 2008). The disparate topographical distribution of some regions leads to what is known as the rain shadow effect. The rain shadow effect, which is the result of a combination of aspect, altitude, slope and dynamic weather conditions, causes non-similar rainfall patterns in the region at different

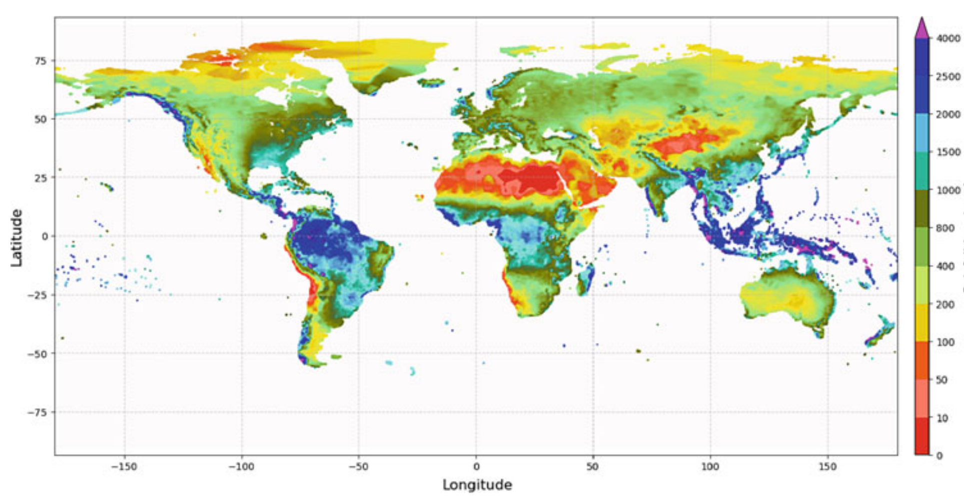


Fig. 14.4 Rainfall average yearly values from 1950 till 2016 (mm/year)

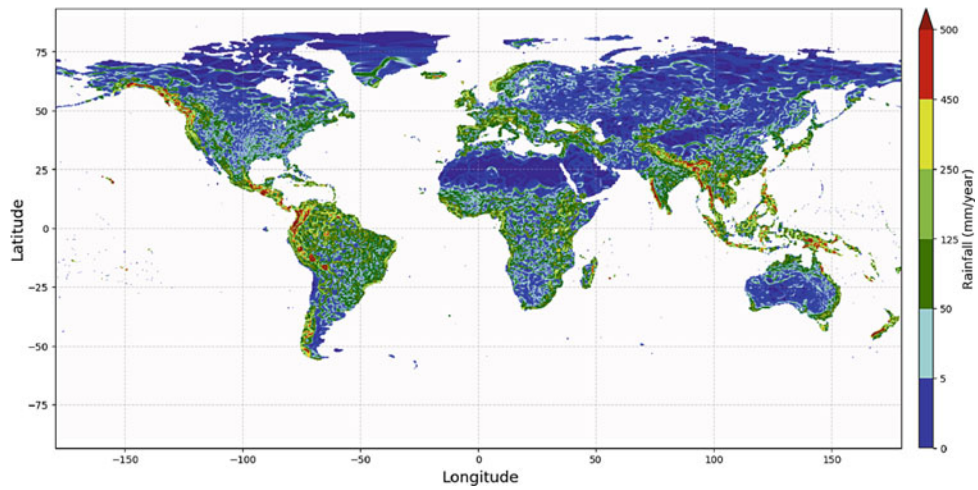


Fig. 14.5 Standard deviation between every cell and surrounding 8 neighboring cells for average yearly rainfall values from 1950 till 2016 (mm/year)

spatio-temporal scales, leading to asymmetrically distributed rainfall volumes. More generally, precipitation is seen to increase with elevation.

14.3.3 Intra-Year Variability

For every cell in the grid, the yearly cycle was determined based on the data from 1950 until 2016. To analyze intra-year variability both the ratio between minimum and mean rainfall (Fig. 14.6) and maximum and mean rainfall (Fig. 14.7) were calculated. Calculating these ratios is advantageous for analyzing intra-year variability. For instance, in some regions, a few months with high rainfall values contribute the most to the precipitation volume whereas in other regions, rainfall is more or less homogeneously distributed throughout the year. The ratio between the minimum monthly and average yearly value describes how strong the effect of the annual cycle is. For some locations where the minimum monthly value is very small as compared to the mean value, the ratio is also very small. In these locations, the effect of the annual cycle is big. On the other hand, in areas where the minimum and the average monthly values are not very different, for example, in most regions of Central Europe, the ratio is greater than 60%. This reflects a low effect of the yearly cycle. The rainfall yearly sum is distributed along the year and not concentrated within few months.

By considering the ratio between maximum monthly and average yearly values, an idea about the locations that are highly influenced by seasonal variations is obtained. For areas, where the ratio is low, around 1, the change within the year is not significant. As for other regions, where the ratio is high, the temporal change within the year is considerable. Most of the yearly sum could be falling in only certain months.

Since the precipitation data are typically skewed, the calculation of standard deviation offers no information on the asymmetry. Therefore, the intra-year variability can be

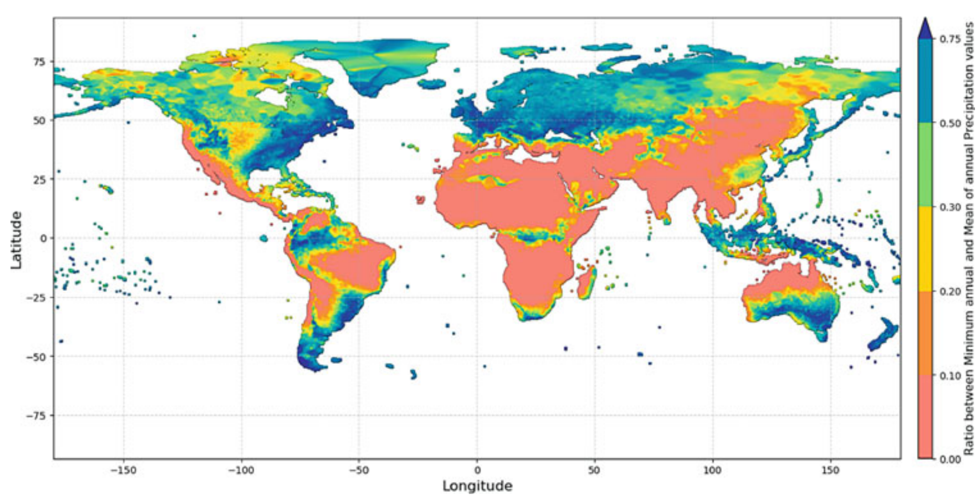


Fig. 14.6 Ratio between minimum and average yearly rainfall values from 1950 to 2016 (mm/year)

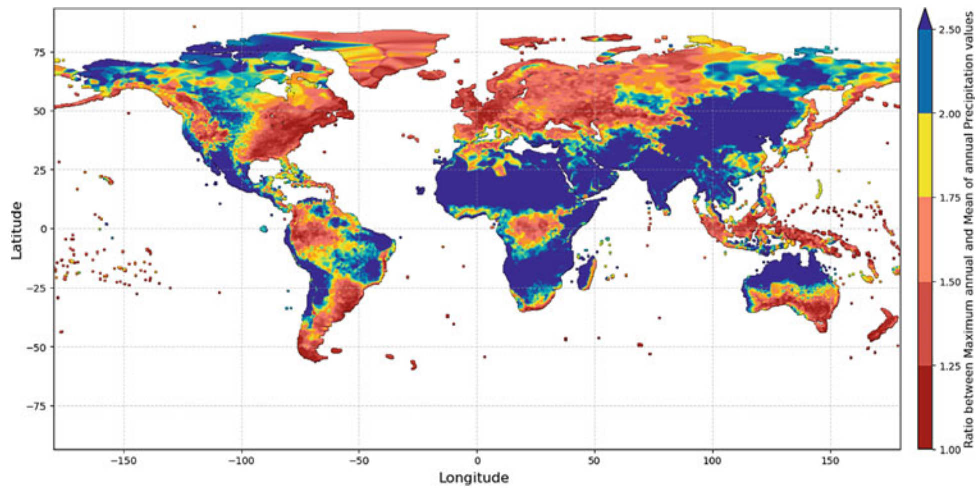


Fig. 14.7 Ratio between maximum and average yearly rainfall values from 1950 till 2016 (mm/year)

better captured with the ratio of maxima and minima to the means, an issue not addressed by the coefficient of variation discussed in Sect. 14.3.5.

14.3.4 Temporal Distribution

For the period from 1950 till 2016, the average monthly rainfall values were calculated at each grid cell. The global precipitation distribution varies from month to month. Figure 14.8 displays the uneven temporal distribution of precipitation.

Based on the average yearly monthly rainfall values, the seasonal variability of global precipitation data is clearly visible. In some areas, the deviation from one month to the other is higher than in others. Some locations present a clear pattern of seasonal rainfall: a distinction between wet and dry periods can be seen. For example, parts of South Africa and Australia present a strong yearly cycle. The wet season occurs between October and March and the dry season, from June through to August. For regions affected by seasonal phenomena such as the monsoon rains, the rainfall varies from average to extreme values. This can be seen in the period from June until September, in a country such as India,

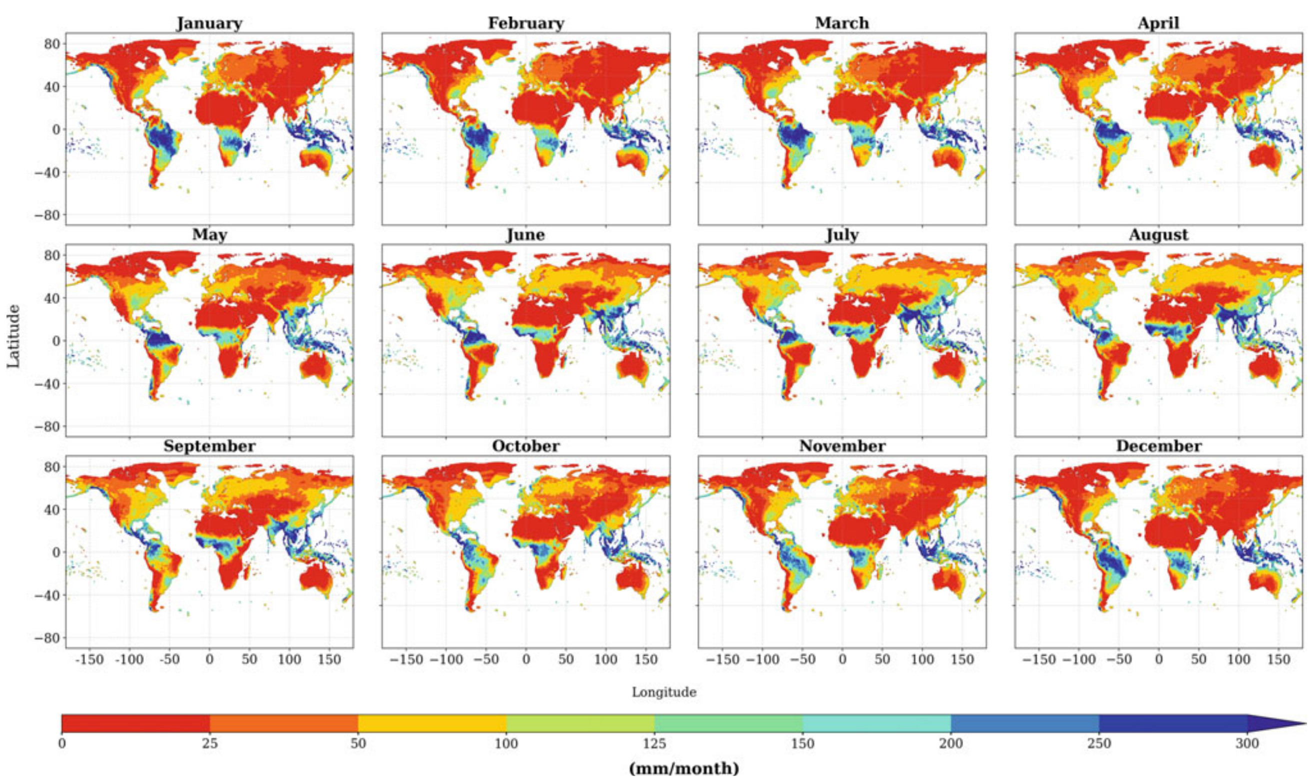


Fig. 14.8 Rainfall average monthly values from 1950 to 2016 (mm/month)

where the monsoon season is characterized by intense rainfall events and areas such as the west coast receives more than 200 mm per month.

Understanding the influence of the inter-annual variability of rainfall on the availability of freshwater resources is a key factor for agriculture in any location. By analyzing how precipitation varies temporally, better management of the water resources can be achieved.

14.3.5 Coefficient of Variation

The coefficient of variation is a measure of the dispersion of the data. Defined as being the ratio between the standard deviation and the mean, it offers information that is essential for understanding rainfall variability. The higher the inter-annual variation, the higher the coefficient of variation is. For example, if for a region, the coefficient of variation has a value of 0.5, the rainfall for that region will vary $\pm 50\%$ from the long term average. This coefficient is unitless and is a statistical measure that allows a relative comparison of the temporal variability between different locations.

Areas that are characterized by extremes where very dry and very wet years alternate, present the highest coefficient of variation. This is also in accordance with regions that display seasonal variation.

In Fig. 14.9, the coefficient of variation derived from the GPCC annual data is displayed.

The coefficient of variation can serve as an index of climatic risk: regions with a high coefficient of variation have a higher probability of large inter-annual variations of reservoir storage volumes and crop yields. Changes in the rainfall intensity, event type, frequency, and volumes have been recorded in many regions. These changes can be individually addressed or in combination. Precipitation is highly variable in space and time. Water availability is therefore spatially and temporally changing. Small scale spatial and temporal precipitation deviation in interaction with topographical heterogeneities and hydrological system responses are interconnected factors in the management of water resources. Agriculture is a one of the main economical sectors that is largely influenced by the intra-seasonal and inter-annual precipitation variability.

14.4 Groundwater Resources of the World

14.4.1 Groundwater Resources

Groundwater is defined as water that is present in interstitial spaces and fractures of subsurface geologic materials. It is the largest accessible freshwater reservoir. In many regions of the world, groundwater is the main source for domestic and agricultural water use. Groundwater contamination risks are lower than for surface water bodies. In times of drought, groundwater is one of the few resilient options for dependable water supply. With growing future demands due to population and economic growth and under the influence of climate change, freshwater resources are under high pressure. As surface supply is becoming less reliable and predictable, groundwater is turning out to be the major source of freshwater for many regions in the world and especially in periods of droughts. Groundwater is a valuable resource that requires sustainable and balanced use. There is a need for an optimal arrangement of the wells for an adequate management of the aquifers.

The groundwater resources map of the world is shown in Fig. 14.10. It displays major aquifers along with their different recharge rates and geological complexity.

Groundwater is a system in which water has a long residence time. Precipitated rainfall is the natural source for groundwater recharge. Observations of large groundwater

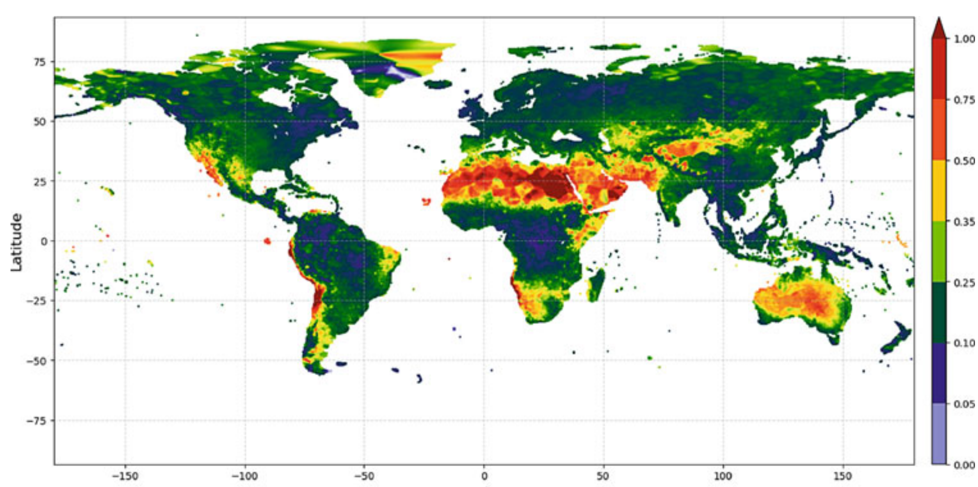


Fig. 14.9 Coefficient of variation for average yearly rainfall values from 1950 to 2016 (mm/year)

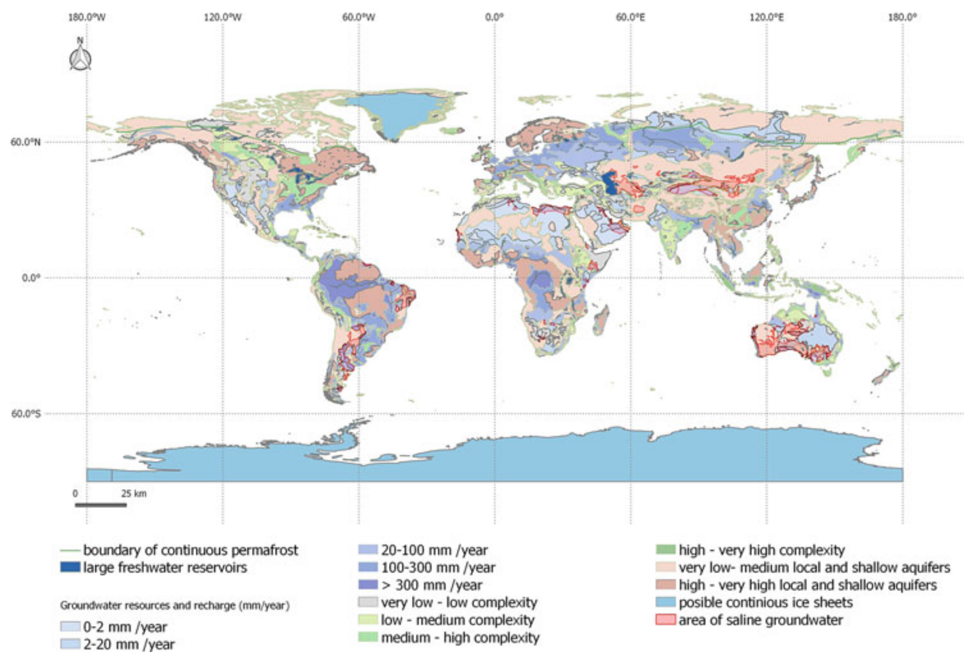


Fig. 14.10 Groundwater resources of the World (BGR and UNESCO 2019)

aquifer systems are generally limited due to high complexity and costs. Complete knowledge of an aquifer's state is seldom available. Almost 35% of the land surface area is underlain by quasi-homogeneous aquifers from which 18% are enriched with groundwater. Some of the aquifers are comprehensive, in complex sub-surface structures. About 50% of the continental regions contain small stores of groundwater that are confined within the near-surface unconsolidated rocks. The corresponding groundwater resources can generally satisfy the needs of modest to intermediate-sized population centers (BGR and UNESCO 2019).

Around the globe, concern about the overuse of the groundwater resources is growing. Based on groundwater levels derived from satellite data, the world's major aquifers in arid and semiarid regions are being depleted rapidly. Local data regarding groundwater use and availability are often limited and uncertain, but remote sensing is emerging as a new reliable technology to estimate groundwater depletion. One-third of the world's largest groundwater sources are in serious trouble according to a new study done by the University of California, Irvine. Groundwater losses were examined from space using the Gravity Recovery and Climate Experiment (GRACE) satellite mission. GRACE measures dips and bumps in the Earth's gravity, which are affected by the weight of water. It also collects data showing all of the change in ice, snow and water storage above and below the ground surface.

Quantifying water stress on groundwater resources is often done by calculating the ratio between withdrawals from and recharge into a certain aquifer. Despite present uncertainties regarding used and available volumes, such a ratio can be relatively easily estimated. The Renewable Groundwater Stress (RGS) ratio is calculated as the ratio between groundwater use and groundwater availability defined by the mean annual recharge. RGS is calculated for the largest 37 aquifer systems in the Worldwide Hydrogeological Mapping and Assessment Program using data from 2003 to 2013 (Richey et al. 2015).

The studied groundwater systems include the world's most productive aquifers supplying the majority of the demand. The land use in each basin plays an important role in estimating the quantity and quality of groundwater. Incorporating this information leads to an improved analysis of the stress within a certain system.

In Fig. 14.11, the stress on the main aquifer systems has been quantified using GRACE satellite data. Most of the world's aquifers are under stress and being overexploited, especially in regions where the population relies heavily on groundwater.

In Fig. 14.12, the Global Groundwater Information System (GGIS) estimated total renewable groundwater (mm/year) per country is displayed. Regions with low renewable groundwater volumes are locations where the recharge of groundwater is the lowest: on the one hand groundwater recharge is minimal, and on the other hand groundwater use is maximal. For the coming years with the increase in population and climate change, the impact of overuse on the aquifers will continue to grow.

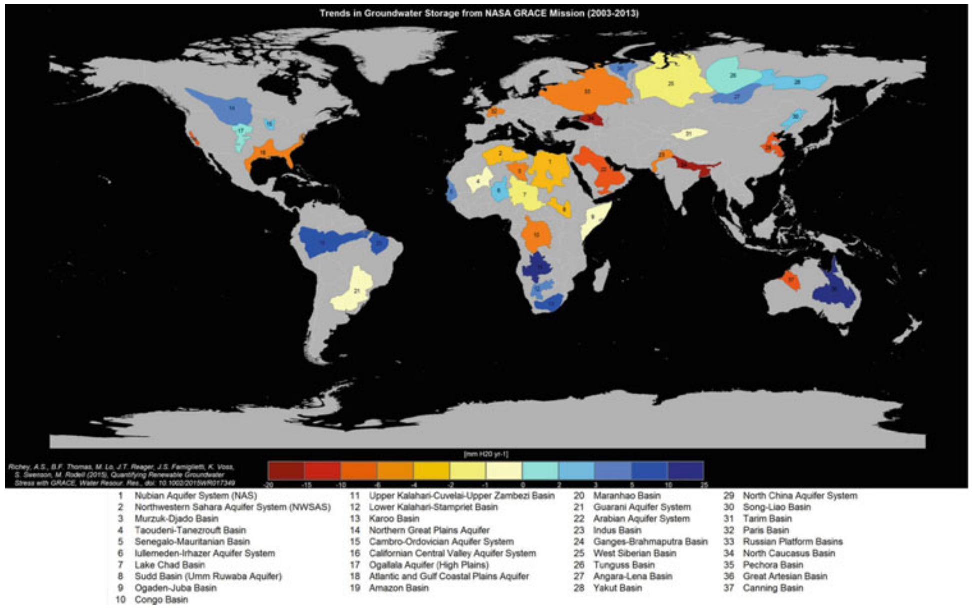


Fig. 14.11 Quantifying renewable groundwater stress with GRACE. *Image Credit* NASA/JPL-Caltech/University of California, Irvine

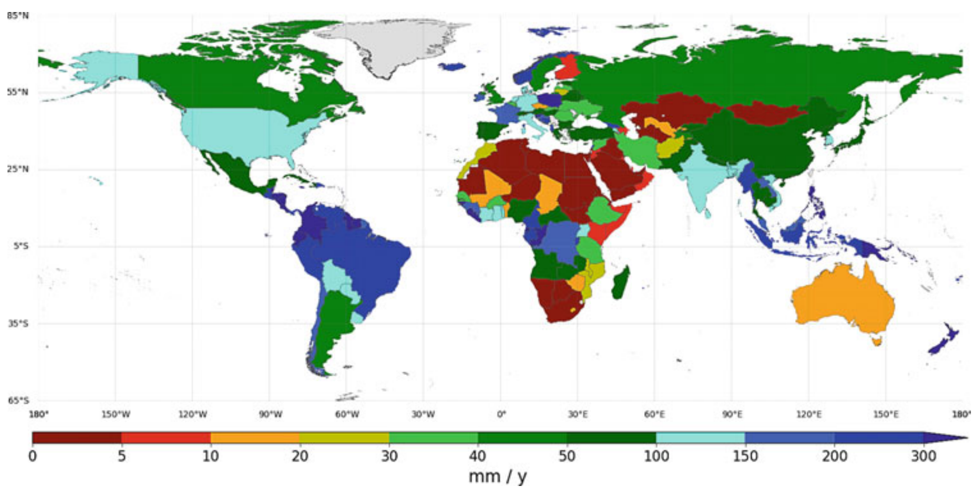


Fig. 14.12 Total renewable groundwater (mm/year). *Credit* Global Groundwater Information System (GGIS) (2019)

14.4.2 Groundwater Pollution

Spills of hazardous waste or of petroleum fuels, leaking septic systems, infiltrating surface chemicals, pesticides, heavy metals and leachate from landfills are some of the main direct and indirect groundwater contamination sources. In agricultural regions infiltrating fertilizers and pesticides are the main source of groundwater pollution. Additionally, spills of toxic contaminants may infiltrate the soil until the groundwater table is reached. Two types of contaminants are present: Light Non-Aqueous Phase Liquid (LNAPL) and Dense Non-Aqueous Phase Liquid (DNAPL). LNAPL is less dense than water and floats on top of the water table. DNAPL has a density higher than water and continues to infiltrate and sink below the water table until an impermeable layer is reached. From that point on different chemical reactions occur for LNAPL and DNAPL. Pollutants in the subsurface move through the pores, depending on the porosity of the ground and the viscosity, and some might be transported with the groundwater flow. Landfills are a source of groundwater pollution. As rain falls on top of the landfill, water comes into contact with toxins from the waste and seeps into the soil below and around the landfill. Once the subsurface has been contaminated by hazardous waste, there is no treatment that will restore the polluted area to its previous pristine state, even with the most advanced remediation techniques. The vulnerability of an aquifer system depends on different factors: contaminant type, land use, aquifer layers, well construction method and well operational practices. Groundwater risk assessment is an approach to enable effective risk management. Vulnerable wells and aquifers are identified, and proactive risk management plans are prepared. This increases the resilience and readiness of a society when facing groundwater pollution.

14.4.3 Groundwater Depletion

Groundwater depletion occurs when water is pumped out of an aquifer at a rate that exceeds the recharging capacities. Due to excessive groundwater pumping, the water level in the system continues to decrease. This is the situation in many regions around the world. Groundwater volumes are quickly being depleted, and aquifers are overstressed. Negative effects on the environment and society occur, such as drying up of wells, increased pumping costs, land subsidence and deterioration of water quality due to the intrusion of contaminated water. Groundwater salinity leads to the contamination of coastal freshwater wells. As the water table depth in the aquifer decreases, the pressure exerted by the water column drops and the high-density saltwater propagates inland. The dynamics of the aquifers are altered by the intrusion of saltwater (United States Geological Survey 2019). If an aquifer has been exposed to salinity and the extracted water is used for agriculture purposes, then tertiary salinity, also known as irrigated salinity, will occur. Part of the water used for irrigation will evaporate and the remainder, carrying all the salt, will infiltrate into the soil; this leads to the accumulation of high concentration of salts in the soil layers. This impacts the type and yield of crops that can grow in these areas.

14.4.4 Groundwater Artificial Recharge

In order to cope with the overstressed aquifers, artificial groundwater recharge is applied to increase the rate of groundwater recharge as compared to natural conditions. With such an intervention, groundwater yield is enhanced, water quality is increased through dilution, and natural filtration is improved. Some common practices for artificial groundwater recharge are surface spreading basins, basin and percolation tanks, injection and recharge wells. Increasing water supply through aquifer recharge presents a cost-effective way of increasing the availability of groundwater.

14.5 Snow, Ice and Glaciers

Water is continually being transferred between the different compartments of the water cycle. In fact, the amount of water in movement within the cycle is much smaller than the amounts stored in the separate compartments.

Antarctica and Greenland are the planet's largest polar ice sheets; together with smaller glaciers and ice caps in mountains around the globe, they cover almost 10% of Earth's land surface and include approximately 74% of freshwater volumes.

In Fig. 14.13 the spatial distribution of major ice sheets and glaciers is displayed.

Water trapped in the form of ice has a direct influence on many components within the water cycle. The high reflection capacity of ice sheets and glaciers can influence weather patterns. The ice has a reflectivity coefficient of almost 90%, so most of the incoming sunlight is therefore reflected, increasing air temperatures and thus affecting wind patterns above and around ice fields. Polar ice sheets present at the planet's northern and southern poles, perform as a buffer and assist in adjusting the global climate. Expansion or reduction of polar ice is governed by the planet's warm and cool eras. Periods of continuous cooling of the planet are known as ice ages and lead to an expansion of the polar ice and glaciers. As part of the natural cycle, the polar ice masses grow and shrink every year. By the end of March, the full extent of the

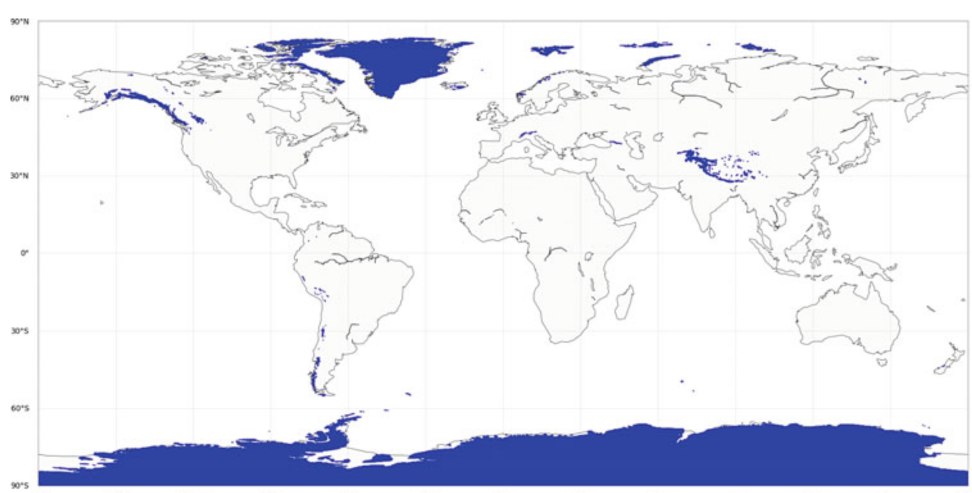


Fig. 14.13 Major ice sheets and glaciers (Made with Natural Earth 2019)

polar ice in both hemispheres is reached, in April the melting phase starts, and the minimal volume is reached in September. This process is highly dependent on temperature. Under the influence of climate change, the global average temperature has been increasing leading to an increase in the melting amounts and therefore a decrease in the volume of polar ice, especially in the Arctic. On one hand, previously captured greenhouses gases are released back into the atmosphere, and on the other hand, as sea water level increases an alteration in the occurrence and intensity of extreme events is induced, especially in coastal areas. If the influx of freshwater resulting from melted ice carries on increasing, the balance between saltwater and freshwater will be modified. Consequently, the ocean circulation patterns will be altered, affecting global temperature and rainfall distributions.

Glaciers are a source of freshwater in many mountainous regions. They play the role of natural reservoirs. In winter, water is stored in solid form and in summer, it slowly melts and functions as a source of fresh water. A high percentage of the melted water is used for hydropower generation and agricultural purposes. A glacier's volume and area change in response to both short-term and long-term deviations in precipitation and temperature values. Increase in the glacier's discharge, due to higher temperatures, seems to be, at least on the short term, beneficial for hydropower production. The streamflow might continue to increase until a limit point is reached; this tipping point is known as the peak flow after which the glacier cannot maintain the rate at which it is providing water. In the long term, this may make it more difficult to meet domestic and agriculture demands. Most studies concerning glaciers suggest a continuous decrease in the area and volume of glaciers. This impacts the natural discharge regime by shifting the timing of the peaks, reducing the available volume, and affecting the water temperature.

Glaciers play the role of natural seasonal water storage reservoirs; as their area and volume decrease, concern grows over the future of many societies who rely on them as their source of freshwater. For instance, in some regions like Lima, Peru, or California, USA, cities that partly or mostly rely on glaciers for the supply of freshwater are facing a water deficit problem. The volume and area of the glaciers are continuously shrinking. The irrigation sector is negatively influenced, and additional stress on the population is exerted.

More information on the state of the glaciers and ice caps around the world is needed to better understand and manage the available resources.

Temporal distribution of precipitation does not always provide the correct image of water availability due to snow accumulation. Many countries, such those in central Asia, depend on the snow dynamics for water. In many drainage basins, the existence of snow cover strongly influences the runoff regime. In many regions, snowmelt spring runoff is a major contributor to annual river runoff. Understanding and analyzing snowmelt is essential for managing water availability in a region. Snow accumulation is a direct product of precipitation volume, areal topography, and elevation. Snow that is intercepted by vegetation is often transported by high winds to different locations, altering the spatial distribution of snow. Local, small scale, deviations in vegetation type, relief, and meteorological conditions affect the accumulated snow volume and the snow water equivalent coefficient. Changes in temperatures induce impacts on the accumulated volumes and on the streamflow seasonal dynamics. In some basins, the runoff regime might be shifted from a combined snowmelt and rainfall regime to a mostly rainfall dominated regime. On one hand, winter discharge, high flows and peak-flows increase, on the other hand, summer discharge decreases and low flow duration increases. This detrimentally affects water availability and management strategies.

14.6 Water Availability and Water Management

14.6.1 Surface Reservoirs

Approximately 70% of global freshwater is trapped with rather long residence times in ice caps, glaciers, permanent snow, and groundwater. For human needs, freshwater, stored in components with low retention times such as rivers, lakes and seasonal snow, is the most accessible source. Nonetheless, the capacity of those components is usually influenced by inter-annual variability (Zhou et al. 2016). Many modern societies are being challenged by water scarcity. To cope with this situation, surface water reservoirs are a means to improve water security. Through these, the stored volume can be operated to satisfy many purposes such as hydropower generation, flood control, irrigation, water demand and regulating the water in a basin. The most intense water demand sector is agriculture. Total irrigation water withdrawals account for about 70% of the consumptive water use globally (White 2005).

For regions where rainfall presents a strong seasonal variability, characterized by a long dry period, surface water reservoirs play a major role in supplying demand during the dry season, bridging the gap between wet and dry periods. The impact of water shortages and stress, as well as the pressure on groundwater aquifers, is then reduced.

Figures 14.14 and 14.15 show a representation of the location of the world's largest storage reservoirs.

The World Register of Dams is the most complete dataset for global distribution of dams. Around 58,000 records of large dams with a storage capacity of more than 3 million cubic meters are available.

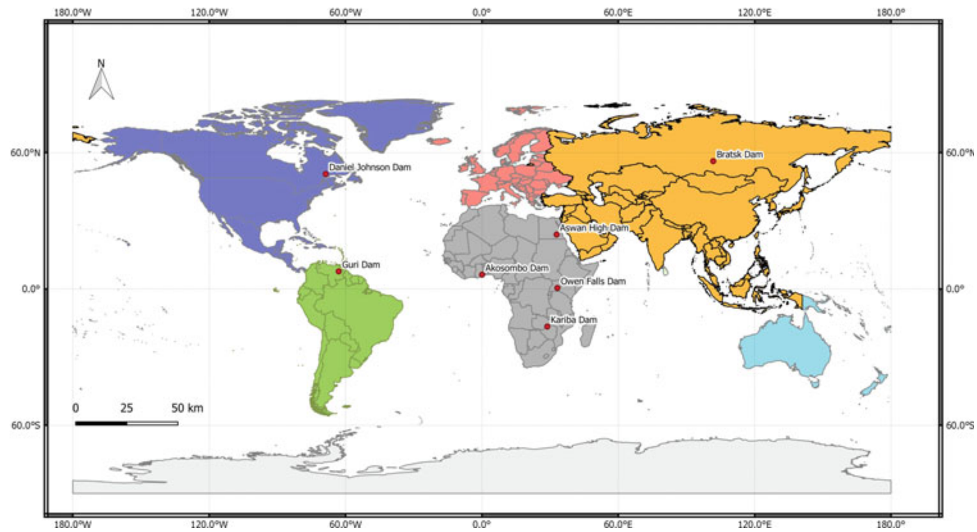


Fig. 14.14 Location of the world's largest reservoirs in terms of storage volume (>100 Km^3)

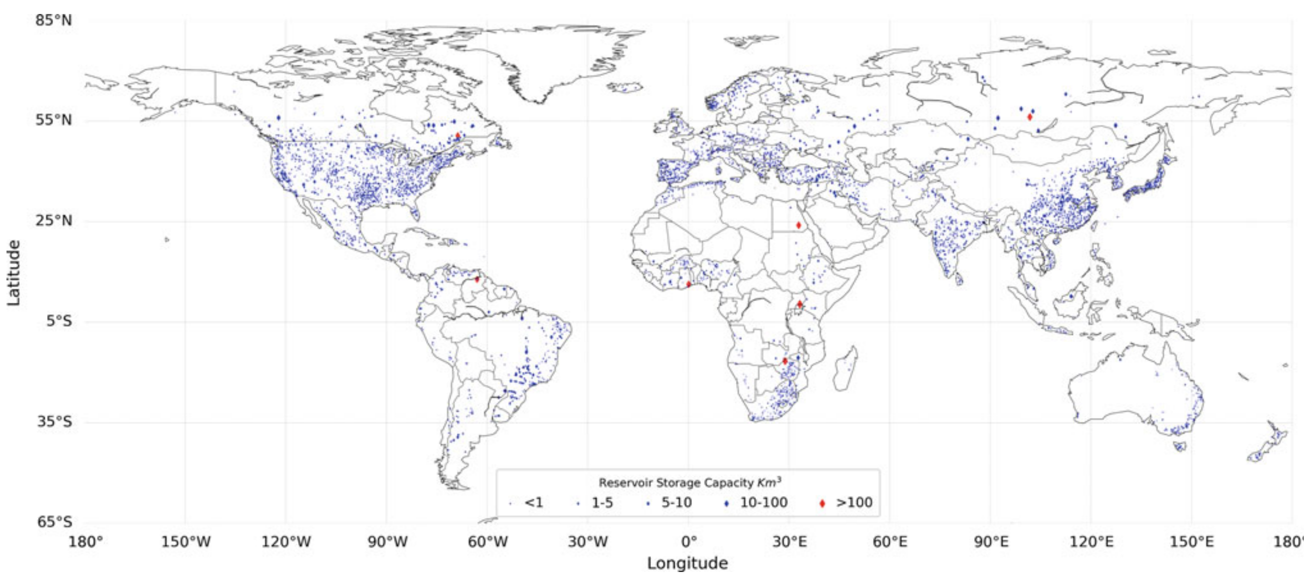


Fig. 14.15 Global distribution of large reservoirs in GRanD database (Lehner et al. 2011)

In Table 14.2, the number of main dams from the ICOLD database and their purpose of use is displayed (International Commission on Large Dams 2019). This offers an idea about the main global common goals for using surface reservoirs.

Even though surface water reservoirs are a means to deliver a requested volume of water at the correct point in time, they do have many negative implications on the natural behavior of any surface water body. For instance, the natural cycle of water fluxes is spatially, temporally and often irreversibly altered by the man-made storage structures. The change in global and regional hydrological cycle is noticeable on the short and long time scales. Seasonal variation of reservoir storage is an important factor in reservoir management. Dominant factors behind seasonal variations in many basins are related to soil moisture and snowmelt.

The planning, designing, and operation of most water reservoirs worldwide are based on previous observations of the water availability and variability. This is mainly dependent on the rainfall amount and duration. In the first decades of the twenty-first century, major changes in water availability, quality and demand occurred. The historical natural

Table 14.2 Main purpose of use of large dams (International Commission on Large Dams 2019)

Description	Dams with this sole purpose	Multiple-purpose dams with this purpose
Flood control	2536	4911
Fish farming	40	1459
Hydropower	6102	3932
Irrigation	13,142	6180
Navigation	96	580
Recreation	1351	3010
Water supply	3339	4534
Tailing	65	9
Others	1543	1353

behavior of rainfall availability and patterns in many regions of the world have been and will be influenced by human activities and climate change. This impacts the design and operation of surface water reservoirs for the coming future.

Anthropogenic impacts on the seasonal fluxes lead to an alteration of the streamflow patterns and natural discharge. Obstructing the natural course of any river by the construction of any impounding structure affects the discharge regime, the flow quantities upstream and downstream. The ratio between high and low discharge is altered. This all leads to a fragmentation of the river ecosystem. The river morphology characterized by the longitudinal slope, the channel width, the water depth, the natural meandering process, and the sediment transport regime is affected by any structure within the river channel. Deposition of sediments upstream and erosion downstream generally occur. With time, an increased sediment build-up in the reservoir results in a reduction of the storage capacity. Reduced sediment load downstream results in erosion of the river banks and a deepening of the river channel. Measures are usually undertaken to manage the problems resulting from sediment excess upstream and sediment deficit downstream of the dam. Sediment deposition along the river channel changes the river cross-section and the river morphological system. Natural habitats of the species living in the river such as fish, macrozoobenthos, microorganisms, vegetation and flora/fauna in the floodplain are usually drastically affected by any impounding structure. Temperature and percentage of dissolved oxygen are major factors that govern what kind of organisms can live in a water body. With an increase in water temperature, the pace of chemical reactions typically increases and the concentration of dissolved oxygen decreases. For the survival of many species in a water body, a minimal amount of dissolved oxygen is obligatory. Within the stored water volume in a reservoir, the temperature profile and the dissolved oxygen concentration are seasonally dependent parameters. In warm periods, the surface water becomes warmer than the bottom layers. Due to the difference of temperature along the water depth, different layers with different temperatures and therefore densities are formed. This process is known as stratification. In normal or cold periods the stratified layers disappear due to the development of an equilibrium of the water density. This often keeps reservoirs from being a suitable habitat for many organisms.

Evaporation from the surface of the reservoir is usually far greater than the evaporation from the same area before construction of the reservoir. This is related to the increase in the surface water area. In warm periods, water loss to evaporation has to be taken into account for reservoir management. Surface reservoirs are a means to supply part of the demand, especially in dry periods. In the coming years, managing surface water reservoir's storage volumes in a sustainable way whilst considering the spatial and temporal variability of precipitation is essential for tackling challenges such as water scarcity and stress. In Fig. 14.15, the representative maximum storage capacity of global reservoirs in million cubic meters is displayed. The data consists of 7320 reservoirs and their associated dams with a cumulative storage capacity of 6864 km^3 (Lehner et al. 2011). The Global Reservoir and Dam (GRanD) database is a joint project of the Earth System Science Partnership (ESSP), and consists of geospatially referenced data set compiling information about dams and reservoirs worldwide. These impound an estimated 20% of the global annual river runoff (White 2005). Some structures are built in-stream, directly in a river; others are built off-stream and water is diverted from the river to the reservoir. These dams and their associated reservoirs grant many services that are crucial for many societies (Tables 14.3 and 14.4).

Table 14.3 Estimated number of main reservoirs per country (Lehner et al. 2011)

Country	Number of reservoirs	Country	Number of reservoirs	Country	Number of reservoirs
United States	1699	Ivory Coast	15	Zambia	4
China	726	Colombia	15	Montenegro	3
Japan	532	Namibia	12	El Salvador	3
India	266	Myanmar (Burma)	12	Azerbaijan	3
South Africa	258	Sri Lanka	11	Guinea	3
Spain	243	Ghana	11	Ecuador	3
Canada	195	Peru	10	Tanzania	3
Australia	181	Uzbekistan	10	Mali	3
Brazil	151	Kazakhstan	10	Latvia	3
Norway	115	Macedonia	9	Laos	3
France	113	Ukraine	9	Ireland	3
Turkey	101	Angola	9	Singapore	3
Zimbabwe	96	Dominican Republic	8	Costa Rica	2
Mexico	95	Netherlands	8	Paraguay	2
United Kingdom	86	Croatia	8	Papua New Guinea	2
Italy	85	Malaysia	8	Lithuania	2
Romania	79	Kenya	8	Syria	2
New Zealand	60	Swaziland	8	Libya	2
Germany	60	Bosnia and Herzegovina	8	Togo	2
Portugal	52	Mozambique	8	Turkmenistan	2
Nigeria	50	Philippines	8	Uruguay	2
Russia	49	Iraq	7	Slovenia	2
Sweden	47	Kyrgyzstan	7	Suriname	1
Bulgaria	46	Vietnam	7	Benin	1
South Korea	45	Ethiopia	6	Bangladesh	1
Burkina Faso	44	Lesotho	6	Belarus	1
Switzerland	37	Madagascar	6	Uganda	1
Czech Republic	35	Botswana	6	Guatemala	1
Algeria	33	Georgia	6	Senegal	1
Morocco	32	Iceland	6	Nicaragua	1
Argentina	32	Cameroon	5	Nepal	1
North Korea	32	Armenia	5	Mauritania	1
Thailand	32	Tajikistan	5	Luxembourg	1
Venezuela	31	Egypt	5	Cuba	1
Poland	28	Taiwan	5	Lebanon	1
Tunisia	25	Congo (DRC)	5	Eritrea	1
Iran	24	Belgium	5	French Guiana	1
Austria	21	Chile	5	Gabon	1
Finland	19	Albania	4	Honduras	1
Greece	19	Cyprus	4	Liberia	1
Pakistan	19	Afghanistan	4		
Serbia	19	Hungary	4		
Indonesia	16	Sudan	4		
Slovakia	16	Panama	4		

Table 14.4 Estimated total maximum storage capacity in millions of m^3 per country (Lehner et al. 2011)

Country	Maximum storage capacity (millions m^3)	Country	Maximum storage capacity (millions m^3)	Country	Maximum storage capacity (millions m^3)
Russia	811311.1	Uruguay	11654	Iceland	2306.1
Canada	803818.5	Portugal	11604.3	Macedonia	2289.9
United States	675536.9	Romania	11354.4	Costa Rica	2271
Brazil	468927.1	North Korea	10406.5	Serbia	2269.9
China	415198.1	France	9931.3	Austria	2102.2
India	244391.4	Angola	9348.7	Chile	1920
Uganda	204800	Netherlands	9234	Guinea	1837
Zimbabwe	190307.5	Sudan	8730	Slovakia	1726.7
Egypt	163508.2	Colombia	8668.3	Togo	1716.6
Venezuela	153341.3	Uzbekistan	8513.4	Belarus	1335.6
Ghana	148539.3	Zambia	8043.1	Taiwan	1199.8
Turkey	133318.8	Laos	7864	Armenia	1059
Mexico	111187.1	Italy	7570.9	Montenegro	1028
Iraq	103430	Myanmar (Burma)	7459	Cuba	1020
Kazakhstan	90630.1	Indonesia	7274	Latvia	1007
Australia	78251.9	Honduras	7090	Croatia	962
Thailand	75580.4	Bulgaria	6518.4	Ireland	699
Mozambique	68860.4	Bangladesh	6477	Namibia	694.7
Argentina	66848.2	Ecuador	6310	Papua New Guinea	665
Spain	53070.9	Philippines	5712	Swaziland	584.7
Ukraine	47200	Sri Lanka	5493.1	Madagascar	508.9
Ivory Coast	37241.2	Turkmenistan	5453.7	Mauritania	500
Nigeria	35796	Panama	5365.9	Lithuania	495.2
Sweden	34039	United Kingdom	4655.3	Guatemala	460
Norway	31704.3	Tanzania	4500	Botswana	448.5
South Africa	29982.6	Burkina Faso	4196	Nicaragua	434.9
Paraguay	29400	Congo (DRC)	4091.5	Senegal	300
Iran	27890	Kenya	4061.9	Hungary	256.4
Pakistan	26490.8	Albania	3890	Liberia	229.6
Malaysia	23719.7	Peru	3871.7	Gabon	220
Suriname	22700	Afghanistan	3783	Cyprus	204.6
Kyrgyzstan	21133	Algeria	3746.9	Lebanon	160
Finland	18603	French Guiana	3500	Belgium	144.3
Japan	18584	Ethiopia	3419.6	Nepal	85.3
Azerbaijan	16159	Switzerland	3289.6	Singapore	74.9
Cameroon	15705.9	Germany	3192.9	Luxembourg	62
Tajikistan	14840.1	Czech Republic	3184.3	Slovenia	33.5
Vietnam	14610	Lesotho	2909.7	Benin	23.5
Morocco	14538.3	Poland	2794.9	Eritrea	20.4
Mali	13615	Bosnia and Herzegovina	2751.4	Libya	10.2
New Zealand	13249.8	El Salvador	2710		
Greece	12322	Tunisia	2367.4		
South Korea	12014.9	Georgia	2362		
Syria	11800	Dominican Republic	2333.5		

14.6.2 Desalination Plants

Water scarcity and global warming are likely to remain problems for the foreseeable future. Continuous pressure on freshwater resources has led to new solutions such as desalination. Desalination is the process of turning seawater to freshwater suitable for supplying part of the demand. One of the common and most applied techniques for saltwater desalination is Salt Water Reverse Osmosis (SWRO); seawater is pressurized against a semipermeable membrane that lets water pass through but blocks salt (Elimelech and Phillip 2011) (Fig. 14.16).

The required energy for delivering the production flow rate differs from one desalination plant to another. The difference in the needed energy depends on the density of the salt water, the water temperature, the percentage of recovery, and the volume of saltwater converted to freshwater.

Main advantages of such a technique are the drought-proof nature of the process and the high water quality resulting at the end. One point of concern is that the carbon footprint of large-scale desalination plants can be consequential. Desalination plants are hugely energy intensive; on average, to transform salt water to fresh water, 4 kWh/m^3 are needed. With continuous technological improvements of the membrane performance, SWRO operation costs are decreasing but are still relatively high.

In Fig. 14.17, the proportion of the main cost components of desalination plants are shown.

The most cost-intensive parts are initial investment, operation, maintenance and energy consumption. The initial investment, especially related to the number of high-pressure pumps to be installed and the corresponding reverse osmosis membranes, is dependent on the size of the desalination plant and the desired capacity. Desalinated seawater can serve different consumer groups, and accordingly the required quality differs. For drinking water requirements, highly technical processes are needed, and therefore the cost of the desalination process increases. For ensuring continuous operation of an SWRO plant with a high recovery rate and steady operation phases, the overall installed system should operate under normal design parameters. In many situations, exceeding the normal capacity of the plant can affect the desalination system in the long run. New equipment or more frequent maintenance of the system may then be needed, leading to additional costs. The operating cost of an SWRO plant is mainly related to power consumption. For the steady operation of a desalination plant, a continuous power supply is needed. Depending on the source of power supply, the costs can differ, but they tend to be high.

Costs for post-treatment of remaining brine also need to be accounted for. If the highly concentrated brine is directly disposed of in the oceans or in landfills, then it is a direct threat to ecosystems. Due to its high density the brine settles on the channel floor in normal flow currents, leading to the formation of a salty layer that affects and alters the conditions for any flora or fauna or even human activities in that area. To avoid such an effect, three processes are essential: mixing, diffusion and dilution of the brine. Mixing can be achieved by disposing of the brine where a strong sea current exists. Through the use of a high-pressure pump and with the installation of nozzles with check valves along the outflow pipe, the diffusion process is enhanced. Dilution is achieved by mixing the brine with another source of water with lower salt concentration before disposal; some options are natural

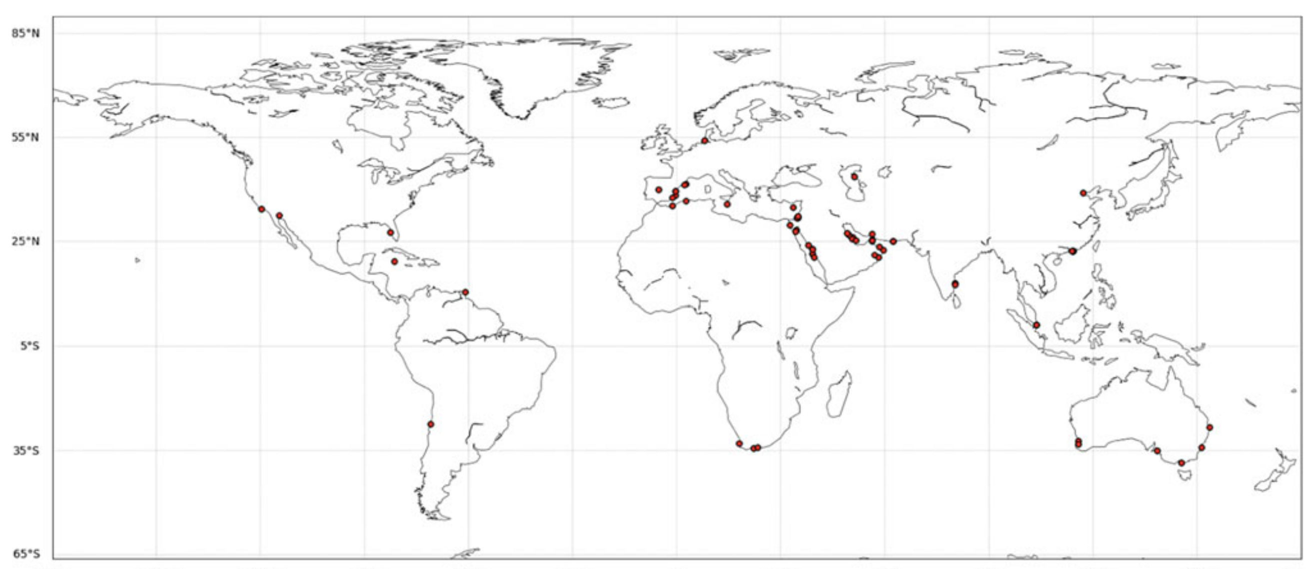


Fig. 14.16 Location of main desalination plants worldwide

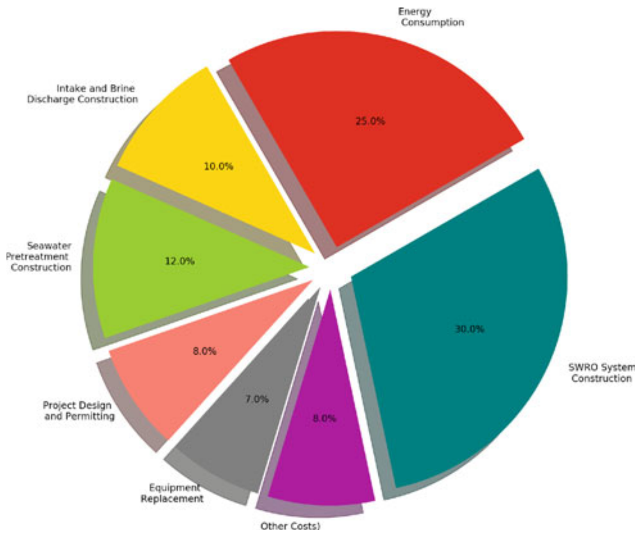


Fig. 14.17 Typical SWRO plant construction cost breakdown. *Credit* WateReuse Association (2015)

fresh water, treated wastewater or even seawater. Other treatment technologies are possible, for example, the use of thermal treatment systems to evaporate the water and to crystallize the salt to solids. Depending on the final disposal location, additional treatment of the residual is required. In locations where the oil and gas industry is present, deep abandoned extraction wells are used for injection of brine, if the underground geology is suitable. Evaporation ponds are a feasible solution in some climates but require large areas and well sealed ponds to prevent infiltration and contamination of underlying layers. The final product of evaporation ponds can be reclaimed to be used as road salt. Solid waste incineration facilities are another possible solution. Brine is mixed with other materials, and as water evaporates during incineration, salts are reduced to ashes which usually need further treatment.

Many desalination plants are operating worldwide. According to the international desalination association (IDA), more than 300 million people rely on desalinated saltwater as their source of fresh water. In Table 14.5 some estimated information regarding global desalination operations are displayed. In 2019 desalination provided around 1% of the world's drinking water.

Table 14.5 Desalination by the numbers

Number of desalination plants world wide	>19,744
Global capacity of commissioned desalination plants (m^3/d)	>99.7 Million
Number of countries where desalination is practiced	>150
Number of people who rely mainly or partly on desalination	>300 Million

For desalination to be an affordable, reliable solution in the future, progress on reducing energy requirements, green desalination, minimal use of chemicals and a lowered carbon footprint are needed. Different innovative solutions are being discussed by the IDA in order to reduce the energy and operation cost of the desalination plants. Innovative new engineered components are planned to be used in the SWRO plants increasing the yield and reducing the costs (Bennett 2012). In coming times, as supplying freshwater for human needs is becoming more challenging, development and application of desalination plants will continuously expand, offering an expensive solution for regional and international conflicts.

14.6.3 Water Availability per Inhabitant

The water availability map in Fig. 14.18 presents the total annual actual renewable water resources per inhabitant per country. The values shown are for the year 2014. 1700 m^3/capita/year was set as an upper limit. This is in accordance with the value defined by the United Nations for water stress. Values below 1000 m^3/capita/year mean that the population faces water scarcity and below 500 m^3/capita/year a situation of absolute scarcity is present. The water availability per inhabitant is a function of the total renewable water resources and the total population. Water stress is an indicator that provides an understanding of the dynamics between human and natural systems. On a local scale, parameters such as location and topography of each country affect the number of renewable water resources.

The main causes of water scarcity are pollution, agriculture, and population growth. Major sources of water pollution are overuse of pesticides and fertilizers, and discharge of untreated industrial or domestic wastewater. Groundwater pollution occurs often since many pollutants infiltrate into underground aquifers. Some effects on the water quality are immediate; others appear only after some time. Degradation of the water quality in the past, especially in non-developed countries, is now resulting in a severe water scarcity problem in the corresponding countries.

Agriculture is the main consumer of freshwater, but most of the water used for irrigation purposes is not easily recoverable. Part of it is lost due to leaks in the irrigation system, a portion is used by the plant, and the remaining part is mixed with different fertilizers affecting its quality.

Between 1970 and 2020 the worldwide population has almost doubled (United Nations, Department of Economic and Social Affairs, Population Division 2015). Under the influence of industrial and economic development, global ecosystems have been widely damaged, resulting in a major loss of biodiversity and natural environments. Wetlands

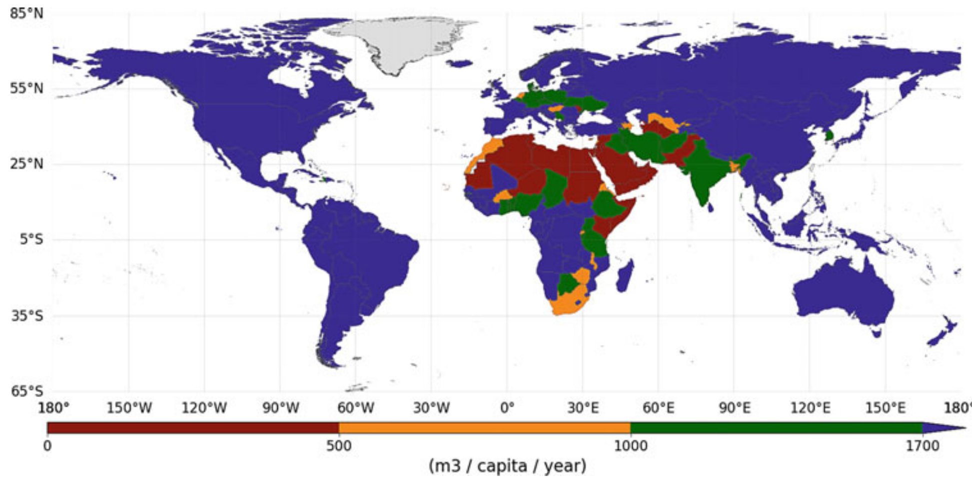


Fig. 14.18 Water availability in m^3 per capita for year 2014. *Credit* The World Bank (2014)

around the globe are being affected by the degrading situation of freshwater resources. There is an urgent need to apply improved methods of sustaining and effectively managing the remaining fresh-water resources on a global scale. Under the impact of climate change, the chances of extreme hydrological events such as floods and drought are escalating. Water availability is not only a problem of a shortage of freshwater but also of an unequal distribution of the available resources.

14.6.4 Lorenz Curve, Water Availability Versus Population

The Lorenz curve offers an insight into the distribution of water availability as compared to the associated population proportion. In the case of equal distribution of the water availability on the population, the curve is a straight line, referred to in Fig. 14.19 as the line of perfect equality. The actual availability, blue curve, seen in this figure is a convex function that shows the inequality in water availability. The curve has been derived from the data available by the World Bank. One can notice that around 80% of the world population has access to only 25% of the water.

14.6.5 Total Renewable Surface Water

Total renewable surface water (mm/year) is the sum of two components: total internal and external renewable surface water resources. An upper value of 2000 mm/year has been set. Countries with yearly amounts above this limit are seen as currently not facing the risk of water scarcity. In Fig. 14.20, the estimated values by the World Bank for the year 2014 are displayed on the global map. Areas of low renewable surface water are identifiable. This provides an insight as to which countries need to better manage their water resources.

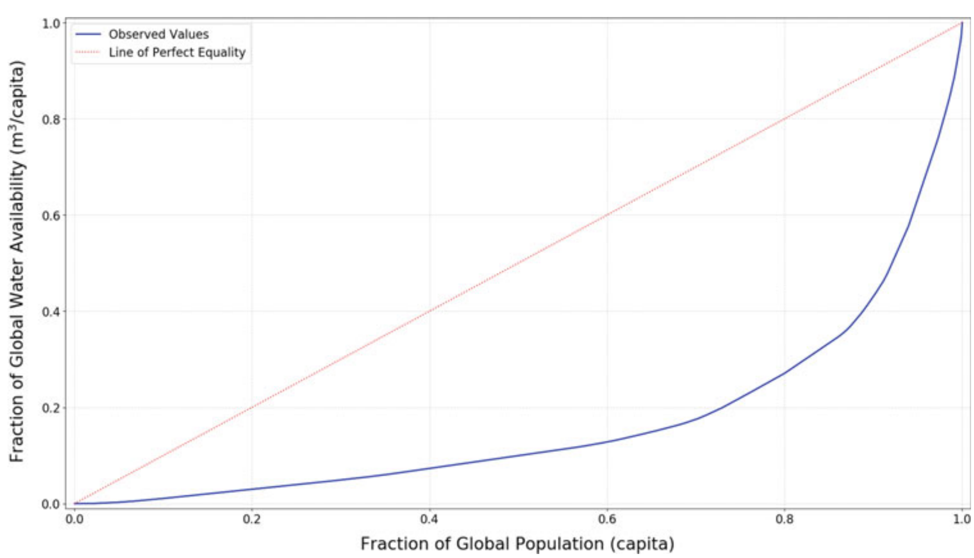


Fig. 14.19 Lorenz curve, fraction of population versus water availability. Derived and calculated based on data from The World Bank (2014)

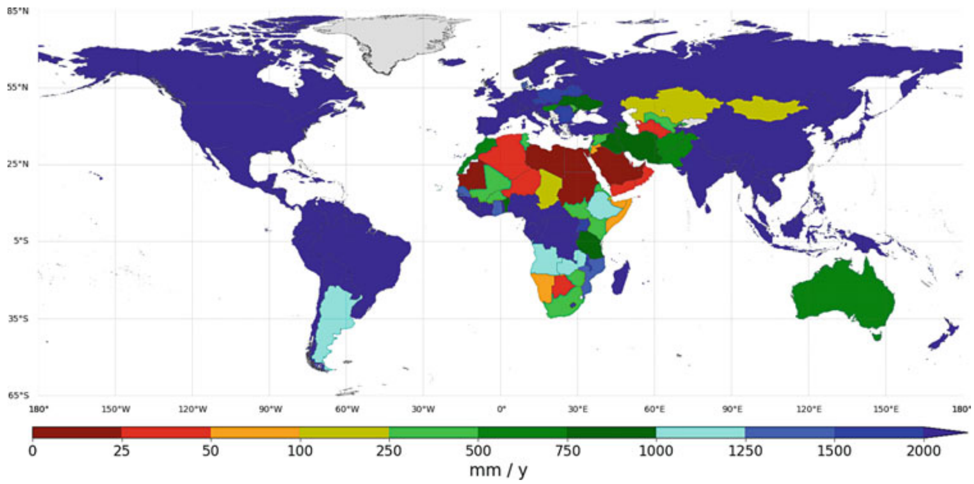


Fig. 14.20 Total renewable surface water (mm/year). Calculated based on data from The World Bank (2014)

14.6.6 Dependency Ratio

The dependency ratio is defined as an indicator expressing the percentage of total renewable water resources originating outside the country. When a certain country has a dependency ratio equal to 0%, the inflow of renewable water from neighboring countries is null. On the other hand, a country with a ratio of 100% receives all its renewable water from upstream countries without producing any of its own. The dependency does not include the possible allocation of water to downstream countries (FAO 2016). In the dependency ratio calculation criteria, estimated surface water and groundwater are accounted for.

The dependency ratio is an important factor, as it allows identifying which countries do not have their own renewable water resources. This means Fig. 14.21 can be seen as a map indicating the need for cooperation between neighboring countries. In regions of Africa and South Asia, such dependencies are not always democratically handled, and many downstream countries suffer under the decisions of upstream regions.

14.6.7 Water Consumption per Sector

Based on the data from the FAO dataset, the percentage of water consumed by every sector as a percentage of total water withdrawal is obtained. The result is displayed in Fig. 14.22. In total, data from 180 countries are available. A first analysis of the data shows that more than 90 countries use 60% of their total water withdrawn for agriculture as compared to almost 20 countries (10%) who use around 60% of their total withdrawal for industrial or municipal water use. In Africa or Central Asia, the countries with high agricultural demand are in general also countries with limited freshwater resources. Irrigated agriculture and livestock activities are greatly dependent on water availability and are the most water intensive sectors. Many aquifers and freshwater resources around the world are stressed, and many aquifers have been depleted. Moreover, water quality is negatively influenced by these sectors. Different pollutants such as fertilizer run-offs, excessive use of pesticides, and livestock effluents deteriorate the water quality.

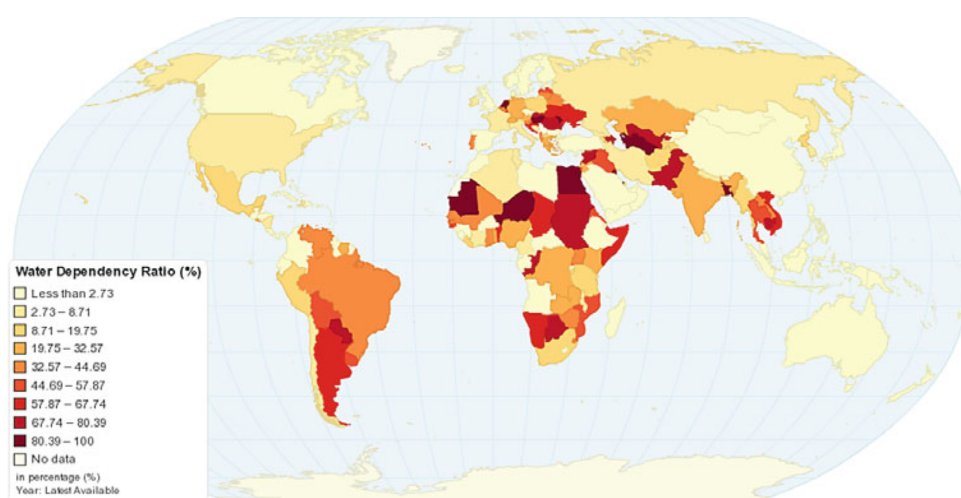
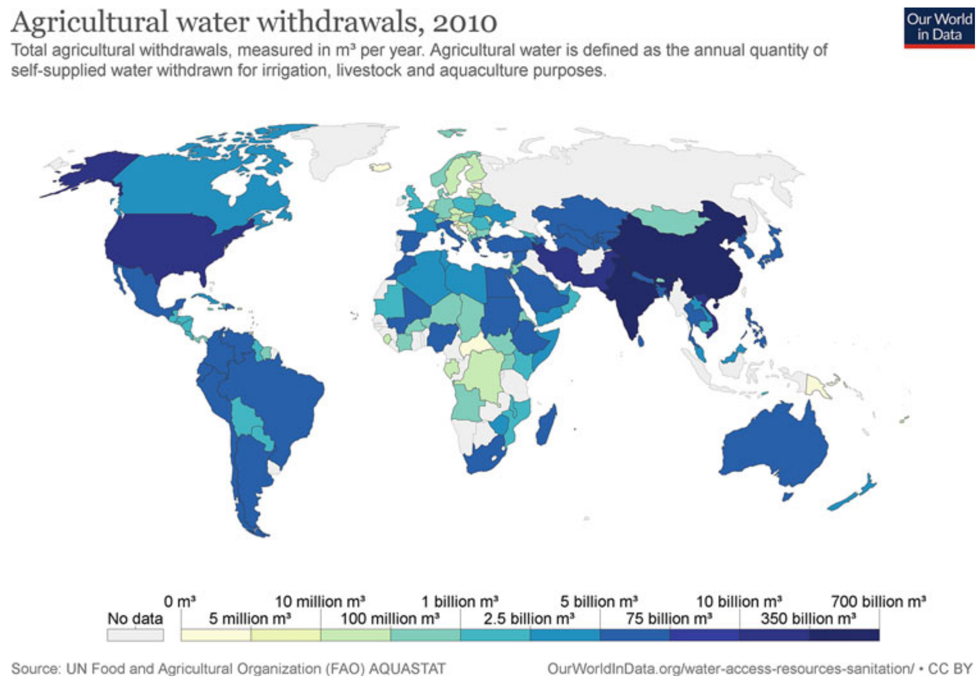


Fig. 14.21 Dependency ratio. *Credit* ChartsBin Statistics Collector Team 2011 (2008)

Fig. 14.22 Agricultural water withdrawal as % of total water withdrawal



Managing fresh water resources is becoming a more challenging task as population and food demands increase.

14.7 Case Study: The Nile River Basin

The Nile basin is perhaps one of the most critical and crucial shared water basins in Africa. As the world's longest river, the Nile has a total length of almost 6825 km. The drainage basin spreads over eleven countries from which five are among the poorest of the World. With a total area of 3.17 million km^2, the Nile basin represents 10.3% of the area of the continent. In 2015 around 270 million people, one third of the African population, lived in the basin and relied mainly on the river as a freshwater source (Fig. 14.23).

Three main tributaries contribute to the Nile. The Blue Nile, starting in the Ethiopian highlands, and the White Nile, with its sources on the Equatorial Lakes Plateau, join at the city of Khartoum in Sudan. Further downstream, the Atbara (Tekezze) river emerges from the Ethiopian Highlands and joins the main Nile River near the city of Berber in Sudan. The Blue Nile is considered as the major source of inflow to the Nile. Since the river flow is mainly driven by monsoon precipitation, it is highly seasonal and accounts for around 60% of the total Nile's water. The White Nile has a different character, its flow is more or less steady with low seasonal variation; it contributes 10–20% of the total river runoff. The Atbara and the Akobo rivers each contribute around 15% of the total river flow (Beyene et al. 2010).

Despite having a large area, the basin drainage waters constitute on average around 2% of the total runoff of the continent. As a result of the basin's diverse topography and climate, the Nile river has very low specific discharge. It is also characterized by a low rainfall/runoff ratio with high sensitivity to changes in temperature and precipitation regimes (Conway and Hulme 1993).

On the borders between Sudan and Egypt, Lake Nasser, one of the world's largest man-made reservoirs with an approximate storage capacity of 132 km^3, provides inter-annual flow regulation for Egypt (Muala et al. 2014). For Sudan and Egypt located in the downstream part of the Nile and characterized as hot and arid regions with infrequent and insignificant rainfall, most of the inflow originates from upstream countries. According to recent estimations, more than 97% of Egypt's and 77% of Sudan's water emerge from upstream. Despite being the most downstream country, Egypt is the largest consumer of the Nile waters. The river is the country's main and exclusive resource for freshwater. The different basin states consider the Nile waters as a vital ingredient for socio-economic development. Collaboration and communication between the countries are essential for good management of the resources and for alleviating poverty in the region.

The countries that are wholly or partly within the Nile basin are displayed in Table 14.6.

The basin is spans five different climatic zones. Starting in the south with an equatorial rainforest region, extending northerly to a tropical savannah and further with a semi-arid

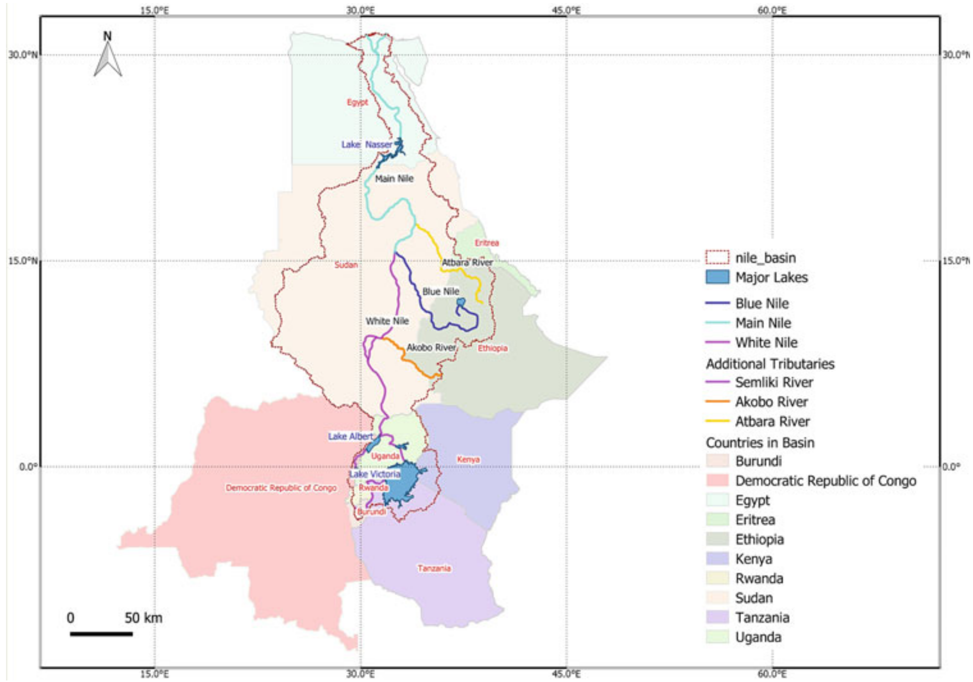


Fig. 14.23 Nile river basin. *Credit* The World Bank (2017)

Table 14.6 Countries within the Nile basin

Country	Total area of the country (km^2)	Area of country in basin (km^2)	As % of total area of basin (%)	As % of total area of country (%)
Burundi	27,834	13,260	0.4	47.6
Dem. Rep. of Congo	2,344,860	22,143	0.7	0.94
Egypt	1,010,000	326,751	10.5	32.35
Eritrea	117,598	24,921	0.8	21.2
Ethiopia	1,104,000	365,117	11.7	33.1
Kenya	580,367	46,229	1.5	8.0
Rwanda	26,338	19,876	0.6	75.5
Sudan	1,886,000	1,414,500	63.1	75.0
Uni. Rep. of Tanzania	945,087	84,200	2.7	8.9
Uganda	241,037	231,366	7.4	95.9
Total Nile Basin	–	3,112,369	100.0	–

Credit Derived from Nile Basin Initiative (2019)

to an arid climate near the Mediterranean sea. On the east side, the Ethiopian plateau is distinguished by a highland climate region. Precipitation over areas of Sudan and Ethiopia is seen to be correlated with El Nino/Southern Oscillation (ENSO) events (Elshamy 2006).

The population of all countries within the Nile basin is expected to rapidly increase in the coming years. The spatial distribution of the population is influenced by different factors, some of which are climate, water availability, soil fertility, and economic and social infrastructures. Within the Nile basin, water availability is a dominant factor. The population density distribution is unequally distributed within the basin area. For countries such as Egypt and Sudan, most human settlements are mainly spread along the course of the river. For example, in Egypt, highly populated locations such as the Nile Delta or the Nile Valley cover almost 5% of the total country. In the upstream part of the basin, areas with high rainfall availability present the highest

Table 14.7 Population projections for the countries within the Nile basin

Country	Total population in 2015 (millions)	Projected population in 2050 (millions)
Burundi	11.18	28.67
Dem. Rep. of Congo	77.27	195.28
Egypt	91.51	151.11
Eritrea	5.23	10.42
Ethiopia	99.39	188.46
Kenya	46.05	95.50
Rwanda	11.61	21.19
South Sudan	12.34	25.86
Sudan	40.23	80.28
Uni. Rep. of Tanzania	53.47	137.14
Uganda	39.03	101.87

population density. The majority of the people live in rural areas and depend on farming and agriculture as main sources for income and food security.

In Table 14.7, the current and an estimate of the projected population for the eleven countries sharing the Nile basin are displayed. It is expected that in most countries the urban population will rise and the rural one will decrease. Due to an exponential increase in the basin population, water availability per capita is continuously decreasing. As the rate of urbanization increases, the water, food, energy demands and the stress on the Nile river throughout the region are expected to also rapidly expand.

The basin is characterized by diverse topographic features including mountainous regions, freshwater lakes, floodplains, depressions and wetlands. It is unique because of its nature, diverse terrestrial ecoregions, and the different species of flora and fauna that are spread along the basin and differ from each sub-basin to the other. In the regions of Ethiopia and the Equatorial Lake lie the highlands, spreading to the desert in Sudan and Egypt. The climate and hydrology of the basin vary from being highly arid in the regions of Sudan and Egypt to being equatorial in the White Nile basin section. On the border between the Democratic Republic of Congo and Uganda lies Mount Stanley which is the highest point in the Nile basin (5109 m). As seen in Fig. 14.24, most of the basin lies below an altitude of 1500 m above sea level (a.s.l.). In the south and east side of the basin thee are highlands with an altitude reaching more than 3000 m a.s.l. These upper parts of the basin have steep slopes and ridge crest topography. It is there where rainfall amounts are the

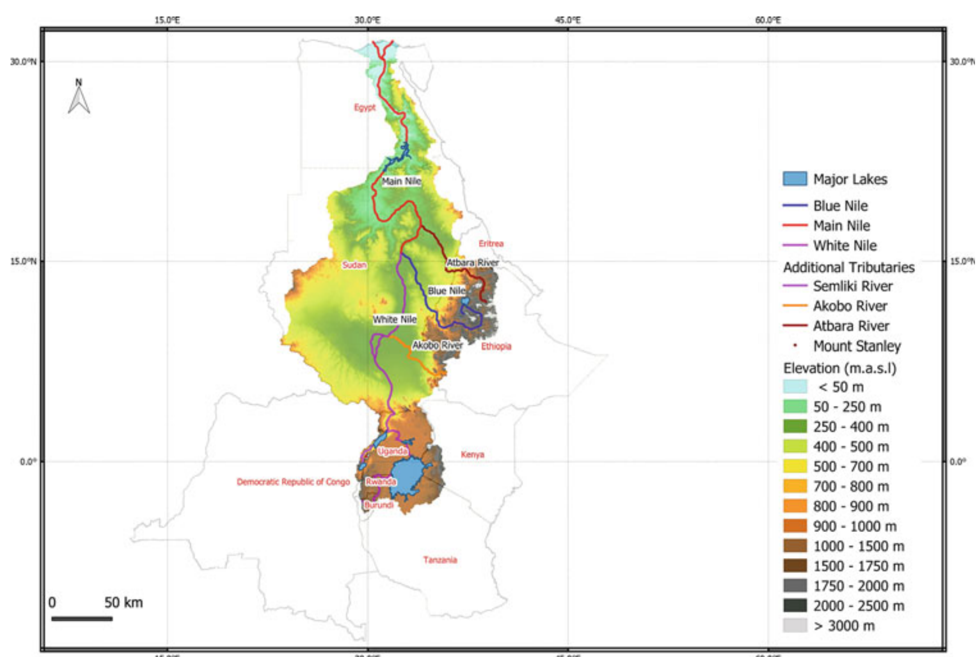


Fig. 14.24 Nile Basin elevation distribution. *Credit* Landsat-8 image courtesy of the U.S. Geological Survey

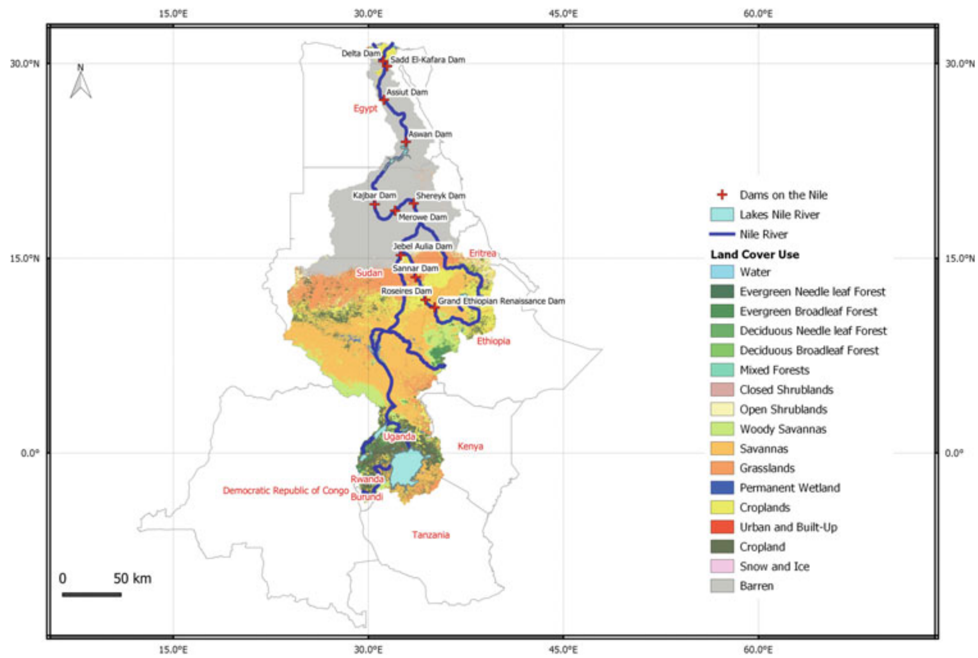


Fig. 14.25 Land use cover in the Nile basin. *Credit* Friedl and Sulla-Menashe (2019)

highest and the White and the Blue Nile originate. As water reaches downstream countries, most of the available flows are being allocated for industrial, domestic and agricultural uses. It is estimated that every year almost 10 km^3 are discharged in the Mediterranean sea.

The land cover use within the Nile basin is displayed in Fig. 14.25. In Table 14.8, the different land cover types, their corresponding area (in km^2) and the percentage of the basin that they cover are listed. The basin is dominated by barren land. Other land cover types in order of decreasing area are forest, cropland, mosaic vegetation and shrubland. In Egypt and Sudan, due to a lack of rainfall, irrigated agriculture is the dominant land use along the river channel. Other regions of the countries are left as barren lands. This is reflected by the high amount of dams along the river channel as seen in Fig. 14.25. Large parts of south Sudan and north Uganda are covered by savanna lands. In the other parts of the basin, land use mainly consists of forests and croplands. The land cover plays an important role in quantifying the evapotranspiration and the water demands over the catchment area. Soil moisture, defined as the water availability in the unsaturated zone, is a key factor in agriculture and irrigation management and is highly related to the soil and crop type. Within the Nile basin, soil moisture is spatially and temporally variable.

In the first decades of the 21st century, changes of the land occurred. In most areas of the basin a continuous decrease of green areas and an increase of cultivated land was seen.

From a hydrological point of view, the basin is sub-divided into eight sub-basins, each with a distinct behavior. The reaction and contribution of the sub-basins are highly different. Some sub-basins have high contribution to the flow in the Nile, while others have a negative water

Table 14.8 Approximate distribution of the land cover in the Nile Basin

Land cover type	Total area (1000 m^2)	Percentage of basin (%)
Baren land	1,004,573	32.0
Mosaic vegetation	358,225	21.9
Cropland	372,640	11.9
Shrubland	358,976	11.5
Forest	685,182	11.4
Grassland	204,157	6.5
Water	972,936	3.1
Wetland	49,536	1.6
Urban	4642	0.2

Credit Friedl and Sulla-Menashe (2019)

Table 14.9 Estimated average rainfall in basin area (mm/year) (Schneider et al. 2018)

Country	Average annual rainfall in the basin area (mm) mean
Kenya	1260
Dem. Rep. of Congo	1245
Uganda	1140
Ethiopia	1125
Burundi	1110
Rwanda	1105
Tanzania	1015
Eritrea	520
Sudan	500
Egypt	15
For Nile basin	615

balance due to high evapotranspiration. An in-depth description of each sub-basin can be found, for example, in the work done by Elshamy (2006).

Table 14.9 shows an estimate of the average annual rainfall amounts for the different countries in the basin. Downstream areas often have low rainfall average volumes. In upstream regions, rainfall is sufficient but is highly variable in space and time. Displayed in Fig. 14.26 is the annual spatial and temporal rainfall distribution. This highly impacts the productivity of rainfed agriculture, which forced the local farmers to invest in drought-resistant but low-yielding crop types.

The ET_0 defines the evapotranspiration for reference crop (mm/day) and is calculated based upon implementation of the Penman Montieth Reference Evapotranspiration (ET_0) equation (FAO 2016). As a fundamental component of the hydrological cycle, evapotranspiration plays a role in determining agricultural water consumption and developing water budgets. As seen in Figs. 14.26 and 14.27 rainfall and evapotranspiration are temporally and spatially variable over the basin. Understanding the interactions between land use, evapotranspiration and rainfall spatial and temporal distributions is fundamental knowledge for managing the resources in the Nile basin.

Recent studies done by the International Groundwater Resources Assessment Centre (IGRAC) showed the presence of twelve highly heterogeneous trans-boundary aquifers within the basin. Part of domestic and local agricultural water demands are supplied by shallow aquifers. Under normal conditions without groundwater overuse, shallow aquifers are actively replenished by rainfall recharge. Deeper regional systems with long residence time are hardly replenished, especially, if being exploited on a regional scale. Often data about groundwater recharge rates, well distributions, well yields, and chemical quality are less consistent and not easily available in all countries. In the Nile delta, few wells have been reported to have salinity problems, but often water quality is altered due to dissolution of iron and manganese from sedimentary formations. Information on groundwater availability and variability within the Nile basin is fundamental for a sustainable use of the resources (Macalister et al. 2013).

Water quality deterioration, mainly due to human intervention, is another challenge within the basin. Different sources and types of pollutants affect the quality of the Nile: domestic (municipal and rural domestic wastewater), agricultural (agrochemical residues, drainage water reuse), and industrial (organic and inorganic effluents). None the less, the river is still considered a relatively clean river. The reason behind this is that through high water discharges, pollutant loads are diluted and the river has a high self cleaning capacity.

It is very clear that the Nile is going through the desert; the water comes from the mountains, especially from the south east side, and flows to the north. A large part of the basin is completely dry. This is why there is an urgent need to store and regulate the water.

Understanding hydrological connections and the hydrological regime between upstream and downstream river sections are essential for decision makers. Since the inflow and the quality of the water in the Blue Nile is controlled by Ethiopia, downstream countries, such as Egypt, which strongly relies on the Nile for water and agriculture, are highly dependent on the policies implemented by Ethiopia. The construction of the Grand Ethiopian Renaissance Dam is a major source of concern, since the filling of the reservoir will strongly impact the amount of water flowing into Egypt. Different competing projects are occurring on the tributaries of the river.

In the absence of clear cooperation and guidelines regarding trans-boundary water management, sustainable development and equitable utilization of the waters is not

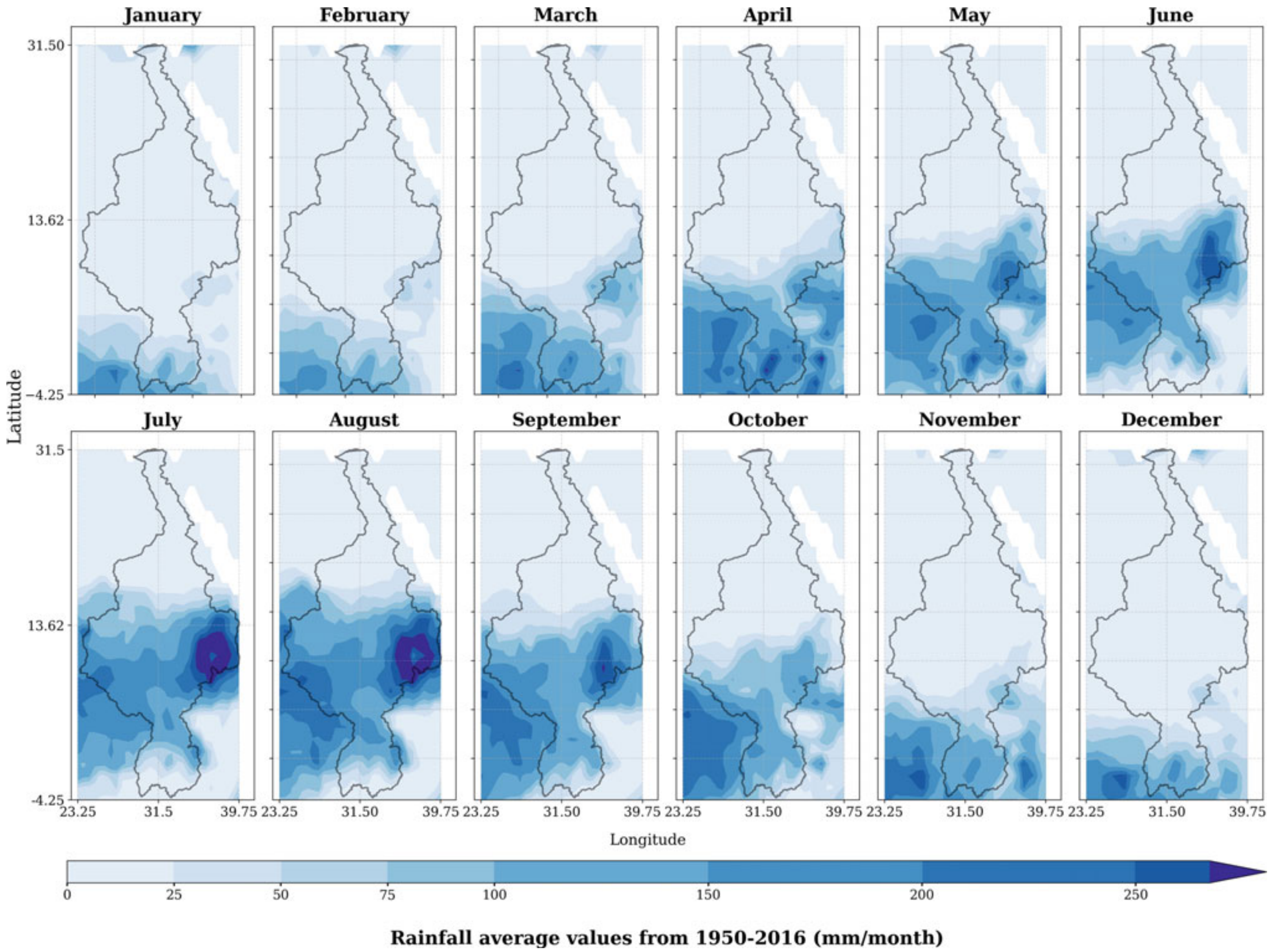


Fig. 14.26 Nile basin rainfall average monthly values from 1950 till 2016 (Schneider et al. 2018)

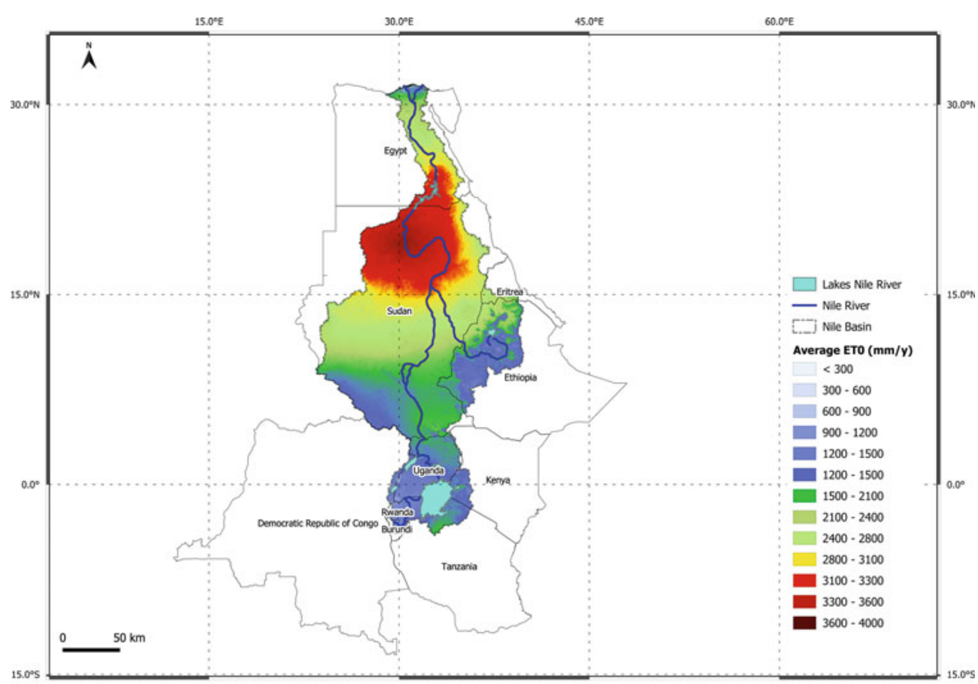


Fig. 14.27 Nile basin yearly average potential evapotranspiration ET_0 derived from the period of 1970–2000 (Trabucco and Zomer 2018)

likely. The Nile Basin Initiative (NBI) is a collaboration between most of the countries within the basin and it has been working on developing and providing a basin monitoring tool. This will aid decision makers, managing governments, water resources offices, and the public in promoting and furthering cooperation (Nile Basin Initiative 2019).

For the near future, conflict and water demand issues are expected to occur and increase in the Nile basin. Eleven countries are sharing the resources of the river, two of them almost completely dependent on upstream areas. With more hydropower structures being planned along the river course, the natural regime and dynamic of the river are undergoing irreversible changes. With the continuous population increase and agriculture requirements, the stress on the Nile river is expected to increase as a direct result. Management plans and regulations are essential for managing the available water quantities in a sustainable way.

14.8 Conclusion

In this chapter, an idea about the global situation of water availability and variability has been presented.

In the first and second section, an insight into the fluxes within the water cycle was given. In the third section, temporal and spatial availability and variability of precipitation were addressed. In section four, a short view of global groundwater availability and situation was presented. In the fifth section, snow, ice and glaciers and their associated roles were discussed. In section six, an overview of the current situation of water availability and their common management strategies was provided. Finally in the last section, a case study related to the water availability in the Nile river basin was presented.

Precipitation is the driving agent for water availability. It varies in space and time. Most regions with high water demands have either low rainfall values or high reliance on upstream regions. The dependency ratio is a measure that shows the potential conflicts between neighboring countries. Most of the world's groundwater aquifers are under stress and are being overexploited, especially, in regions where the people rely heavily on groundwater. Being a vital source of freshwater in mountainous regions, glaciers are showing a continuous decrease in their area and volume. Changes in temperature affect the snowmelt spring runoff mechanism. Effects on the accumulated volumes and the seasonal dynamics are observed. More surface reservoirs and desalination plants are being built to reduce the extent of water scarcity. One of the goals is to improve the resilience of societies to water stress. The number of countries facing water scarcity problems is increasing. Promoting solutions under the influence of population expansion, non sustainable use of resources, and degradation of water quality is a challenging task ahead. The most water intensive sector is agriculture. In many countries agricultural water withdrawal is rising to meet the food demands. For the Nile river, a large highly complicated trans-boundary river, different competing countries and demands are leading to local conflicts and non-sustainable use of the resources. Water is available but extremely unequally distributed in space and time. Cooperation between the different states is crucial for ensuring peace and preserving the river, a vital resource for most of involved countries.

Freshwater is an indispensable resource for human life. Unfortunately, it is irregularly distributed with respect to time, space and population needs. Water availability is not only a problem of too few freshwater volumes but also of an unequal distribution of the available resources.

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András Bárdossy has been chair of the Department for Hydrology and Geohydrology at the University of Stuttgart since 2003. The focus of his work is on the application of statistical methods for environmental modelling. He studied mathematics at the ELTE University in Budapest where he received his doctorate in mathematics in 1981. He received his doctorate in civil engineering from the University of Karlsruhe in 1993 and his habilitation in 1994, also in Karlsruhe.

Abbas El Hachem is an engineer pursuing an International Doctoral Program Environment Water (ENWAT) at the University of Stuttgart. He holds a Master of Science in "Water Resources Engineering and Management" from the same university as well as a Master of Science in Water Science from the University of Saint Joseph (ESIB) in Beirut, Lebanon. Among other experiences, Abbas served as a student assistant at the Institute of Modelling Hydraulic and Environmental Systems of the University of Stuttgart, Germany.

Assessment of Land/Catchment Use and Degradation

15

Fabrice G. Renaud, Zita Sebesvari, and Animesh K. Gain

Abstract

Agricultural conversion of land and rapid urbanization are the primary drivers of land cover and land use change (LCLUC) globally, resulting in massive deforestation, drainage of wetlands, effects on the water cycle, alteration of sediment budgets, and acceleration of land degradation and desertification. This has taken place across various spatial and temporal scales. This chapter provides an overview of hydrological impact of land use change at these multiple scales. It also reviews the state of the art in analyzing LCLUC impacts on water quality outcomes and showcases where different techniques have been used to reveal the relationship between the two. Finally, the chapter addresses the impacts LCLUC generated within entire basins can have on delta landscapes, which constitute very dynamic and fragile environments with typically high economic activities and population densities.

Keywords

Communities • Pollutants • Ecosystems • Evapotranspiration • Land cover and land use change • Water quality • Deltas • River basins • Urban areas • Sediment transport

Abbreviations

BOD5	5 Day Biological Oxygen Demand
DO	Dissolved Oxygen
EC	Electrical Conductivity
ET	Evapotranspiration
GIS	Geographic Information System
Gt/y	Giga-tonnes per year
IPCC	Intergovernmental Panel on Climate Change
km^2/y	Square kilometers per year
LCLUC	Land Cover and Land Use Change
mm/y	Millimeters per year
Mt/y	Million-tonnes per year
NbS	Nature-based Solutions
SCS-CN	Soil Conservation Services Curve Number
TDS	Total Dissolved Solids

15.1 Introduction

In order to meet growing demands for food and shelter, humans have altered approximately 41–50% of the Earth's surface, replacing natural vegetation such as forests and wetlands with anthropogenic land cover such as agricultural lands and built-up areas (Klein Goldewijk et al. 2011; Waters et al. 2016). Conversion to agriculture constitutes the most common manmade land cover and land use change (LCLUC) and natural vegetation removal generates major changes to water resources in terms of water quantity, quality, infiltration, and runoff (Foley et al. 2005). This happens at different spatial scales ranging from the global to the local.

At the global scale, land-cover and land-use change interferes with the carbon, nitrogen, and water cycles. These cycles are connected through numerous feedback loops. In addition, land cover change has a strong effect on the global hydrological cycle through altering available energy,

F. G. Renaud (✉)
School of Interdisciplinary Studies, University of Glasgow, Rutherford/McCown Building,, Dumfries DG1 4ZL, UK
e-mail: Fabrice.Renaud@glasgow.ac.uk

Z. Sebesvari
United Nations University Institute for Environment and Human Security (UNU-EHS), Bonn, Germany
e-mail: sebesvari@ehs.unu.edu

A. K. Gain
Department of Urban Studies and Planning, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA
e-mail: again@mit.edu

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available water, photosynthesis rates, nutrient levels, and surface roughness (Liu et al. 2017). These effects trickle down to the river basin and catchment scales and combine with local effects of LCLUC, generating multiple impacts in terms of water quantity, quality, and sediment budgets. At the scale of urban centers, an increase in impervious surface area accompanied by urban development significantly alters hydrological response, in particular by increasing the 'flashiness' or quickness to and magnitude of peak flow from rainfall events (Miller et al. 2014). As impervious surface area increases, the entire water balance of the basin is altered, with increased surface runoff and decreased groundwater recharge and evapotranspiration. The size of the impervious area, and the size and location of the basin determine the magnitude of hydrological impact. For example, smaller basins experience relatively greater impacts than larger ones (McGrane et al. 2016). Due to urbanization, the increased precipitation can be observed within the city and up to 50–75 km downwind of a city during the summer months (Shepherd et al. 2002).

Water quality is also drastically affected by LCLUC. With the inputs of fertilizers and pesticides in agriculture, and the concentration of livestock and/or aquaculture within small areas, the pollution of surface and groundwater has the potential to substantially increase. A sound understanding of the links between LCLUC and water quality and the quantification of this relation is critical from human health and watershed management perspectives, especially in areas with drinking water abstraction. Knowledge and awareness for the linkages between land use and water quality is necessary to support the development of land use planning strategies sensitive to water management outcomes as well as for drinking water companies in selecting optimum water extraction locations. Following the first theories recognizing and describing the link between land use/cover and water quality in the 1970s and 1980s, the availability of scientific tools to quantify watershed characteristics and patterns increased drastically through the use of geographical information system (GIS), image processing and remote sensing technologies, and multivariate statistical techniques. Studies performed since the mid-1990s used spatially-distributed data and multiple regression analyses in order to quantify the relation between water quality and a set of landscape variables. Most studies have focused on nutrients such as nitrogen, phosphorus, or nitrate, and the turbidity from suspended solids; few on heavy metals, organic contaminants, and microbial indicators. The extent of urbanization, soil properties, extent of aquaculture and tidal regime explained, for example, the variance of surface water quality attributes in the Mekong region (Wilbers et al. 2014).

Changes in land use and land cover, and in water hydrology and quality, are more often than not interlinked. This is visible in multiple landscapes but is arguably most observable in deltaic environments which are dynamically linked to changes in water and sediment supplies and which can accumulate sediment-bound and dissolved substances. In many cases this can be beneficial and many deltas around the world have become high agricultural production areas thanks to sediments and nutrients deposited by rivers (Kuenzer and Renaud 2012). In other cases, this can be detrimental when pollution coming from upstream accumulates in deltas and when human activities developed within deltas, such as when intensive agriculture and aquaculture release large quantities of pesticides, nutrients, antibiotics and microbial pollution in surface and groundwater (e.g. in the case of the Mekong delta in Vietnam, see Giang et al. 2015; Wilbers et al. 2014; Toan et al. 2013). Pollution from upstream and generated within deltas threaten the health of both human populations and aquatic ecosystems as well the livelihoods of households and communities. Changes in water and sediment supplies, when combined with other factors such as human-induced land subsidence and/or sea-level rise, can threaten the very physical existence of deltas, which are landscapes that have generally seen population growth and high population densities as well as rapid economic development (Kuenzer and Renaud 2012; Renaud et al. 2013; Syvitski et al. 2009).

In this chapter, we describe the main LCLUC processes and their impacts in particular on river basins and the consequences human activities have on deltaic environments, but also on the urban environment and on water quality.

15.2 Quantitative Aspects of Land Cover and Land Use Change

Besides climate change, land use change is a dominant driver of global environmental changes. The global need to provide food, fiber, water, and shelter to the then more than six billion people is the main driving force for the changes to forests, farmlands, waterways, and air (Foley et al. 2005). In order to meet growing demand for food and shelter, humans have altered approximately 41–50% of the Earth's surface, replacing natural vegetation such as forests and wetlands with anthropogenic land cover such as agricultural lands and built-up areas (Klein Goldewijk et al. 2011; Waters et al. 2016). Global croplands, pastures, and urban areas have expanded in recent decades, accompanied by large increases in energy, water, and fertilizer consumption, along with considerable losses of biodiversity. These changes have substantially affected Earth's climate at different scales through altered biogeochemical and biogeophysical processes that change carbon, energy, and moisture fluxes to the atmosphere (Liu et al. 2017). Land use and land cover change impacts water resources at different scales i.e., global, basin, catchment and local, including urban. Vörösmarty et al. (2013) stated that the alteration of the water cycle is one of the principal and most influential effects of the LCLUC that directly affects human populations, agriculture, forestry, and sustainability of natural ecosystems.

15.2.1 Impact of Land Use Change at Global Scale

At the global scale LCLUC is an important contributor of greenhouse gasses as these activities directly interfere with the carbon, nitrogen and water cycles. According to recent statistics (Pongratz et al. 2014; Le Quéré et al. 2015), LCLUC has contributed about 50% to the atmospheric CO_2 increase since pre-industrial times and about 10–20% during the past decades (2005–2014). Deforestation and other land use changes released CO_2 with an amount equivalent to about half of the emissions from fossil fuel combustion and cement production into the atmosphere from 1750 to 2011 (IPCC 2013). LCLUC has significantly contributed to the combination of gas- and particle-phase emissions, which provides a range of direct and indirect effects on climate. The land surface–climate relationship is further complicated by the changing land surface either through direct emissions of greenhouse gases or through indirect pathways (e.g., aerosols on clouds, the role of secondary pollutants such as nitrate oxydes or NOx on greenhouse gas concentrations) (Liu et al. 2017).

Land-cover change alters the water cycle through direct changes to the timing and magnitude of evapotranspiration (ET) via two interrelated mechanisms: (i) direct alteration of the hydrological pathways by LCLUC engineering works (e.g., reservoirs, canals, and irrigation and drainage systems); (ii) LCLUC-associated alteration of albedo, surface roughness, and properties of vegetation (e.g., stomatal conductance). The land-cover change alters available energy, available water, photosynthesis rates, nutrient levels, and surface roughness at the land surface. Climate modeling at the global scale suggests that irrigation and impoundment of water in reservoirs enhance ET and precipitation and can cool surface air temperatures (Gordon et al. 2005).

Based on a database of over 1,500 ET observations for discrete land-cover types and a spatial analysis (using Geographic Information System (GIS)) at 5 min resolution, Sterling et al. (2013) found that anthropogenic land-cover change reduces annual ET by approximately 3,500 $km^3 yr^{-1}$ (5% of potential land cover). Although this global average shows reduction of terrestrial ET due to clearing forest and wetland for cropland, LCLUC also contributes to increase ET through irrigation and reservoir creation. The largest reduction in ET is associated with wetland loss, whereas, the largest increases in ET are associated with reservoir creation (Gordon et al. 2005).

According to Sterling et al. (2013), the hotspots of reduced ET occur in the North American mid-west, Eastern Europe, south-east Asia and sub-Saharan Africa, while, the hotspots of increased ET occur in the western USA, Pakistan, central Asia and southern Australia. The reduced ET is associated with the conversion of savannah and forest areas to non-irrigated cropland and grazing land, whereas, the increased ET is due to the conversion of grassland, open and closed shrubland to irrigated cropland and reservoirs. The location of areas with increased ET often overlie areas of high water demand (Vörösmarty et al. 2000), indicating land-cover change may play a significant role in exacerbating or relieving water shortages in these areas. Further, the hotspots of ET change overlie areas of strong land–atmosphere coupling (suggesting that land-cover change can strongly alter the precipitation cycling rate), such as West Africa and north-central USA (Koster et al. 2004).

Land use can disrupt the surface water balance and the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow. Surface runoff and river discharge generally increase when natural vegetation is cleared. Thus, land-cover change is probably acting to transform regional water vapour-flow patterns, as hotspots of increased and decreased ET are in different locations. This information on the initial forcing due to land-cover change facilitates clearer interpretations of coupled scenarios in which there is atmospheric feedback. Land surface model simulations support these evapotranspiration changes, and project increased runoff (7.6%) as a result of land-cover changes. Sterling et al. (2013) and Pielke et al. (2011) found that land-cover change alters annual global runoff to a similar or greater extent than other major drivers (e.g., climate change induced meteorological forcing), confirming the important role of land-cover change in the Earth System.

Water demands associated with land-use practices, especially irrigation, directly affect freshwater supplies through water withdrawals and diversions. Agriculture alone accounts for 85% of global consumptive use. As a result, many large rivers, especially in semiarid regions, have greatly reduced flows, and some routinely dry up. In addition, the extraction of groundwater reserves is almost universally unsustainable and has resulted in declining water tables in many regions (Foley et al. 2005).

15.2.2 Impact of Land Use Change at River Basin or Watershed Scale

The study of hydrological response of a river basin or a catchment to land use change is very complex (Kumar et al. 2017). There are complicated inter-relationship between various hydrological components (e.g. precipitation, evaporation, transpiration, infiltration, and runoff). The land use changes have adverse implications on the natural hydrologic system in terms of variation in the runoff regime, evapotranspiration, subsurface flow, and infiltration. Land cover change has a strong effect on the hydrological cycle through altering available energy, available water, photosynthesis rates, nutrient levels, and surface roughness. In many river basins of the world, the annual river discharge has increased significantly since 1900, and research suggests that land-use change may be directly responsible for more than 50% of this increase, which is larger than the contribution of climate change (Piao et al. 2007).

At river basin and catchment scales, the impacts are diverse and include alteration of the magnitude of evapotranspiration, surface runoff, and groundwater recharge driven by infiltration during and after precipitation events and water uptake by different vegetation types from subsurface layers (Talib and Randhir 2017). The major factors contributing to land use change includes demographic changes, climatic variability, national resource conservation policies, and socio-economic factors (Dwarakish et al. 2015). The other factors that drive land-use change in any watershed include the altitude, slope, distance from the river, soil erosion coefficient, distance from major roads, distance from a built-up area, and population density (Lin et al. 2009).

The magnitudes of the impacts depend on catchment properties, original and replacement vegetation, and management type (Ochoa-Tocachi et al. 2016). Management activities such as crop cultivation and afforestation affect the entire range of discharges, particularly low flows. The impacts of grazing have the largest effect on the catchment hydrological regulation. In a recent study on Andean catchments, Ochoa-Tocachi et al. (2016) found that land use change results in increased streamflow variability and significant reductions in catchment regulation capacity and water yield, irrespective of the hydrological properties of the original biome.

Petchprayoon et al. (2010) assessed the hydrological impacts of land use/land cover (LULC) change in the Yom watershed in central–northern Thailand over a 15-year period using an integration of remote sensing, GIS, statistical methods, and hydrological modelling. The results showed an expansion of urban areas by 132% (from 210 km^2 in 1990 to 488 km^2 in 2006). Using regression analysis, the rate of change in discharge after changes in LULC showed a systematic increase over a range from 0.0039 to 0.0180 $m^3 s^{-1} day^{-1}$ in different hydrologic stations along the Yom River over a 15-year period.

Talib and Randhir (2017) simulated watershed processes in the Sudbury-Assabet-Concord (SuAsCo) River watershed in Massachusetts, USA, using a calibrated and validated Hydrological Simulation Program Fortran model. They found that the combined change in land cover and climate reduces ET with loss of vegetation and increases surface runoff significantly by 2100 as well as stream discharge. According to their estimate, the combined change in land cover and climate cause 10% increase in peak volume with 7% increase in precipitation and 75% increase in effective impervious area.

Nobre et al. (2016) found that due to deforestation to open areas for agriculture, the Amazonian tropical forests have been disappearing at a fast rate in the last 50 years posing high risks of irreversible changes to biodiversity and ecosystems. Climate change poses additional risks to the stability of the forests. Nobre et al. (2016) suggested “tipping points” not to be transgressed: 4 °C of global warming or 40% of total deforested area by 2050, compared to ‘business-as-usual’ scenario. Mwangi et al. (2016) assessed the relative contribution of land use change and climate variability on discharge of upper Mara River, Kenya and the results suggested that land use change, attributed to deforestation at the headwaters of the watershed, was found to be the main driver of change in discharge accounting for 97.5% of the change. Climate variability only caused a net increase of the remaining 2.5% of the change.

Several methods and tools are available to evaluate the impact of land use changes on water resources at river basin or catchment scale. Choi and Deal (2008) combined a semi-distributed hydrologic model and a dynamic urban growth model for examining the implications of urbanization on the hydrological processes in the Kishwaukee River basin (USA). He and Hogue (2012) also used a semi-distributed model to evaluate the impact of future urbanization on flow regimes and found that increasing development increases the total annual runoff and wet season flows. Integrating land use models with a precipitation-runoff model provides quantitative information about the effects of land use intensities and strategies on hydrological output.

The concept of nature-based solutions (NbS) promotes the protection, sustainable management, and restoration of ecosystems as a means to address multiple concerns simultaneously (Cohen-Sacham et al. 2016; Kabisch et al. 2016).

In order to address the impact of land use change at river basin or catchment scale, several NbS have recently been explored. Restoration of wetlands and streams, for example, are often considered as NbS that can provide a multitude of services of great social, economic and environmental value to humankind. The main benefits of wetland restoration include carbon sequestration, water quality protection, coastal protection, groundwater level and soil moisture regulation, flood regulation, and biodiversity support (Thorslund et al. 2017).

15.2.3 Impact of Land Use Change at the Urban Scale

Urbanization refers to the gradual increase in the proportion of people living in urban areas. Due to high population growth, the expansion of urban areas continues to pose a significant threat to natural habitat. According to recent statistics (UN 2016), 54.5% of the global population live in cities and by 2030, urban areas are projected to house 60% of people globally. The process of urbanization results in land use alterations. The changes in land use associated with urban development have resulted in significant changes in the physical properties of the land surface consequently increasing impervious surface area. Imperviousness is the most critical indicator to analyze the impact of urbanization on the hydrology. The urbanization is generally considered to have considerable effect on the hydrological response, such as: faster response, greater magnitude of river flow, higher recurrence of small floods, reduced baseflow and groundwater recharge (Miller et al. 2014; Braud et al. 2013).

Land use and other human activities influence the peak discharge of floods. Floods occur when large volumes of runoff flow quickly into streams and rivers. The peak discharge of a flood is influenced by many factors, including the intensity and duration of storms and snowmelt, the topography and geology of stream basins, vegetation, the size of the impervious area, the size and location of the basin, and the hydrologic conditions preceding storm and snowmelt events (McGrane 2016). As building density increases and larger neighbourhood areas emerge, greater impervious surface area modifies the way rainfall is translated into runoff at the surface and near-surface levels (Miller et al. 2014).

In an area with forests and grasslands, rainfall and snowmelt are stored on vegetation, in the soil column, or in surface depressions and when this storage capacity is filled, runoff flows slowly through soil as subsurface flow. Once natural vegetation is converted to urban areas, the permeable soil is replaced by impermeable surfaces (e.g., roads, roofs, parking lots, and sidewalks) that store little water, reduce infiltration of water into the ground, and accelerate runoff to ditches and streams (McGrane 2016). Walsh et al. (2005) stated that the presence of widespread impervious surfaces alters the dynamics of infiltration and results in contrasting impacts on base-flow behaviour at a range of scales. Expansion of urban space results in an increase of impervious landscape and expansion of artificial drainage networks that can facilitate dramatic changes to the magnitude, pathways and timing of runoff at a range of scales, from individual buildings to larger developments (Dams et al. 2013).

The fabric of individual buildings can alter the way rainfall is translated into runoff and the interconnected nature of pervious and impervious surfaces impact the effectiveness of the water storage capacity (Fox et al. 2012). With less storage capacity for water in urban basins and more rapid runoff, urban streams rise more quickly during storms and have higher peak discharge rates than do rural streams. In addition, the total volume of water discharged during a flood tends to be larger for urban streams than for rural streams. A recent study by Verbeiren et al. (2013) identified that a small increase in sealed surface area results in “considerably higher peak discharges”, especially true in peri-urban catchments. In addition, the hydrologic effects of urban development often are greatest in small stream basins than larger river basins where areas with natural vegetation and soil are likely to be retained (McGrane 2016).

A recent study carried out by Nair et al. (2016) quantified the impact of land use changes due to urbanization on surface and subsurface hydrology in Cochin, one of the fast developing second tier metros in India. Using the SCS-CN method and remote sensing images, they found a significant reduction in the amount of groundwater recharge and as a consequence, the area for shallow water table gets decreased for the past three decades clearly depicting an increasing depth trend.

Common consequences of urban development are increased peak discharge and frequency of floods. Sediment and debris carried by floodwaters can further constrict a channel and increase flooding. Small stream channels can be filled with sediment or become clogged with debris, because of undersized culverts. The effects of development in urban basins are most pronounced for moderate storms following dry periods. This creates a closed basin with no outlet for runoff. Erosion in urban streams represents another consequence of urban development. Frequent flooding in urban streams increases channel and bank erosion. Where channels have been straightened and vegetation has been removed from channel banks, streamflow velocities will increase, allowing a stream to transport more sediment. In many urban areas, stream-bank erosion represents an ongoing threat to roads, bridges, and other structures that is difficult to control even by hardening stream banks.

Urban development has also demonstrable impact on meteorological dynamics. The concentration of heat-absorbing materials, heat-generating processes and lack of cooling vegetation contribute to increased temperatures in urban areas (McGrane 2016). This is further impacted by the presence of natural and anthropogenic aerosols, which contribute to thermal insulation and act as condensation nuclei for cloud-microphysical processes. These resultant changes to the surrounding atmosphere can have a profound impact on precipitation intensity and variability (Shepherd 2005). Shepherd et al. (2002) found a 28% increase in warm-season, downwind precipitation around six cities in the southern United States, with a more modest increase in rainfall within the metropolitan areas (5.6%).

The artificial thermal properties and increased particulate matter from urban areas enhance downwind precipitation and may enhance the generation of convective summer thunderstorms. Ashley et al. (2012) found the role of the urban heat island in the emergence of convective summer thunderstorms in Atlanta and a resultant increase in precipitation in downwind areas, again highlighting the scaling effects of micro-perturbations to regional-scale climate dynamics.

For reducing urban impact of land use change, several NbS exist. These include: (i) increased provision of urban green spaces such as parks and street trees to ameliorate high temperature in cities; (ii) green roofs and walls that serve to reduce temperatures and to increase related energy savings through reduced cooling loads as well as improve air quality; (iii) a sponge city concept (Kabisch et al. 2016). A sponge city refers to sustainable urban development including flood control, water conservation, water quality improvement and natural ecosystem protection. This approach promotes natural and semi-natural measures in managing urban stormwater and wastewater, eliminating water logging and preventing urban flooding, improving urban water quality, mitigating impacts on natural ecosystems, and alleviating urban heat island impacts (Li et al. 2017).

15.3 Impact of Land Cover and Land Use Change on Water Quality

Land use and land cover not only influences the water cycle on global and catchment scale but also erosion and pollution patterns. The most common man-made land use change in river catchments originates from land clearing for agriculture leading to water quality and ecological deterioration of stream and river ecosystems (e.g. Vörösmarty et al. 2010). Clearing for agriculture leads to soil erosion which releases nitrogen, phosphorus, and sediments into surface waters and causes a variety of negative impacts e.g. increased sedimentation, turbidity and eutrophication. Next to agriculture, urbanization and industrial land uses are frequently considered in studies. Pollution patterns vary depending on the land use type and interrelate with climate, seasons, but also geology, hydromorphology and topography leading to a number of co-determinants to be considered when relationship between land use and water quality is to be established. Sound understanding of the links between land use/cover and water quality and the quantification of this relation is critical from the watershed management perspective, especially in areas with drinking water abstraction. Awareness for the linkages between land use and water quality supports the development of land use planning strategies sensitive to water management outcomes as well as for drinking water companies to define suitable locations for water extraction. They also support water quality prediction in unmonitored watersheds.

The influence of land use on water quality has been a concern since the 1970s (Rimer et al. 1978). The key concern is to improve our understanding for the cumulative effects of different land uses within the same watershed on water quality at different spatial and time scales (Randhir and Hawes 2009). Nevertheless, studies establishing a sound linkage between land use and water quality outcomes are surprisingly scarce as attribution of pollution to a certain land use is not always straightforward and requires good datasets. In the following, an overview is provided about the (i) land uses, scales and temporal variations usually considered in studies, (ii) water quality parameter reported (physico-chemical properties, pollutants), (iii) species considered for biomonitoring as well as (iv) the methodologies used to establish the cause-effect relationship between land use and water quality outcomes. This is followed by an (v) overview of established relationships between land use and water quality in the reviewed studies as well as a (vi) discussion of the limitations of currently available studies and knowledge.

15.3.1 Types of Land Uses and Water Bodies Considered in Studies

Available studies typically focus on water quality outcomes related to urbanization (Bahar et al. 2008; Lee et al. 2009; Ding et al. 2015; Vrebos et al. 2017), agriculture (Honisch et al. 2002; Johnson and Angeler 2014; Miller et al. 2011; Reyes Gómez et al. 2017; Whiles et al. 2000), a mix of both

(Bu et al. 2014; Kändler et al. 2017; Meneses et al. 2015; Robinson et al. 2014; Shi et al. 2017; Tong and Chen 2002), or different land uses in a catchment (Kaboré et al. 2016; Kellner and Hubbart 2016; Sundermann et al. 2013; Zampella and Procopio 2009; Wang et al. 2017; Wronski et al. 2015).

The majority of the studies do not involve comparisons among different catchments but focus on a land use distribution and water quality outcome within a catchment or sub-catchment. Exceptions include studies comparing two different sites (Kellner and Hubbart 2016) or different agricultural production systems (Honisch et al. 2002). On the contrary, a comparison of a large number of sites is an established procedure in studies involving macroinvertebrate monitoring in order to explain the root causes of variability in the biological indices or traits used (Baattrup-Pedersen et al. 2016; Dahm et al. 2013; Johnson and Angeler 2014; Leps et al. 2015; Miller et al. 2011; Törnblom et al. 2011; Turunen et al. 2016; Whiles et al. 2000; Wronski et al. 2015) and also to predict the ecological status of non-monitored water bodies (Villeneuve et al. 2015).

Most studies miss a real temporal dimension, meaning that they do not monitor the impacts of land use *change* but rather analyze the impact of a given land use as a snapshot. Exceptions include few longitudinal studies of land use change (e.g. Meneses et al. 2015; Shi et al. 2017) or changes in land use practices (Honisch et al. 2002).

A more often considered temporal dimension relates to the seasonal differences in land use and water quality. These studies typically involve a replication of the monitoring in different seasons (Bu et al. 2014; Ding et al. 2015; Shi et al. 2017). For example, BOD5, DO and EC have been shown to exhibit significant seasonal differences (Shi et al. 2017).

15.3.2 Physico-Chemical Properties and Pollutants

Often considered parameters and pollutants are pH, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), chloride (Cl), sulfate (SO_4), biological oxygen demand (BOD5), ammoniacal nitrogen (NH_3−N), total nitrogen (TN), nitrite nitrogen (NO_2−N), nitrate nitrogen (NO_3−N), orthophosphate (PO_4), and total phosphorus (TP). Most studies have focused on various forms of nutrients (Honisch et al. 2002; Huang et al. 2013; Bu et al. 2014; Ding et al. 2015; Kändler et al. 2017; Vrebos et al. 2017), biological or chemical oxygen demand (Bu et al. 2014; Lee et al. 2009; Meneses et al. 2015; Shi et al. 2017; Vrebos et al. 2017) and turbidity from suspended solids (Miller et al. 2011; Shi et al. 2017). Only few studies focus on the linkages between land use and heavy metals (Kändler et al. 2017) or microbial indicators (Miller et al. 2011; Meneses et al. 2015), while pesticides and other analytically challenging substances are largely missing. Few studies involved working with stable isotopes (Wang et al. 2017).

15.3.3 Land Use and Ecological River Quality

Land use and land cover has a multitude of impacts which are interrelated and thus land use actually integrates various pressure types to one metric. Several recent studies highlight the impact of catchment land use on the ecological quality of rivers mainly relating different land use percentages to the variation of biological metrics (e.g. Clapcott et al. 2012; Dahm et al. 2013; Törnblom et al. 2011). Erba et al. (2015) developed the LUIr index (Land Use Index—reach), which combines information on land use with associated alterations. Using organisms such as fish, macroinvertebrates, phytobenthos, phytoplankton and macrophytes, together with physico-chemical and hydromorphological parameters allows to assess the ecological status of surface waters in a more comprehensive way. Since different organism groups respond to stressors differently due to their ecological and biological preferences, they also can be used to distinguish between different stressors such as changes in river hydromorphology, water physico-chemistry, riparian and catchment land use (e.g. Dahm et al. 2013). Functional trait composition e.g. of aquatic plants is influenced differently by eutrophication and hydromorphological degradation of streams reflecting that the mechanisms behind changes differ and thus can be used to trace the root cause of changes in trait composition (Baattrup-Pedersen et al. 2016). Dahm et al. (2013) showed that organisms responded to catchment and, to a lower degree, to riparian land use parameters, which is consistent with the results of Erba et al. (2015). Stressors measured at the catchment scale are particularly powerful for upscaling since they may affect biota in a similar way for different stream types (Dahm et al. 2013).

15.3.4 Methodologies to Establish a Relationship Between Land Use and Water Quality Outcomes

The attribution of water quality parameters to land use patterns is challenging as there are several contributing factors such as climate, geology or point-source pollutions. Typically, water samples are taken from several sampling points with different land use patterns and analyzed. Water quality is then assessed in relation to the various land uses associated with the respective drainage basins using statistical methods such as Pearson Correlation analysis (Lee et al.

2009; Zampella and Procopio 2009; Reyes Gómez et al. 2017), Spearman's rank correlation (Tong et al. 2002; Dahm et al. 2013), linear regression (Bu et al. 2014; Zampella and Procopio 2009), stepwise regression (Miller et al. 2011), best subset regressions (Erba et al. 2015), hierarchical cluster analysis (Kaboré et al. 2016), and Principal Component Analysis (e.g. Bahar et al. 2008; Vrebos et al. 2017; Wang et al. 2017; Wilbers et al. 2014; Johnson and Angeler 2014; Sundermann et al. 2013; Tanaka et al. 2016; Törnblom et al. 2011; Turunen et al. 2016) to explain water quality variation in a watershed. There are few studies exploring a combination of statistical methods and modelling approaches. Kändler et al. (2017) used a hierarchical cluster analysis to group sub-catchments into classes according to land use and water chemistry. Classes of similar land-use patterns and, in the second step, groups of dominant hydro-chemical signatures were identified. A redundancy analysis (RDA), followed by a Monte Carlo permutation test was used to reveal the effects of land use on physico-chemical parameters (Kändler et al. 2017). Villeneuve et al. (2015) developed an initial explanatory model using a regression method to link water quality to biological indices. The model was used to quantify the effect of predictors on biological indices and quantify the relative effect of each predictor. Significant variables were then used as input variables for a second model aimed at predicting the ecological status. This predictive model was developed by using the conditional inference tree method in order to extrapolate the probable ecological status of the non-monitored water bodies (Villeneuve et al. 2015). One particular method also involves the selection and comparison of watersheds dominated by different land uses (e.g. Lenat and Crawford 1994; Mallin et al. 2009).

15.3.5 Overview of Established Relationships Between Land Use and Water Quality

The reviewed literature established various relationships between land uses and water quality (Table 15.1). However, results are rather indicative as they are highly context specific. For example, Shi et al. (2017) showed that human settlements close to the river bank have a strong impact on COD, TSS, and NH_4^+−N. However, the authors also show that the effect depends on the season and the spatial scale (reach, riparian, catchment) considered. Effects were more significant at the reach scale and during the wet season. In the same study, agricultural land use showed a positive correlation with pH, DO, and NO_3^-−N, with higher influence on water quality at the catchment scale than at the reach scale. Next to season and scale, Honisch et al. (2002) showed that also different land management practices adapted on the same land use type influence surface water pollution considerably. Although the relationship between land use and water quality is highly context-specific, patterns emerge in the reviewed literature and may be indicative also for other catchments.

15.3.6 Impact of Land Use on Aquatic Communities

In invertebrate communities the overall diversity was most influenced by land use at the catchment level (Erba et al. 2015). A new index was developed (the LUIr) to interpret invertebrate community variation from land use modification at the reach scale (Erba et al. 2015). Macrophyte diversity was shown to decrease while benthic diatom diversity increased with elevated nutrients in a study with 35 lowland European streams (Johnson and Angeler 2014). Leps et al. (2015) showed for large rivers that the riparian land use is less important in determining community structure of benthic invertebrates suggesting that the influence of small-scale management is likely overridden by the influence of catchment-wide land use. Leps et al. (2015) argued that large-scale influences on river water quality should be considered more systematically to manage, protect and restore running waters. Robinson et al. (2014) analysed the influence of land-use, habitat, and water quality on the spatial distribution of aquatic macroinvertebrates in human-dominated catchments and concluded that the spatial relationships of environmental attributes like land-use, habitat, and water quality influenced the spatial distributions of macroinvertebrates in human-dominated catchments of Switzerland.

Sundermann et al. (2013) studied 83 sites in Germany with respect to the response of biological indicators (benthic invertebrates) to environmental factors such as (i) artificial surfaces (ii) arable land and permanent crops, (iii) pastures and heterogeneous agricultural areas and (iv) forest and other "natural" cover. The results showed that water quality and catchment-scale land use best explained benthic invertebrate assemblages. In particular, the concentration of chloride, oxygen, total organic carbon and the share of artificial surfaces and arable land influenced benthic invertebrates. The authors concluded that given the influence of catchment-scale characteristics, structural restoration at a reach scale may yield a low benefit–cost ratio and may be considered inappropriate investment.

15.3.7 Nature-based Solutions to Improve Water Quality in Catchments

As land use and land cover characteristics influence water quality outcomes, land use planning at different scales can be

Table 15.1 Established relationships between land use and water quality based on the reviewed literature

Source	Land use (as classified in the publication)	Water quality parameter (surface water if not stated otherwise)	Relationship established
Bahar et al. (2008)	Residential area	Concentration of K^+, Mg_2^+, Ca^{2+}, NO_3^-, HCO_3^-, and TMI (total major ions)	Significant positive relationship
Bahar et al. (2008)	Urban developing area	Concentration of Ca^{2+}, Cl^-, HCO_3^-, EC and TMI	Significant positive relationship
Clapcott et al. (2012)	Urbanization	water quality, benthic invertebrates, fish	Negative relationship
Ding et al. (2015)	Urban land use	Concentration of TN and NH_3–N concentrations	Positive relationship
Miller et al. (2011)	Urban watershed	Concentration of Ortho-P	Significantly positive relationship
Lee et al. (2009)	Urban areas	BOD, COD Only fall: TP	Significantly positive relationship
Ren et al. (2003)	Urban areas	NH_4, coliforms and metals	Strong positive relationship
Wilbers et al. (2014)	Urban areas	Total coliforms	Strong positive relationship
Bahar et al. (2008)	Farmland	Concentration of NO_3^- and SO_4^{2-}	Significant positive relationship
Huang et al. (2013)	Cultivated land area	Concentration of NH_3–N	Positive relationship
Miller et al. (2011)	Agriculture	Total suspended solids	Significantly positive relationship
Wang et al. (2017)	Agriculture	Nitrate concentration in groundwater	Positive relationship
Bu et al. (2014)	Paddy land	EC, Cl^-, SO_4, NH_3–N, only rainy season: SiO_4, TN	Significantly positive relationship
Bu et al. (2014)	Paddy land	DO only rainy season: pH	Significantly negative relationship
Bu et al. (2014)	Dry farmland	EC, Cl, NH_3–N only rainy season: TDS, SO_4, SiO_4, TN only dry season: NO_2–N, TP	Significantly positive relationship
Bu et al. (2014)	Dry farmland	In dry season: pH, DO	Significantly negative relationship
Shi et al. (2017)	Urban and agricultural lands	Concentration of nutrients	Likely positive relationship
Alford (2014)	Mixed forest (% coverage)	Concentration of fecal coliforms	Positive relationship
	Forest (more than 70% cover)	Concentration of nutrients and heavy metals	Negative relationship

(continued)

Table 15.1 (continued)

Source	Land use (as classified in the publication)	Water quality parameter (surface water if not stated otherwise)	Relationship established
Kändler et al. (2017)			
Lee et al. (2009)	Forest (%)	COD Only fall: BOD	Significantly negative relationship
Meneses et al. (2015)	Loss of coniferous forest and the increase of transitional woodland-shrub	pH	Negative relationship

used to improve water quality. Different studies suggest different scales to be considered in the planning process. Sundermann et al. (2013) showed that water quality and catchment-scale land use best explained benthic invertebrate assemblages, which suggests the importance to plan at a catchment scale. However, other studies emphasize also the role of the land use closer to the river stretch itself as well as green structures put in place to improve water quality. Well known examples are buffer zones and buffer strips along rivers. Buffer strips have been shown to improve water quality by holding up sediments, filtering nutrients, and other pollutants (Shen et al. 2015). In order to investigate the effect of scale, Shen et al. (2015) applied buffers of different width in their analysis and compared the influence of land use on water quality at these different scales. The study found that the characteristics of a 100 m buffer zone along the river influenced water quality outcomes slightly stronger than the landscape characteristics of the entire catchment. Riparian buffers in the Atlantic Forest region (Itapúa, Paraguay) and San Francisco River (Paraná, Brazil) were shown to protect stream ecosystems from pesticides and other agricultural pollution (Hunt et al. 2017) while Tanaka et al. (2016) showed that the absence or reduction of riparian forests cover caused higher nutrient concentrations in streams. Since water quality is generally better in areas with high share of forest (e.g. Lee et al. 2009; Kändler et al. 2017), forest protection or reforestation has the potential to improve water quality (Bastrup-Birk and Gundersen 2004) although in planted forests, impacts on water quality change with the lifetime and management type of the forest. While afforestation itself significantly improved stream temperature, nutrient and sediment concentrations and microbial contamination within 4–6 years of planting in New Zealand, impacts of timber harvesting on water quality were observed during clear-cut harvesting (Baillie and Neary 2015). Similarly, changes in land management can lead to improved water quality outcomes. Honisch et al. (2002), for examples, showed that different land use practices adapted on the same land use type influence surface water pollution considerably. For example, mulching, minimum tillage, fallow strips helped to minimize lateral loads to the surface water.

In terms of ecological quality of rivers and streams there is a recognized influence of land use on riparian and catchment scales, stressing the clear need to expand both the assessments as well as the solutions from the river environment and the riparian zone towards catchments. Authors assume that a land use change at a riparian and/or catchment scale is required to restore river ecosystems (Dahms et al. 2012; Törnblom et al. 2011) since physico-chemical water quality at the site scale mainly reflects the degradation in the upstream catchment. Ecosystem-based measures often take a landscape approach and thus respond to land use change needs in order to achieve water and ecological quality improvements.

15.4 Consequences of Land Cover and Land Use Change on Sediment Transport and Delta Development

15.4.1 Delta Progradation, Aggradation and Retrogradation

Deltas, as landforms, are highly dynamic environments that are dependent on processes taking place in their river basins and on the coast, and on processes taking place locally, particularly if the delta is densely populated. Delta formation requires trapping sediments at the mouth of a river and when this supply is disrupted in such a way that it does not allow for progradation (delta growing seawards) or aggradation (delta growing upward) anymore, the physical integrity of the subaerial delta plain can be compromised with retrogradation taking place (Anthony 2015).

Disruption of sediment fluxes are generally human-induced, particularly when taking place over relatively short time spans and are at play for both progradation/aggradation and retrogradation. An example of the former can be taken from Maselli and Trincardi (2013) who showed that for four southern European deltas (Ebro, Rhone, Po and Danube), two periods of aggradation when large scale anthropogenic deforestation linked to increased population and population activities took place (Roman Empire—peaking around 250 years AD, and Little Ice Age—1400–1850 AD, periods). A consequence of this was the generation of increased erosion allowing for more sediments to reach delta regions. An example of the latter can be taken from the same publication whereby two phases of retrogradation of these deltas were observed due to reduction in sediment fluxes. The first followed the Roman Empire era when population densities and human activities decreased leading to afforestation; and the second which covers the current period when dams have started preventing sediments to reach the delta regions (Maselli and Trincardi 2013).

A similar example, over a shorter time span can be taken from the Huanghe (Yellow) river delta. Bi et al. (2014) showed that because of dam construction, sediment discharge to the coast from the Huanghe river decreased from 1.33 Gt/y pre-1968, to 0.84 Gt/y during 1969–1985, to 0.4 Gt/y during 1986–1999, and finally to 0.15 Gt/y during 2000–2005 which resulted in an erosional phase of the delta. However, in 2002, the implementation of a Water–Sediment Regulation Scheme allowed for increased sediment fluxes and an increase in sediment particle size which, combined with the presence of groins built after 2005 that allowed the trapping of some of the sediments, contributed to an accretion of the active Huanghe lobe (Bi et al. 2014; Wu et al. 2015).

15.4.2 The Impact of Infrastructure

A key factor in terms of physical extent of a delta is linked to the development of dams and reservoirs across the mainstream and tributaries of rivers which trap sediments (Kuenzer and Renaud 2012), but also due to diversion of river water for e.g. irrigation of agricultural lands. An example is the Indus river where important irrigation-related and flood control infrastructure have been developed from the nineteenth century onwards (levees to protect agricultural lands from floods, dams and irrigation canals, diversions), resulting in a drastic reduction in sediment transport from > 270 Mt/y before that period to ca. 13 Mt/y currently, which, combined with other factors, contributed to a mean mass net loss of sediments in the Indus delta of ca. 47 Mt/y and since 1944, to an annual loss of 12.7 km^2 of land (Syvitski et al. 2013 and references therein). The consequences in terms of livelihoods in general (agricultural livelihoods in particular), and impacts on natural systems such as mangroves are extremely severe (Syvitski et al. 2013).

More locally, portions of a delta can also see sediment fluxes reduce rapidly when infrastructure are built such as dykes and levees to protect agricultural areas and communities from regular, natural flooding events. These can also affect flood risks within the delta and more generally the delta-wide water balance (e.g., Tran et al. 2018). Coastlines can also experience further sediment starvation (i.e. rivers not transporting enough sediments to the coastline) from the excessive removal of sand from river beds which is used in the building industry (Anthony et al. 2015).

Table 15.2 summarizes the above impacts of human activity within a river basin on sediment supply to a delta environment. The listed factors are often inter-dependent (e.g., a reservoir can be designed to develop agricultural activities, leading to land use conversion and the development of irrigation infrastructure) and therefore can act synergistically, increasing sediment starvation to deltas (e.g. development of reservoirs and irrigation infrastructure) or can lead to opposite effects in terms of sediment supply (e.g. reservoir leading to land conversion which results in increased sediment supply). The outcome for a delta will be an integration of all the factors within the basin and often results in a net reduction of sediments to the delta environment.

15.4.3 Threatened Deltas

Reduction in sediment supply can threaten deltas' physical integrity particularly when combined with other anthropogenic processes such as accelerated land subsidence due to, for example, over-abstraction of underground natural resources (water, gas, minerals, etc.). Syvitski et al. (2009) showed that for 33 major deltas they surveyed, six of them experienced sediment reduction in excess of 75% over a 50-year period preceding their publication (Chao Phraya, Colorado, Indus, Krishna, Nile, Yellow), while another 10 experienced sediment reductions in the range 50–75%. A scenario with high levels of reduction in sediment delivery affecting delta aggradation rates, if not compounded by rapid subsidence induced by subsurface extraction of natural resources, limits (but does not eliminate) the risk of flooding if local relative sea-level rise remains moderate (e.g. the Indus delta); but scenarios where both sediment starvation and rapid subsidence take place can become untenable in the long run when combined with high rates of sea level rise (most of the 6 deltas already mentioned above and others experiencing rapid subsidence) (Syvitski et al. 2009). In addition, reduction in sediment supply can lead to severe coastal erosion. Anthony et al. (2015) attribute the net loss of

Table 15.2 Disturbances on river mainstream and tributaries and potential impacts on sediment supply (*For references, see text in section*)

Anthropogenic factor	Potential impact on sediment supply
Dams and reservoir on mainstream and tributaries	Trap sediments, drastically reducing sediment supply to delta regions
Land use change	Conversion from natural systems to other systems (e.g. conversion of forested areas to agricultural land) leads to increased supply of sediments through erosion Reforestation of previously converted land leads to a reduction of sediment supply by limiting erosion extent
Development of irrigation infrastructure	Diversion of water and sediment supplies away from river network, thus reducing sediment supply
Local infrastructures such as dykes and levees, within a delta	Prevents natural supply of sediments at the local level contributing to land subsidence and loss of nutrient supply

surface area (at rates ranging from -0.575 km^2/y to -2.715 km^2/y depending on time period and location) along 380 km (out of a total of 600 km) of the Mekong delta's coastline to a reduction in sediment supply, among other factors, during the period 2003–2012.

Subsidence is not uniform across a delta, however, as demonstrated by e.g. Brown and Nicholls (2015) in a review of the Ganges–Brahmaputra-Meghna delta and who showed a range from an uplift of 1.1 mm/y to subsidence rates reaching ca. 44 mm/y. For a 10,000 km^2 area of the eastern part of the Ganges–Brahmaputra, Higgins et al. (2014) reported subsidence rate in the range 0–18 mm/y, depending principally on lithology. In the Mekong delta, Minderhoud et al. (2017) modelled average subsidence rates related to groundwater extraction over a 25-year period to be 11 mm/y, with some extremes at 25 mm/y and rates in Ho Chi Minh City (just outside the delta) as high as 70 mm/y. Land use change within a delta therefore plays an important role in terms of its survivability as often, groundwater extraction to satisfy agricultural production needs as well as for domestic and industrial water supplies linked to demographic change and expansion of urban areas, is a major cause of land subsidence.

The combination of sediment starvation and anthropogenic changes at the delta scale could lead to deltas collapsing in the long run (Renaud et al. 2013; Giosan et al. 2014) through excessive erosion, inundation, and salinization of freshwater resources. Perhaps long before that, the slow erosion of livelihoods in some portions of deltas, might make it untenable for populations to survive and trigger or accelerate already observed migratory fluxes out of delta regions.

15.4.4 Protecting Deltas

Too many human interventions upstream and locally combined with intensification and increased frequency of coastal hazards can threaten deltaic landscapes with the risk of collapse in the longer run. As many deltas are densely populated, the social consequences could be severe. To protect deltas, the entire system, particularly, the links between the social and ecological subsystems, needs to be understood. Human interventions can change deltas (which are naturally dynamic) rapidly, particularly when sediment supply is altered (see the examples from the southern European deltas, the Huanghe delta and to a lesser extent, the Mekong delta described above). Actions are therefore required upstream, within deltas themselves, and at the coastline to ensure the sustainability of these landscapes.

Sediment starvation is an important cause of coastal erosion in deltas. When considering upstream activities (e.g., building of hydroelectric dams or of reservoirs, and land use change), it is critical to factor in the impacts these will have on the water and sediment reaching the deltaic regions. Strong national/sub-national (depending on governance regime) and/or international (for transboundary basins) mechanisms are required to negotiate major basin-scale transformations to optimize benefits and minimize negative impacts in all parts of the landscape. This is, however, often difficult to achieve in transboundary contexts given the multitude of actors/stakeholders to consider and the power plays at hand between and within countries (see e.g. Kuenzer et al. (2013) in the case of the Mekong river basin). It however remains the only way to resolve disputes and ensure the integrity of deltas from the upstream threat perspective.

Syvitski et al. (2009) showed that activities within deltas can have significant impacts on their sustainability as landforms. A particular concern is land subsidence which in many cases, far exceeds eustatic sea level rise. It is therefore critical to limit human-induced land subsidence which typically results from abstraction of natural resources and over-abstraction of groundwater resources (Syvitski 2008). This generates conflict between the potential for income generation and therefore supporting a nation's development, the maintenance of local livelihoods by improving water access, and environmental degradation concerns which can have serious short and long terms consequences for delta social-ecological systems. When it comes to groundwater resources, Wagner et al. (2012) proposed, for the Mekong delta, to reduce extraction of the best quality groundwater, keeping it principally for domestic consumption, use appropriate exploitation strategies to limit wastage and pollution problems, increase recharge, and mix high quality water with poorer quality water for specific usages. These measures though need to be accompanied by access to other sources of freshwater to ensure in particular domestic supply (for consumption and hygiene).

Protection against natural hazards, particularly coastal hazards has generally been achieved through armoring the coastline with, for example, seawalls, breakwaters, groins, jetties and ripraps. Gittman et al. (2015) have estimated that about 14% of the US coastline has been armored. Similarly, Liu et al. (2018) referring to previous work, indicated that about 61% of the Chinese mainland coastline is artificial. This has detrimental effects on natural ecosystems such as wetlands. It also does not systematically protect people from hazards and as noted by Rangel-Buitrago et al. (2018) in Colombia, engineered infrastructure have often enhanced and/or displaced problems they were supposed to address, such as coastal erosion. Alternatives include ecosystem-based approaches (see e.g. Cohen-Shacham et al. 2016 discussing nature-based solutions; Renaud et al. 2016 for ecosystem-based disaster risk reduction) and/or eco-engineering solution (Whelchel et al. 2018) such as coastal vegetation (including mangrove) restoration, coral reef conservation, and hybrid solutions. The application of these concepts is not limited to coastal fringes of a delta but can and should be applied at the basin scale too (Sebesvari et al. 2017). More generally speaking, in a review of delta-level adaptation options, Kuenzer and Renaud (2012) identified as series of measures that are or could be put in place to reduce the effects of climate change including a series of technological and ecosystem-based approaches similar to those noted above but also considered policy-related interventions and education/awareness raising with a wide range of stakeholders. Protecting deltas can only be achieved when all these dimensions are addressed simultaneously.

15.5 Conclusions

Land-cover and land-use change has important impacts globally, leading to changes in hydrology and sediment transport, contributing to green-house gas emissions, deteriorating water quality and thus affecting directly and indirectly aquatic organisms and human health, and shaping coastal and deltaic regions through changes in water and sediment supply. In many cases, the most detrimental negative effects can be reversed. For example, restoring degraded landscapes can re-establish hydrological regimes and sediment generation and transport, and at the same time reducing water quality degradation. Changes in land use can reduce the requirement for irrigation and thus of sediment trapping in reservoirs. Nature-based Solutions should be increasingly considered at the decision and policy levels to address these issues.

It is clear that LCLUC consequences need to be studied at the landscape scale so that all repercussions can be accounted for. If not, through a combination of forces, entire landscapes such as delta regions could be irreversibly lost in the mid to long term. Actions to reverse these trends should be based on robust scientific evidence which is sometimes lacking (see Sect. 15.3 in particular) thus the call from e.g. Giosan et al. (2014) for a push for monitoring and research to effectively support the science-based management and protection of deltas globally.

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Fabrice Renaud is Professor of Environmental Risk and Community Resilience at the School of Interdisciplinary Studies, University of Glasgow, Scotland, UK. His main fields of research are ecosystem-based approaches for disaster risk reduction and climate change adaptation, and the analysis of vulnerability, risk and resilience of social-ecological systems exposed to environmental hazards. His focus is mainly on coastal and deltaic regions.

Zita Sebesvari heads the Environmental Vulnerability and Ecosystem Services (EVES) Section at United Nations University, Institute for Environment and Human Security. Dr Sebesvari is an environmental scientist with a research focus on ecosystem-based disaster risk reduc-tion (Eco-DRR) and adaptation (EbA) guided by social-ecological vulnerability and risk assessments, and the interplay between soil and water degradation and disaster risk.

Animesh Gain is a researcher based in Massachusetts Institute of Technology (MIT). His research is focused in the interdisciplinary field of water resources management. He is currently working on transboundary water management. Dr Gain is the recipient of prestigious fellowships (e.g., Marie Curie, Alexander von Humboldt), Grants (e.g., Leverhulme Trust, European Commission) and awards (e.g., 'Outstanding Young Scientists Award 2016' of European Geosciences Union).

Freshwaters: Global Distribution, Biodiversity, Ecosystem Services, and Human Pressures

16

Klement Tockner

Abstract

Freshwaters are among the most dynamic, diverse, and complex ecosystems globally. Lakes, rivers, and ponds cover about 1% of the Earth's surface; however, these systems contain 10% of all animals and one-third of all vertebrates. In addition, freshwaters provide a wide range of ecosystem services that are fundamental for human well-being, including clean water, recreation value, and food. At the same time, freshwaters are under immense human pressure due to overexploitation, habitat degradation, invasion, climate change, dam construction, as well as emerging stressors such as light, noise, and synthetic chemicals. Consequently, freshwater biodiversity is declining three to six times faster than biodiversity in marine and terrestrial realms, and ecosystem services are being eroded in unprecedented ways. Globally, wetlands have declined by 75% over the past decades, and out of 242 rivers longer than 1,000 km, only 86 remain free flowing. Hence, one-third of all freshwater species are currently threatened, and global freshwater megafauna populations even declined by 88% from 1970 to 2012. We need to carefully, and fundamentally, rethink future management strategies for freshwater ecosystems due to conflicting interests for conservation and exploitation. Freshwaters must be managed as hybrid systems, i.e., as a resource for human use as well as extremely valuable and diverse ecosystems. Furthermore, we must establish a blueprint of freshwater life to increase awareness about the enormous value of freshwaters and their rich biodiversity. Most importantly, however, we need to preserve the remaining free-flowing rivers, intact wetlands, and unspoiled lakes—for the sustainable benefit of humans and nature alike.

K. Tockner (✉)
Senckenberg Gesellschaft für Naturforschung, Frankfurt, Germany
e-mail: klement.tockner@senckenberg.de

Faculty of Biosciences, Goethe Universität, Frankfurt, Germany

Keywords

Freshwater biodiversity • Ecosystem services • Freshwater habitats

16.1 Freshwaters and Humans

The spread of humans across the globe was primarily driven by climate and access to water. Indeed, our human ancestors lived close to forests and trees (for shelter) and along the edges of lakes, rivers, and seashores (for resources). According to Finlayson (2014), *Homo sapiens* was an evolutionary response to the scattered distribution of water in time and space. Moreover, a key question is: Did water make people humans? Certainly, Finlayson (2014) makes a strong case. Other, more controversial, hypotheses worthy of mention are the aquatic ape hypothesis (Hardy 1960) and the waterside ape model (https://www.bbc.co.uk/programmes/b07v0hhm), which state that strong affinity to water affected the evolution of the ancestors of modern humans, who most likely were more aquatic than other apes. Recently, Cunnane and Stewart (2010) have emphasised in their "shore-based diet scenario" that there seems to be a close correlation between aquatic diet and human brain evolution.

Freshwaters (i.e., lakes, rivers, wetlands, and groundwaters) are pivotal for both nature and human well-being. People depend on freshwater as a resource as well as on freshwaters as valuable ecosystems. Human civilisations evolved along the shores of major rivers such as the Nile, Euphrates, Indus, Mississippi, or Huang He. Today, about 50% of the world's human population lives closer than 3 km to a surface freshwater body, and only 10% of the human population lives further than 10 km away (Kummu et al. 2011). Fang and Jawitz (2019) have assessed the coevolution of humans and water resources in the conterminous US between 1790 and 2010. They have demonstrated that humans had moved closer to major rivers in pre-industrial

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periods but moved farther away after 1870, reflecting the dynamic reliance on rivers for trade and transport in past times. Since industrialisation, humans have preferred areas overlying major aquifers, primarily due to the increasing accessibility to groundwater.

Globally, freshwater (as a resource) is unevenly distributed, both in time and space. Climate change, land-use alteration, and increasing human exploitation will further increase the pressure on water as a resource for human welfare as well as on inland waters as ecosystems, thereby intensifying the uneven distribution of freshwater—fostering conflicts between the exploitation of water and the conservation of freshwater-related ecosystems. Concurrently, the World Economic Forum's Global Risks Report (GRR) has listed water crises as among the top five risks in terms of impact for eight consecutive years (https://www.weforum.org/reports/the-global-risks-report-2019), and according to the World Health Organization, one in three people globally do not have access to safe drinking water (https://www.who.int/).

16.2 Freshwaters: Coupled Meta-Ecosystems

Freshwaters are unique ecosystems because they (i) form linear or mosaic landscape elements, embedded into the terrestrial matrix; (ii) are located at the topographically lowest points in the landscape and, therefore, integrate the various processes and pressures of the surrounding matrix; (iii) may rapidly expand and contract in area and/or volume; and (iv) are "open systems", which are vertically, laterally, and longitudinally connected to belowground, atmospheric, terrestrial, and marine systems. Consequently, freshwaters are among the most complex, dynamic, and diverse ecosystems on Earth. Given their unique position in the landscape, freshwater systems are particularly susceptible to the natural and human influences exerted by their surrounding terrestrial environment, both the immediately adjacent riparian zones as well as the entire catchment that they drain.

Landscapes, including freshwaters, are composed of interconnected ecosystems that mediate ecological processes and functions—such as material fluxes and food web dynamics—and control species composition and diversity. Freshwaters are closely linked to adjacent terrestrial systems through reciprocal flows of energy, materials, information, and organisms. On the landscape scale, these flows are controlled by the composition, configuration, boundary conditions, and linkages of individual ecosystem types, thereby forming what are known as meta-ecosystems (Gounand et al. 2018; Turnbull et al. 2018, and references therein). The relative importance of individual ecosystem types depends on the intrinsic properties of the landscape elements, or ecosystem types (ecosystem traits); the setting within the landscape; and the characteristics of the interfaces (e.g., shape, permeability) that control cross-system fluxes. For example, the juxtaposition of particular ecosystem types (i.e., their composition and configuration) may alter the magnitude of landscape processes as well as the directions of flow among ecosystem types (e.g., Marleau and Guichard 2019). The meta-ecosystem concept might be very helpful in landscape management, ecosystem design, and eco-engineering. It provides a framework for quantifying ecosystem diversity, a neglected component of biodiversity, and for testing its effects on genetic and species diversity, as well as the functional performance in coupled ecosystems (Harvey et al. 2020, and references therein).

Many freshwater systems, including river and cave networks, have a dendritic structure. These systems are not only hierarchically organised, but their topology and physical flow dictate the distance and directionality of dispersal and movement (Altermatt 2013, references therein). Furthermore, riverine assemblages are governed by a combination of local (e.g., habitat conditions) and regional (e.g., dispersal) processes. There is empirical evidence that the position within the river network (i.e., stream size) drives the composition and diversity of riparian plants, aquatic invertebrates, and fishes (for general information, see Turnbull et al. 2018).

Freshwater bodies are key biochemical reactors. Although they occupy only a small portion of the terrestrial land surface, freshwaters are pivotal ecosystems for the global carbon and nutrient cycles. Collectively, freshwaters respire ~40% and store ~20% of the 2.7 Pg of allochthonous carbon (i.e., carbon from outside sources), and denitrify or store ~60% of the 118 Tg of nitrogen they receive each year from terrestrial ecosystems (Cole et al. 2007; Aufdenkampe et al. 2011).

The master variables controlling ecosystem processes and biodiversity in freshwater systems are the flow and thermal regimes. Most recently, Wohl et al. (2015) have broadened the natural flow regime concept (Poff et al. 1997) and emphasised the role of sediment inputs, transport, storage, and interactions with water and plants. The sediment regime is critical for maintaining a shifting mosaic of aquatic and terrestrial habitats across entire succession gradients. Natural flow, sediment, and thermal regimes are required to maintain the ecological integrity of riverine ecosystems. Ecological integrity means the capability of a system to support and maintain physical, chemical, and biological functions and processes essential for ecosystem sustainability (Richter et al. 2003).

16.3 Global Distribution of Freshwater Systems

Although freshwaters are a very common feature of the land surface, we still lack accurate estimations of the global distribution of the various freshwater types (rivers, lakes and ponds, wetlands, groundwaters, and artificial water bodies). Indeed, it remains a challenge to calculate the spatial distribution, total area, volume, and residence time of freshwaters globally, primarily due to their dynamic nature, their diversity, and the manifold human alterations to which they are subjected.

In total, about 4.6 million km^2 of the land surface is covered by inland waters, corresponding to less than 1% of the total Earth surface (Downing et al. 2006). In addition, inland wetlands cover between 12 and 15 million km^2, corresponding to about 3% of the total Earth surface (Downing 2009). A sheer number of 304 million lakes and ponds cover a combined area of 4.2 million km^2. On the other hand, artificial ponds cover 77,000 km^2, with a strong upward trend. Messager et al. (2016) calculated that the median hydraulic residence time of all lakes is 456 days. They included 1.42 million lakes in their calculation, covering an area of 2.67×10^6 km^2 and with a total shoreline length of 7.2×10^6 km (four times the shoreline length of the oceans). The total volume of these lakes is 181.9×10^3 km^3, corresponding to 0.8% of the non-frozen terrestrial water stock.

Global estimates of the fluvial area (rivers and streams) range between 485,000 and 662,000 km^2. Hence, rivers and streams cover 0.30–0.56% of the global land surface (Downing et al. 2012). Moderately sized rivers (stream order: 5–9) comprise the greatest share, with less area covered by low- and high-order streams, while global stream length, and therefore the riparian interface, is dominated by first-order streams. Most recently, Grill et al. (2019) have calculated the total length of all rivers longer than 10 km. The total length is 11.7 million km, corresponding to 308,000 individual river segments. This number may increase by up to two orders of magnitude if first- and second-order streams are added. Concurrently, more than 50% of the global river network falls dry at the surface (i.e., intermittent rivers and streams). For example, dry rivers account for 94% of the river network of Arizona (USA), along with 66% of Californian streams and rivers (Levick et al. 2008). At the same time, the extent of intermittent rivers and streams and the duration of dry periods are rapidly increasing due to climate change, land-use alterations, and increased human water use (e.g. Datry et al. 2014).

Furthermore, a total of 500,000 reservoirs (larger than 1 ha) cover an area of 507,000 km^2. Their storage capacity is about 8,000 km^3 of water (Lehner et al. 2011). For comparison, the annual runoff of the Rhine River is about 60 km^3.

Fluet-Chouinard et al. (2015) have developed a downscaling method for inundation data (from Multi-Satellites, GIEMS) to produce a global inundation map. The total inundation area ranges from an annual minimum of 6.5×10^6 km^2 to a long-term maximum of 17.3×10^6 km^2, corresponding to a maximum of about 3.4% of the Earth's surface area, or 12.9% of the global landmass area.

Less is known about the global distribution and storage of groundwater. According to Gleeson et al. (2016), the total calculated volume of groundwater in the upper 2 km of the continental crust is approximately 22.6 million km^3, of which 0.1–5.0 million km^3 (average: 1.3 million km^3) are less than 50 years old—compared to about one-million-year-old groundwater in the Sahara region. The total young groundwater component corresponds to a $\sim$3 m deep water body across the global land surface. The global recharge of groundwater is calculated as $5–497 \times 10^3$ km^3 $year^{-1}$ (published estimates: $12–24.8 \times 10^3$ km^3 $year^{-1}$; see Gleeson et al. 2016, and references therein).

16.4 Freshwaters: Hot Spots of Biodiversity

Freshwaters are centres of global biodiversity, similar to tropical rainforests and coral reefs. Although freshwaters (excluding wetlands) cover less than 1% of the Earth's surface, they contain about 10% of all animal species, one-third of all vertebrate species, and 40% of all fish species globally (Table 16.1).

For example, there are about 16,000 fish species globally that spend all or part of their life in freshwaters. About 240 additional fish species are described per year (average value over the past 10 years), without any clear asymptotic tendency in total species increase. The Amazon, the Congo, and the Mekong Rivers jointly contain more than 1/3 of all freshwater fish species (Pelayo-Villamil et al. 2015). In Europe, the Balkan is a (freshwater) biodiversity hot spot of global importance. At least 200 native fish species are described for this region, of which 81 are listed as threatened. However, many species are listed as data-deficient, and the number of threatened species is most likely much higher as currently stated because many species still remain undescribed (Kottelat and Freyhof 2007).

Wetlands, including riparian zones, are keystone ecosystems for humans as well as biodiversity hot spots of

Table 16.1 Number of described species in surface waters (excluding wetlands) and in ground waters (after Balian et al. 2007; Stoch and Galassi 2010)

Taxonomic group	Surface waters	Groundwaters (Stygobionten)
Insects	75,908	18
Vertebrates	18,238	163
Crustaceans	13,054	3400
Other Phyla	7227	116
Arachnida	6149	650
Molluscs	4998	350
Annelida	1761	78
Total	**127,749**	**4775**

global importance. An inventory of the terrestrial fauna in Switzerland found that 85% of the regional species pool (a total of 4,036 species in 12 taxonomic groups) occurs in riverine floodplains, although they cover less than 0.3% of the country (Tockner and Ward 1999). The disproportionately high species richness in floodplains and riparian zones has been confirmed for mammals, birds, plants, or molluscs, and in many regions. In addition, there is empirical evidence that many terrestrial upland species seek temporary shelter in riparian zones during hot and dry weather conditions, further increasing the value of floodplains (and wetlands) as refugia for otherwise obligate terrestrial species. Hence, the conservation and restoration of floodplains and riparian zones must be given utmost priority. A natural flow regime, an unconstrained river corridor, and a dynamic sediment and large wood regime are required to maintain the high biodiversity characteristic of entire river corridors (e.g. Tockner and Stanford 2002; Naiman et al. 2010).

Wetlands are particularly species-rich ecosystems because they provide habitats to aquatic, amphibian, and terrestrial species. A comparison of seven globally important wetlands (Canadian peatlands, Florida Everglades, Pantanal, Okavango Delta, Sundarban, Tonle Sap, and Kakadu National Park) confirms high plant and vertebrate diversity, while information on invertebrates remains scarce (Junk et al. 2006). All seven wetlands are critical for long-distance migratory bird species. However, the number of endemic species remains low, except for the Everglades, primarily due to the high degree of connectivity with surrounding ecosystems. At the same time, human pressures are increasing in all major wetland types.

16.5 Ecosystem Services of Freshwater Systems

The benefits people receive from ecosystems, known as ecosystem services (ESS), contribute substantially to human health, well-being, and sustainability. Ecosystem services include provisioning (e.g., fishery), supporting (e.g., biodiversity), cultural (e.g., recreation), and regulating (e.g., carbon storage) services. Moreover, the importance of the ESS concept reframes the relationship between nature and humans, with humans as part of nature (e.g., Daily 2003).

Freshwaters provide a wide range of ESS that are of fundamental importance to human well-being, including clean water, food, water storage, and recreation value, among many other services. For 2011, Costanza et al. (2014) calculated a total value of US$ 145 trillion/year for all ecosystems combined, and a loss of ecosystem services ranging from US$ 4.3–US$ 20.2 trillion/year since 1997 due to land-use change. The combined value for tidal marshes, mangroves, swamps, floodplains, lakes, and rivers is US$ 38.7 trillion/year. However, the aerial estimation of wetlands and surface freshwaters in Costanza et al. (2014) is much lower compared to recent estimates (see above). Indeed, ESS (per area unit) provided by wetlands and surface waters are highest among all ecosystem types, except for coral reefs. Wetlands, for example, provide an average value of ESS of US$ 140,000 ha^{-1} $year^{-1}$—compared to US$ 4,900 ha^{-1} $year^{-1}$ for forests. The average value of ESS provided by lakes and rivers is three times higher than the value provided by grasslands (Costanza et al. 2014).

Floodplains are, in particular, hot spots for multiple ecosystem services, including flood mitigation, carbon sequestration, nutrient retention, and biodiversity (e.g., Tomscha et al. 2017). Indeed, the entire river corridor needs to be considered when managing floodplains for ESS and biodiversity. On the other hand, groundwater–related ecosystem services have been rarely quantified, despite the enormous role groundwater plays for human health and well-being. Griebler and Avramov (2014) have emphasised the lack of information on groundwaters as ecosystems, their spatial extent, and their degree of connectivity to other systems, food webs, and key processes, functions, and related and dependent ecosystem services.

The success of river restoration can also be assessed using the ESS approach. Comparisons across Europe have demonstrated a median value of total ESS for rivers of € 1,500 ha^{-1} $year^{-1}$; restoration almost doubled the total value of ESS (provisioning, regulating, cultural ESS) (Vermaat et al. 2016). For example, the restoration of the Emscher River and its tributaries (Germany), one of the largest and most challenging restoration projects globally (estimated costs: ~€ 5.3 billion), have created market and non-market values of about € 130 million per year. This is considered a minimum value because many services such as carbon sequestration and biodiversity have not been included in the calculation. Nevertheless, it demonstrates the possibility of using the ESS concept as a guiding principle in river restoration (Gerner et al. 2018). Indeed, a robust assessment of ESS is required to support the sustainable implementation of water and biodiversity policies. Ultimately, this implementation depends on the availability of data—for Europe, for example, a good and comprehensive data basis has been collated as part of implementing the EU Water Framework Directive.

Up to now, ESS have not been included in the calculation of national GDP and therefore have not been valued in the way they should be. Some of the ESS estimates are based on virtual, not real prices. We need to raise awareness of the value ecosystems provide, and the manifold losses due to ongoing and accelerating land use degradation, pollution, climate change, and fragmentation. At the same time, the economic calculation of ESS presents a key dilemma of an otherwise very valuable concept. Fu et al. (2014), for example, have listed hydropower as an important service provided by ecosystems. However, hydropower is a geosystem rather than an ecosystem service as discharge and slope are only required to produce energy. Similarly, navigation is not an ecosystem service; in fact, a natural system may even constrain navigation (and hydropower generation). In this context Bogardi et al. (2013) identified the water cycle as a fundamentally planetary service whereby ecosystems play a regulating role. Hence, we need to exercise care when applying the ESS concept because a purely economic calculation may lead to long-lasting harms to the biodiversity and other ESS freshwaters provide.

Unfortunately, ESS are, in most cases, restricted to provisional and supporting services, and only to a lesser extent to regulating services, and even less to cultural services. The economic valuation is becoming the dominant driver, with unwanted trade-offs for nature and humans (e.g., bioeconomy, green infrastructure, bioenergy). Moreover, benefits from ecosystems are more than just economic and monetary values. Indeed, we are currently witnessing a widespread domestication of ecosystems, particularly of freshwaters (Tockner et al. 2011). It means that these systems have been optimised for a few ESS that provide major, short-term economic benefits to humans, yet concurrently cause unforeseen changes in other ecosystem attributes. In its simplest form, domestication of ecosystems means that nature is exploited and controlled (Kareiva et al. 2007).

A key challenge is to link biodiversity to ESS. Do we require 80%, 60%, or just 40% of the contemporary biodiversity to maintain key ESS? The tight linkage between biodiversity and ESS—as it is the case in IPBES (Intergovernmental Platform on Biodiversity and Ecosystem Services)—may cause a potential threat to biodiversity because there is a risk that some ESS will be valued much above biodiversity. Overall, there remains a fundamental lack in understanding the long-term and large-scale relationships between biodiversity, ecosystem processes, and ESS.

16.6 Freshwater Ecosystems Under Major Threats

Today, humans are shaping our environment, and especially freshwater systems, in global, profound, and, in most cases, irreversible ways. The transformation of the Earth by humans can best be demonstrated by the distribution of biomass. Human and livestock biomass (in total, ~0.166 Gt carbon) is more than one order of magnitude higher than the biomass of all wild mammals combined (~0.0076 Gt carbon; Bar-On et al. 2018).

Freshwaters are under immense pressure due to overexploitation, pollution, habitat degradation, invasion, infectious diseases, and climate change. Reid et al. (2019) have documented 12 emerging threats to freshwater biodiversity that are either entirely new since 2006 (Dudgeon et al. 2006) or have since intensified: (i) changing climate; (ii) e-commerce and invasion; (iii) infectious diseases; (iv) harmful algal blooms; (v) expanding hydropower; (vi) emerging contaminants; (vii) engineered nanomaterials; (viii) microplastic pollution; (ix) light and noise; (x) freshwater salinization; (xi) declining calcium; and (xii) cumulative stressors (Table 16.2).

Lebreton et al. (2017), for example, have estimated that between 1.15 and 2.41 million tons of plastic debris enter the ocean per year from rivers, with the top 20 countries—mainly located in Asia—accounting for 67% of the total load. Furthermore, the major proliferation of synthetic chemicals—including pesticides—has not yet been included in most analyses of global change. Bernhardt et al. (2017) have reported a global production of 116×10^6 metric tons of N fertilizer, 38×10^6 metric tons of P fertilizer, and 6×10^6 metric tons of pesticides. Expenditures for pesticides amount to $29 billion per year, and global pharmaceutical consumption amounts to even $760 billion per year. The increase in synthetic chemical production is outpacing the other agents of global change such as habitat destruction and rising atmospheric CO_2 concentrations (Bernhardt et al. 2017). At the same time, data and knowledge about the

Table 16.2 (from Reid et al. 2019): Characteristics of emerging threats to freshwater biodiversity: geographic extent, severity of effects, potential ecological changes, degree of understanding, and potential mitigation options. For more details see: Reid et al. (2019)

Emerging Threat	Geographic Extent	Severity of Effects	Ecological Changes	Degree of Understanding	Mitigation Options
Changing climates	Global	Already causing extinctions; likely to cause more.	Alters species size, range, phenology and survival.	Moderately well understood but high unpredictability.	Global commitments; expand protected areas; restore thermal refugia.
E-commerce & invasions	Global *(primarily developed markets)*	Significant role in trade of nonnative plants and animals.	Creates novel modes of long-distance dispersal.	Largely unregulated activities that are poorly understood.	Online consumer accountability tools; awareness campaigns.
Infectious diseases	Global *(especially tropical systems)*	Already causing extinctions; likely to cause more.	Alters species survival, with clear ecosystem effects.	Increasingly well understood but high unpredictability.	Improve surveillance; management to favour ecosystem controls.
Harmful algal blooms	Global *(warm, nutrient-rich areas)*	Linked to species losses; likely to cause more.	Reduces species growth, survival and reproduction.	Increasingly well understood, some unpredictability.	Improve surveillance; management to favour ecosystem controls.
Expanding hydropower	Global *(primarily emerging markets)*	Already causing extinctions; likely to cause more.	Fragments river systems, inhibiting species movement.	Well understood, but interactive stressor effects unclear.	Ameliorate passage infrastructure; assess all project impacts.
Emerging contaminants	Global *(primarily developed markets)*	Unclear how biodiversity will be changed.	Alters some species health, abundance and reproduction.	Largely understudied and thus poorly understood.	Improve medication disposal; advance wastewater treatment.
Engineered nanomaterials	Global *(primarily developed markets)*	Unclear how biodiversity will be changed.	Causes minimal acute toxicity in some species.	Considerable uncertainty around long-term effects.	Improve detection and characterization; create targeted formulations.
Microplastic pollution	Global *(primarily developed markets)*	Unclear how biodiversity will be changed.	Potentially detrimental effects on species health.	Considerable uncertainty around long-term effects.	Reduce plastic usage; enact legislation to curb use of specific products.
Light & noise	Global *(primarily developed markets)*	Linked to species disturbance; likely to continue.	Alters behaviour and physiology of some species.	Well understood, but ecosystem-level effects unclear.	Identify less harmful types; reduce usage; educate users.
Freshwater salinization	Coastal lowlands	Linked to species losses; likely to cause more.	Reduces species growth, survival and reproduction.	Increasingly well studied and understood.	Control point sources; strategic release of freshening flow.
Declining calcium	Softwater lakes	Linked to species declines; likely affecting foodwebs.	Causes shifts in lake invertebrate assemblages.	Increasingly well understood, but solutions unevaluated.	Further reduce acidic precipitation; replenish calcium in watersheds.

combined effects of synthetic chemicals, and the interaction with other anthropogenic stressors, remain in their infancy.

Hydropower dam construction is another major threat to freshwater biodiversity and ecosystem processes and services. Hydropower is a renewable but not an environmentally friendly or climate-neutral energy source. In 2016, 71% of renewable energy was from hydropower. In the US, 82,000 large dams and over 2 million small, low-headed dams have been constructed to date. Currently, more than 3,700 large dams are either planned or under construction globally, further fragmenting the remaining free-flowing rivers. At the same time, we are observing a major shift in dam construction towards the Global South (Zarfl et al. 2015). Indeed, the same problems we have faced in Europe, North America, or in Japan are being repeated in the Global South, regarding the multifold consequences of large dam construction on both humans and nature. For example, the cumulative effects of dams are practically unknown because careful environmental assessments are lacking. In addition, we need to include climate change into the planning due to anticipated alterations in the flow regime and therefore energy production. We also need to be very cautious in not overestimating the benefits and underestimating the costs—unfortunately, a common strategy in megaproject planning and design (Tockner et al. 2016; Moran et al. 2018).

While large dams are mostly being planned and constructed in the global South, we are seeing a boom of small hydropower plants in large parts of Europe, despite the European Water Framework Directive, with its key aim not to deteriorate the ecological status of their waters. Let´s take Austria as an example: two-thirds of its total electricity is produced by hydropower. There are already 2,900 hydropower plants in operation, which feed electricity into the public grid (Wagner et al. 2015). However, 84% are small hydropower plants, contributing less than 5% to the total electricity produced. Less than 15% of the rivers and streams are remaining in a good ecological status. At the same time, about 350 hydropower plants—mainly small facilities—are planned, under construction, or have recently been finished.

Two-thirds of these plants are located in critical zones, i.e., in protected areas or along rivers and streams with at least a good ecological status (Wagner et al. 2015). Indeed, the cumulative effects of small hydropower plants, and their interactions with other stressors, are rarely considered in planning, in Austria as well as globally (Lange et al. 2019), albeit the fact that the environmental footprint per MW is most likely higher for small than large hydropower plants. Ziv et al. (2012), for example, have demonstrated how dam configuration can minimise the harmful effects on fish while still producing high levels of hydropower.

Dams are responsible for the high degree of fragmentation of rivers and streams. A recent study has demonstrated that out of 242 rivers longer than 1,000 km each, only 86 rivers remain free flowing (Grill et al. 2019). The free-flowing rivers are mainly restricted to the Arctic region as well as to the Amazon and Congo Basins. In SE Asia, only two long rivers remain free flowing, namely the Irrawaddy and the Salween. Assuming the completion of all large dams planned and under construction, the river flow volume already affected by dams would almost double (Grill et al. 2015, 2019). In Europe, the free-flowing Tagliamento River (NE Italy) and Vjosa River (Albania) are reference ecosystems of continental importance. Otherwise, only small remnants of free-flowing rivers and streams remain. Concurrently, in the US and in Europe, dam removal is increasing in importance (O'Connor et al. 2015), with the Glines Canyon and Elwha River (USA) as well as the planned Sélune River (France) dam removal projects as the largest in North America and Europe, respectively.

While we are fragmenting rivers longitudinally, we are connecting river basins and even entire continents laterally. In Europe, for example, 28,000 km of navigable canals and rivers are creating a pan-continental ecoregion, leading to an increasing homogenisation of freshwater fauna. While contemporary fish richness is higher—compared to the historic state in the mid-nineteenth century—in all major catchments assessed (251 European catchments larger than 2,500 km^2; average net gain: 5.7 species per catchment), this gain is mainly due to the introduction of exotic and the translocation of non-native species (Sommerwerk et al. 2017).

Dams and water transfer projects are considered as suitable engineering solutions to meeting increased water demands, while water distribution is becoming more uneven due to climate change, land-use alteration, and direct human exploitation—both in time and space. For example, during the coming decades, we may expect a nine-fold increase in the volume of water transferred across basins—and even continents. At present, 34 water transfer megaprojects exist, and 76 megaprojects are either proposed, planned, or under construction (Fig. 16.1). These future projects, if realised, will transfer 1,910 km^3 of water per year, corresponding to the total volume of about 30 Rhine Rivers, across a total distance of 80,400 km (Shumilova et al. 2019). Hence, water transfer projects must be included in global hydrological models, and internationally agreed criteria must be established to assess the social, economic, and ecological consequences of these megaprojects.

Wetlands, including floodplains and delta regions, are highly threatened ecosystems. Davidson (2014) has compiled 169 reports of historical wetland loss and calculated a decline between 69 and 75% in the twentieth century (coastal wetlands: 62–63%). Of the remaining wetlands, only 11.3% are protected (Reis et al. 2017). This study also emphasizes that terrestrial protection does not adequately protect freshwater systems. Indeed, high human impacts, even in protected areas, underscore the urgent need to maintain and restore wetlands, their immense biodiversity as well as the fundamental services they provide for humans.

River deltas and floodplains are wetland ecosystems of global importance, for both humans and nature. Worldwide, 500 million people live in deltas, including megacities such as Dhaka, Bangkok, and Shanghai. In fact, humans are fundamentally altering the functioning of deltas on the global scale due to the truncation of sediment inputs, raising sea water levels as well as naturally high subsidence rates, which are further exacerbated by human activities. The Nile and the Indus Rivers are carrying 98 and 94% fewer sediments today, respectively. The Rhone and the Danube Rivers are carrying 85 and 60% fewer sediments, too. And one-fifth of the Indus delta plain has been eroded since the river was dammed in 1932 (e.g., Syvitski et al. 2009; Giosan et al. 2014).

Along the 28 largest European rivers, floodplains (connected and disconnected) cover a total area of 470,000 km^2. These floodplains are home to 62 million people, who generate a combined calculated GDP of US$ 1.3 trillion per year (K. Tockner, unpublished data). This demonstrates the tight linkage between ecosystems and humans, but it also highlights the increasing risks to people and infrastructure, considering the higher probability of extreme flood events in the future due to climate change and land-use alterations.

As a consequence of the widespread and intense direct and indirect modifications of rivers and their basins, biodiversity and its related ecosystem services are being eroded much faster in freshwaters than in most other ecosystems. Indeed, freshwaters are among the most threatened ecosystems globally, and the decline in biodiversity is 3–6 times faster than in marine and terrestrial realms. In fact, one in three freshwater species is already threatened with extinction. Since 1970, freshwater species populations have dropped by 83% (Loh et al. 2005).

Charismatic freshwater megafauna (species > 30 kg) are umbrella or flagship species, representative of overall freshwater biodiversity (Fig. 16.2). Globally, freshwater megafauna populations declined by 88% from 1970 to 2012, with the highest declines in the Indomalaya and Palearctic realms

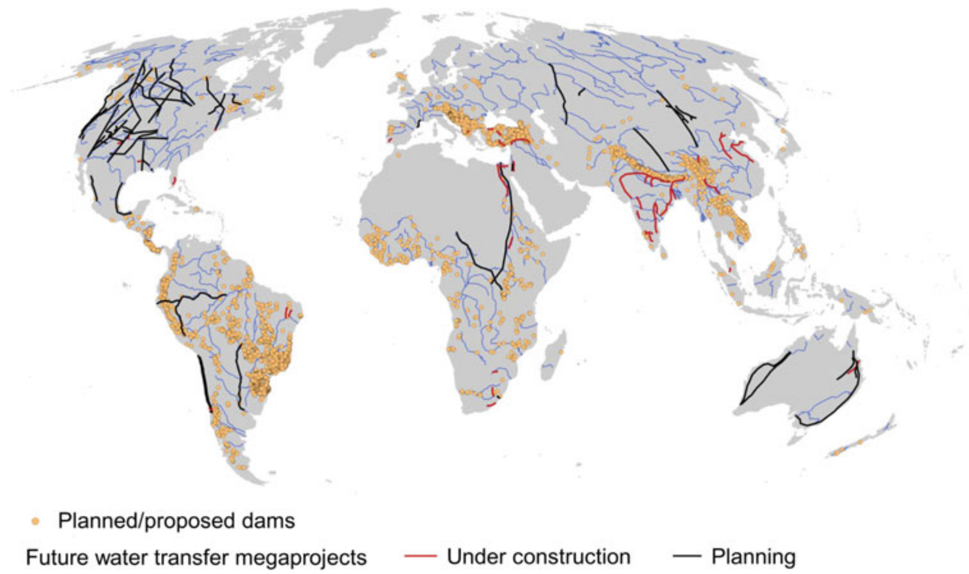

Fig. 16.1 Spatial location of global water transfer megaprojects, either under construction or in the planning phase (modified after Shumilova et al. 2019)

(−99% and −97%, respectively; He et al. 2019). Among taxonomic groups, mega-fishes exhibited the greatest global decline (−94%). Sturgeons, for example, survived 200 million years of global change—including cold and hot times; however, it took less than 150 years to bring them close to extinction. Today, 24 out of 26 sturgeon species worldwide are threatened with extinction or are already extinct in the wild. Furthermore, freshwater megafauna has experienced major range contractions. For example, distribution ranges of 42% of all freshwater megafauna species in Europe have contracted by more than 40% compared to historical areas. The main threats to freshwater megafauna include overexploitation, dam construction, habitat degradation, and pollution. Overall, 54% of the 155 megafauna species assessed are listed as threatened by the IUCN Red List (He et al. 2017, 2019; Fig. 1). A very recent example is the global extinction of the Chinese paddlefish, a charismatic mega-fish that was up to four metres long and lived in the Yangtze River (Zhang et al. 2020).

In China, 1,323 freshwater fish species are currently known. 877 species are endemic, and about 15% are listed as threatened (Xing et al. 2016) compared to 38 and 41% in Europe and North America, respectively (Kottelat and Freyhof 2007). However, the estimation of threatened species is a clear underestimation because the past decades have not been taken into account in the determination of the conservation status of China´s freshwater fish species.

Among the 1,280 freshwater crab species globally, more than one-quarter are threatened with extinction, only about one-third are not at risk, and the remainder lack sufficient evidence to assess their status (Cumberlidge et al. 2009). Indeed, the percentage of species at risk of extinction may only be greater for amphibians and aquatic reptiles.

In the European Union, according to the European Environmental Agency, only 10.5% of all rivers are in a very good ecological status (country range: 0.0–24%) and 31% are in a good ecological status (range: 0.8–66%; https://www.eea.europa.eu). The goal of the Water Framework Directive (WFD) is to reach a good ecological status for all rivers by the year 2027. However, there is no possibility of reaching this goal; indeed, in most countries, we are seeing no or only slight increases in the ecological status of rivers and streams. Moreover, a high proportion of ecologically valuable rivers and streams are not yet protected—and we may experience a further deterioration of many of these rivers despite the "no deterioration" principle of the WFD. A key reason for the deterioration of the ecological status of European rivers and streams is the ongoing boom in hydropower plant construction. Furthermore, the WFD is in competition with directives in the agriculture, energy, and infrastructure construction sectors. Hence, there is an urgent need to develop synergies among the different sectors, which would require a more systemic and holistic view of the challenges we are facing, and the solutions we must develop and implement.

Moran et al. (2018), for example, have proposed innovative solutions for hydropower: (i) environmental and social impact assessments (EIA, SIA) need to be carried out by firms and organizations serving citizens and not dam builders, (ii) functioning fish passage must be constructed and mimicking seasonal flow regime allowed, (iii) better governance must be established around dams, (iv) greater transparency about the true costs associated with dam construction are required, and (iv) innovative techniques which prohibit the construction of huge barriers must be developed and finally implemented.

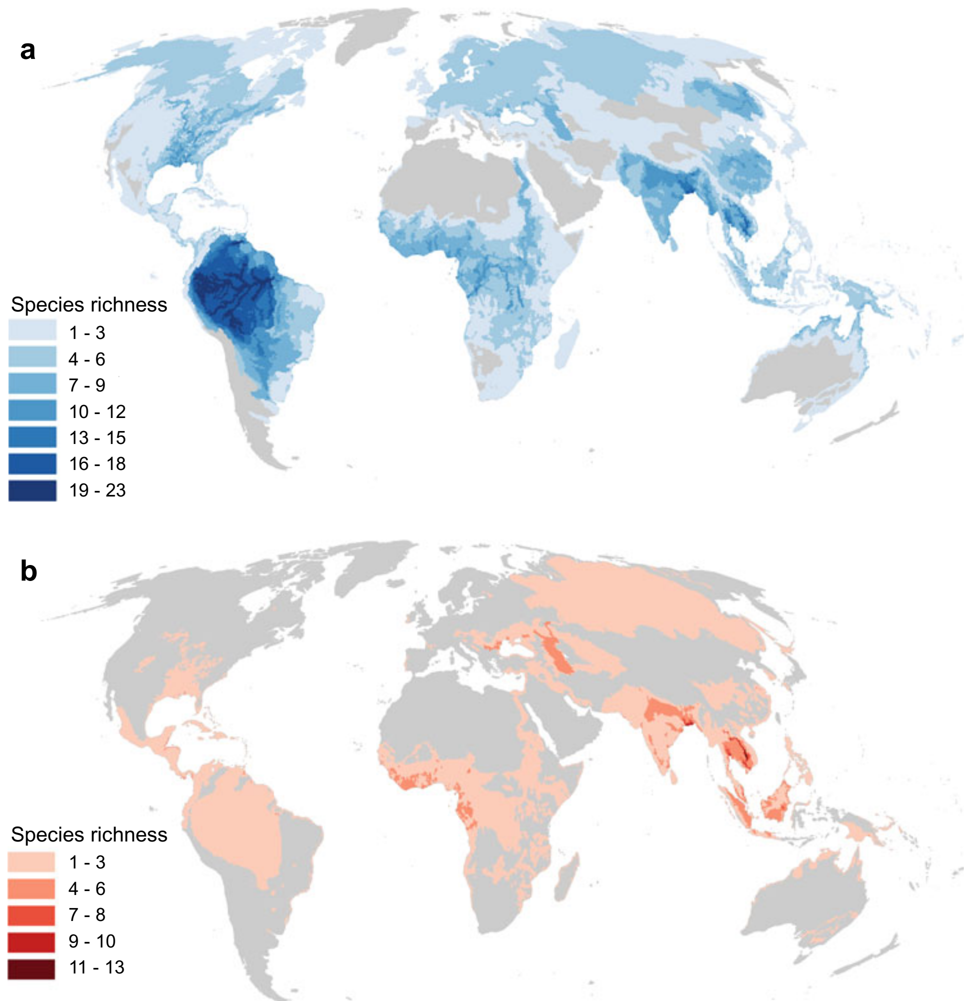

Fig. 16.2 **a** Global freshwater megafauna diversity and **b** number of threatened freshwater megafauna species (modified after He et al. 2019, unpublished)

Renewable energy is an important contribution in meeting growing energy demands and mitigating climate change. However, hydropower clearly has the greatest environmental effects of the main renewable energy sources (wind, solar, and hydropower), despite the fact that hydropower is booming in ecologically highly sensitive regions such as in the Amazon and Congo Basins, as well as in SE Asia, the Balkans, and in Anatolia (Gibson et al. 2017).

In Europe, we need to improve the coherence among the various environmental and sectorial EU policies and directives to prevent biodiversity loss and to support a wide range of ecosystem services. Synergies between the WFD and Nature Directives, as well as with other directives, must be developed. Ecosystem-based management presents us with a way forward; however, there is a risk of establishing yet another strategy without a clear political will of implementation. The current degradation of streams and rivers due to a boom in small hydropower plants and unsustainable agricultural development demonstrates the existing limitations of the WFD. Hermoso (2017), for example, has stated that weak legislation regulating hydropower project approval may cause irreversible damages to freshwater biodiversity and ecosystem services and, hence, freshwaters could become the biggest losers of the Paris Agreement.

16.7 An Engineered Water Future

Globally, freshwater is unevenly distributed, both in time and space. Climate change, land-use alteration, and increasing human exploitation will further increase the pressure on water as a resource for human welfare and on inland water ecosystems, thereby intensifying the uneven distribution of freshwater.

There is a growing belief that we may solve the increasing challenges in the water sector with major engineering solutions, including the construction of dams, water transfer projects, desalinization plants, or the like (e.g., Zarfl et al. 2015; Shumilova et al. 2019). However, many engineering projects, in particular so-called megaprojects, are often high-risk projects because they require major financial investments, demand long time frames from planning to completion, and may have major socio-economic and environmental ramifications. Concurrently, the social, economic, and environmental consequences of these projects do not receive adequate attention in the decision-making process. Furthermore, we need a systemic approach—due to path dependencies—and a transformative knowledge base to cope with the immense challenges humankind is facing.

We need global databases and maps, including temporal trends, of major water engineering projects (e.g., dam, water transfer, desalinization, restoration projects)—current, under construction, planned, and proposed (these data are either already available or must be complemented). These data must be linked with data on other pressures relevant for water systems (e.g., roads, artificial light, mining areas), and with data on biodiversity (e.g., freshwater megafauna) and ecosystem processes and services. We must ensure major engineering projects (megaprojects) are included in global and basin hydrological models. In addition, we need internationally agreed criteria to assess the ecological, social, and economic impacts of megaprojects, and the water-energy-food nexus must be extended to include further components such as mining and cultural diversity. Alternative solutions to mega-engineering projects, such as green infrastructure, linked natural and technical systems, local solutions, etc., must be considered, too (see Box 16.1). It is obvious that the discussion of alternative options will finally lead to better solutions. Overall, transdisciplinary research approaches are required, integrating academic and societal knowledge.

16.8 A Blueprint for Freshwater Life

Freshwater ecosystems must be put on the world map in terms of their conservation values, service values to humanity, and for their amazing diversity of life, which is so poorly understood and recognised today. The *Alliance of Freshwater Life* is a global initiative, uniting specialists in research, data synthesis, conservation, education and outreach, and policy making. This expert network aims to provide the critical mass required for the effective representation of freshwater biodiversity at policy meetings, to develop solutions balancing the needs of development and conservation, and to better convey the important role freshwater ecosystems play in human well-being (Darwall et al. 2018).

A blueprint of freshwater life will: (i) build greater global awareness of the values of freshwater ecosystems and their species; (ii) mobilise the huge body of existing research information, such as on the functioning of wetlands, for application to the sustainable management and conservation of the world's freshwater ecosystems; (iii) fill the extensive information gaps on freshwater ecosystems as needed to inform sustainable development; and (iv) bring forward the science of freshwater ecosystems to develop and inform conservation and development policy (Darwall et al. 2018). Indeed, we need to manage freshwater(s) as hybrid systems, i.e., as a resource for human use as well as highly valuable ecosystems. To do so, we need global databases and maps, including solid information on temporal trends, environmental drivers, human pressures, and biodiversity and ecosystem services. This will enable us to identify areas of high value and high risk and serve as a base for decision-making (e.g., Schmidt-Kloiber et al. 2019).

Species distribution data are crucial for improving our understanding of spatial and temporal changes in biodiversity (see detailed information: Schmidt-Kloiber et al. 2019). This is especially the case for freshwater systems, which are strongly affected by global change. Currently, freshwater biodiversity data are often difficult to access because systematic data publishing practices have not yet been adopted by the freshwater research community. The Freshwater Information Platform (FIP; www.freshwaterplatform.eu)—initiated through the EU-funded BioFresh project—aims at pooling freshwater-related research information from various projects and initiatives to make it accessible to scientists, water managers and conservationists, as well as the interested public. The FIP consists of several components, three of which are mentioned: (1) The Freshwater Biodiversity Data Portal aims at mobilising freshwater biodiversity data, making them available online. Datasets in the portal are described and documented in the (2) Freshwater Metadata base and published as open-access articles in the Freshwater Metadata Journal. The use of collected datasets for large-scale analyses and models is demonstrated in the (3) Global Freshwater Biodiversity Atlas that publishes interactive online maps featuring research results on freshwater biodiversity, resources, threats, and conservation priorities. Data and information are the basis for knowledge, and if publicly funded, these data must be made openly accessible, considering ethical issues and intellectual property rights (Schmidt-Kloiber et al. 2019).

Reid et al. (2019) advocate hybrid approaches that manage freshwaters as crucial ecosystems for human life support as well as essential hotspots of biodiversity and ecological function. Indeed, we need to manage freshwater(s) as hybrid systems, i.e., as a resource for human use as well as extremely valuable ecosystems. At the same time, we are not fully aware of the extent to which humans have and are planning to re-engineer the global hydrological network and flows through the construction of large dams, water transfer megaprojects, and other engineering projects. Indeed, we most likely are merely at the beginning of the "great acceleration" of the Anthropocene and therefore underestimate the environmental alterations we will face in the near future, in particular in the water sector.

Box 16.1: Three examples of large-scale restoration and management schemes

The **Four Major Rivers Restoration** project was the most important component of South Korea's national Green Growth Policy (e.g., Lah et al. 2015). At least US$ 19 billion was invested into this multi-purpose megaproject. Although it is too early to assess the overall achievements of the project, it has helped improve water quality, minimise water scarcity, reduce flooding risks, and stimulate local economies. However, it is more of an engineering project than a restoration project by building 16 dams, dredging 570 million m^3 of sand and gravel, and deepening nearly 700 km of riverbed. Indeed, the project was criticized by many scientists who accused the government of ignoring data and expert recommendations (e.g., Normile 2010).

The **Emscher River** (catchment area: 793 km^2) **restoration** is one of the largest water management projects in Europe, located in the densely populated "Ruhr Metropolitan Area" of the Federal State of North Rhine-Westphalia, Germany (for details, see Gerner et al. 2018). The project started in 1990, converting previously highly modified open wastewater channels with concrete beds into near natural river channels. An underground sewer network of more than 400 km has been constructed to separate waste and river water, and concrete river walls have been removed, piped rivers opened, stream profiles widened, and artificial wetlands created. The estimated costs of this project are approx. €5.3 billion.

The **Comprehensive Everglades Restoration Plan** (CERP) was approved in 2000. It consists of over 60 civil works projects that have been designed and implemented over a 30+ year period, with an estimated cost of more than US$ 10 billion. It seeks to correct an earlier attempt at water management in South Florida and improve water availability during the dry season and reduce flooding of urban and agricultural areas during the wet season (see Perry 2004; Sklar et al. 2005). The main aims are to restore, preserve, and protect the South Florida ecosystem while providing for other water-related needs of the region, including water supply and flood protection.

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Klement Tockner received a PhD in zoology and botany from the University of Vienna and a Titular Professorship at ETH Zurich. He is Director General of the Senckenberg Gesellschaft für Naturforschung and Professor for Ecosystem Sciences at Goethe Universität in Frankfurt, former president of the Austrian Science Fund (FWF), professor for Aquatic Ecology at the Free University Berlin, and former director of the Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin. He is member of several international scientific committees and advisory boards, and elected member of the German National Academy of Sciences, Leopoldina, and the Austrian Academy of Sciences.

17 Water-Energy-Food Relation in Gulf Cooperation Council

Mohammed Darwish and Rabi H. Mohtar

Abstract

Gulf Cooperation Council (GCC) countries are the world's poorest in terms of total and per capita availability of freshwater resources. Agriculture in the GCC depends mainly on Groundwater (GW), which is generally over-exploited, depleted, and poor quality. Water scarcity severely limits agriculture food production and is a major obstacle to achieving food self-sufficiency. The possibility of using the GCC's abundant energy resources to generate desalinated seawater (DW) or treated wastewater for agriculture offers a partial solution to the water scarcity challenge. The feasibility of the scenario and the interdependent relations between water, energy, and food resources are discussed.

Keywords

Groundwater • Wastewater • Desalination • Fuel • Renewable energy • Food • Water energy food nexus

Abbreviations

AC	Air Conditioning
AFED	Arab Forum for Environment and Development
AGR	Annual Growth Rate
bbl/d	Barrel per day
BC	Bio-capacity
BP	British Petroleum
CC	Combined Cycle
D/S	Distillate Product/Supplied Steam
DW	Desalted/Desalinated Seawater
EF	Ecological Footprint
EP	Electric Power
FAO	Food and Agricultural Organisation (of UN)
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
gha	Global Hectares
GJ	Gigajoule
GT	Gas Turbine
GW	Groundwater
IBRD	International Bank for Reconstruction and Development
IMF	International Monetary Fund
IWRM	Integrated Water Resources Management
Kg/OE	Kilogram/Oil Equivalent
ME-TVD	Multi effect-thermal vapor compression
MIGD	Million imperial gallons per day
MSF	Multi stage flash
WW	Municipal Waste Water
NG	Natural Gas
KSA	Kingdom of Saudi Arabia
PP	Power Plant
SWRO	Seawater reverse osmosis
Toe	Ton of oil equivalent
UAE	United Arab Emirates
UK	United Kingdom

M. Darwish
Qatar Environment and Energy Research Institute, Qatar Foundation, Doha, Qatar

R. H. Mohtar (✉)
Dean of Faculty of Agricultural and Food Sciences, American University of Beirut, Beirut, Lebanon

Professor, Texas A&M University, College Station, USA
e-mail: mohtar@aub.edu.lb; mohtar@tamu.edu

17.1 Introduction

Recent and ongoing challenges facing the management of the primary resources water, energy, and food have shown that with population growth and climate change, ‘business as usual’ management of these resources is inadequate. The tightly interconnected resources carry a significant gap in achieving their sustainability as we move forward to the

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future (Daher et al. 2018, 2017; Mohtar and Daher 2017). The interdependencies of these resources, the inequity in their availability across the societal mosaic, and the inequity in their physical distribution around the world have made access to these primary resources very challenging and as such will significantly affect our ability to achieve the universal sustainable development goals and other national development goals (Mohtar 2017).

Moving forward, on top of the actions to balance the gap between the supply and demand of these primary resources, is the business model we currently have for managing and allocating them. We must admit that this model has failed: supply is not meeting demand, and the gap between the two is increasing. Thus, a new business model is required: one based on social, economic, environmental and ecological values, in addition to the financial values that have prevailed thus far. The new business model must consider these values and costs in managing these resources moving forward (Mohtar 2017). The water, energy, food nexus approach comes to address the gap in such a new business model, providing a platform to describe their interconnectedness, to quantify their interlinkages, to identify the areas of intervention needed, the tradeoffs between these interventions, and the levers in the areas of water, energy, and food management (Mohtar and Daher 2012, 2014, 2015, 2016). The "levers and interventions" being the policies, technologies, and behavioral incentives to be coordinated for potential synergies (Mohtar and Daher 2016).

Here we wish to emphasize that the nexus as a platform is not a substitute for the disciplinary knowledge and ongoing disciplinary activities in the water, energy and food sectors. We also highlight that the nexus can only be successful through strengthening these three sectors and benefiting from the immense disciplinary knowledge of water productivity, energy efficiency, and integrated primary resource management. The nexus approach builds on these disciplinary strengths to create a platform in which managing water, managing energy, managing food are done in a more coherent manner and within a framework of societal demand, governmental policies, and business supply chain constraints. Of course, all of these are within the bigger constraints of technology, political pressure, trade, global population, climate change, and rising economies. The nexus as such is a mosaic of all of these interlinkages and constraints and offers a new opportunity that allows us to attempt to manage our primary resources sustainably (Stephan et al. 2018).

However, the Nexus is not only the knowledge, the tools, and the analytics to help us manage water, energy, and food: it is much more. The Nexus aims to connect with stakeholders and allow them to choose between the different pathways and interventions in a more informed, sustainable manner by using the platform to understand the trade-offs in terms of the levers of policies, technologies, and social behaviors (Daher et al. 2017; Mohtar 2017). The Nexus allows the user, in this case the policy- or decision-maker, to choose among a variety of levers and to rank those levers in terms of their social, environmental, and economic sustainability. It also allows for dialogue and interaction among the stakeholders of the water, energy, and food sectors. These interventions must be discussed among potentially conflicting stakeholders in an inclusive and transparent setting that allows for synergy rather than competition over resource allocation. The dialogue must also be inclusive vertically and horizontally, encompassing the wide disciplinary and hierarchy distribution of the stakeholders. This distribution begins with the local and proceeds to the national and even the global level. It includes a multiplicity of horizontal stakeholders, from the multiple sectors of water, energy, and food. It includes everyone from the government to public sector, academia to nongovernmental organizations, and the private sector. The nexus thus becomes a pathway toward sustainable management of the primary resources and an assistive tool to achieving water, energy, and food security.

This chapter outlines the water-energy-food relationships within the context of the GCC, the Gulf Cooperation Council. Why is the GCC a relevant example for managing the water, energy, food nexus? The extreme geophysical conditions prevailing in the Gulf region well illustrate the intimate ways in which water, energy and food resources are interconnected. The majority of the water resources in the GCC are produced using desalination: an energy intensive process that carries high energy and environmental footprints. Still, desalination is the only feasible pathway for the GCC member states to provide for their population the necessary water resources (Darwish and Mohtar 2012a, 2012b; Darwish et al. 2012; Mohtar and Darwish 2013; Darwish and Mohtar 2013; Llewellyn-Smith and Mohtar 2012; Darwish et al. 2013; Darwish et al. 2015). That very tight interconnectedness is an extreme example of how these resources are interdependent. There are also attempts to use some of the desalinization processes toward food production, which makes for a perfect nexus among water, energy, and food resources. If we can sustainably manage this complex system in the GCC and learn to understand the intricacies of the nexus connection, then those lessons can be applied in other areas of the world that are also prime hotspots for nexus management.

This chapter seeks to understand the interconnectedness of these primary resources; how to manage them; and hopefully, how to scale them to other areas in other hotspots while maintaining a systems approach toward their resolution. We review some of the challenges facing the GCC countries in as they attempt to address the challenges of water, energy, and food allocations. We look at current practices, consumption, and demand, as we attempt to understand the renewable sources, particularly of water and food production. We look at the interdependencies between water and agricultural production and at the role that recycled wastewater can play in agricultural production. We look at desalination as an example of these highly, tightly, interlinked systems. We look at the food portfolio for the GCC region, constituted from a portfolio of different resources, and give an example of how to manage this portfolio as a bundle of water, energy, food resources. We close with some examples of conclusions that could be useful to the community worldwide, and then conclude with some recommendations (Mroue et al. 2019; Dargin et al. 2019; Daher and Mohtar 2015; Daher et al. 2017).

The Gulf Cooperation Council (GCC) countries, Saudi Arabia (SA), United Arab Emirates (UAE), Oman, Kuwait, Bahrain, and Qatar, comprise an arid region, the world's poorest in per capita and total freshwater resources. Agriculture requires arable land, water and energy to cultivate animals, plants, and other life forms to produce food, fiber, bio-fuel and products essential to human life, (International Labor organization 1999). Water requires energy for pumping, distribution, and treatment. For its water resources, the GCC relies on desalinated seawater (DW) and treated wastewater (TWW). Both are non-conventional resources that consume extensive amounts of energy in production. The scarcity of natural fresh water resources and the high cost of DW and TWW, make attainment of food self-sufficiency highly questionable in the GCC. Given the scarcity of natural water, and the fact that the production of one kilogram of wheat requires about 1,400 kg of water, GCC cereal production is very limited. Table 17.1 illustrates the reduction in cereal production in SA 1990–2010 (Sadik 2012). Table 17.2 illustrates the projected decline in GCC's renewable per capita water resources through 2050 (Sadik 2012). Together, the two tables illustrate that agriculture consumes vast quantities of water and energy, extremely limited renewable water resources (RWS) in the GCC, to produce the required commodities.

Water, energy, and food are closely interlinked to strategic requirements of significant security concern and should be considered together, as a single system (Fig. 17.1). Optimal management of this system represents a key challenge for the GCC's long-term standard of living and sustainable growth.

Natural water resources are limited throughout the Arab world. Figure 17.2 illustrates the decline in their per capita availability over time (1961–2008): from more than 3000 cubic meters per year per capita (m^3/y.ca), to 800 m^3/y.ca (Saab 2012). The projected per capita RWS for 2015 is less than 1/10 of the worldwide average of 6000 m^3/(y.ca), less than 100 m^3/y.ca (Table 17.2) in all GCC except Oman and as low as 7, 20, and 33 m^3/y.ca for Kuwait, UAE, and Qatar respectively.

Arable land is another obstacle to GCC food production. Cropland, in 2008, was 4.1 million (M) hectare (ha), of 203 M ha of productive land and water, (Saab 2012). The GCC experienced rapid economic growth following the discovery of prime energy resources (oil and natural gas) and subsequent development of their export market. Populations increased by more than 13 M (2003), reaching 46.8 M at the end of 2011 (GCC Population 2012). Qatar alone doubled its population three times from 2001–2013, surging from 0.62 M to 1.95 M (CIA Qatar Demographics 2013), see Fig. 17.3, (Qatar Population 2012).

Qatar National Bank studies predicted the GCC's Gross domestic product (GDP) would reach $1.5 trillion by 2013, and forecasted that its real GDP growth would reach 4.6% from 2012 to 13. The International Monetary Fund (IMF) predicted global GDP growth to reach only 3.6% in the same period. The GCC's real GDP annual growth was 4.7% between 2007 and 11, compared with global growth rate of 2.8%, (Sambige 2012). Nominal GDP, US $ 341.6

Table 17.1 Cereal production in the GCC, (Sadik 2012)

Country/Sub-Region	Area (1000 ha)		Productivity (kg/ha)		Production (1000 ton)	
	1990–92	2008–10	1990	2010	1990	2010
Bahrain	0	0	0	0	0	0
Kuwait	0.3	1.1	3653	3415	1.1	3.76
Oman	2.8	3.1	2160	18,987	6.05	58.86
Qatar	0.2	2.1	2897	4795	3.48	10.07
Saudi Arabia	1121.9	317.4	4245	5631	4,762.4	1,787.3
UAE	1.4	0	2216	0	3.1	0
GCC	1124.6	323.7	4236	5746	4,776	1860
Yemen	730	927.3	908	1092	663	1013
GCC & Yemen	1857.6	1251	2928	2296	5439.4	2872.6

Table 17.2 Renewable water resources and per capita share in the GCC, (Sadik 2012)

Country/Sub-region	Natural water resources (million m^3)	Average share (m^3/y.ca)		
		2010	2030	2050
Bahrain	116	92	70	64
Kuwait	20	7	5	4
Oman	1400	503	389	374
Qatar	58	33	24	22
Saudi Arabia	2400	87	62	53
UAE	150	20	14	12
GCC	4144	95	68	59
Yemen	2100	87	51	34
GCC & Yemen	6244	92	61	47

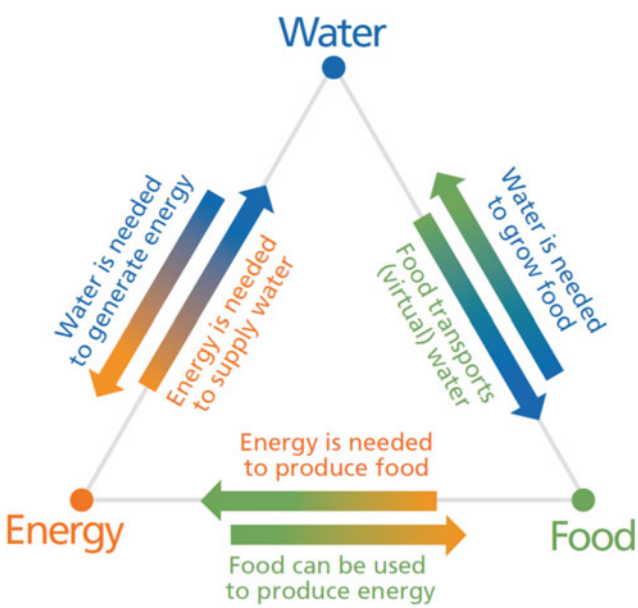


Fig. 17.1 The Water-Food-Energy Nexus

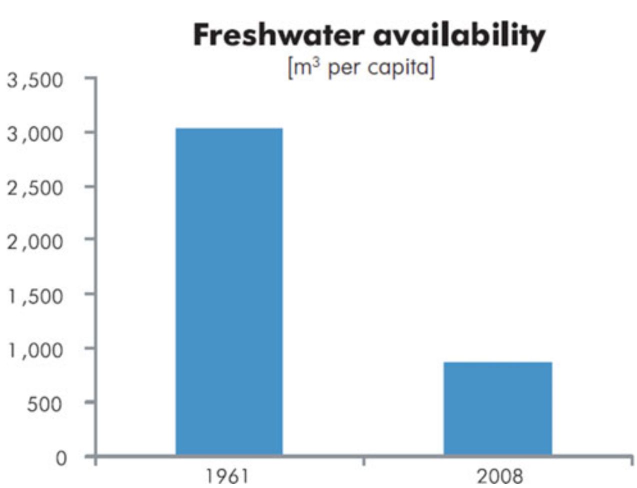


Fig. 17.2 Fresh water resources per capita, (Saab 2012)

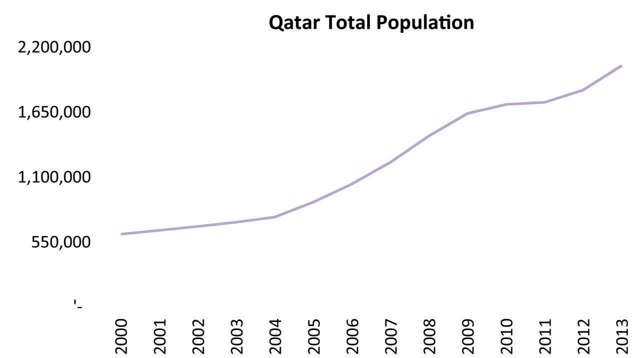


Fig. 17.3 Qatar historic population increase, (Qatar Population 2013)

billion in 2000, was forecast to soar to US $2 trillion by 2020.

Although rich in crude oil and natural gas (NG), all the GCC partners except Qatar, face NG shortages for operation of their own power plants and either import NG or seek alternatives, such as nuclear and solar. Excessive consumption of energy drains fuel resources (wealth) at rates higher than production rates. Water scarcity and harsh summer environments necessitate extensive production of DW and electric power (EP). While DW satisfies most of the municipal water requirement, (99.9% in Qatar and 93% in Kuwait), EP, used primarily for air conditioning (AC) systems, is responsible for 70% of the summer load and more than 50% of total consumed EP in Kuwait and most of the GCC, Fig. 17.4 (El-Katiri 2011).

Consumption of EP and DW are rising at alarming rates. All produced fuel could be consumed locally within 2–3 decades in some GCC locations. Most fresh natural groundwater (GW) is over-exploited and deteriorated. GW is used inefficiently in irrigation systems that produce very low shares of required food. While agriculture has begun to benefit from TWW, municipal wastewater must be treated before disposal into the environment. Additional treatment consumes additional energy at lower rates than desalination

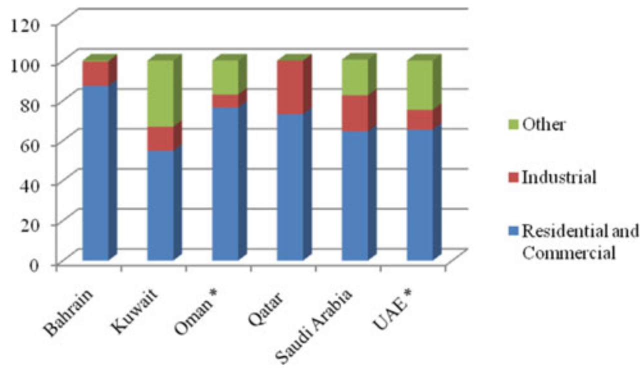


Fig. 17.4 The GCC electric power consumptions by sectors (percentage) in 2009, (El Katiri 2011)

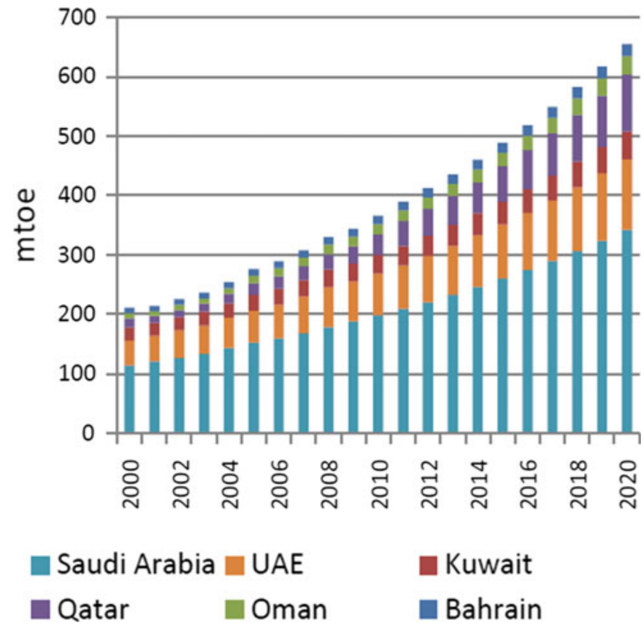


Fig. 17.5 GCC primary energy consumption in million tons of oil, with projections to 2020, (BP 2012)

and can achieve standards suitable for agriculture. Nearly all of the EP produced in Qatar, UAE, Oman, and Bahrain are generated from power plant (PP) operated by natural gas (NG). In SA and Kuwait, oil is also used. Water is required to extract NG from underground sources and then to generate EP from chemical energy produced by NG combustion. Water is injected by pumps into oil reservoirs to recover pressure and extract the oil. Steam injection, like water flooding, can be used for enhanced oil recovery. Most recent PPs in GCC use gas turbines (GT) in combined cycle (CC).

This chapter presents the current status and interrelation of energy, water, and food in the GCC. It explores the inter-linkages of these resources and calls for a holistic and integrated approach for water, energy and food resource management and allocation.

17.2 Energy

In the GCC, primary energy (oil and NG) consumption is continuously on the rise. Figure 17.5 gives the present and expected primary energy consumptions in million (M) tons of oil equivalent (toe). One toe is the unit of energy released by burning one ton of crude oil, about 42 gigajoule (GJ). GCC oil and NG production/consumption are shown in Tables 17.3, 17.4, and 17.5, (BP 2012). The tables show the oil production rate increasing at nearly 20%, while oil consumption rate increased nearly 120% between 2000 and 10.

SA's oil consumption, from 2000 to 2011, grew from 1.578 million barrels per day (Mbbl/d) to 2.86 Mbbl/d. SA's annual per capita oil consumption in 2011 was 37.2 bbl, compared to 5 bbl in Brazil and 10.5 bbl/y.ca in Germany (Krane 2012). Table 17.5 shows that production of NG exceeds consumption for the GCC as whole, but only Qatar produces more than it consumes: for all other GCC partners, consumption equals or exceeds their respective productions, meaning that all GCC countries except Qatar expect to import NG. In 2010, oil consumption to production ratios reached 27% in SA, 25% in UAE, and 18% in Kuwait. For NG, it reached 124% in Kuwait, 117% in UAE, and 100% in SA (Krane 2012).

Continuous increase in local demand for primary energy reduces export availability, the main income of these countries. Figure 17.6 shows the consumption in kg of oil equivalent (kg/oe) in the GCC as a whole compared with the USA and other selected countries (The Economist 2010). SA currently consumes over one-quarter of its total oil production, about 2.8 Mbbl/d (Lahn and Stevens 2011). The 'business as usual' trajectory of its consumed oil and export is given in Fig. 17.7a, (Lahn and Stevens 2011). If oil consumption continues as usual in SA, consumsption will equal production by 2028, leaving no oil for export. Figure 17.7b illustrates a similar trend in Kuwait, for "business as usual" scenarios (Darwish et al. 2008).

Current consumption patterns are neither sustainable nor easy to manage. Average annual EP consumption in the GCC was about 12,000 kWh/y.ca in 2010, the population and economy continue to grow. Heavy subsidies that keep energy prices unrealistically low encourages over consumption: Fig. 17.8 shows that per capita consumed EP in GCC is already higher than in some selected countries (World Bank Data 2014).

For the same year, the reported figures were 14,997 kWh/y.ca for Qatar, 18,320 kWh/y.ca for Kuwait, 11,044 kWh/y.ca for UAE, 9,814 kWh/y.ca in Bahrain, 5,933 kWh/y.ca in Oman, and 7,967 kWh/y.ca kWh/y.Ca in SA, (World Bank Data 2014). These figures give the EP consumption measured by the production of power plants and

Table 17.3 Oil productions in GCC (in terms of 1000 bbl/d and in M tons/y), (BP 2012)

Country	Oil production in 1000 bbl/day			Oil production in million tons		
	2000	2010	% increase	2000	2010	% increase
Kuwait	2206	2508	13.69	109.1	122.5	12.28
Oman	956	865	−9.52	46.4	41	−11.64
Qatar	757	1569	107.27	36.1	65.7	81.99
Saudi Arabia	9491	10,007	5.44	456.3	467.8	2.52
UAE	2620	2849	8.74	122.1	130.8	7.13
Average			25.12			18.46

Table 17.4 Oil consumptions in GCC (in terms of 1000 bbl/d and in M tons/y), (BP 2012)

Country	Oil consumption in 1000 bbl/d			Oil consumption in M tons		
	2000	2010	% increase	2000	2010	% increase
Kuwait	249	413	65.86	11.3	17.7	56.64
Oman						
Qatar	60	220	266.67	2	7.4	270
Saudi Arabia	1578	2812	78.2	73	125.5	71.92
UAE	396	682	72.22	20.1	32.3	60.7
Average			120.74			114.8

Table 17.5 Natural gas production and consumptions in GCC countries, (BP 2012)

Country	NG production in BCM			NG consumption in BCM		
	2000	2010	% increase	2000	2010	% increase
Kuwait	9.6	11.6	20.83	9.6	14.4	50
Oman	8.7	27.1	211.49			
Qatar	23.7	116.7	392.41	9.7	20.4	110.31
Saudi Arabia	49.8	83.9	68.47	49.8	83.9	68.47
UAE	38.4	51	32.81	31.4	60.5	92.68
	130.2	290.3	122.96	100.5	179.2	78.31

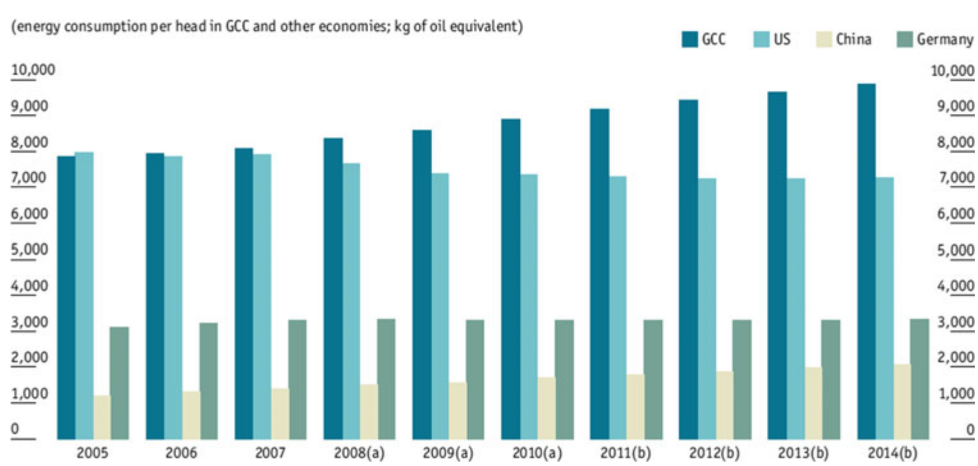


Fig. 17.6 Energy per capita in the whole GCC compared to other countries, (The Economist 2009)

cogeneration power desalting plants less transmission, distribution, and transformation losses and own use by heat and power plants. The annual consumed EP in GCC between 2000 and 2008 increased at a rate of 7% in Bahrain, 5.1% in Kuwait, 6.3% in Oman, 5.6% in SA, 6.3% in UAE, and 9.3% in Qatar. The EP consumed per capita in Qatar and

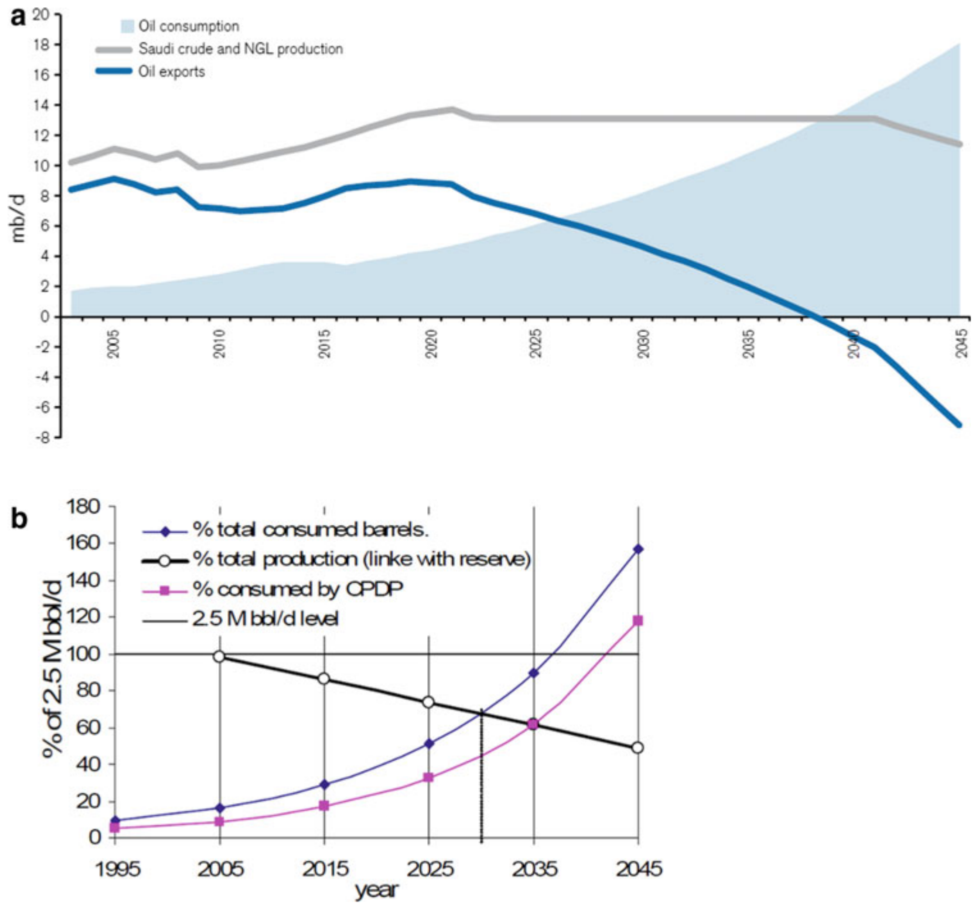


Fig. 17.7 **a** Saudi Arabia's oil balance on a business-as-usual trajectory, (Lahn and Stevens 2011). **b** Expected % fuel consumption, by sector and CPDP, % total fuel production linked with reserve (open circles), (Darwish et al. 2008)

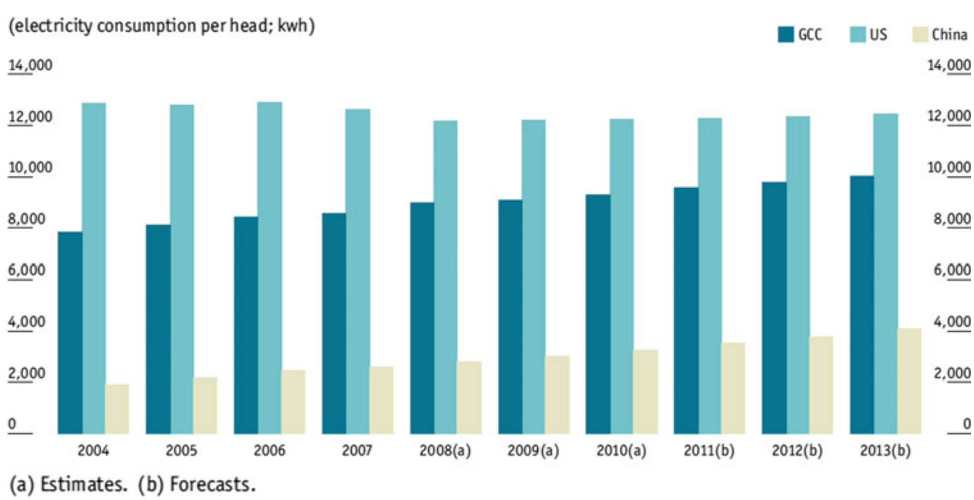


Fig. 17.8 Annual electric power consumption in kWh/y.Ca, (The Economist 2009)

UAE are the highest in the world, as consequently are the CO_2 emissions, Figs. 17.9 and 17.10 (Zeitoon 2012).

The cost of EP to end users reflects on consumed EP: high consumption in the GCC is an outcome of its low cost to the consumer, see Fig. 17.11 (Krane 2012). In Abu Dhabi, the EP cost/kWh (2006) was 1.4 US cents for nationals and 4 US cents for expatriates: the average consumed EP there is 71,000-kWh/y.ca by nationals, but only 26,500-kWh/y.ca by expatriates. Pricing policy for EP consumption should be reviewed and subsidies reduced, as a measure to end energy waste.

NG and oil are the primary fuels used in EP production. NG impacts the environment less negatively and is cheaper than oil: it is (and should be) the preferred fuel for use in power plants in the GCC, (El-Katiri 2011). SA and Kuwait are heavy users of oil in power plants, due to their shortage

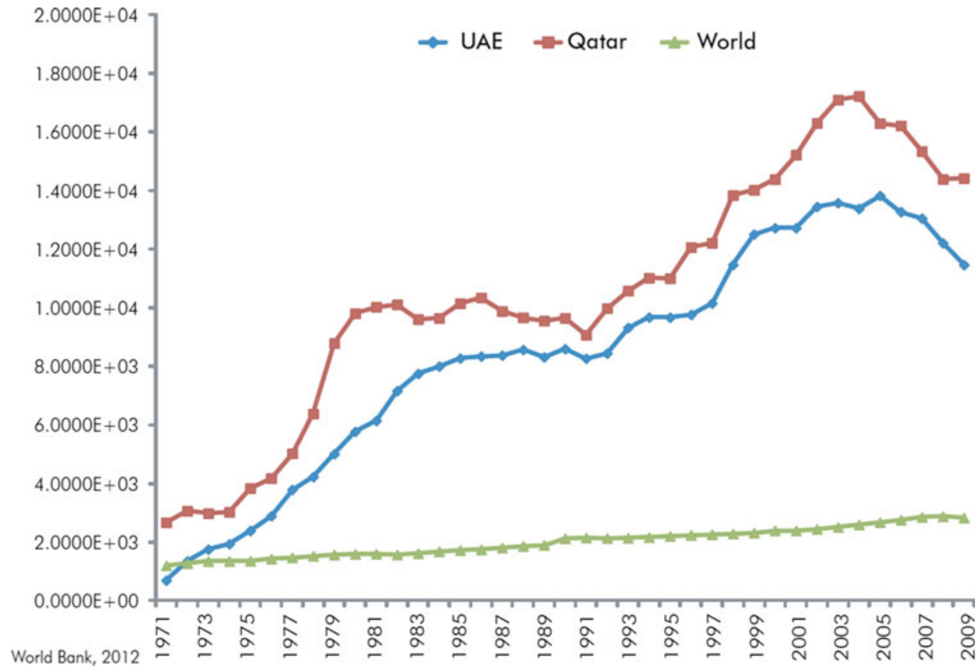


Fig. 17.9 Electrical power consumption (kWh) per Capita in Qatar and UAE, 1971–2009, (Zeitoon 2012)

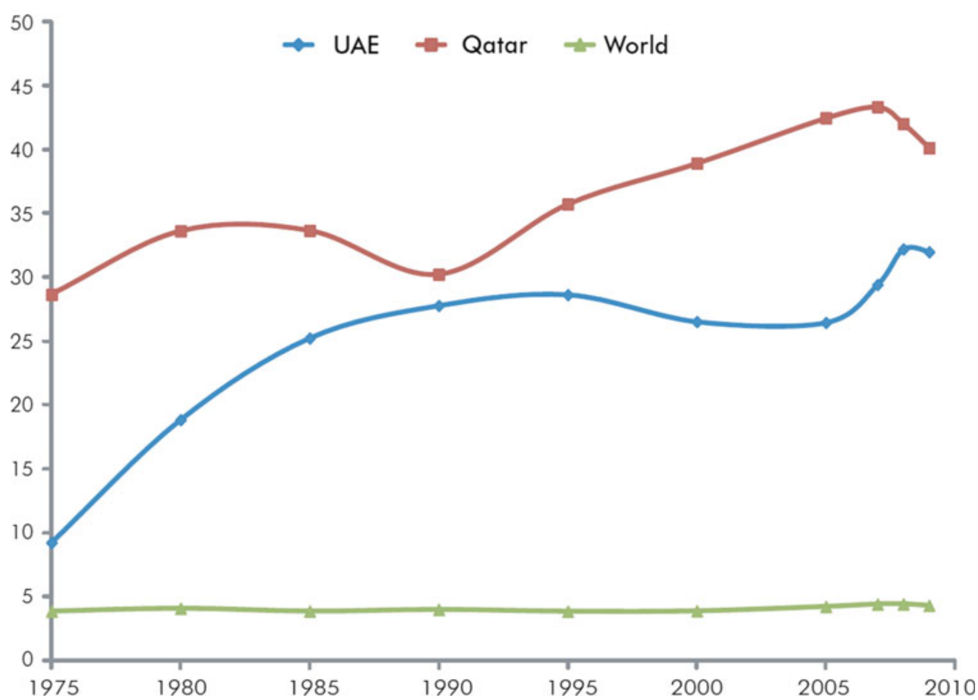


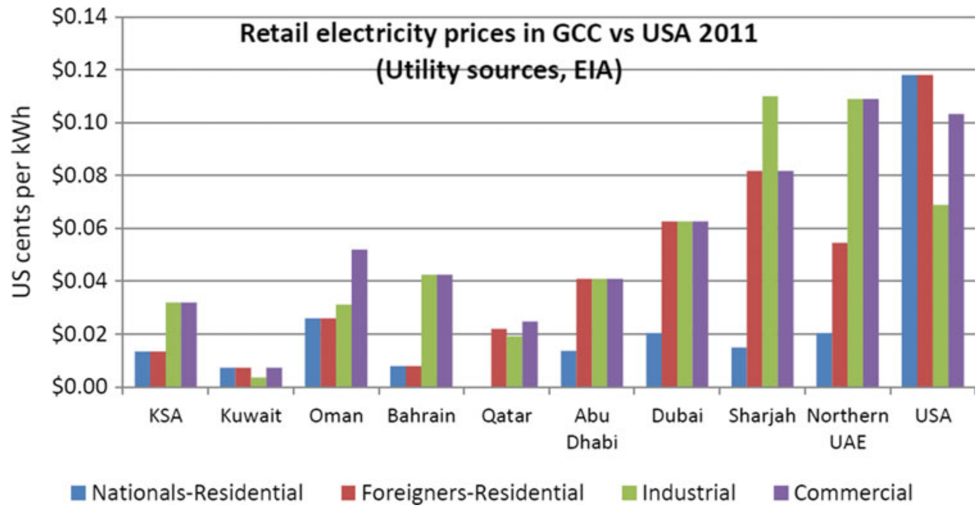
Fig. 17.10 CO_2 Emissions (tons) Per Capita in Qatar and UAE, 1975–2009, (Zeitoon 2012)

of NG and abundance of oil as shown in Fig. 17.12 (El-Katiri 2011).

Policies should be reviewed and changed to improve energy efficiency for both supply (power stations and industry), and demand (consumption). Reducing water demand is necessary to reduce energy demand in desalination plants. Utilization of renewable energy resources such as solar and wind energy are to be considered (Al Ansari 2013, Maulbetsch and DiFilippo 2006).

Sustainable development in GCC demands curbing rising energy consumption. Measures need to be comprehensive, beginning with fuel extraction and refining and extending to electric power and desalination: both production and consumption. One obvious solution is to raise the efficiency of

Fig. 17.11 Electricity prices in comparison across sectors and countries, (Krane 2012)



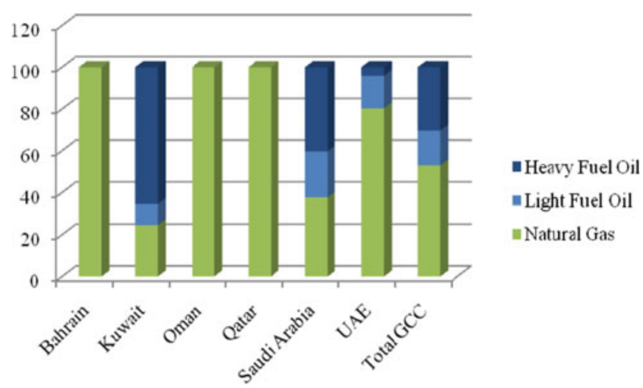


Fig. 17.12 Percentage of oil and NG used in EP production in the GCC, (El Katiri 2011)

EP generation by adding heat recovery steam generators and steam turbines to the simple gas turbine (GT) cycle, thereby creating a GT combined cycle (CC) and increasing efficiency from 30 to 45%. A second obvious measure is replacing current desalination methodologies for DW production with more energy efficient systems. EP generation companies should purchase their fuel at prevailing international costs; final cost to consumers should be calculated accordingly.

Building energy codes should be introduced to reduce AC cooling loads, such that peak demand is decreased by up to 50%. Buildings consume as much as 2/3 of produced EP: strict energy codes that reduce the cooling load should be applied. The notion that fuel is abundant and lasting is false.

17.3 Water

17.3.1 Renewable Water Resources and Their Abstraction

In spite of its energy wealth, GCC is an arid region, in the 'minimum survival level' range, with RWS of less than 100 m^3/y.ca (Table 17.6). The quantity of GW is far below the poverty line of 1000 m^3/y.ca, yet over-exploited and of deteriorated quality. Due mainly to continuous population growth, reported values for RWS (m^3/y.ca) during 2002–2010 declined: 164 to 92 in Bahrain, 8 to 7 in Kuwait, 88 to 33 for Qatar, 102 to 87 in SA, 51 to 20 in UAE, and 212 to 87 in Yemen, (FAO 2011, FAO 2012).

Water is essential for food production, household use, and industry. Its scarcity in the GCC poses severe challenges: the high costs of generating DW and TWW. The challenges are worsened by tapping non-renewable GW sources, depletion and pollution of GW, degradation of soil in irrigated areas, and wasteful use of developed water supplies (as encouraged by subsidies and distorted incentives influencing water use). Population growth and improved standards of living contribute to increased water demand for the production of food. While domestic and industrial sectors use far less water than the agricultural sector, consumption in these two sectors is rapidly growing and uncontrolled. SA suffers the greatest gap between renewable supply and demand, with only 2.4 km^3/y of

Table 17.6 Threshold values: water stress within a region (in m^3/y), (Praveena 2010)

Characteristics	Threshold	Situation
Water Surplus	>10,000	Sustainability of water after fulfilling the needs of all aspects of the economy
Water Abundant	> 4000–10,000	Able to cater to the needs of all sectors of the economy and also for the future
Adequate	>1700–4000	Water sufficient to meet the present needs of the economy
Water Stress	<1700	The economy or human health may be harmed due to lack of proper drinking water, health and sanitation Chronic
Water Scarcity	<1000	Frequent Water shortages both short term and long term
Absolute water stress	<500	The region completes its water supply by desalting seawater and over exploiting aquifers
Minimum Survival level	<100	Water supply for industry and commercial purpose is compromised so as to fulfill demand for all other uses
Water stress	>20%	Severe water supply problems, Reusing wastewater, overexploiting aquifers (by 2–30 times), desalinating seawater

RWS, yet SA consumes 23.67 km^3/y of RWS. Estimated RWS in Qatar, for example, was 58 Mm^3/y, and per capita average share in 2010, was 33 m^3/y.ca (FAO 2011, 2012). Total water withdrawal in 2009 was 400–444 Mm^3/y (almost 7 times its replenishment rate). The withdrawal includes 236 Mm^3/y for agriculture, 8 Mm^3/y for Industry, and 156 Mm^3/y for domestic use, resulting in severely over-exploited GW. As shown in Tables 17.7, 17.8, and 17.9, the situation throughout the GCC is very similar (Sadik 2012). Another growing concern is deteriorating GW quality. The brine produced by certain farm processes is discharged back into the ground, raising the salinity of the remaining GW, which is later deployed for irrigation and other agricultural uses, thereby further increasing soil salinity (Loy et al. 2018; Tahtouh et al. 2018). Substantial parts of GW reserves show salinity levels above levels suitable for irrigation.

Fossil GW is finite and irreplaceable once mined: it is a national wealth. Of 24,000 farms in Abu Dhabi and the Western and Al Ain regions of the UAE, nearly 8,000 are abandoned (or near abandonment) (Malek 2013). Concern is growing about the quantity and quality of GW. In Qatar, over-exploitation resulted in depletion of GW resources, deteriorated water quality and abandonment of some farms, Fig. 17.13, (Qatar National Vision 2030, 2009). As the water table falls, remaining water becomes more saline, with consequent, devastating effects on agriculture. Alternatives, such as desalination, are very expensive. Although mining GW may appear useful in the short term, it is a genuine loss in the in the longer term.

17.3.2 Water Demand

Water demand in GCC is continuously rising: consumed water per capita is among highest in the world. The 2012, DW production in Qatar was about 1.2 Mm^3/d, GW withdrawal about 0.68 Mm^3/d, and total water withdrawal

Table 17.7 Renewable water resources and per capita share in the GCC, (Sadik 2012)

Country/ Sub-region	Natural water resources (M m^3)	Average share (m^3/capita)		
		2010	2030	2050
Bahrain	116	92	70	64
Kuwait	20	7	5	4
Oman	1400	503	389	374
Qatar	58	33	24	22
Saudi Arabia	2400	87	62	53
United Arab Emirates	150	20	14	12
GCC	4144	95	68	59
Yemen	2100	87	51	34
GCC and Yemen	6244	92	61	47

Table 17.8 Water withdrawal and uses of natural water (2009) in the GCC, (Sadik 2012)

Country/Sub-region	Withdrawal	Agriculture	Industry	Domestic
	million m^3			
Bahrain	400	180	24	196
Kuwait	900	486	18	396
Oman	1300	1144	26	130
Qatar	400	236	8	156
Saudi Arabia	23,700	20,856	711	2133
United Arab Emirates	4000	3320	80	600
GCC	30,700	26,222	867	3615
Yemen	3600	3276	72	252
GCC and Yemen	34,300	29,498	939	3863

Table 17.9 Water withdrawal in the GCC as percent of annual fresh water resources (2009), (Sadik 2012)

Country/Sub-region	All uses (%)	Agriculture use (%)
Bahrain	344.8	155
Kuwait	4500	2500
Oman	92.3	82
Qatar	689.6	407
Saudi Arabia	987.5	869
United Arab Emirates	2666.6	2213
GCC	740	633
Yemen	171.9	156
GCC and Yemen	549.3	472

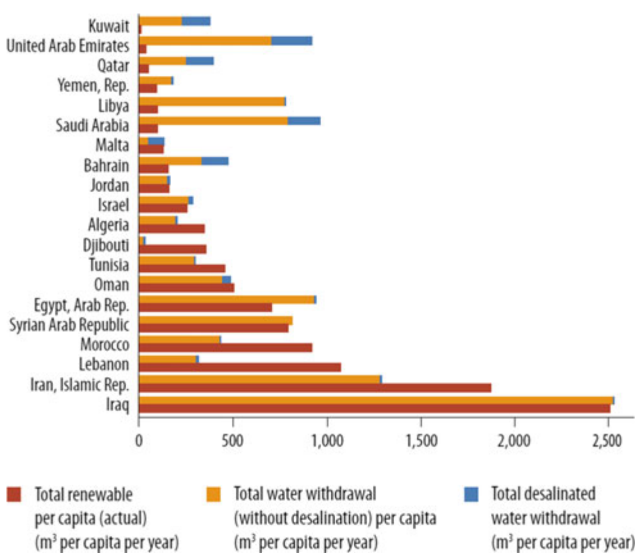


Fig. 17.13 Renewable fresh water, water withdrawal, and DW in Arab countries including GCC, (World Bank 2012)

1.88 Mm^3/d. For a population of less than two million in that year, the daily consumed municipal water, in liters per capita (l/d.ca), was more than 600; total water withdrawal was more than 940 l/d.ca. SA and UAE consume respectively, 91 and 83% more water per capita, than the global average and about six times more water than the U.K. Water consumption in Qatar and Oman are also above the global average, despite their desert climates (Booz & Co 2012). The situation is similar in other GCC locations. Tariff reforms, restricting agricultural usage and adoption of new technologies must be considered to limit water over-consumption and enforce more conservative household and business use. The situation is similar throughout GCC, (Fig. 17.14, IBRD/World Bank 2012) where water withdrawal (GW and desalinated in yellow and blue, respectively) is much more than the RWS (in brown). GW extraction is even greater than DW. This is not sustainable: GCC partners should develop a sustainable water supply strategy.

Water tariffs should be reformed to limit subsidies to basic water needs. Any water consumed, beyond basic needs, should be considered wasteful and penalized by charging its full cost to customers. Currently, DW generation is used to meet growing water demand in the GCC. DW is very costly, energy-intensive, and negatively impacts the environment: it is not a solution to the problem.

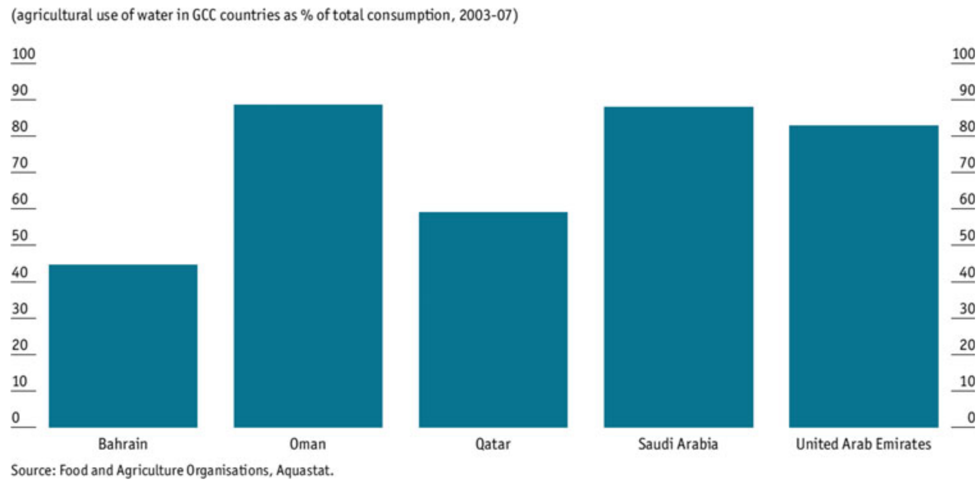


Fig. 17.14 Agricultural use of water in GCC countries as % of total consumption, 2003–07, (The Economist 2009)

17.3.3 Water Use in Agriculture

A primary share of water withdrawal is directed to agriculture (Fig. 17.14, FAO 2011) despite this sector minimal contribution to GDP. Agriculture should be limited to areas with RWS and should concentrate on crops that require less water. Efficient irrigation technologies should be adopted. SA should phase out locally produced wheat by 2016 and discourage its production to reduce the burden such production imposes on SA's water resources. Irrigation technologies in Qatar, involving flooding fields and leading to high evaporative loss, should be replaced by more efficient technologies like drip irrigation, which has a much higher yield per unit of water.

17.3.4 Recycled Treated Wastewater

Municipal wastewater (WW) should, in any case, be treated before disposal to sea or land. With slight additional treatment, its reuse in agriculture or any other application becomes plausible. WW reuse combines the benefits of freshwater conservation, GW resource protection, and total water supply augmentation. Table 17.10 shows that only very limited amounts of total withdrawal are currently treated in GCC (Water Reuse in Arab World 2011): more wastewater should be treated and reused. Treated wastewater (TWW), is a guaranteed, valuable water resource that increases with population growth. It can provide a high percentage of total domestic water use (up to 80% in Israel). However, delivering recycled water to every potential user requires infrastructure: investments are needed to extend collection and treatment networks and to allow public awareness campaigns for increased acceptance of TWW. In Qatar, TWW accounts for only 14.9% of water use; nearly 40% of treated effluent is discharged into septic lagoons.

The GCC should make far more extensive use of TWW, which costs about one quarter of DW (Qatar National Development Strategy 2011; Bhojwani et al. 2019). Water demanded for irrigation can be satisfied by properly treated wastewater, rather than further depletion of already over exploited and irreplaceable GW. TWW produced with tertiary level treatment of municipal wastewater was found adequate for irrigating ornamental plants and fodder; it may also be suitable for irrigating trees. More advanced treatment technology is required for irrigating crops intended for human consumption and for recharging groundwater aquifers. Qatar lags behind UAE and Kuwait in utilizing TWW as a water resource (Table 17.10). In Qatar, only 14.9% of the produced wastewater (about 90% of domestic water supply) is treated, but only 65% is reused. In UAE and Kuwait, 91 and 95.6% of wastewater produced is treated, and 55% and 33% reused. In Qatar, Doha North Sewage Treatment Plant, under construction in 2010, will have a peak capacity to treat wastewater of 439,000 m^3/d. This will be the largest wastewater treatment and reuse facility in Qatar. It is clear that treating wastewater to such levels carries a cost (Fig. 17.15), but the cost remains far less than desalination of seawater (IRDB-WB 2012).

In Abu Dhabi, roughly 550,000 m^3 of wastewater is generated daily and treated in 20 wastewater treatment plants. Facing further urban growth, the government has embarked on the Strategic Tunnel Enhancement Program: a new 40-km wastewater tunnel meant to accommodate increased wastewater flows and result in increased opportunities for reuse in agriculture. While costs vary according to quality and transportation, one m^3 of treated effluent in Kuwait costs $0.66 to bring to potable condition, while the cost of a cubic meter of desalinated water produced thermally exceeds $3/$m^3$. The health-risk to consumers of agricultural goods produced from untreated or inadequately treated wastewater and from GW polluted by infiltration of contaminated irrigation water.

Table 17.10 Water withdrawal, wastewater produced, treated wastewater, and reused TWW, (Water Reuse in Arab World 2011)

Countries	Total water withdrawal (10^9 m^3/ year)	Total wastewater produced (10^9 m^3/ year)	Volume of treated wastewater (10^9 m^3/ year)	Volume of Treated water reused (10^9 m^3/ year)
Saudi Arabia	23.67 in 2006	0.73	0.652	0.166
Bahrain	0.3574	0.0449	0.076	0.0163
Egypt	68.3	3.76	2.971	0.7
UAE	3.998	0.5	0.454	0.248
Iraq	66	0.575	0.098	0.0055
Libya	4.326	0.546	0.04	0.04
Jordan	0.941	0.117	0.111	0.102
Kuwait	0.913	0.25	0.239	0.078
Oman	1.321	0.098	0.037	0.0023
Qatar	0.55	0.444	0.066	0.043
West Bank/Gaza	0.418	0.05	0.03	0.00544
Yemen	3.4	0.074	0.046	0.06

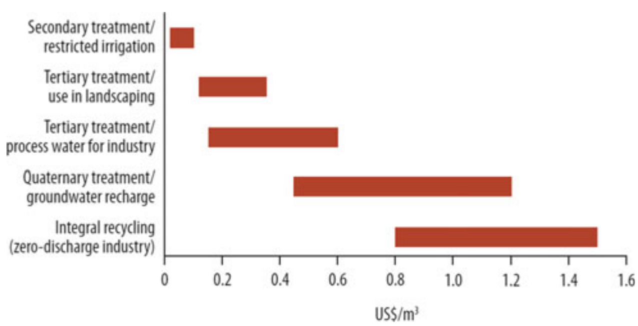


Fig. 17.15 Cost range for water reuse, (World Bank 2012)

17.3.5 Desalinated Seawater (DW)

Desalinated seawater generated in GCC has drinking water quality and is the main source of municipal water in most of the GCC. DW is used directly or blended with low percentage of GW (1% in Qatar, 4% in Kuwait). Despite its cost, DW is often the only option in GCC to secure municipal water. Between 2000 and 09 desalination added 325 Mm^3/y in Qatar, 20,439 Mm^3/y in SA, 3,370 Mm^3/y in UAE, 763 Mm^3/y in Oman, 508 Mm^3/y in Kuwait, and 226 Mm^3/y in Bahrain (World Bank 2012). There is strong link between water and energy consumption because of the large share of DW consumed: 99% and 93%, and about 66% of municipal water in Qatar, Kuwait and SA, respectively. Additionally, DW is transported long distances from inland production plants, further increasing costs through additional energy consumption.

In 2010, GCC DW capacity was 39% of world production capacity, with 68% thermally operated processes, and 32% seawater reverse osmosis (SWRO). The number of desalination plants is increasing (Fig. 17.16, Ansari 2013), in spite of DW being an energy intensive process that negatively impacts the environment. One quarter of Saudi oil and gas production is used locally to generate EP and DW; this fraction could reach 50% by 2030 (Arab Water, 2010). Desalination capacities (Mm^3/d) in 2011 were: 12.5 in SA, 9.5 in UAE, 1.7 in Kuwait, 1.9 in Qatar, 1.6 in Oman and 1.4 in Bahrain. GCC's estimated production of DW in 2012 was 26.937 Mm^3/d: 17.245 Mm^3/d through thermally operated processes such as multi stage flash (MSF) and multi effect thermal vapor compression (ME-TVC), and 9.690 Mm^3/d by SWRO (Table 17.11 Desal Data, 2013).

Taking fuel energy consumption per m^3 for MSF and ME-TVC systems at 200 MJ/m^3 and for SWRO as 50 MJ/m^3 (Darwish et al. 2010), the GCC's 2012 fuel energy consumed by thermal desalination was 3.49 MGJ/d, equivalent to 0.5654 Mbbl/d at daily cost of $56.54 M/d, when the barrel cost is taken at $100/bbl. Similarly, for SWRO, the product is $7.93 M/d, or a total of $64.48 M/d or $ 23.557 billion per year for fuel cost only. When NG is used in place of oil, fuel energy costs can be about 50% less. [Fuel cost/m^3 produced by SWRO is $0.825/$m^3$ with specific consumption of 5 kWh/m^3, and about $ 3.3/m^3 for thermal processes.] If fuel cost alone represents 70% of the total DW cost, the annual cost of DW production in GCC is $ 33.65 B, or $ 3.42/m^3, much more than $ 1/m^3 reported in literature, which is for SWRO below 4 kWh/m^3 of specific consumption.

DW carries a very heavy economic burden. Qatar consumed 373 Mm^3/y DW in 2010 at a cost of $ 1.275 B. It is expected to reach $ 2.55 B before 2020. Yet, there are

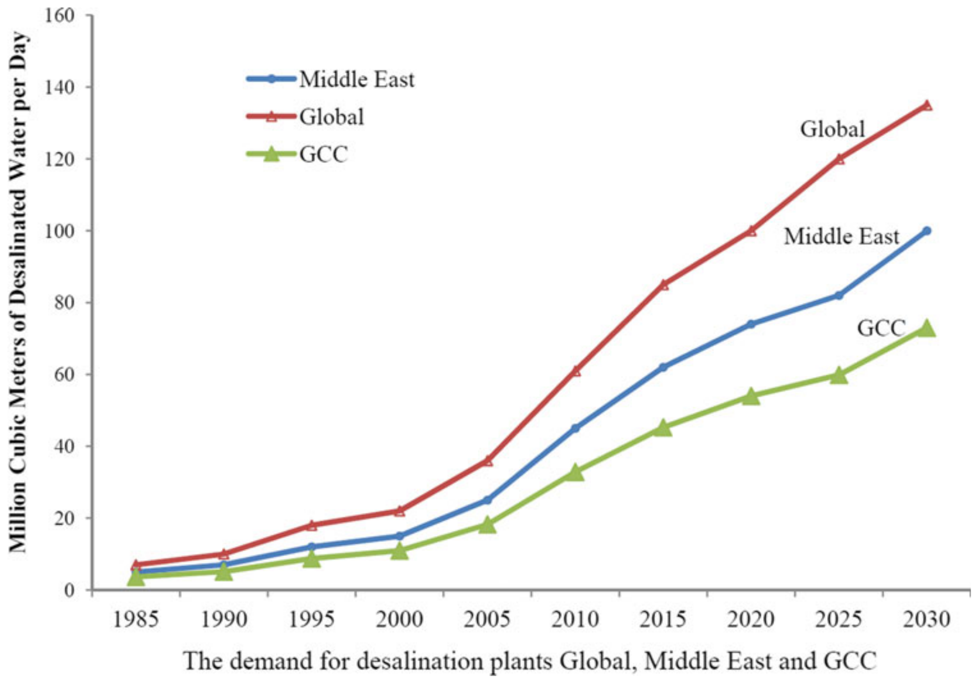


Fig. 17.16 Current and expected demands for DW in GCC, Arab countries, and world, [Ansari 2013]

Table 17.11 The 2012 estimated daily desalted water production in the GCC [Desal Data 2010)

Country	Thermal + SWRO + BW	Thermal processes	SWRO
SA	13,530,973	5,426,131	5,479,792
UAE	9,753,024	7,411,069	2,209,065
Kuwait	2,134,253	1,461,136	275,254
Qatar	1,944,195	1,771,638	155,160
Oman	1,626,149	417,990	988,888
Bahrain	1,398,064	756,967	582,667
Total	**30,386,658**	**17,244,931**	**9,690,826**

several ways to reduce the cost of DW production. First, SWRO technologies are more energy efficient and should be used in place of the currently used MSF and ME-TVC systems. Using relatively cheap NG fuel, compared to oil, will further reduce DW production cost. The DW quality is sufficiently high to justify limiting its use to cooking and drinking; TWW should be used for applications not requiring such high water quality, i.e. toilet flushing, gardening, etc. The 600 l/d.ca municipal water consumption reported for Qatar is far beyond that of other countries: 246, 215, and 104 l/d/ca in US, Sweden, Netherlands respectively (Gleick 1966). Kuwait and UAE have similarly high per capita water consumptions, while the lowest in GCC is Oman at 146 l/d.ca (Al Rukaibi 2010). *S*ubsidies should be allowed only to cover basic water needs, not for excess use of water. In order to stop high rate of waste, stricter regulations regarding efficiency of everyday usage for fixtures (faucets, showerheads and toilets) should be applied. GCC governments should restructure their water tariff policies so that pricing follows usage, and heavy users pay the most for excessive quantities. Such pricing would both increase economic efficiency and reduce waste.

17.4 Food

17.4.1 Food, Arable Land and Water Shortage

There is a huge disparity between consumed and produced food, with the percentage of arable land at 1.7% (SA) and 3.0% (UAE), compared to 18.4% (US), 23.7% (UK), 16.3% (China) and 51.6% (India). SA leads the GCC in food production, providing cereals, vegetables, fruits, poultry, and dairy products. The UAE and Qatar produce mostly fruits, vegetables and fish; Kuwait mostly vegetables and fruits. Oman is a major producer of fish and Bahrain produces fish and red meat. Food production in the region totaled 11.2 million metric tons in 2007 (Alpen Capital 2011).

Nevertheless, GCC countries still rely heavily on imports to meet most of their food needs, as much as 37.2 M metric tons in 2007, more than three times the amount of food produced locally. In 2010, the self-sufficiency in cereals stood at 1.01% (Qatar), 1.61% (Kuwait), and 22.92% (Yemen) (Arab Agriculture 2011).

The drive to increase food production resulted in over-exploitation of already scarce GW resources. In Qatar, many farms ceased production due to depleted GW. The cost of importing the deficit in food was $ 25.8 B in 2010, over 3% of the region's GDP, with SA accounting for 65% of the value. The cost of food imports is expected to reach $ 53.1 B by 2020, with SA accounting for two-thirds of the total (Table 17.7). Soaring food prices in 2007, and 2008, (Fig. 17.17, Alpen Capital 2011) motivated GCC governments and private investors to explore wide-ranging purchases of arable land for agricultural production around the world.

The forecast for per capita food consumption in the GCC region is expansion at an annual growth rate (AGR) of 2.1% from 2011 to 15 (Fig. 17.18); this must be compared to an estimated AGR of 0.9% over 2007–2010 (Fig. 17.19, Alpen 2011). This increase in the pace of overall food consumption is due to fast growing population and rising income. An AGR of 4.6% over 2011–2015, is expected to reach 51.5 M metric tons in 2015 (compared to 4.1% in 2007–10) (Alpen Capital 2011). Historical food imports in GCC (EIU 2009) and types of foods imported to Qatar are shown in Figs. 17.20 and 17.21 (GCC 2020, 2009). The estimated value for GCC imports to member countries (Table 17.12) suggests that the cost of imports will increase more than 40% in 2010–15 (Alpen, 2011). Water scarcity makes domestic agricultural production very costly. SA plans to phase out domestic wheat production by 2016 (The Economist 2010). The GCC has taken initiatives to enhance domestic production while, at the same time, secure food imports through international agricultural investments.

The ratio of food imports to consumption in 2007 are shown in Table 17.13: GCC partners were nearly fully dependent on imported food for requirements of wheat, rice,

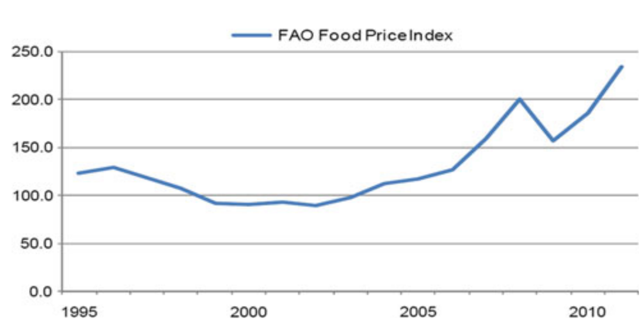


Fig. 17.17 Food inflation rise after falling in 2009, (Alpen Capital 2011)

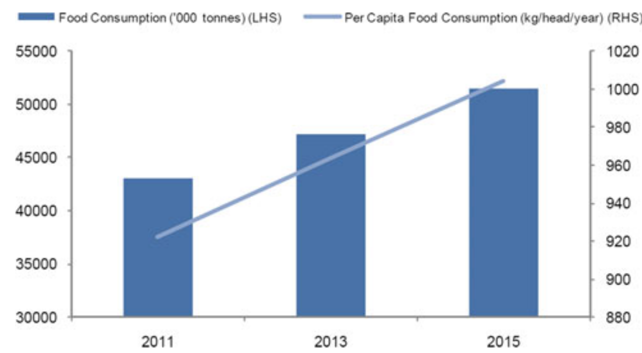


Fig. 17.18 GCC food consumption, per capita consumption, [Alpen Capital 2011]

and pulses. The only exceptions were SA (which met its wheat demand through production), Bahrain and Oman (both of which exported a surplus of fish). Despite all GCC efforts to increase local agricultural production through financial assistance and subsidies, the 2008 agricultural input to GDP was 0.5% (Bahrain), 0.1% (Qatar), 0.3% (Kuwait), 1.4% (Oman), 0.9% (UAE) and 2.7% (SA) (GCC Agriculture 2010). The percentage of the arable to total land area was 2.9% (Bahrain), 1.6% (Qatar), 0.8% (Kuwait), and 0.1% (Oman), 0.8% (UAE) and 1.7% (SA) (Alpen Capital 2011). GCC percentage of population engaged in agriculture varies: between 1997 and 2006 it ranged from 0.8% (Qatar) to 9.1% (SA), with Oman being an exception at 35.4% (GCC Agriculture 2010).

For various reasons, arable land has decreased from about 0.2 ha per capita in 1961 to less than 0.15 ha per capita in 2003. Most GCC partners completed national soil maps to identify the percentage of land highly to moderately suited for large-scale irrigation farming, these figures are: 13.7% (SA), 7.07% (Oman), 3.5% (Kuwait), 5.4% (UAE) and 3.9% (Qatar), (GCC Agriculture 2010). The question is whether the GCC has sufficient water resources to farm these areas.

17.4.2 Water Requirements for Food Production

International norms established by the World Health Organization and UNICEF hold that each person requires a minimum of 20 l/d of water for drinking and basic hygiene. While daily drinking water requirements per person are met at 2–4 L, between 2 and 5,000 L of water are required to produce one person's daily food (United Nations University 2013). Michel et al. (2012) gave the amount of water required to produce one kilogram of selected commodities: wheat 1827 l, barley 1423 l, olives 3015 l. Producing dairy, meat, and poultry can be even more water intensive and necessitate appreciable amounts of freshwater to grow feed, provide drinking water, and care for the animals. The

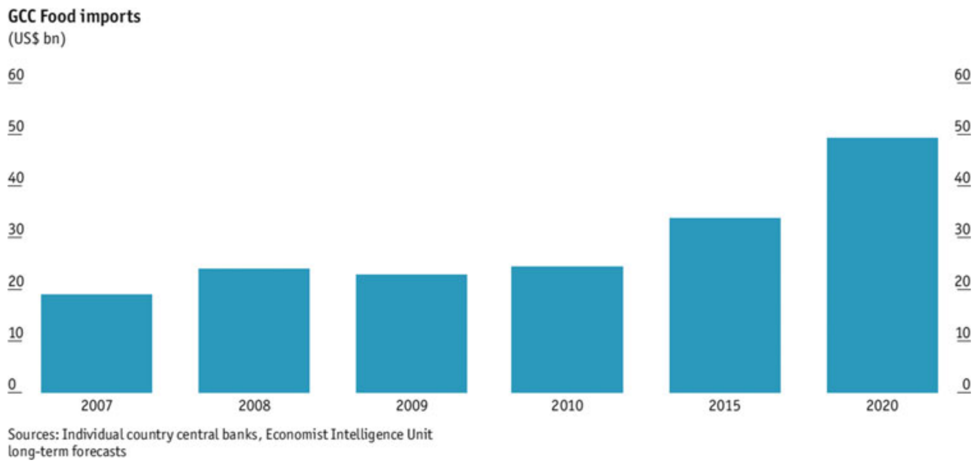


Fig. 17.19 The historical food imports to the GCC, [The Economist 2009]

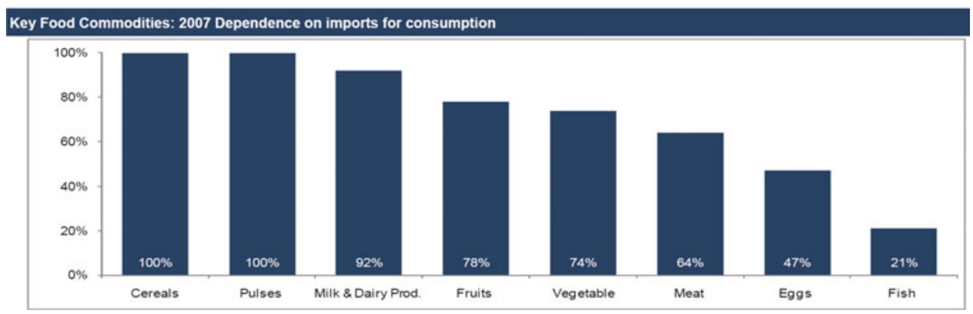


Fig. 17.20 Percent of food commodities depends on imports in 2007, [Alpen Capital 2011]

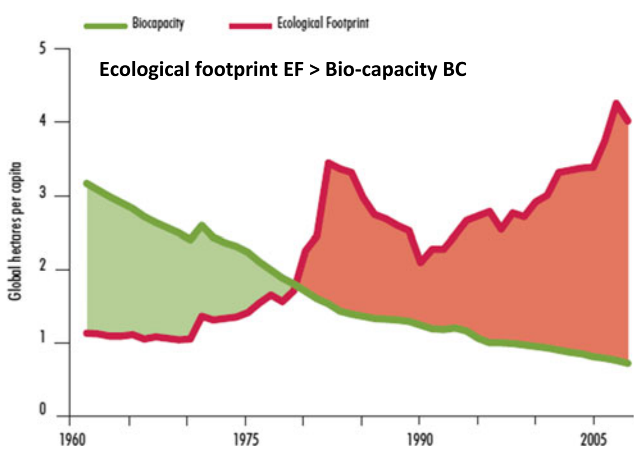


Fig. 17.21 Ecological Footprint and Biocapacity (gha/capita) in GCC Countries, 1961–2008, [Saab 2012]

average water demanded to raise one kg of beef (l/kg) is 15,415 and corresponding amounts (l/kg) are 10,412 for lamb, 3265 for eggs, and 1020 for milk. SA used about 3,000 m^3 water per ton of wheat produced, three times the global norm, (Mitchel et al. 2012). DW is very expensive for agricultural use; most of the water used for agriculture in the GCC is drawn from aquifers and treated wastewater. The GCC is using more water than they have.

GW accounts for about 36% of water used predominately for agriculture in Qatar (Qatar General Indicators 2011). These resources are rapidly dwindling: many wells have ceased to provide the previous quantities or quality; in some cases, the government has prevented further exploitation. Recycled water (TWW), the only water 'surplu' in Qatar, accounts for only 14% of water used in irrigation. TWW can and should play larger role in industrial processes, district cooling and watershed management.

The GCC's dependence on external markets for its food needs creates vulnerability, not only to price fluctuations but also to changes in food policies of exporting countries, such as blanket bans on export of certain food commodities. Solutions to this problem should focus not only on imports and agricultural policy, but also on integration of food security with energy and water policies directly affecting food security. TWW is a resource that should be utilized for agriculture, directly and through aquifer storage and recharge.

Dependence on current DW technologies to produce food, along with current agriculture practice, will lead to prohibitively expensive food products. Calculating a realistic cost of food production requires including both water and energy in the formula. It is certainly not acceptable to produce a kg of potatoes by consuming 0.5m^3 of desalinated

Table 17.12 GCC Food Imports Estimates (USD billion), [Alpen Capital 2011]

Country	2010E	2015E	2020E
Bahrain	0.7	1.1	1.6
Kuwait	2.3	3.6	5.3
Oman	2.1	3.3	4.8
Qatar	1.3	2.1	3.3
SA	16.8	24.5	35.2
UAE	3.6	5.5	8.4
GCC total	25.8	36.3	53.1
Country	2010E	2015E	2020E

Table 17.13 Food imports as a proportion of consumption (2007), (Alpen Capital 2011)

Country	Bahrain (%)	Kuwait (%)	KSA (%)	Oman (%)	Qatar (%)	UAE (%)	GCC (%)
Wheat and flour	100	99	2	99	100	100	39
Maize	100	92	91	100	93	100	92
Rice	100	100	100	100	100	100	10
Barley	100	96	100	92	98	100	100
Potatoes	100	17	−2	76	100	91	19
Pulses (total)	100	100	100	100	100	89	98
Vegetables (total)	78	41	22	36	86	62	37
Fruits (total)	77	73	35	23	77	47	40
Meat (total)	62	62	44	73	89	80	56
Fish	−51	64	40	−74	36	29	16
Eggs	43	37	−4	53	63	62	19
Milk & Dairy Products	91	92	72	64	93	83	77

Table 17.14 Energy required to deliver 1 m^3 of clean water from different sources, (Cramwhinkel 2011)

Source	Energy required (kW-h/m^3)
Lake or river	0.37
Groundwater	0.48
Wastewater treatment	1–2.5
Wastewater reuse	0.62–0.87
Seawater	2.58–8.5

water generated by MSF at cost of \$ 3.5/m^3. The same applies for meat, milk, wheat production, etc.

17.5 Examples of the Water, Energy, and Food Nexus in GCC

The nexus between water, energy and food is expressed in the huge discrepancy between the bio-capacity (BC) and the ecological footprint (EF). BC measures the bio-productive supply available within a certain area of arable land, pasture, forest, productive sea. EF uses prevailing ecology to measure how much bio-productive area (land or water) a population requires to sustainably produce the renewable resources it consumes, and absorb the waste it generates. When EF is larger than BC, renewable resource accounting results in deficit (no sustainability). When EF is smaller than BC, an ecological reserve exists. EF decreases as population declines and/or as higher resource use efficiency, or technology, prevail (Schaefer et al. 2006).

Figure 17.22 shows the history of EP and BC in the GCC, and indicates the deficit in ecological resources since

1980. Although the GDP has significantly increased in GCC, this is not sustainable. The Arab Ecological Footprint and Bio-capacity Atlas analyzes the demand for resources (footprint) and available supply (biocapacity), expressed in global hectares (gha). It shows that there is a vast deficit in the region's ecological resources, largely bridged by imports and over-exploitation of finite local resources: an unsustainable strategy. Dependence on global trade imports introduces concerns of economic insecurity, often driven by soaring food prices, disruption in global supply chains, and trade restrictions. Carrying debt to finance imports burdens economies and limits future wellbeing (AFED 2010 and 2012).

The SWRO consumed energy is almost 1.2 times the energy consumed by the feed water pump, or 4.728 kWh/m^3. This power consumption depends on feed water temperature, see Fig. 17.23, and the seawater salinity, which varies with time (Water Reuse Assoc 2011).

Energy efficient SWRO should be the only method used for desalting seawater: its pumping energy is low (about 4–6 kWh/m$^{3)}$ and the desalting cost is in the range of \$1–1.5/m^3. The high cost of producing DW by thermal technology is the reason behind its decreasing share: from about 55% in 2003 to 34.8% in 2012, (see Figs. 17.24a, b, Tonner 2011).

There is a link between food prices and energy prices. In 2007–08, world oil prices dramatically increased to reaching about US\$150 per barrel at its peak. According to FAO, the higher fuel costs increased production and transport costs for agricultural commodities. Recent studies have established that energy was a key driver in the food price surge to the highest levels in nearly 50 years, (Energy smart food 2012). The food sector depends on fossil fuels. Energy from fossil fuels increases farm mechanization, boosts fertilizer production and improves food processing and transportation.

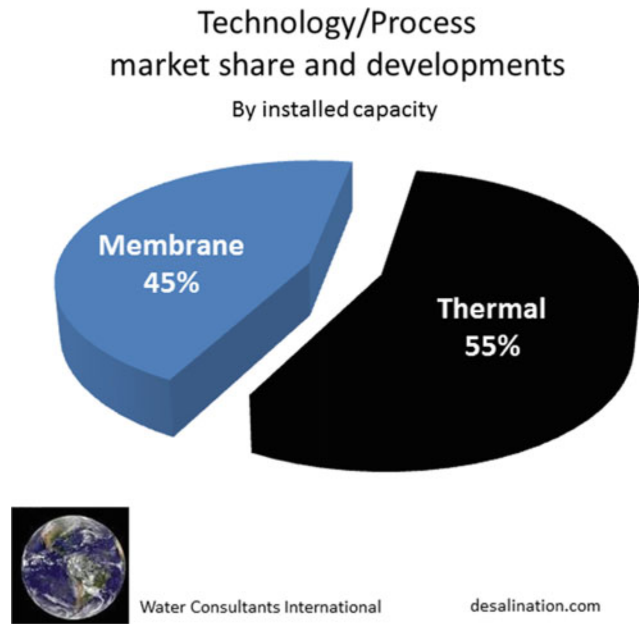


Fig. 17.23 The share of different dealing technologies in 2003

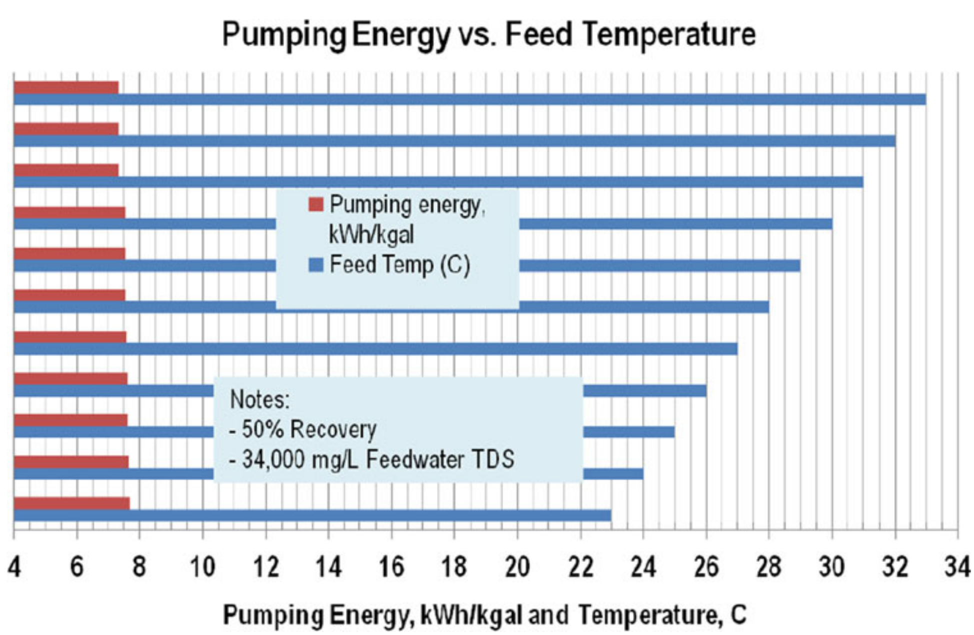


Fig. 17.22 Dependence of pumping energy in SWRO on SW temperature, (Seawater desalination power consumption 2011), one kWh/kgal = 3.75 kWh/m^3

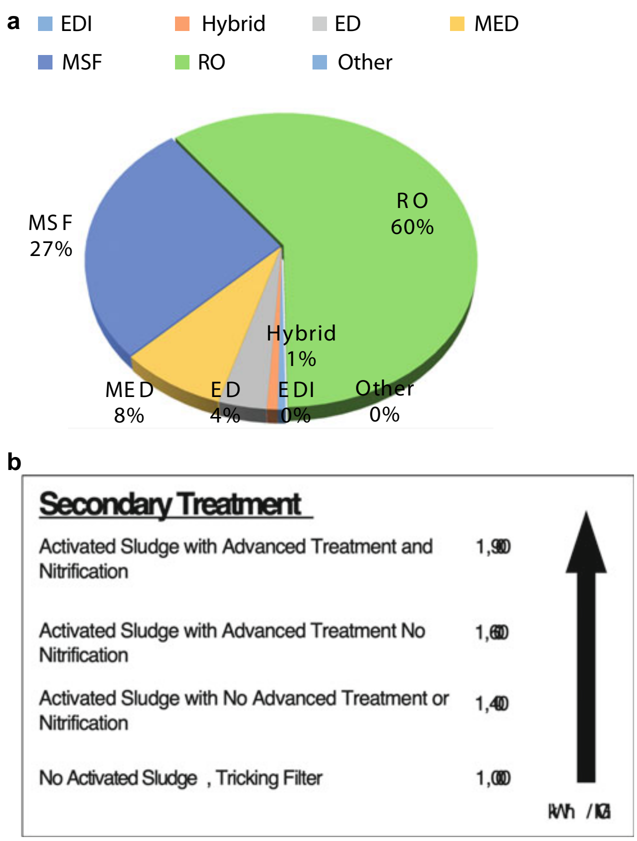


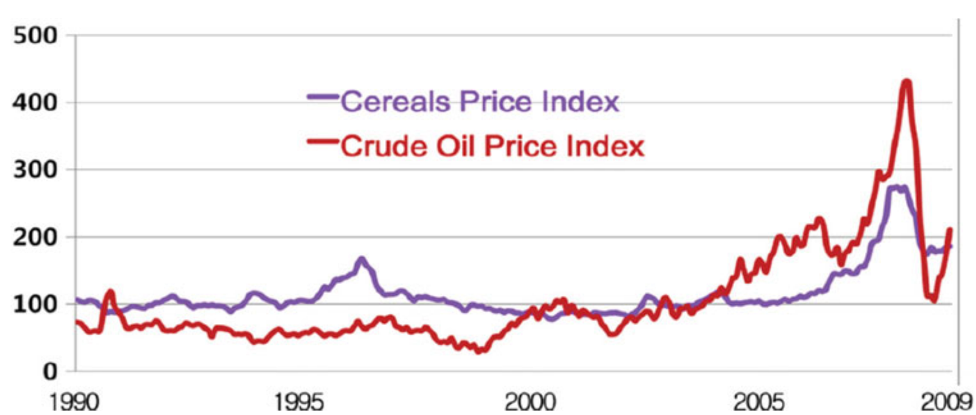
Fig. 17.24 **a** Desalination technology market. **b** Energy benchmarks for selected treatment processes

Commodity prices tend to be linked with global energy prices: as energy prices fluctuate, so do food prices, Fig. 17.25, FAO 2011).

17.6 Treated Wastewater Energy Consumption and Relation with Agriculture Production

Municipal Wastewater (WW) effluent from homes should be treated before disposal to avoid danger to human health and unacceptable damage to natural environment. TWW requires additional treatment before use in agricultural and landscape irrigation, or aquaculture. The quality of TWW effluent affects the performance of the wastewater-soil–plant or -aquaculture system (Loy et al. 2018). The required quality depends on the crop to be irrigated, soil conditions, and the effluent distribution system. TWW used in agriculture should meet the microbiological and chemical quality requirement at low cost and with minimal operational and maintenance costs. Higher-grade effluent may be necessary: design of WWT plants is usually based on reducing organic and suspended solids to limit pollution of the environment. Pathogen removal is an objective for effluents used in agriculture. Constituents that may be toxic or harmful to crops, aquatic plants and fish should be removed. The energy cost in WWT plants is estimated to be as much as 60% of total operating cost (Daw et al. 2012). Figure 17.26 outlines the energy consumption for various WWT processes, and shows how energy demand increases for more complex processes. In this figure energy is benchmarked as kWh per million gallons (kWh/MG), which can be converted to kWh/m^3 by dividing kWh/MG by 3780, as one million US gallons is 3780m^3. Typical energy consumption for a wastewater treatment plant is shown in Fig. 17.27 (Greenberg 2011).

Fig. 17.25 Comparative trends of crop commodity and oil price indices, 1990 to 2009 (baseline, 2004)



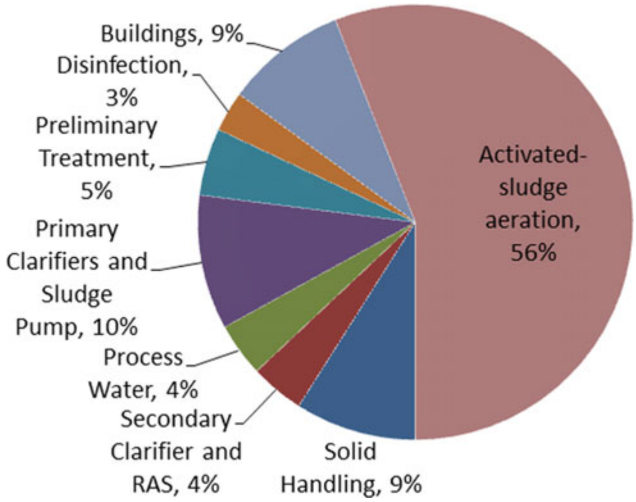


Fig. 17.26 Typical energy consumption for a wastewater treatment plant

17.7 Conclusion

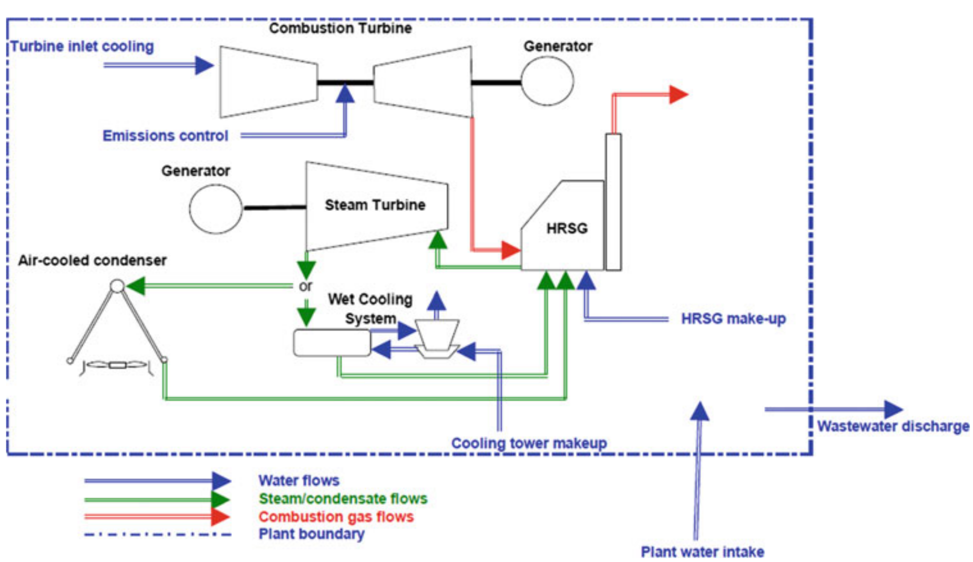
While energy seems abundant, all GCC countries except Qatar suffer a shortage of natural gas to run their PPs. Primary energy (oil and natural gas) resources are finite and consumed at much higher rates than produced. The oil production may also be fully and locally consumed within 2–3 decades if the same high consumption continues. NWS are extremely limited in GCC. Most municipal water needs are satisfied by DW whose production is energy extensive and costly (Bhojwani et al. 2019). Food and water security are major challenges for GCC countries. Minimal local food production is consuming the GW, already of deteriorated quality, and severely depleted. Seventy percent of water withdrawal in the GCC is supplied DW plants. The desalination process is expensive, energy intensive, and negatively impacts the land, air and marine environments (Loy et al. 2019, Tahtouh et al. 2019). The GCC depends heavily on food imports due to insufficient water and lack of arable land. Qatar, the UAE and Kuwait import over 85% of their food requirements, making the growing population of the GCC vulnerable to fluctuations in global food production, trade policies and commodity prices.

Increasing desalination capacity is not a solution to water scarcity. The real value of water, energy, and food must be understood in relation to each other: over-consumption of water and energy are genuine reasons to revisit the values of these commodities. Promoting sustainable agriculture should be studied carefully, in view of water and energy costs, when considering the potential for increasing food production within the GCC (Mohtar and Daher 2019; Bhojwani et al. 2019; Loy et al. 2019; Tahtouh et al. 2019; Mroue et al. 2019).

17.7.1 Greater Implications for the Nexus Approach as a Whole

To date, most of the nexus contributions are abstract; the perspectives presented here are very contextual. The GCC is an ideal nexus case study as it offers a location in which to study the interlinked systems water, energy, and food. The projection and scenarios outlined and already existing in the GCC are those that will be faced, in the future, in other locations. While some have argued that Nexus implementation is easier in countries where decisions are centralized, such as GCC, and it is easier to implement solutions that may not be popular, ultimately there is no choice but to develop a more coherent structure in which to manage our

Fig. 17.27 Schematic of water uses in a combined-cycle plant



primary resources. The authors point to work done by a transdisciplinary team of more than 50 scientists in Texas, USA, and in which the governance structure is quite different from that of the GCC. The lessons learned are positive, and recently published in a special issue of the Journal of the Science of the Total Environment (Mohtar and Daher 2019a; Aldaco-Manner et al. 2019; Daher et al. 2019a, 2019b; Mohtar et al. 2019). These lessons are briefly outlined here.

1. There are economic incentives for implementing the system level solutions proposed by the Nexus.
2. There are savings in primary resources to be gained by using such holistic solutions for water, land, energy.
3. The challenges posed by governance issues, must be addressed.
4. The additional challenges to be addressed lie in communicating and messaging: understanding the tradeoffs inherent in the choices made.
5. A nexus governance cannot be copied across all locations: it must be developed locally, and in adherence to existing culture, awareness, customs, and resources.

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Mohamed Ali Darwish Qatar Environment and Energy Research Institute Hamad Bin Khalifa University, Qatar Foundation Professor Mohamed Ali Darwish is a Mechanical Engineer with a B.Sc. from Alexandria University in 1960, and a Ph.D. from Kansas State University in 1969. He taught desalination in King Abdel Al-Aziz University from 1976 to 1985 and in Kuwait University from 1985 to 2009. He worked as a consultant to the Kuwait Foundation for the Advancement of Science (KFAS) from 2009 to 2011, and in the Qatar Environment and Energy Research Institute from 2011 to present. He has more than 100 publications in peer reviewed journals as well as several books. He received several awards from the Interna-tional Desalination Association (IDA) for outstanding contributions to the field of desalina-tion science, and from the College of Engineering, Kuwait University as a best researcher.

Rabi H. Mohtar , Professor and Dean, Faculty of Agricultural and Food Sciences (FAFS) at the American University of Beirut (AUB) and TEES Research Professor at Texas A&M Uni-versity (College Station), has used over $16M in funded research grants to address global re-source challenges: developing a Water-Energy-Food Nexus framework linking science to poli-cy, characterization of the soil-water medium through thermodynamic modeling, understand-ing the efficacy of non-traditional water using physical-based methodologies. In more than 400 research articles, book chapters, policy briefs, and conferences within the US and global-ly, Mohtar addresses Water, Energy, and Food Security Issues through a Holistic Nexus Ap-proach. He has trained 75 PhD and MSc students from the MENA region, Africa, Latin America, and the United States. He founded and coordinated A&M's Water-Energy-Food Resource Nexus Initiative and the Water-Energy-Food-Health (WEFRAH) initiative at AUB. Both initiatives focus on the needed research and education to address global resource chal-lenges and implement the SDGs. Mohtar is a Fellow of the American Society of Agricultural and Biological Engineers, Executive Board member of the of the International Water Re-sources Association (IWRA), and Governor of the World Water Council. He advises the UN Framework Convention on Climate Change (Momentum of Change), and is a Senior Fellow of the OCP Policy Center. He served on the World Economic Forum Global Agenda Councils on Water Security and Climate Change, was founding director of the Qatar Environment and Energy Research Institute, Qatar Foundation. He is adjunct professor at Texas A&M Qatar and at Purdue University, where he was inaugural director of Purdue's Global Engineering Programs and co-founder of the Division of Environmental and Ecological Engineering.

Examples of Water Resources Management Options: Protective Structures and Demand Management

18

Hans Peter Nachtnebel and K. D. Wasantha Nandalal

Abstract

This chapter provides two different kind of examples illustrating the large variety of potential technical and non-technical options of water resources management. The first set of examples focus on protective infrastructures of flood control. Levees, dikes, polders and other alternatives of flood retention, as well as diversion measures of flood flows are discussed. Design principles, advantages and disadvantages are highlighted along with several solution examples. The second example introduces water demand management and its application in context of urban water supply schemes. It is followed by a review of effectiveness of demand management interventions, including water conservation and mechanisms for regulating water demand and price.

Keywords

Bypass channel • Dams • Design principles • Embankments • Flood plain • Flood risk • Levee • Reservoir • River diversion • Decreasing and increasing block tariffs • Price mechanisms • Pricing • Rationing • Rebates • Water conservation • Water demand management • Water rights

List of Abbreviations

CIRIA	Construction Industry Research and Information Association
FEMA	Federal Emergency Management Agency
IBT	Increasing Block Tariff
ICOLD	International Commission on Large Dams
SCADA	Supervisory Control and Data Acquisition
UNFCCC	United Nations Framework Convention on Climate Change
USACE	US Army Corps of Engineers
USGS	United States Geological Survey
WC	Water Conservation
WDM	Water Demand Management
masl	Meters above sea level

18.1 Introduction

The first part of this chapter (Sections 18.2, 18.3 and 18.4) focuses on the technical solution of flood control and flood protection. Several types of protective structures are discussed. The design and engineering layout of the structures depend on the prevailing hydrological, geological and hydraulic conditions. Further, land use and economic aspects of the river basin are essential factors which influence the choice of technical options. The basics of hydrologic design and construction principles are outlined. Reliability and failure modes of the various systems as well as their benefits and disadvantages are discussed. Protective structures require additional hydraulic equipments, such as weirs and gates for their operation. Dependent on the location within a catchment and the corresponding hydrological conditions different protective structures may be used. Often combinations of different structural schemes are used.

18.1.1 Technical Solutions of Flood Management

Flood protection structures (levees, dikes, reservoirs, bypass channels, river diversions) have been developed already

H. P. Nachtnebel (✉)
Department of Water-Atmosphere-Environment, University of Natural Resources and Life Sciences, Vienna, Austria
e-mail: hans_peter.nachtnebel@boku.ac.at

K. D.W. Nandalal
Department of Civil Engineering, University of Peradeniya, Kandy, Sri Lanka
e-mail: kdwn@pdn.ac.lk

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centuries ago. The oldest examples date back to about 2000 BC and can be found in all the ancient cultures such as in China, India, Egypt and Mesopotamia (Pavol 1982). In general, these structures served local needs such as to reduce the inundation frequency up to a certain level. Today, a basin wide perspective considers local requirements as well as potential adverse impacts for the downstream part of the river. Any water management structure provides economic benefits but has also adverse impacts on the environment. Especially river morphology is changed together with the sediment regime.

Although high annual investments for flood protection measures are reported since decades, at least for the economically developed countries, the documented damages increase substantially while the number of fatalities is decreasing in general (Kundzewicz and Takeuchi 1999; de Moel et al. 2011; Barredo 2009; Paprotny et al. 2018). These facts clearly underline the need for a revised flood risk management strategy considering among several other items a basin wide approach, harmonization of land development in former flood plains exposed to residual flood risks, awareness raising of the concerned people, and non-structural measures.

Structural measures protect an area from flooding up to a certain water level occurring with a low probability. If this level is exceeded the structure fails and, dependent on the design and layout, the system may collapse causing extremely large damages. There are numerous examples throughout the world for levee or dam failures.

In general, flood protection systems either try to limit the inundation area by blocking structures, by increasing the conveyance capacity and by diverting the water quickly downstream, or by retaining the water to reduce the flood peak downstream (Fig. 18.1). According to the principle alternatives displayed in Fig. 18.1 various types of structural measures are discussed subsequently.

No doubt that the choice of technical options to alleviate floods and the damage they cause depend very much on the type of the floods to deal with. Starting with the most upstream part in a catchment settlements along torrents are mainly exposed to flash floods or/and to mudflows, but at least to floods combined with high sediment load. Further downstream, so called riverine flood events dominate which are characterized by their intensity (magnitude) and duration. Sometimes it is necessary to discriminate among summer and winter floods. Local events, like pluvial floods occur independently from any water body when heavy rainfall events exceed the infiltration capacity of the top soil and a surface flow is formed, which floods topographic depressions, often found in urban areas. In lower parts of the catchment groundwater flooding may be also an issue. Such events can occur with some delay after long lasting floods or after subsequent flood events. In coastal zones, also storm surges and sea level rise due to cyclones (and tsunamis) have to be considered.

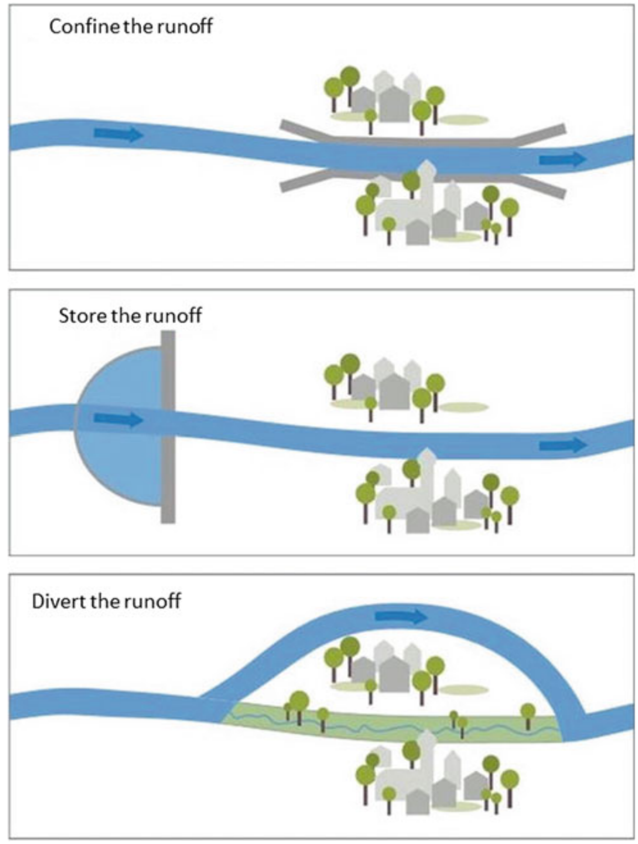


Fig. 18.1 Technical options to cope with river floods (Bayerisches Staatsministerium für Umwelt und Verbraucherschutz 2014)

Sections 18.2, 18.3 and 18.4 present and discuss advantages and disadvantages of different types of protective infrastructures of flood control and management.

18.1.2 Water Demand Management

Demand for water is continuously increasing while water available to cater for the demand is limited. This stresses the importance of effective management of demand for water. The second example presented in this chapter in Sect. 18.5 outlines many strategies that could be implemented to achieve efficient and sustainable use of scarce water resource. Water demand management is a promising option of water resources management especially in case of high value water use, such as municipal water supply.

18.2 Protective Infrastructures: Levees, Dikes and Polders

A levee, dike or embankment is a linear engineering structure along a river, a lake or sea shore to contain, control, or divert the flow of water to confine the inundation area. The term levee, dike or embankment are often synonymously used. The term "dike" emerged from Dutch language while "levee" originated from French meaning that something is raised. Very probably it was incorporated into the English language when flood protection works were implemented in New Orleans. There, the first levee was constructed along Mississippi around 1720. Sea dikes, often closely following the shoreline are developed to protect the hinterland from flooding. Their purpose is the same as river dikes but the technical design differs because of the different forces acting on the structure.

Ring levees completely encircle an area subject to inundation from all directions (Figs. 18.2b, c). Such structures are found in head water areas as well as in lowland part of a catchment. In headwaters they protect only a few farm houses while in low land areas even large cities like Amsterdam or New Orleans are encircled by levees. Dependent on the duration of a flood event and the hydraulic conditions a pumping system is required to keep the protected area dry from seepage and inundation due to local rainfall.

Polder is the Dutch word for an area which is protected by a perimeter levee system (Fig. 18.2c). In low laying areas permanent water management such as pumping out of seeping water is needed to preserve the area from flooding. About one third of the territory of the Netherlands has been reclaimed from the sea by numerous polders (about 3000) which require permanent pumping to keep them drained (Hoeksema 2007). Nowadays polders along our major rivers have gained attraction in flood management as they provide a valuable retention capacity in case of extreme flood events. See also Fig. 18.2b.

Spur levees are considered as training dikes which direct the flow direction during floods and which protect the main levee from erosive processes (USACE 2000).

Setback levees are built landward of existing levees. Their purpose is to subdivide the hinterland into subunits to avoid the flooding of the whole area in case of malfunctioning of the levee. Such levees are also found where a stepwise development of the levee system has occurred.

In general, levees are located landwards from the river banks to ensure a sufficiently wide profile to release floods downstream and to avoid erosive processes acting on the levee body. Open levees ensure drainage of the hinterland (Fig. 18.2b). The downstream point of an open levee together with its height defines the extent of flooding of the riverine land. Usually such systems are used when major areas require permanent drainage and pumping would be too costly. Another application is seen in the case when some wetlands in the former flood plain are exposed to at least partial flooding to maintain their characteristic wetland features.

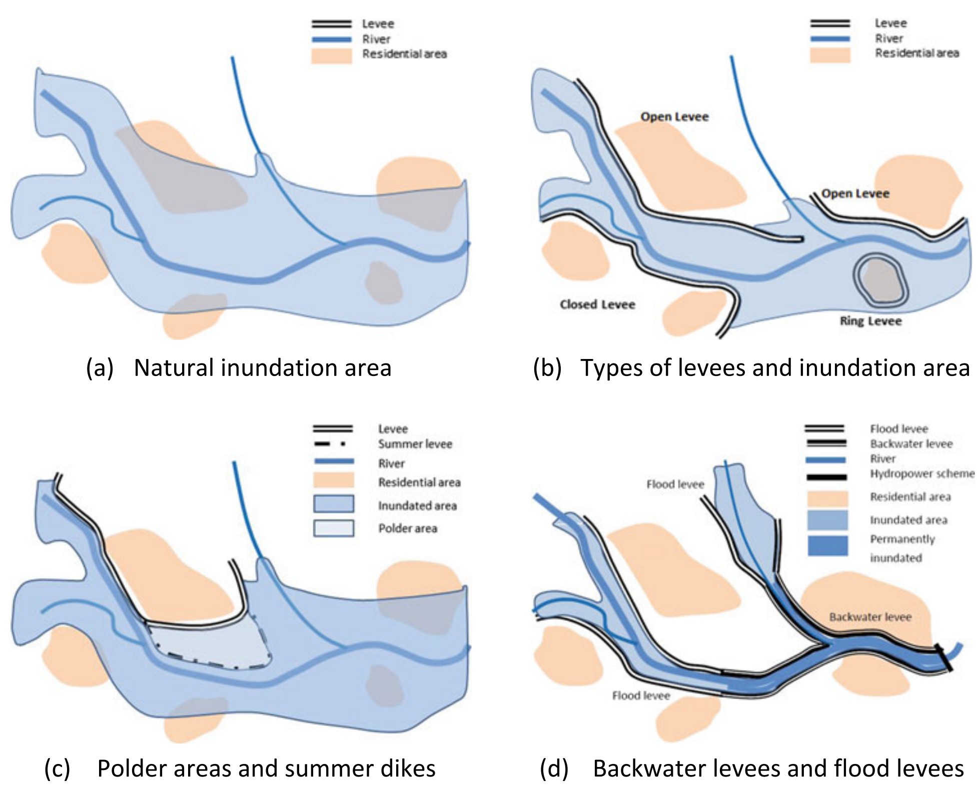


Fig. 18.2 Layout of levee systems

Closed levees together (Fig. 18.2b) with the edges in the terrain encircle an area in the Hinterland and prevent it from flooding, up to a certain load. In this case a small detention reservoir has to be additionally implemented in the protected area to avoid flooding from local rainfall and/or seepage. Further, culverts have to be integrated into the levee to drain the local catchment area. Such culverts are often equipped with automatically closing pipe plugs and secondary closing equipment.

To utilize the flood plain for agricultural purposes a second levee is sometimes implemented in low land areas, the so called summer dike (Fig. 18.2c). It exhibits a lower dike crest and protects part of the flood plain from frequent seasonal flooding that it can be utilized for other agricultural activities. In cities located along the river the levee follows closely the river banks to provide space for intensified land use. This demands for higher levee crests and additional safety measures. Also the management of the groundwater regime could become relevant, especially when levees serve also as backwater dikes (Fig. 18.2d). Such dikes are permanently exposed to a higher water table and require protective layer on the water side as well as careful zoning of the levee together with drainage measures (Fig. 18.2c, d).

18.2.1 Technical Layout and Main Components of a Levee

Detailed descriptions of levee systems can be found in CIRIA (2013). Dependent on the location within a catchment, geotechnical settings and land use patterns in the hinterland different levee systems have been developed from which several will be discussed below.

Sometimes, in the lower parts of large river basins, two levees are found in a river profile (Fig. 18.3a, b) to support land use in partially protected areas. The summer levee is designed with a lower inclination on the land side to resist overtopping. The flood protection levee (winter dike) is situated landwards to provide a sufficient cross section for release of the main floods.

The technical design depends on the stability and permeability of the soil layers in the underground, the height of the levee, duration of flood events, the erosive power of the river system, and dynamics of flood characteristics. In general, homogeneous and structured levee types are discriminated. Often, homogeneous structures are used along rivers. This is due to the fact that many levees were built to protect farm land from frequent flooding and thus, simple structures were implemented (Fig. 18.3b). A simple structured levee consists of an earthen bank that may be constructed with a clay core or cut-off, depending on the underlying foundation material.

The design depends also on the location of a levee within a catchment. A levee which is exposed for longer time to high water tables requires a low permeable core wall with a drainage filter on the land side (Fig. 18.3c, d). Levees exposed to wave actions need to be protected on the water side (revetment), usually by riprap or an asphalt layer (Fig. 18.3d, e). Dependent on the stability and permeability of the soil layers at the construction site underground foundation works such as cut-off walls are obligatory.

A backwater levee or backwater dam (Fig. 18.3f) is permanently exposed to a high river water table and requires careful control of seepage. An interesting engineering design was developed for the backwater levee in the city of Vienna where a hydropower scheme at the Danube has been combined with improved flood protection for the city (Brandl 1997). A construction requirement was to preserve the historical groundwater dynamics to avoid any damage to foundations of buildings. A cellular cut-off wall system has been developed accompanied by two well galleries, one on the water and the other on the land side (Fig. 18.3f). Along a major river section upstream of the power station, the highest water table is reached in low flow periods while during flood events the gates have to be opened to release the flood water downstream. Thus, to preserve the dynamics in the riverine groundwater regime it has to be recharged during floods via the landward well gallery (high discharge) while it has to be pumped during low flow conditions. A set of groundwater monitoring wells is used for ensure proper management. The system is successfully operated since 1996.

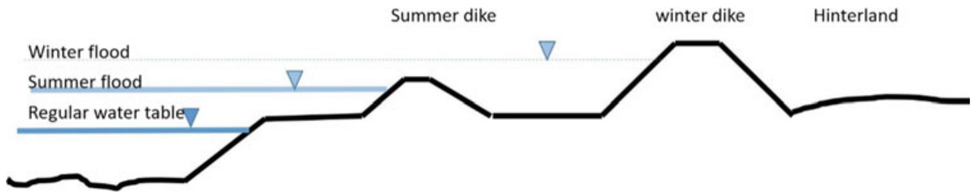
Sometimes, due to limited space, a levee or its upper part is replaced by a protection wall which requires sound foundation works to prevent from erosion or scouring and mechanical stability is needed to resist the water pressure. In urban areas gates (passages) are integrated to provide access to the water front in harmless periods.

Sometimes, embankments are combined with flood walls to increase the protection level of the structure as shown in Fig. 18.4.

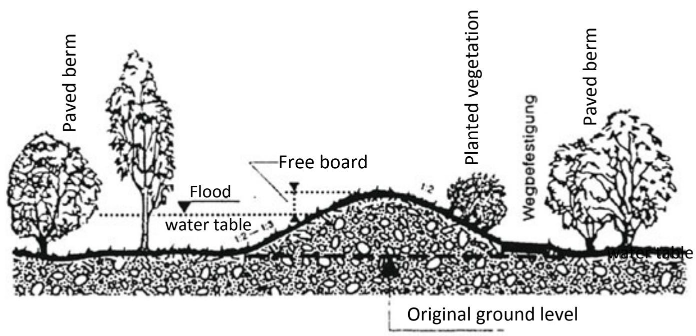
18.2.1.1 Super Levee

The reliability of levees is subjected to several failure modes from which earthquakes need special consideration. The coincidence of an earthquake with a severe flood event is quite low but in some regions, like in Japan, the joint occurrence of such events has to be considered. To minimize the risk of levee failures in densely populated areas the super levee system was developed in Japan. This high standard levee improvement project (a super levee project) was started in 1987 along the six large rivers in Tokyo and Osaka, and later on, in 2011, (Arakawa-Karyu River Office 2013)

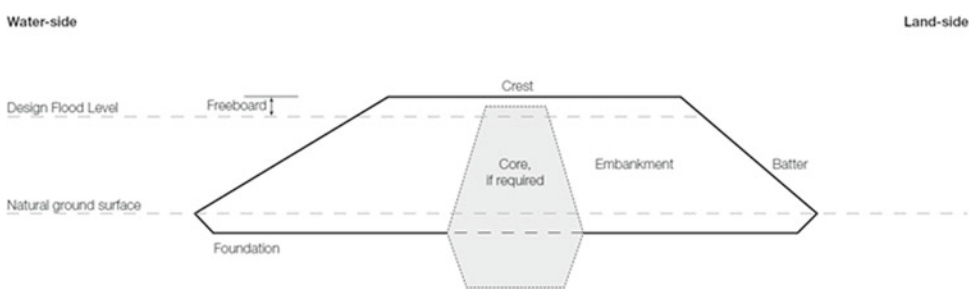
Fig. 18.3 Cross sections of levee types



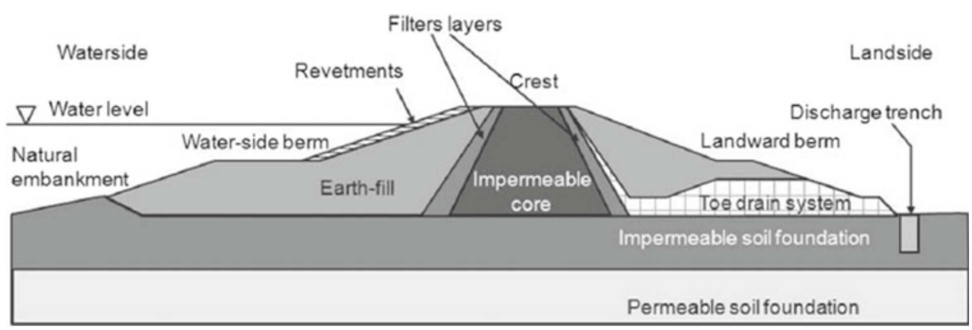
(a) Profile with a summer and winter dike



(b) Profile of a homogeneous levee

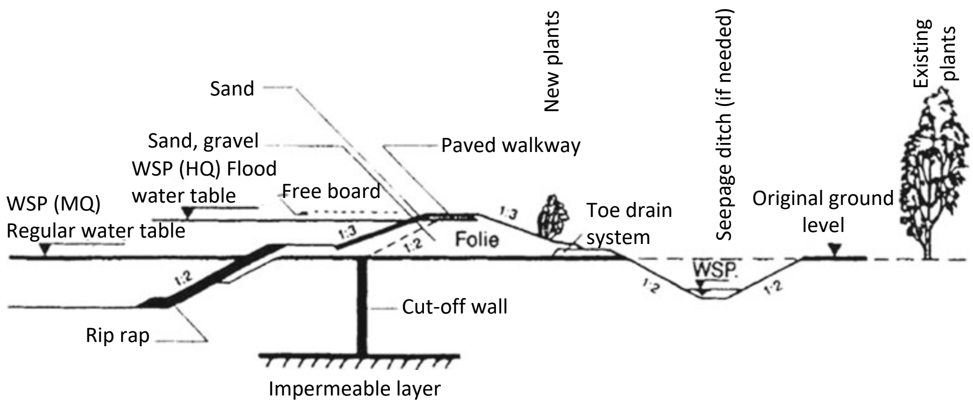


(c) Profile of a levee with a low permeable central core

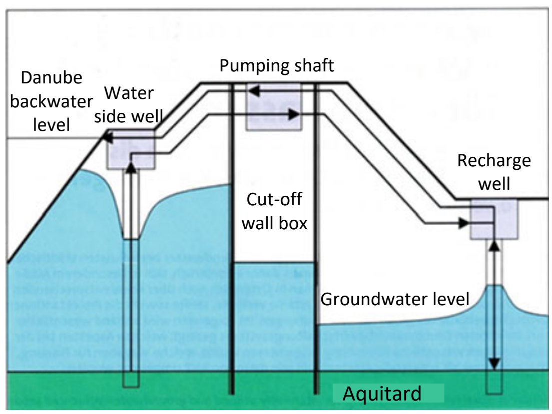


(d) Layered (non-homogeneous) levee with water side protection (revetments), low permeability core, filter layer connected to a land side drain (CIRIA, 2013)

Fig. 18.3 (continued)

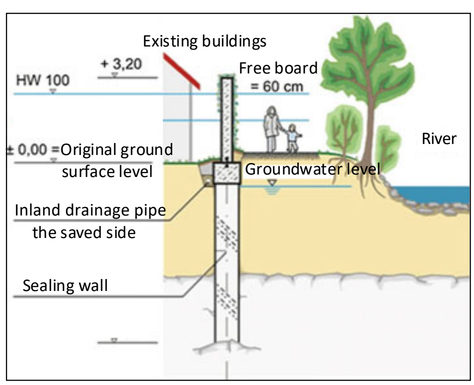


(e) Profile of a levee with water side protection, underground sealing and land side filter with a drain



(f) Impoundment dam with well gallery to manage groundwater table in the Hinterland of right impoundment dam of hydropower station Freudenau, Vienna (Brandl 1977)

Fig. 18.4 Flood walls (Photo source: WWA Donauwörth, Bavaria)



(a) schematic profile of embankment with flood wall (Wasserwirtschaftsamt Aschaffenburg, 2016) *(HW: flood level)*

(b) example of implementation (from WWA Donauwörth, Bavaria)

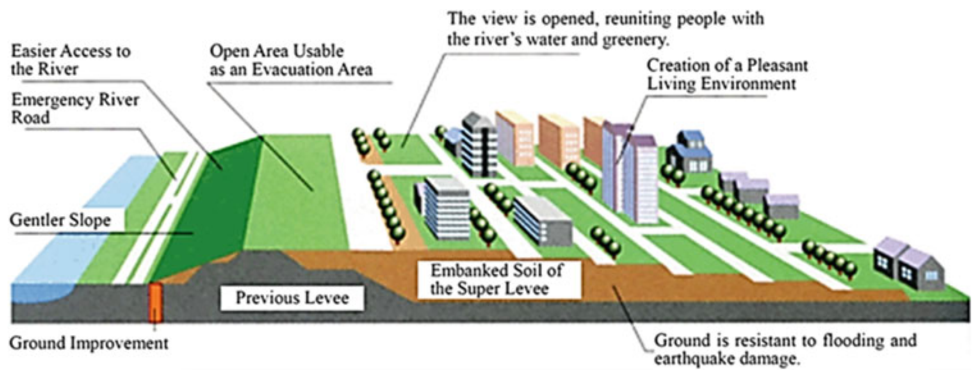


Fig. 18.5 Schematic diagram Super levee (Arakawa-Karyu River Office 2013)

narrowed down to a few areas. As shown in Fig. 18.5 a super levee is characterized by its broad width which can withstand even overflow conditions (Stalenberg and Kikuori 2008; Nakamura et al. 2013) or earthquakes without consolidation. It is about 30 times as wide (about 200 m to 300 m) as a regular flood levee. Smooth slopes on both sides provide easy access to the river.

Coastal dikes are exposed to extreme tidal and wave forces and thus their design differs in several aspects from a levee structure.

Coastal dikes have been extensively utilized as flood defenses in the Netherlands over the past several hundred years. Based on this long lasting experience a typical profile has been developed as depicted in Fig. 18.6. The toe of the dike is protected by riprap and the water side is often protected by bedded rockfill or asphalt layer. The dike core is usually composed of sand to ensure that entering water can be drained. The core provides support for the cover layer and gives the structure sufficient volume and weight to resist high water pressures (Barends 2003). The levee crest and the landward side need also to be well protected because under extreme load overtopping may temporarily occur. On the landward toe a drainage filter is needed to safely drain the sand core.

Dikes, levees, polders, dams need to be additionally equipped with technical structures to control surface water flow to/from the hinterland. Along rivers simple gated structures (Fig. 18.7a) are integrated into the levees to

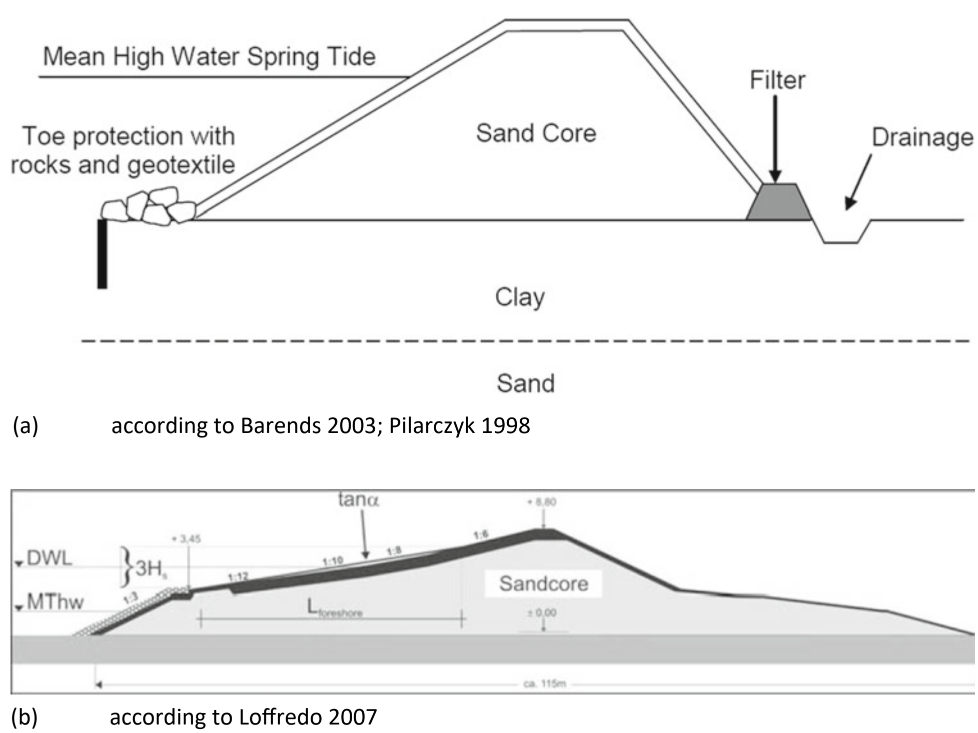


Fig. 18.6 Schematic cross section of a sea dike

Fig. 18.7 Gated structures integrated into levees (Source for photo a) IGH Ing.-Büro Ger. Höllig Dessau)

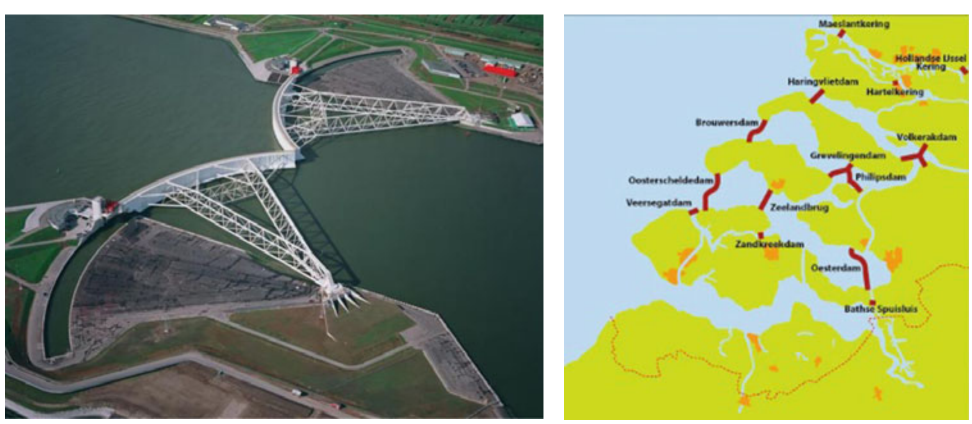
(a) gate controlled culvert (b) non-return flap

control the flows to and from the hinterland. Gated culverts are usually open to release discharge from the Hinterland while they are closed under flood conditions. Smaller pipes are equipped with non-return flaps closing automatically under increasing water table (Fig. 18.7b). In most of the cases a manually operated gate is added because of potential blocking of the flap due to floating debris which might block closure of the flap.

In the low land areas, especially in the coastal zone major hydraulic works such as gates, weirs, or barriers are combined with the sea dikes to close the shore line. The flood defense system in the Netherlands, consisting of dikes along the coast and lowland rivers, has been designed to withstand flood levels occurring with a probability 1: 10 000 (Vrijling 2001; Voortman 2003). Considering coastal zones storm surges may also endanger the land by entering via the river mouths. Thus, these natural drainage systems have to be efficiently closed in case of emergency. Storm surge barriers and closure dams are large-scale coastal defense projects, capable of protecting tidal rivers and estuaries from occasional storm surge events (UNFCCC 1999). Various storm surge barriers can be found throughout the world, such as in the Netherlands, the Thames barrier downstream of London, in Nagoya (Japan), Venice (Italy) and St. Petersburg (Russia). As examples two quite different technical solutions are explained here. Several other barriers are in discussion, for instance for protecting Ho Chi Minh City and Shanghai to cite a few. According to the Report of the Asian Development Bank (2010) Ho Chi Minh City will reach 20 million inhabitants by 2050 and due to climate change the frequency and intensity of tropical storms and typhoons will increase. As a consequence, a flood that would today affect some 26% of the city's population will, by 2050, affect 62%. Large scale protection measures are in discussion.

The Maeslantkering storm surge (Fig. 18.8) barrier is part of the Delta project (Deltawerken online) and it serves to protect the city of Rotterdam. Construction works started in 1991, the structure was completed in 1997 and it was in operation for the first time in 2007. Total costs summed up to 450 million €. Under extreme storm surges, occurring once in about ten years, the water way from the sea to the harbor of Rotterdam can be closed. In a river profile, measuring 360 m in width, a flat base was formed on the channel bed to provide a solid and tight foundation for the two arms of the floatable barrier, each with a length of 240 m. Each arm is fixed via a ball-and-socket joint with a diameter of

Fig. 18.8 Maeslantkering storm surge barrier (**a**) Photo from Rijkswaterstaat: https://beeldbank.rws.nl/MediaObject/Details/Luchtfoto_van_de_gesloten_Maeslantkering_in_de_nieuwe_Waterweg_nabij_Hoek_van_Holland_158813. (**b**) http://www.deltawerken.com/Deltawerke/557.html



(a) Maeslantkentering storm barrier (Riteco, 2017) (b) barriers within the Delta works (Deltawerken online)

10 m on the banks of the channel. Under regular conditions each arm of the flood wall is contained in a dock-type shelter. Based on online measurements and weather forecasts computerized decisions are taken upon closing the water way. In case of emergency the arms of the barrier are floated in the docks and then they are turned into the channel which is closed within about 30 min. Then, the doors are flooded to sink down to the ground closing tightly the profile. The barrier should protect against a sea side water level of 21.5 m above foundation works. Future climate scenarios already demand for a higher protection level due to raising of sea water level and expected higher frequency of cyclones (Jonkman and Schweckendiek 2015).

The flood protection system of the city of St. Petersburg, with 5 million inhabitants is located in the Newa delta which drains into the eastern part of the Baltic Sea, called Newa bay or Gulf of Finland, has been quite differently designed. The city is exposed to frequent flooding with about two events per year during the last 25 years and storm surges create substantial flood risk for major parts of the city. Already in the 1970-ties a flood protection system was planned but finally it was realized between 2004 and 2011. In the design of the project the intensive ship base transport had to be considered as well as the water quality in the new confined Newa bay which receives all the effluents from the city. Further, the circulation pattern in the bay area had to be maintained because of ecological consideration and also ice formation was an issue.

The barrier, located in the Eastern Baltic Sea area with a distance of about 20 km in front of St. Petersburg (Fig. 18.9b), spans from the northern side of the bay to the Kronstadt island and continues to the southern banks of the Baltic Sea (Stroyproekt Engineering Group Association 2014; Hunter 2012). When the barrier is closed the discharge from Newa river has to be accumulated in the shallow part of the bay area, which may lead to an increase of the water level of about 5 m, dependent on the period of closure. The scheme has been designed to protect St. Petersburg from up to a 10 000 years flood event. The Flood Protection Barrier has an overall length of 24.5 km consists of an embankment dam with two navigation openings, six water sluices to accommodate river flow and 11 earth dams. Each of the six sets of water sluices is the size of the Thames Barrier and has 10 or 12 individual gates which are weighted with concrete to protect from ice damages. Each gate is 24 meters wide and 4 meters to 6.5 meters high. One navigation channel is two hundred meters wide with two large sector gates, similar to the Maeslantkentering barrier, and the second one has a width of 110 m closed by a vertical gate. A highway with 6 lanes is located on the top of the embankment dam plus bridges crossing the smaller navigation channel and the weir while road tunnel passes under the main navigation channel. Total costs are given with 2 billion €.

18.2.2 Design Principles for Levees

There are two design principles, either probability or risk based approaches, to define the crest level of the protective structure. The crest level is defined by the flood water level and the freeboard (MacArthur and MacArthur 1991; FEMA 2018; Bruggemann and Correia 2016) (Fig. 18.10). The freeboard is defined by the vertical distance between the top design water level and the levee crest. This supplementary increase of the height of the structure considers hydraulic uncertainties such as water waves, changes of the river bed level, wind induced effects on the water table. The guidelines for freeboard design differ among countries and even within a basin. In general, the estimation of the freeboard incorporates important local physical processes such as stability of the river bed, wind induced impacts on the water level, highly turbulent flow conditions etc. Sometimes it is defined as a safety margin by adding 0.5 m along unshipped rivers and 1.0 m along navigable rivers to the design level.

In the probability based approach (Gumbel 1958; Katz et al. 2002), which is frequently applied, the design discharge or corresponding water level is defined by a predefined probability of exceedance. In other words, the reliability of a protective system is specified dependent on land use in the hinterland. Residential areas should be protected at least against a flood event with a return period of 100 years. Thus, the probability of exceedance is less equal to 0.01 in a year. Critical infrastructure, densely populated areas should be protected with a lower probability of exceedance, dependent on national regulations. For instance, storage areas in the Netherlands are protected against a ten thousand years' flood (Bottelberghs 2000). Similar safety levels are also reported for larger cities like London and Vienna which are protected against a flood event with a return period of several thousand years (Stadt Wien 2017). These protection levels refer to the most critical flood causing events, such as tidal floods in London and river floods from the Danube in Vienna. Local flooding due to flash floods is not considered in this assessment.

The design level h^* is obtained as $P(h > h^*) = 0.01$ for a flood event h^* with a return period of 100 years.

In the risk based approach (Ministerie van Verkeer en Waterstaat 2005; Jonkman et al. 2008; Vergouwe 2016; Kind 2014) the costs of protection $C(h^*)$ and the remaining flood risk $R(h^*)$ are jointly minimized. The latter is the mean of all damages (or expectation value) occurring from potential floods larger than the protection level h^*. The higher the protection level the lower is the remaining risk while the construction costs increase with the protection level (Fig. 18.11).

(a) dam with small navigation channel (b) map of Newa bay and St. Petersburg

(c) large navigation channel (d) sluices in winter

Southern section Northern section

Fig. 18.9 The St. Petersburg storm surge barrier (**a**) photo sources: https://www.google.com/search?q=st.+petersburg+storm+surge+barrier&client=firefox-b-d&source=lnms&tbm=isch&sa=X&ved=2ahUKEwjj7fyks5zuAhURxIUKHfkdDLIQ_AUoAXoECAUQAw&biw=1186&bih=629#imgrc=ecde4T9AMScoQM. (**b**) https://www.transmost.ru/en/projects/integrated_projects/artificial_structures_of_the_st_petersburg_flood_protection_barrier/#gallery-2. (**c**) https://external-preview.redd.it/bs0G0yrE8waUlRtXAW3uyslKFqyO8w9bIjJf2N3jNWc.jpg?auto=webp&s=bb4219700354f7ef3ac01c50e86a6d1a638dbd7f. (**d**) https://georgesteinmetz.com/wp-content/uploads/2015/10/STNMTZ_20130107_06779.jpg

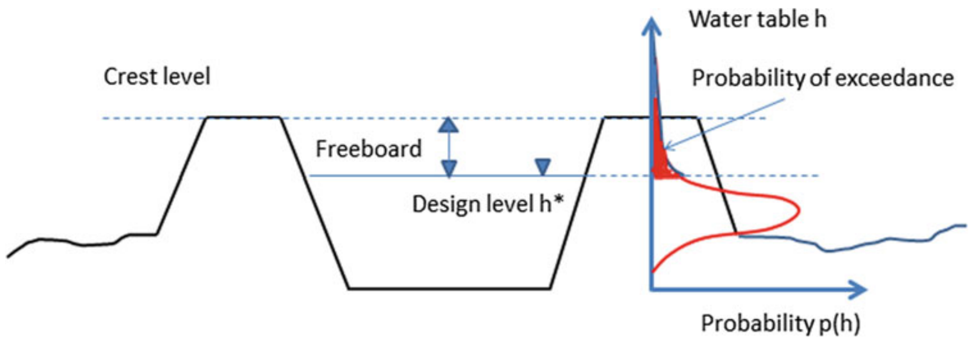


Fig. 18.10 Cross section of a river and probability of flood water levels p(h)

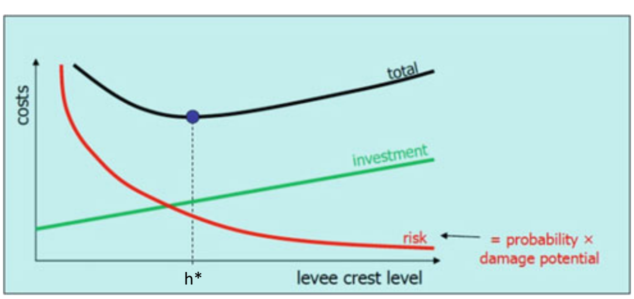
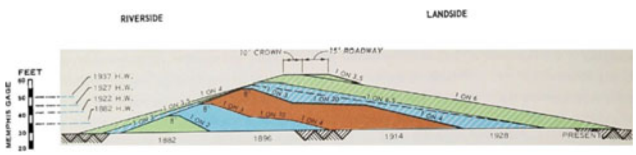


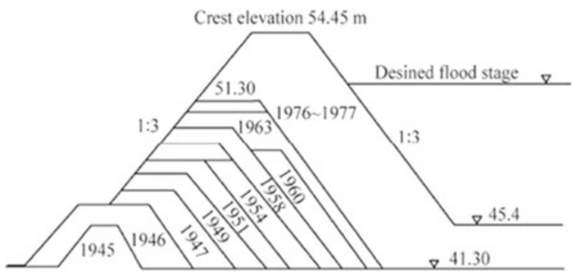
Fig. 18.11 Schematic diagram of risk based design approaches: red: remaining risk, blue: investment costs of the protective structure, black: total costs, h* optimal design level

$$R(h^*) = \int_{h^*}^{\infty} p(h) * D(h) dh$$

h	crest level or corresponding discharge of extremes
$p(h)$	probability density function of h
$D(h)$	damage function for an event of intensity h
$h*$	is optimal design level (either probability based or risk based)



(a) Temporal enlargement of levees along the Mississippi river 1882-1972 (Moore 1972)



(b) Temporal development of the grand levee at Taiqian in Henan province along Yellow river (Wang et al., 2015)

Fig. 18.12 Examples of increase the height of levees

$$h* = \text{Min}\{C(h) + R(h)\}\text{for all h}$$

In this equation a minimum of total costs composed of residual risk and investment costs provides the optimal protection level h*. So far, in both approaches it was assumed that the probability of hazardous events, characterized by p(h) as well as the damage function D(h) do not change in time. Obviously, these assumptions neglect climate change together with its possible impacts on extremes and also changes in land use which impacts on the damage function and also on runoff. One of the responses to cope with flood protection in an unsteady environment is to increase the height of the levees (Fig. 18.12) by enlarging the body of the levee on the land side.

18.2.3 Overview of Levee System

According to a draft European inventory of technical flood protection measures (EURCOLD LFD-WG Meeting 2016) there about 9 000 km of levees in France from which about 1,000 km refer to marine coastal structures. Similar figures are reported from Germany with about 10,000 km of levees from which 80% are fluvial protective systems. The levees protect there about 12 million people. In the Netherlands levees are mainly located along the coast line forming the primary flood defense. 30% of the levees are implemented along estuaries and only 3% along rivers. About 60% of land and about 70% of population/economy would be exposed to flood risk without levees. From Spain several thousand km of typically 3–5 m high levees are reported which are mainly located in the Ebro, Duero and Guadiana basins, mostly to protect cultivated areas and small towns. According to the draft inventory about 8,000 km of levees exist in England, ranging between 1 and 6 m in height. 70% of them are placed along rivers, another 18% along estuaries and 10% along the coast. In Hungary there exist about 400 km of river levees due to the remarkable flood risk in the country where about 25% of the land and the population are exposed to flood risk.

Protection and design standards were compared at the global scale by Scussolini et al. (2016). Of course, the protection levels vary largely, even within a river basin. High standards of protection are reported for North America, ranging from events with about a 380-year return period on the west coast of the United States, to about 20 years in Mexico. In Europe, protection levels range from about a 250-year return period in regions of western Germany to about a 20-year return period in eastern European countries, while some cities like Vienna, Paris and London exhibit a protection level higher than a 500-years event. In Russia, Australia, Saudi Arabia and Oman, often design values around 50-year return period are applied with higher protection for densely populated areas.

Flood protection levels range in South America (Scussolini et al. 2016) from about a 45-year return period in Uruguay and Chile, to six in Bolivia, Paraguay, Guyana and French Guiana. Flood protection levels range in Africa from 16 years return period in northern and in southern countries, to values of two in Saharan, sub-Saharan, tropical and western Africa, with peaks of more than 100 years in Egypt and 45 in Equatorial Guinea. Protection in Asia ranges from levels of about 150 in Japan, to values around 2 years in countries like Myanmar, Cambodia, Afghanistan or Nepal.

Flood protection along the two main rivers in China, Yellow river and Yangtze river, is based on extended levee systems which are increasingly supported by reservoir structures. The flood control system along the Yangtze consists of the 3,570 km long grand levees, more than 30,000 km of levees along the tributaries, riparian lakes, and canals, on a local scale, and protective walls in municipalities (Wang et al. 2015). Training of the Yellow River has a history of more than 3,000 years. Levee construction was the major strategy of flood control until 1998. The nation has spent $1 billion for flood control and saved $500 billion in flood losses. To stabilize the channel and protect the villages and towns by levees, numerous spur dikes have been constructed. Statistically, about half of the spur dikes are effective for stabilization of the channel. Despite all the taken protection measures the flood in 1998 killed more than four thousand people and caused economic losses of about US$25 billion (Pittock and Xu 2011; Yu et al. 2009) in the Yangtze basin. Triggered by events like in the Yangtze basin, the Chinese government (CCICED 2010) developed a new flood fighting approach by promoting the restoration of flood plains (Gleick 2002), resettlement programs for farmers, afforestation measures in the head waters, and improvement of flood retention capacity by large reservoirs.

According to the National Levee Database (USACE and FEMA 2018) about 15,000 floodwalls and almost 22,000 levees are maintained in the US. According to (Bernhardt et al. 2011; ASCE 2009) there are more than 160,000 km of levees protecting over 220,000 km^2, mostly agricultural land. In the recent USACE (2017) Infrastructure Report only 48,000 km of levees are listed from which 97% are constructed as earthen embankments. This remarkably smaller number in total levee length is probably due to consideration of old levees with a small crest height in the 2009 inventory. The Mississippi levee system represents one of the largest levee systems in the world. It comprises over 5,600 km of levees along the Mississippi.

Also in Bangladesh, which is exposed to river floods as well as to storm surges, flood control measures are mainly limited to building of earthen embankments, polders, and drainage. In a normal year, river overflows and drainage congestions cause the inundation of 20–25% of the country's area, while 10-, 50- and 100-year floods are projected to flood 37, 52 and 60% of the total country's area (MEFGB 2005), respectively. In total, 5,695 km of embankments, including 3,433 km in the coastal areas, 1,695 flood control/regulating structures, and 4,310 km of drainage canals are included in Khalequzzaman (2004). The WMO-GWPS report (2003) lists 10,000 km of embankment and levees, 1 dam and 4 barrages being used for flood protection.

At the global scale the largest annual number of people exposed to floods is found in India. Twenty-three out of thirty-two-states/union territories in the country are subject to floods and roughly one-eighth of the country's geographical area is prone to floods. The main flood protection measures refer to levees and embankments, and sometimes by diversion of flood waters and the implementation of dams to store at least partly the flood water (Gupta et al. 2003). Several levee failures associated with numerous fatalities and large damages are reported. In case study for the state Bihar, the 12th largest state in area and 3rd largest by population, which is most flood-prone State in India, the levee system and the failure modes have been analyzed (Srivastava et al. 2013). Approximately 76% of the population of northern Bihar lives under the recurring threat of flood devastation. Bihar, at present has more than 3,627 km of levee embankment but often levees failed. The reasons were due to inappropriate levee geometry with steep slopes, as dense and deep rooting vegetation on the land side of the levees and missing protection measures to cope with erosion on the water side. In other river basins levee failures were reported due to sedimentation in the river bed reducing the carrying capacity of the profile (Sanyal 2017).

18.2.4 Advantages and Disadvantages of Levees

Levees are in use since ancient times and even today they constitute a key element in structural flood protection. The reason is in the simple and comparable cheap construction. But they require careful design and maintenance and often both are disregarded. National inventories are needed including the main constructive features of the levee and its actual state to maintain these structures properly.

Often, river training works are needed in any case, for instance to stabilize the river course and the level of the river bed or to support navigation. The incremental costs for a larger design to support flood protection are small favoring levee systems.

Several counter arguments against levees are often raised: their unreliability in flood protection (Wood 1977; Zimmaro et al. 2018), the belief of people and planners in safety behind the levee, their potential impact on the sediment regime (Kesel 2003; Wohl et al. 2015; Wang et al. 2015), their hydro-morphological impacts (Surian and Rinaldi 2003), and adverse impacts on riverine eco-systems due to reduced connectivity between the flood plain and the river course (Ward and Stanford 1995; Kondolf et al. 2006). These points will be subsequently discussed.

From an engineering perspective one should discriminate among the case that a levee fails before the design discharge is reached and the case that the levee is overloaded by an event exceeding the design flood. Different from levees the design of a dam obligatory requires to incorporate a flood release structure to release the flood water above the design level without any damage to the structure itself. Of course, there is an upper limit of the carrying capacity of such release structures. In other words, there is also a probability that the capacity will be exceeded and that the dam will be destroyed. Contrary to this safety based approach most of the levees are not equipped with flood releases and this results in numerous failures globally.

18.2.4.1 Levee Failures

A levee failure occurs when the protective capacity of the levee is (partially) lost. This refers to quite different hydraulic and hydrologic situations (Simm et al. 2012; Jonkman and Schweckendiek 2015) and ranges from partial failure modes to a complete collapse. Overtopping is frequently addressed in risk assessment studies but levees exhibit also geotechnical failures which may occur before the design level is reached (Wolff 1997). Besides overtopping possible failures may arise from scouring of foundation (Huang et al. 2015), seepage/piping of the levee body (El Shamy and Aydin 2008; Polemio and Lollino 2011), under-seepage of the levee or crevasse (Meehan and Benjasupattananan 2012). Slope sliding and erosive processes of the levee (Vrijling et al. 2011; Zhang et al. 2016) contribute also to levee failures.

These failure modes are triggered by frequent and long lasting floods, dynamic forces due to waves or fast changes in water levels, either increasing but more critical due to a fast decrease of the water level, biological activities like development of an extended and deep root system or by development of holes and a pipe system originating from animals, such as rodents.

These failure modes can be reduced by sound engineering design of the levee and by improved maintenance works. A crucial issue is in overtopping of levees. While dams, closing a cross section in a valley and thus blocking the runoff from the upstream catchment, must be equipped with a spillway, levees lack in most cases such flood release structure. The integration of spillways into levees (Nachtnebel and Faber 2009) would substantially decrease the collapse. Even in densely populated areas the controlled spillage of flood water would contribute to sound flood management practice.

Many levee failures are reported from the Indus River flooding (Syvitski and Brakenridge 2013). In Bangladesh most of the flood control embankments experienced breaching since their completion, and thus demonstrated that they are not very effective in reducing the damage to the environment, economy, and property. The 1998 flood in the Yangtze River (Wang et al. 2015) caused 1,075 levee breaches causing inundation of 321,000 ha.

During the 1993 flood in the US, some 1,082 levees, out of 1,576 levees on the Upper Mississippi and Missouri River basins were either overtopped or failed (Larson 1996). Most of the failures (1,043) occurred at non-federal levees. This fact is probably an indicator for the diligence of maintenance works. The hurricane Katrina's storm surge in 2005 caused overtopping in approximately 50 locations for a variety of reasons. At least four levees/floodwalls breached before their design capacity was exceeded (Brougher 2011). In greater New Orleans submerging 80% of the city and two-thirds of inundated area are due to levee breaches. This list could be extended by numerous examples throughout the world.

18.2.4.2 Belief of People and Planners in Safety

Levees confine the inundated area and reduce the inundation frequency and these facts generate the illusion of safety for the people living behind the levee, but still their home and properties are in the former flood plain. Land development and land use changes behind the levees are observed everywhere leading to an increase in population density and thus of damage potential. Simultaneously, as indicated in the previous chapter, vulnerability of levee systems remains an important policy issue globally.

A levee protects the hinterland from flooding up to its design level, in the best case. Thus, levees decrease the flooding frequency but they cannot eliminate flood risk at all, and in case of failure, an uncontrolled process is initiated which can happen anywhere along the levee, associated with quite high damages. Flood risk is defined as the likelihood of adverse consequences of flooding. Flood risk for assets and people at any location in a floodplain is a function of flooding probability at that location and the exposure and vulnerability to the flood hazard. In protected areas, the remaining risk is often referred to as "residual risk" (Shabman and Scodari 2014). And this residual risk needs to be communicated among the concerned population. It has to be accepted that there is no safety but a certain low probability of flooding associated with large damages remains. Every new building or extension behind the levee will increase the residual risk. Even in more densely populated areas an integration of a flood release structure into the levee is preferable because it contributes to save the protective structure and the inundation of the hinterland becomes a controlled and

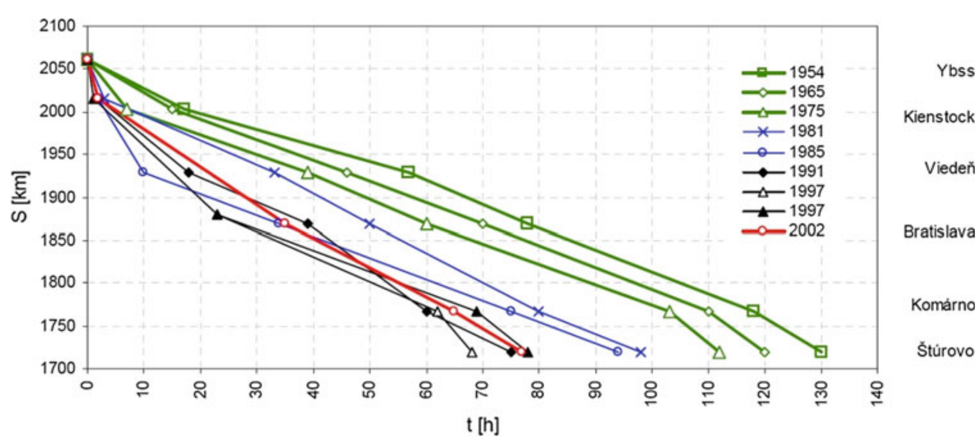


Fig. 18.13 Propagation of flood waves downstream the Danube from gauging station Ybbs (Austria, stream km. 2058) to Sturovo (Slowakia, stream km. 1718) (Miklanek et al. 2003)

delayed process. Independently, restrictions for planners and developers are required as well as building guidelines to reduce the damage potential.

18.2.4.3 Impacts on Environment

Another important impact of levees is in the change of the river regime. Levees cut off major parts of the flood plain and thus they reduce the runoff profile for floods as well as the retention capacity. As a consequence, the flow velocity is increased together with the shear stress acting on the river bed. Due to the losses of inundation areas the flood risk is slightly enlarged downstream and the floods arrive faster. As an example of a highly engineered river system the flood propagation over a 300 km section along the Danube is given in Fig. 18.13.

In the mid 1950s, flood protection measures existed in this Danube section along major settlements and large flood plains were located in between exhibiting a lower protection level. Gradually, runoff-river hydropower schemes and levees were developed until the year 2000. While in the mid-fifties a flood peak propagated within 130 h over a distance of 300 km it needs today only about 70–80 h. This has some implications for flood forcasting and the implimentation of temporary flood protection and emergency measures. Similar trends are found along the Rhine. There, after the river training project was completed in 1872, the length of the river course between Basel and Karlsruhe was shortened leading to a reduction of flood travel times from 64 to 23 h (Buck et al. 1993, Belz et al. 2001, Wang et al. 2015 p. 727).

Another adverse impact of levees refers to the modification of the sediment regime. As pointed out already river flow is always connected with sediment, nutrient and biological transport processes. Due to channelization two effects, either degradation or aggradation, may be observed.

As long as the river is in its un-engineered state flooding of the riverine plains is associated with sediment exchange. These processes depend on the ratio between transported gravel and suspended material and also on the residence time of the water in the flood plain. Often, due to channelization and increased flow velocities, the river bed suffers from degradation. As a result of the river corrections works of Tulla (Blackbourn 2006; Bernhardt 2000), which was executed between 1817 and 1876, the river bed of the Rhine degraded up to 7 m during the period 1860–1960.

Dependent on the gradation curve of transported sediments and the hydrological processes also opposite development is observed. For instance, along the lower Mississippi section, most of the flood plains have been cut off. They acted as a sediment trap, especially of suspended sediments. The Mississippi's alluvial flood plain attains a maximum width of 130 km above Baton Rouge. 67,340 km^2 of flood plain was inundated during the 1927 flood; 52,608 km^2 in the 1973 flood, and 40,404 km^2 in the 1993 flood (Rogers 2008). Suspended sediments tend to elevate the river's bed when flood surges subside.

Natural flood plains are among the most biologically productive and diverse ecosystems on earth (Robertson et al. 2001; Tockner and Stanford 2002) because of sufficient water supply and nutrient input. The levees interrupt the water and nutrient supply as well as the morphological changes which has severe impacts on the ecosystem. Globally, riverine flood plains cover more than 2 million km^2, however, they are among the most threatened ecosystems. Floodplain degradation is closely linked to the rapid decline in freshwater biodiversity; the main reasons for this is in habitat alteration, flow and flood control, species invasion and pollution. In Europe and North America, up to 90% of flood plains are already 'cultivated' and therefore functionally extinct. In the developing world, the remaining natural flood plains are disappearing at an accelerating rate, primarily as a result of changing hydrology, reflected in reduced inundation and thus a lack of interaction of the river with its former flood plain (Tockner and Stanford 2002).

According to the United States Geological Survey (USGS), approximately half of the original wetland habitats in the USA have been already lost. Due to flood protection works and agricultural development the wetland degradation in Louisiana is particularly serious; it accounts for 80% of wetland losses of USA (Dahl and Allord 1996). Between 1956 and 1990, nearly 3,460 km^2 of coastal wetlands reverted to open water, and more than 600 km^2 of wetlands have disappeared in the last decade (Stokstad 2005). Natural frequent flooding and nutrient input via sediments into the riverine swamps has been eliminated by levees. Dependent on the hydraulic conditions the sediment load may either increase the river bed or the river sediment is transported into the Gulf of Mexico instead of allowing it to be distributed over the coastal wetlands.

18.3 Protective Infrastructures: Dams and Reservoirs

Dams are structural barriers built mainly for water management to serve irrigation, hydroelectric power generation and/or flood control. Here, in this context, flood storage reservoirs are addressed. Other terms frequently applied refer to flood detention reservoirs, flood retention basins which are permanently partly filled, and sometimes, especially for smaller storage structures in an urban environment, the term balancing pond is used.

Various types of dams were developed already 3000 B.C. and perhaps earlier in several dry regions, such as Egypt, Yemen, India, Iran (Votruba and Broza 1989; Rodda and Ubertini 2004). It can be presumed that earth dams were

Fig. 18.14 Check dam in headwaters (Anker 2007)

built even earlier. Reservoirs can also be traced long back in India; on the outskirts of Madras alone, there were about 50,000 reservoirs. In the Near East King Solomon built a system of reservoirs near Jerusalem in the 10th century B.C. This technology was also well known in ancient Persia (Iran), mostly applied for irrigation purposes. In the 6th century B.C., the most important reservoir was Bend-e-Ramdjerd, near Persepolis, on the river Kor.

While levees and diversions try to enhance the runoff, reservoirs store some volume of the flood peak to reduce the downstream discharge to an acceptable level. After the flood has decreased the stored water is slowly released. In other words, the retention capacity of a basin is increased by technical measures.

A simple type of barrier, a so-called check dam, is often implemented in head waters to reduce the flood peak but more predominantly, to reduce the transport of coarse material and woody debris (Fig. 18.14). High sediment transport rates are a trigger for an instable river bed which increases the flooding probability. Such structures are exposed to heavy loads and are mostly designed as very robust concrete structures. The medium size sediment should be released slowly after the flood but the large boulders and coarse material have to be removed during low flow periods.

Downstream of torrential flow conditions smaller reservoirs are developed to mitigate the flood peak and also to trap sediments. With respect to the location of the reservoir two design principles are discussed. In the case of the runoff type scheme (online reservoir) the river flows through the reservoir and the dam closes the whole profile of the valley. In the bypass type the reservoir (bank side reservoir, offline reservoir) is located along the river and the flood water is either discharged via a spillway or via operated gates into the reservoir (Fig. 18.15).

These two systems have quite different impacts on the shape of the downstream flood hydrograph and also on the

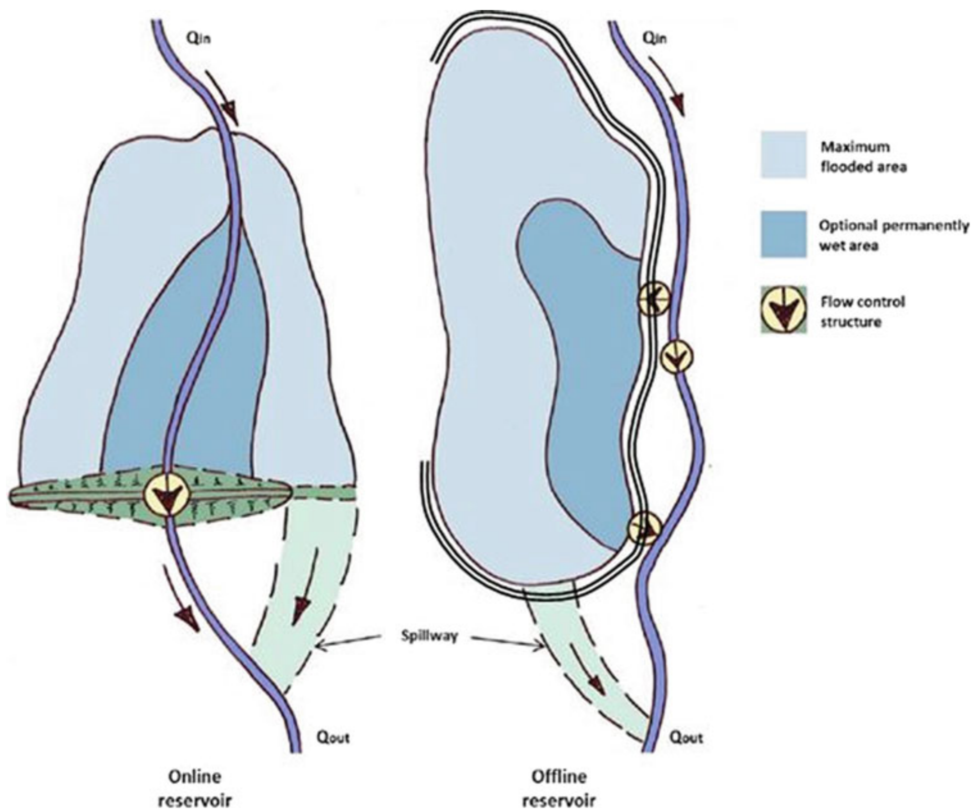


Fig. 18.15 General layout of flood reservoirs (Patterson et al. 2016)

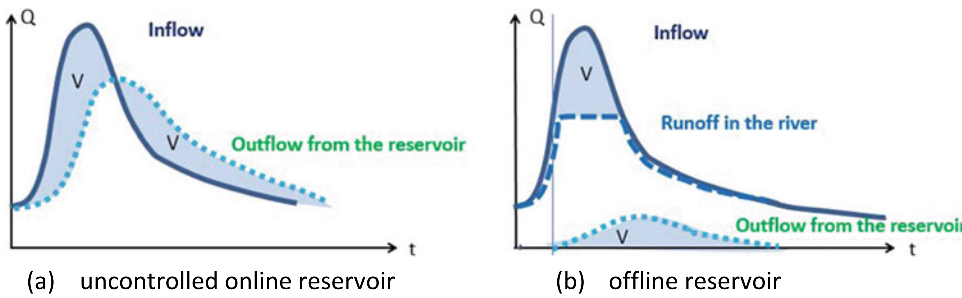


Fig. 18.16 Modification of flood hydrograph

environment. Assuming a part of the inflow hydrograph is accumulated in the reservoir and dependent on the water level the outflow increases until it equals to the inflow. Then, the outflow from the reservoirs is larger than the inflow until the stored volume is released downstream (Fig. 18.16a). The outflow hydrograph depends on the hydraulic design of the outlet structure. Online reservoirs trap most of the sediment inflow and thus repeated dredging of the sediments is required to maintain the storage capacity of the reservoir.

For the offline reservoir (Fig. 18.16b) the inflow to the reservoir depends on the design of the inflow structure, mainly on the water level when inflow starts. Then, the reservoir is filled up until the discharge in the river decreases the critical level. The outflow from the reservoir depends on the operation mode; in general the reservoir is slowly releasing the stored water volume. Downstream of the reservoir both components, the runoff in the river and the outflow from the reservoir have to be added. Bed load transport is bypassing the reservoir and only suspended material which settles in the reservoir needs to be removed from time to time.

While smaller flood reservoirs are found in headwater areas large polders and reservoirs are located in the lower parts of the basin. Large reservoirs are operated in controlled mode and thus the outflow hydrograph depends on the pre-defined reservoir operation rule.

Along major rivers, like the Rhine, old levee systems were modified to revitalize the flood plain and to manage the flood regime. Former polder areas can be either opened by removing the river side section of levee, or the crest level can be lowered (Fig. 18.17a) or can be additionally equipped with gates to utilize the polders like an offline reservoir for flood management (Fig. 18.17b). Various inflow and outflow structures are applied.

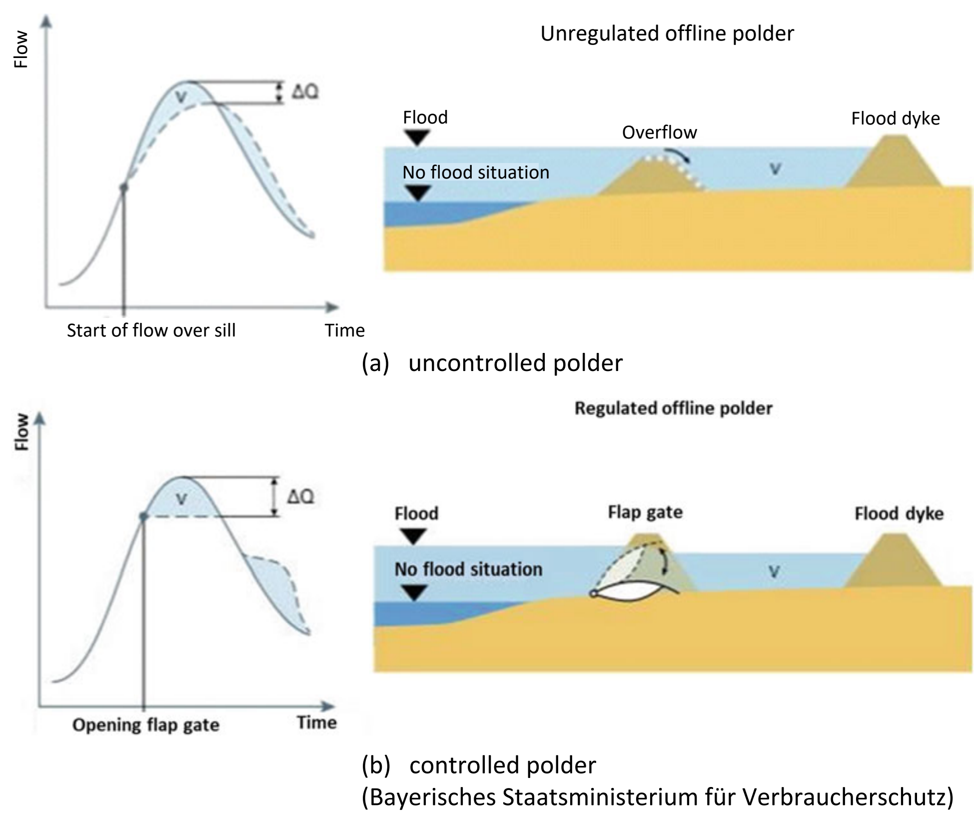


Fig. 18.17 Modification of flood hydrograph due to polders

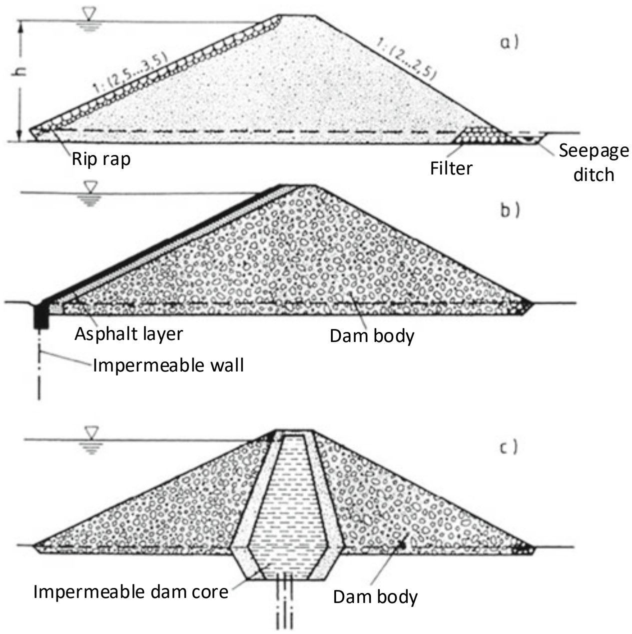


Fig. 18.18 Cross section of earth fill dams (from Lange and Lecher 1993)

18.3.1 Technical Layout of Flood Reservoirs and Dams

Four structural units have to be considered. The inflow control structure, the dam, the release structure and the spillway. The inflow control structure needs to be considered only for the offline reservoir.

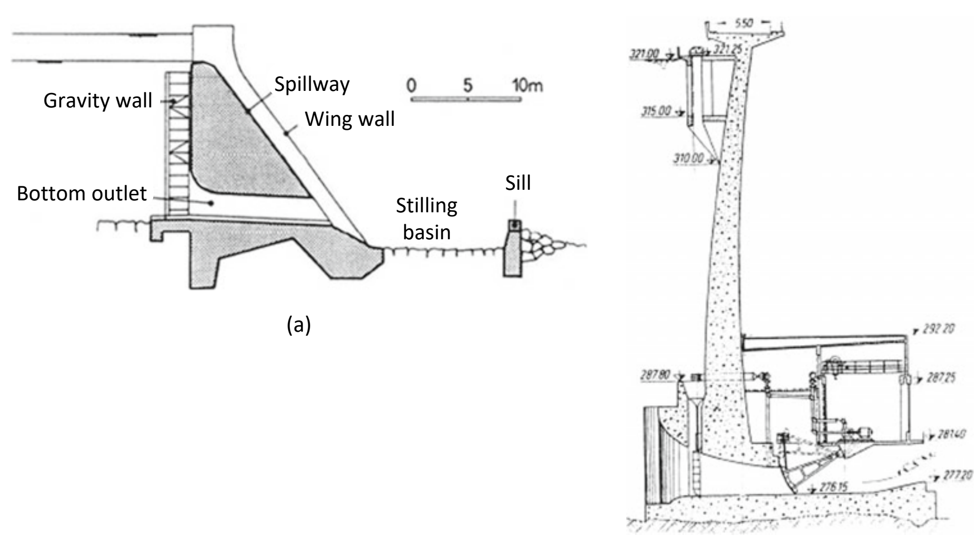
Similar to levees different technical designs of dams are used: earth fill dams, rock fill dams, gravity dams, and also dam walls (Fig. 18.18).

The dam in Fig. 18.18 is simple designed with a homogeneous body with a rip rap protected water side (a). To control seepage a filter and drainage ditch is integrated on the landside toe. The cross section in example (b) exhibits an impervious lining, often asphalt, which is connected to a grouting curtain on the water side to avoid under-seepage. In the case that the linings might be exposed to mechanical damage the sealing layer is in the core of the dam (c), or preferred more on the water side of the cross section of a rock fill dam (Fig. 18.19).

A gravity dam (Fig. 18.19a) is constructed either from concrete or masonry, the latter is also called masonry dam. The weight of the dam resists the horizontal load of the water pressure as well as uplifting forces. It is essential to avoid underseepage and lateral flow formation. The selection of the most appropriate construction type depends on the geology, height of the dam, seismic risks and the mode of operation, and the height of the highest storage level. In designing dams special attention is given to the spillway which is often integrated into gravity dams while earth dams and rock fill dams are usually separated from the spillways. The purpose of the spillway is to release floods larger than the design flood without endangering the dam itself. In contrast to levees dams have to be legally equipped with spillways.

Globally, there are millions of dams offering an aggregate storage capacity over 6,000 billion m^3. According to ICOLD classification (ICOLD 2017) large dams are higher than 15 m or dams exhibiting a storage capacity of more than 3 million m^3 and a height ranging between 5 and 15 m. The present ICOLD world register (2017) contains more than 58,000 dams. Many of the small dams are not found in inventories, not even at the national level. With respect to storage capacity 2% of it is created by more than 150,000 small dams (5–15 m) and 1% is contributed by other small

Fig. 18.19 Concrete dam structures (**a**) gravity dam (**b**) arch dam



(a)

(b)

dams, each with a storage capacity below 100,000 m^3. It is worth to consider that natural lakes store a global water volume 25 times as much as the volume of artificial reservoirs existing in the year 2000 (Lempérière 2003) and cover an area which is three times larger than of the respective reservoir area. According to the ICOLD dam inventory, about two thirds of all dams are earth dams, about 13% rock fill dams and 13% gravity dams. The rest refers to various types of arch dams. Most of the dams below 30 m refer to earth fill dams while with increasing height the concrete dams and walls dominate.

Large reservoirs are developed to serve multiple purposes ranging from irrigation, to hydropower, water supply schemes, to flood protection and recreational purposes. About one third of the reservoirs are multi-purpose schemes but figures are differing in inventories, perhaps of different classification schemes and different date. According to ICOLD about 50% of the single purpose reservoirs serve irrigation, while about 10% of the dams were built for flood control purposes. About 19% of the multi-purpose schemes serve also flood protection needs.

A typical example of multi-purpose reservoir is the Three Gorges project at the Yang Tse river in China. The Yangtze is one of the most important rivers and it includes large urban areas like the cities of Wuhan, Changsha and Nanchang. Over 400 million people live in the basin and about 40% of China's gross domestic product is generated in the area (Yang et al. 2007). The primary flood region extends along the lower course, downstream of the Three Gorges Dam. The flood of 1931 inundated an area of 77,700 km^2 including large cities like Nanjing and Wuhan city. More than 300,000 people were killed and homes of about 40 million people were destroyed. The 1998 flood killed more than four thousand people and inflicted economic losses of US$ 25 billion (Yu et al. 2009). Initial plans for a large scale project just downstream of the three gorges date back to 1919 with the objectives to improve flood control, to support navigation, and to generate hydropower. Finally, in 1992 it was decided to build this scheme and construction works lasted from 1993 to 2012 when the system became fully functional. A concrete gravity dam with integrated power houses and flood spillways raises the water level up to 175 masl with a potential maximal level of 180.4 masl. The dam is 2,335 m long and 185 m high (Fig. 18.20). The dam impounds the Yangtze river over a length of about 600 km including the so-called three gorges which constituted a major obstacle for navigation. With an installed capacity of 22,500 MW it is the world's largest power plant. Two parallel sets of ship locks support navigation together with a ship lift for tourist boats. The total storage capacity of the Three Gorges dam is 39.3 10^9 m^3 from which 22.15 10^9 m^3 are allocated to flood storage. The total capacity of flood spillways adds up to 120,600 m^3/s (Hayashi et al. 2008). According to the seasonal climate, floods occur between June and September. The operation of the reservoir tries to provide enough storage capacity during this period that a ten years flood event today will be observed in the future once in 100 years. Thus, starting in January the water level is slowly decreased from 175 m to 135 m in June, which is kept until beginning of October (Hayashi et al. 2008). During the 2010 flood event in July, inflows into the reservoir reached about 70,000 m^3/s, which was higher than the 1998 flood, but the runoff could be kept below 40,000 m^3/s without causing major damages downstream. Of course, the efficiency of flood management depends not only on the peak but also on the duration of the flood event. Hayashi et al. (2008) concluded that the 1998 flood could be only slightly reduced in the downstream Dongting area. Lai and Wang (2017) underline the benefits of the flood reduction of the Three Gorges reservoir for the middle and lower part of the Yang Tse River but they also conclude that some sensible areas, like the Dongting Lake, remained. The reason is due to previous modification in land use, reduction of the lake area and thus in a decreased flood storage capacity. Flood management is always linked to impacts on the sediment regime. The Yangtze river exhibits a high sediment load which created in the past an increase of the river bed in sections with very low slope, just downstream of the Three Gorges. After construction of the dam vast amount of sediments has been accumulated in the reservoir that reduced the sediment load downstream (Fig. 18.20) causing erosion in the delta as well as in the river channel. According to Zheng et al. (2018) the total volume of net erosion from the 565 km downstream channel amounted to 1.85 billion m^3. Over the last 15 years

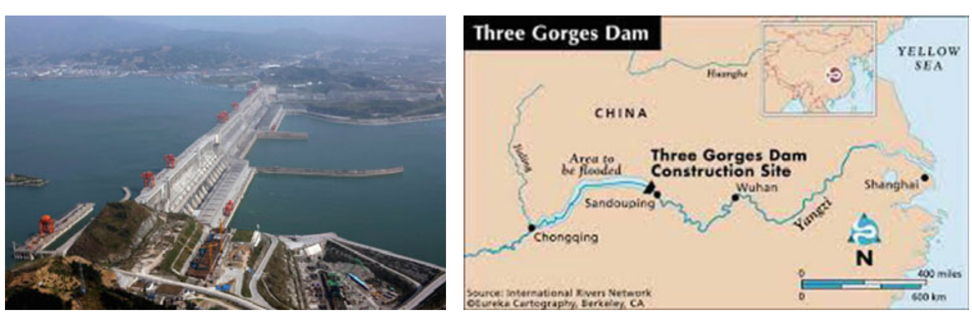


Fig. 18.20 View and location of the three Gorges project (China) (Source: E. Moloney, Eco News, 2018)

the average annual bed degradation for about 465 km just downstream the dam has been estimated at 0.04 m/a while in the remaining lowest 100 km, including the Delta area, the erosion rate reached up to 0.08 m. The sediment issue has been recognized from the early planning stages and a sediment management strategy was elaborated based on lowering the water level from 175 to 145 m during the wet period and to flush deposits downstream (Wang and Hu 2009). The length of the reservoir is about 600 km and thus the flushing of sediments is only partially successful. The lower spillways are operated for this procedure (Fig. 18.21) to initiate a higher flow velocity at the bottom of the riverbed to increase the bottom shear stress and to flush sediments.

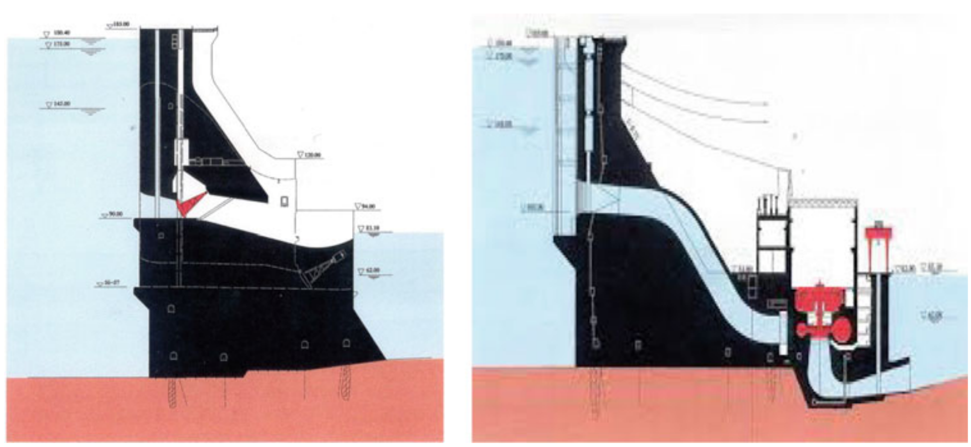
18.3.2 Hydrological Design Principles of Dams

Design principles for dams differ in several aspects from the design of levees, but there are also some similarities in the procedure. The main objective of a dam is to limit the downstream discharge to a critical value. Any surplus in discharge above a critical level has to be stored and released after the decay of the flood. The critical flood level is defined in the same way as for levees while for the design of the reservoir a volume has to be defined which is based on a design flood hydrograph. Often, several different design flood hydrographs are simulated and the respective volumes are estimated. Based on a statistical analysis the necessary storage volume is derived. Due to the fact that there is always a probability of overloading a system a spillway is part of the storage scheme which has the task to release overloads downstream without endangering the dam and its components. Dependent on the storage volume and the height of the maximum water level in the reservoir the spillway is designed to release an extremely rare flood peak with a return period from 1,000 years to 10,000 years. Because of large uncertainties in estimating such rare events sometimes the possible maximum flood (PMF) approach is applied (Salas et al. 2014; Quranos 2015). Spillways can be controlled by gates or are uncontrolled. Most spillways with flood peaks under 1,000 m^3/s consist of ungated flood release structures where the discharge is dependent on the water level in the reservoir. In the case of earth and rock fill dams the spillways are located besides the dam to avoid any damage to the dam while the concrete dams are often combined with the spillway. For larger discharges (above 1,000 m^3/s) gate controlled release structures are in use (Lempérière 2003). These spillways contribute about 25–33% to total dam construction costs and often they are not in use throughout the lifetime of the reservoir.

A flood reservoir should be empty most of the time except of a flood event. There is an uncountable number of smaller reservoirs with less than 15 m height which are exclusively used for flood protection and then there about 40,000 larger dams (see Table 18.1) which are mostly used as multi-purpose schemes. According to ICOLD (2017) there are recently 58,519 dams listed from which 2,480 or 9% of large dams serve flood protection exclusively. Considering also multi-purpose schemes about 4,861 or 19% assist also flood protection. Sometimes, differences in tables and listed numbers are found which is due to counting date and type of classification.

18.3.3 Advantages and Disadvantages of Dams

Reservoirs store water and thus reduce and delay the flood peak over a long river stretch downstream of the reservoir. Thus, numerous riparian residents would benefit. However, a basin wide hydrological analysis is needed because the delayed peak might coincide with peaks from tributary basins and thus aggravate the flood risk further downstream the confluence. Dams serve numerous purposes like water storage for irrigation and drinking water supply, hydropower



(a) Spillway (b) power house

Fig. 18.21 Cross section of the three Gorges Dam (Source: https://de.scribd.com/document/312071151/Three-Gorges-Dam-Project-Major-Reference-PDF uploaded by CT0011 May 10th, 2016) generation, recreation and navigation. Here, in this section only flood protection measures were addressed.

Considering the large number of dams, their adverse impacts should be also discussed. The impacts on the sediment regime are quite different for online and off-line reservoirs. While in the case of online reservoirs the whole sediment load is transported into and partially through the reservoir, the offline reservoir does not receive any bed load input but partial load of suspended material. Due to the slow downstream release of flood waters from the reservoir most of the sediments are trapped and will lead to siltation of the storage volume. To avoid this effect the sediments have to be removed from the reservoir after the flood event and the river should be slowly fed with the excavated material under consideration of the carrying capacity of the downstream section. A task which would be too costly and time consuming. In some flood reservoirs the deposited material is being excavated and sold as construction material, if suited.

Dams, as well as weirs, constitute a barrier for fish migration. Thus, such structures interrupting longitudinal connectivity of the river and its flood plain require by pass systems to support migration and release of biomass. Various systems have been developed, even fish elevators are in use. In general, the difference between upstream and downstream water level is divided into several smaller steps that consist of a pool and a short steeper flow section. In order to function properly these systems require sufficient discharge and space with lower flow velocity for resting periods (FAO/DVWK 2002).

18.3.3.1 Dam Failures

Like levees, dams may fail due to overtopping, internal erosion, slope instability, tectonic processes etc. In Zhang et al. (2009), 900 cases of dam failures were analyzed indicating a high failure rate of earth dams (Fig. 18.22) from which about 47% were built in the last 20 years. In an updated recent publication (Zhang et al. 2016) 1,443 cases of failures of constructed dams, 1,044 cases of landslide dam failures, and 1,004 cases of dike failures were elaborated and analyzed. The most common causes of failure of concrete dams refer to is internal erosion in the foundation followed by overtopping, both contributing together about 80% of all failures. Further information about dam failures in relation to flood protection is found in Lempérière (2017).

The largest disaster related to dam failures happened in 1975 due to collapse of the Banqiao reservoir dam (China) causing more than 170,000 fatalities. An extreme rainfall event in August 1975 with more than 1,000 mm precipitation within 24 h generated a flood exceeding by far the reservoir capacity and the capacity of the spillway leading to a collapse of the dam (McCully 2001). The downstream flood wave inundated an about 10 km wide area with a height of several meters. The floodwaters from the reservoirs and tributary basins inundated thousands of square kilometers with numerous villages. Approximately 26,000 people were immediately killed by the flood event while 145,000 died in the weeks after due to epidemics and famine.

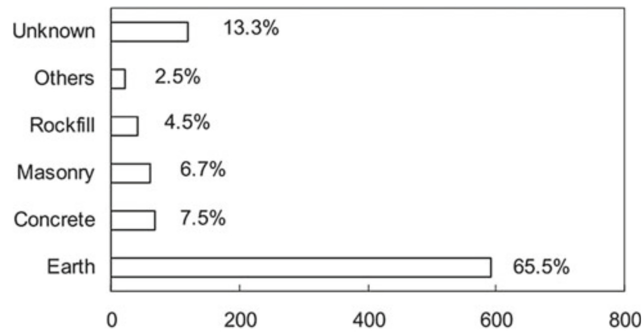


Fig. 18.22 Statistics of dam failures (Zhang et al. 2009)

18.3.3.2 Recreational Benefits/Losses

Reservoirs with permanent water storage provide an opportunity for additional recreational purposes. Hogeboom et al. (2018) assessed the economic benefits of 2,235 reservoirs under consideration of benefits from irrigation, power generation, drinking water supply and recreation. Recreation is ranked high in developed countries but in general the specific benefits from recreation, expressed in $/m^3, were rated low.

18.4 Protective Infrastructures: Diversion Measures

Another structural engineering measure to cope with floods is to increase the conveyance (Fig. 18.23) of the runoff system. This can be achieved by,

- Increasing the conveyance by reducing the roughness, increasing the slope of the river bed and stabilizing the river bed
- Bypass channels during floods
- Underground flood release

18.4.1 Increasing Conveyance

In densely populated areas, but also in the case of torrential flows carrying high sediment loads, technical structures were implemented to release the inflow quickly downstream

Fig. 18.23 Engineered river profile (city of Vienna): straight and low roughness (**a**) during a flood event (**b**) at low flow conditions (Photo source: MA45 Vienna)

through the residential area. Due to limited space for the torrent or river its course was straightening which resulted in an increased slope and additionally, the roughness coefficient of the river bed had to be reduced. These measures resulted in an increased conveyance. But, in designing such systems it must be considered that either sediments are trapped at the beginning of the engineered section or that the sediments are transported throughout the section without being deposited. In such a case, without armoring the whole river bed, degradation processes have to be expected. Figure 18.23 exhibits an artificial cross section of a small river in the city of Vienna. The whole profile is either made of concrete or rubble masonry.

Most of the major European rivers were channelized in the 19th and 20th century. Typical examples are found along longer sections of the Rhine and the Danube. Originally, these large gravel bed rivers exhibited a dynamic regime associated with frequent changes of the river course together with the formation of side arms and large gravel bars during major floods which endangered the whole valley floor. Besides flood protection, an important trigger for river channelization was also the development of large scale navigation demanding for a stable river bed ensuring sufficient navigable depth. In Fig. 18.24 the changes in layout view of the Upper Rhine is displayed for 1820 (un-engineered state), 1872 after Tulla's river training works, and for 1963 with the diversion channel for hydropower generation.

In such cases a widely applied river engineering approach is to design a double trapezoidal cross section with sufficient runoff capacity during floods on one or on both sides of the river (Fig. 18.25). The flood plain is restricted on both sides by levees. The new river bed cuts through the old river bed to shorten the thalweg to increase flow velocity. Due to higher flow velocity the shear stress on the river bottom increases and protective measures has to be taken to avoid scouring and to stabilize the bed. Along smaller rivers vegetation layers have to be removed regularly from the new cross section to maintain the conveyance of the flood plains, which have been substantially narrowed compared to natural conditions.

According to Tulla's project (1817–1876), the river course between Basel and Karlsruhe had been shortened by 14% and the section between Karlsruhe and Mannheim by about 37%. In the 20th century side channels were developed parallel to the Rhine river bed to ensure navigation and to develop hydropower. Altogether, the river course was shortened, the flood plains have been narrowed, the runoff processes have been accelerated and the sediment regime has been drastically modified (Galluser and Schenker 1992).

18.4.2 Advantages and Disadvantages of River Training Works (Increased Conveyance)

The need for these engineering measures was to improve flood protection by stabilizing the river course and by increasing the runoff capacity. This goal could be achieved by cutting off all the river branches between Basel and Breisach and by cutting through all the meanders

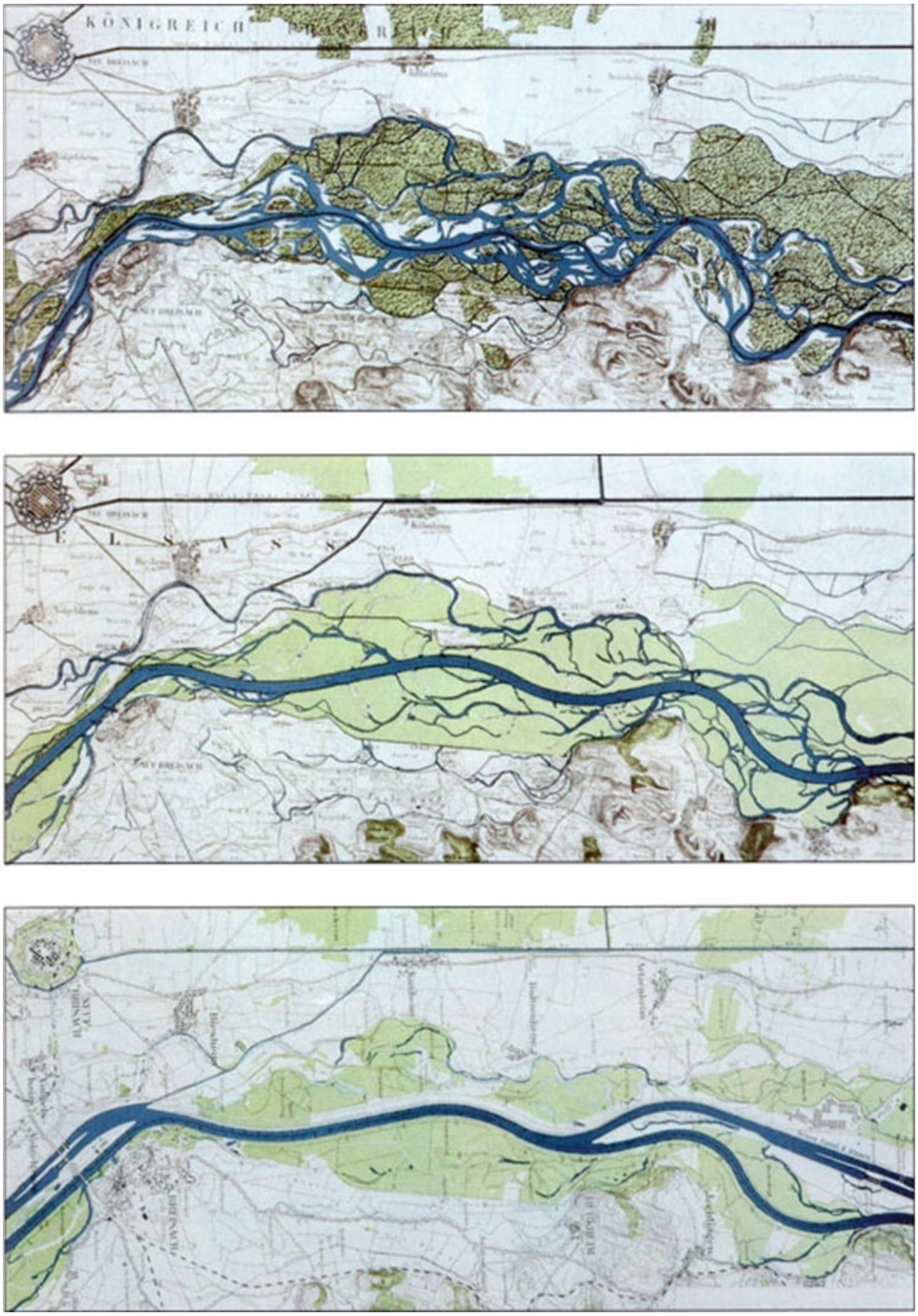


Fig. 18.24 Rhine section Breisach/Kaiserstuhl in 1828, 1872, 1963, top-down (from Buck et al. 1993, p. 77)

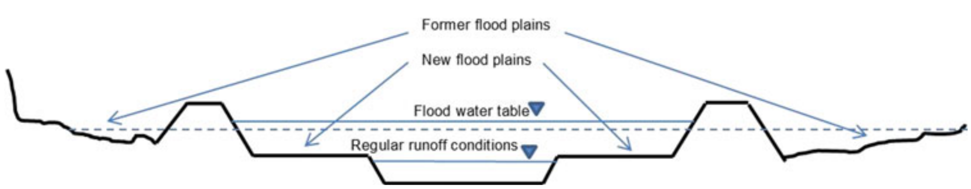


Fig. 18.25 Double trapezoidal cross section

downstream to Mannheim. The former flood plain was open to intensified land use. A stabilized riverbed was also in the interest of navigation.

Because of the increased conveyance, the sediment transport capacity was also increased and the riverbed degraded quickly with a rate of about 70 mm/year. Bed erosion reached section wise 6–8 m accompanied by a corresponding lowering of the riverine groundwater table. Also, the confluences of tributaries exhibited mayor degradations. Before Tulla's river training works about 2,000 gravel islands existed between Basel and Mannheim, a river section of about 260 km. Most of islands disappeared and were transformed into farmland. Obviously, the straightened river together with the sediment transport capacity resulted in a completely modified landscape. Measures had to be taken to stabilize the river bed and in the last few decades polders have been reopened to mitigate the increased flood peaks along the Rhine (Belz et al. 2001; Lammersen et al. 2002: Reichelt and BUND 1986).

18.4.3 Protective Infrastructures: Bypass Channels

The main goal of bypass systems is to increase the conveyance in a river section by diverting the water additionally via a flood release channel downstream or to convey floodwater across designated land. The types of release channels range from a pure technical structure to a release via an old side arm or the former flood plain along a river (Fig. 18.26).

A technical bypass in a river system is only used during flood events. The water level in the bypass can be managed by weirs regulating inflow. Such a system has been developed along the Danube in the city of Vienna (Stadt Wien 2017). The former scheme of a braidening unstable river has been transformed the first step into a straight river (1869–1875) with a flood plain on the left side and later, to improve the conveyance, a bypass has been implemented (1972–1988) together with a new levee system. The changes in the river system are given for three time slices in Fig. 18.28 while the schematic cross sections are displayed in Fig. 18.27.

The bypass has a width of about 200 m and a length of about 21 km. The total area of the island between river and bypass is about 4 km^2. The island is accessible by metro and except from major floods, the water table in the bypass is controlled by weirs without any inflow from upstream. Thus, the water quality is excellent and can be used for water based recreation. The system is able to release an extreme flood event with a return period of several thousand years safely downstream and it proved its efficiency during flood events with a return period of more than 100 years. The main river bed has a release capacity of 8,800 m^3/s and the bypass has a conveyance of additionally 5,200 m^3/s (Fig. 18.27).

The old river regime of the Danube (1863–1866) in the region of Vienna was similar to the Rhine river downstream of Basel before Tulla's correction. The Danube consisted of several dynamic side arms and gravel islands covering a cross section of a several kilometers. Both, flood protection and navigation demanded for a channelization of the river (Fig. 18.29).

A similar development was also observed along the Mississippi river. As shown in Fig. 18.12a) the levee systems were enlarged, the side arms were cutted off and finally, due to increasing flood risk, parts of the former flood plain had to be opened again for bypasses and flood water storage (Fig. 18.26). A large outlet along the Mississippi, the Morganza Spillway (Fig. 18.30), was developed and completed in 1954 to control diversion of flood water threatening New Orleans, Baton Rouge and other major cities on the lower Mississippi. It is the largest of a system of spillways and floodways along the Mississippi.

The floodway, 32 km long and 8.0 km wide, includes a stilling basin, an approach channel, an outlet channel, and two guide levees. From there, diverted water enters a neighbouring river basin, the Atchafalaya Basin. Since its completion in 1954, the Morganza Spillway has been operated twice, in 1973 and 2011.

An example of a soft engineered floodway (bypass) is given in Fig. 18.31. Under regular runoff conditions the water flows in its old river bed and after exceeding a threshold level the water surplus is release via a short cut which is partly protected from scouring at the inlet. Given a further increase in runoff the valley floor will be progressively flooded. In this case the meandering river system is maintained while the runoff capacity has been increased to release floods faster downstream.

18.4.4 Protective Infrastructures Underground Flood Release

Bypass systems include also underground conveyance structures like in Bangkok or Tokyo (Fig. 18.32). Underground pipes, similar to sewer systems, with diameters of 10–15 m convey inflow surplus through the endangered region and release it downstream, either by pumping or due to sufficient hydraulic gradient.

Also in Bangkok, a large underground bypass system assists in flood protection and management. Bangkok is located in the flat Chao Phraya Delta (40 km from its mouth). The city has 5.7 million registered residents and an estimated total population of over 10 million people. Located only 1–2 meters above mean sea level, Bangkok is naturally prone to flooding. Floods originate from heavy

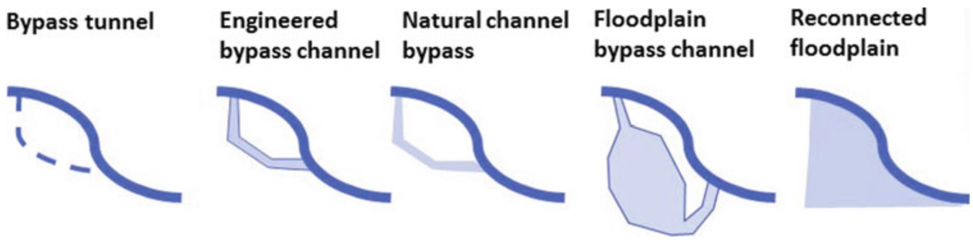


Fig. 18.26 Schematic diagram of bypass systems (Kondolf and Llobet 2012)

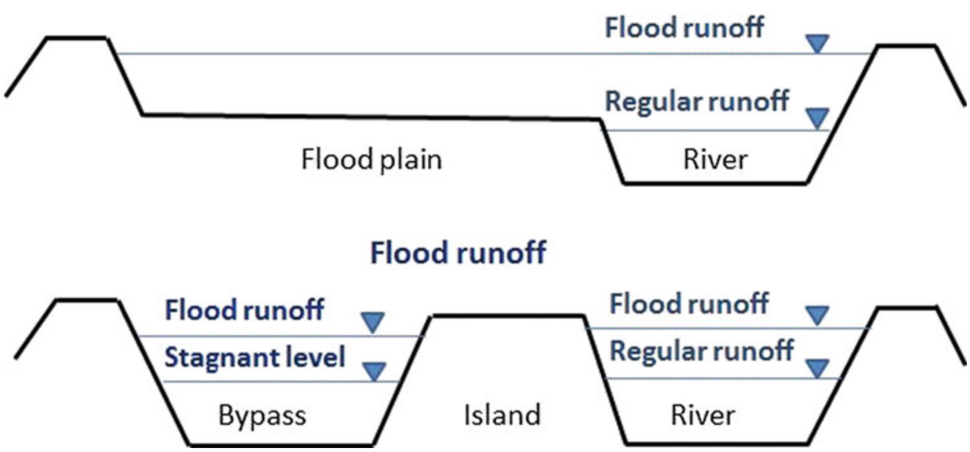


Fig. 18.27 Cross section of the Danube in the city of Vienna (**a**) with a flood plain (1875–1972) on the left side (above) and (**b**) the bypass and river (1988) (below)

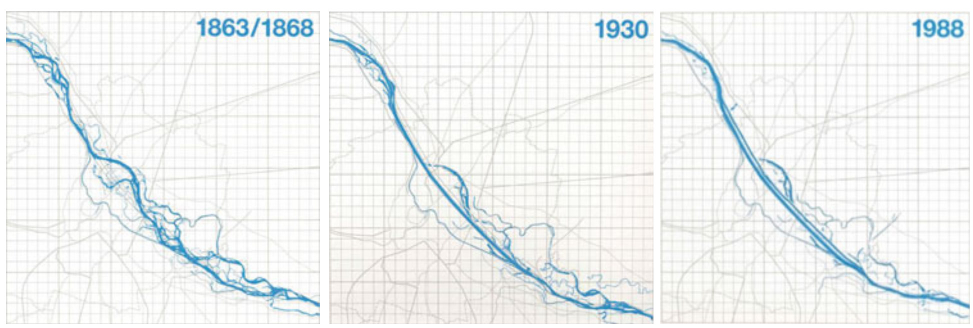


Fig. 18.28 Changes of the river network and river engineering works at the Danube in the city of Vienna, Austria (MA 18 2008)

Fig. 18.29 Flood bypass channel in the city of Vienna (before construction of hydropower station Freudenau) seen from downstream. From left to right: confluence of a side arm (Danube channel), middle: Danube river, Danube island (artificial), and right: flood channel (photo source: Verbund AG, Vienna)

Fig. 18.30 Morganza floodway consisting of a concrete weir equipped with 125 gates to control the flood release. At the land side scouring protection measures are added (photo source:Mississippi River Commission, 2007)

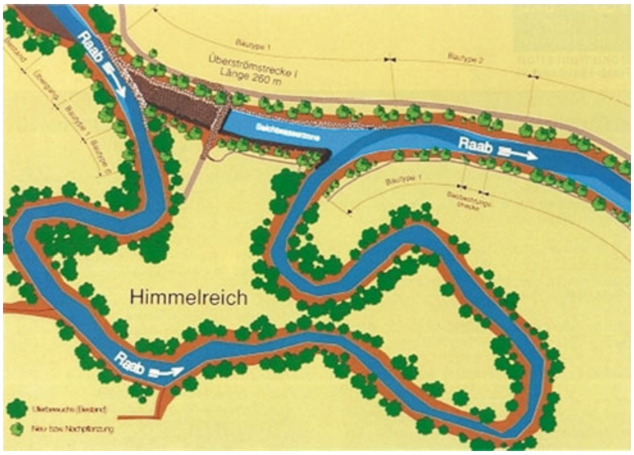


Fig. 18.31 Environmental friendly bypass channel (Amt der Steiermärkischen Landesregierung 1978)

rainfall in the city area and from river floods in the basin (DRR Team, 2016). Additionally, sea level raise and land subsidence (Lorphensri et al. 2011) aggravate flood risk. Besides levees along Chao Phraya, the flood protection system includes a dense network of open channels that drain rainfall water quickly through the city. Altogether, 1,682 channels with a length of 2,600 km plus 6,400 km of road drainage pipes constitute the city drainage system. Additionally, seven deep underground bypass tubes with a total length of 19 km provide an additional drainage capacity of 155 m^3/s. The discharge from the large tubes and from numerous channels must be pumped back to the river downstream of the city. To cope with heavy rainfall, retention spaces in the city area were developed. Today 25 storm water ponds exist in the city area offering a storage volume of 12.88 million m^3.

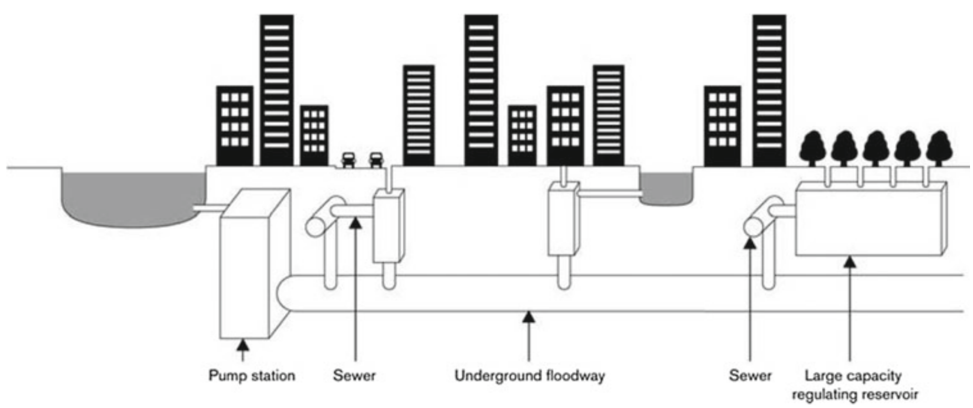
In 2011, a catastrophic flood event happened in the Chao Phraya basin and flooded Bangkok for months (Haraguchi and Lall 2014). It was the costliest natural disaster in the country's history, with direct damages estimated at US45 billion (Kundzewicz and Takeuchi 1999). The post disaster period proved that the protection level is by far too low corresponding to a return period of about 20–30 years. The Bangkok administration developed an action plan to improve the flood protection level. It was decided to increase the drainage capacity by dredging 860 channels and to develop additional large underground pipes to bypass the water downstream. The construction of six new tunnels is under planning, each with a diameter of approximately 5 m, with associated pumping stations.

18.5 Water Demand Management

Effective management of water resources has become very vital at present as water availability is limited while demand for water is continuously increasing. To achieve efficient and sustainable use of scarce water resource it is very much needed to implement strategies aimed at influencing demand, which is called water demand management (WDM). It can be viewed as one of the elements of a broad spectrum of long-term water resources planning and management. An effective WDM programme would have strong support from communities concerned with environmental issues, too.

In this chapter the discussion on WDM is limited to managing urban demand for water to achieve a balance between economic, social equity and environmental integrity. Hamaideh et al. (2015) stated that WDM as an objective-oriented approach aimed at reducing or modifying the timing or level of demand for fresh water to match it with available supplies level and to achieve a more efficient and cost-effective water use so as to ultimately have a more

Fig. 18.32 Underground flood release channel in Tokyo (Stalenberg and Kikumori 2008)



sustainable water resource management. Optimal demand management programs may incorporate measures that improve water use efficiency, offer the opportunity to reuse and recycle water and minimize water waste.

As Maggioni (2015) indicated weather, rates, income, household composition, housing characteristics, frequency of billing, type of outdoor irrigation, consumers' behaviors, attitudes and believes are drivers of residential water demand. Demand management programs are designed to promote conservation either through changes to the stock of resource using equipment or changes in consumer behavior. Behavior change of consumers can be promoted via education campaigns or through economic instruments such as pricing (Hamaideh et al. 2015).

18.5.1 Water Conservation and Water Demand Management

Water Conservation (WC) could be defined as the minimization of loss or waste, care and protection of water resources. It includes the efficient and effective use of water whereas, WDM is the practical development and implementation of strategies aimed at reducing demand and it has been defined in many different ways.

WDM is defined as the practical development and implementation of strategies aimed at reducing demand (Savenije and van der Zaag 2002). The study stressed that WDM can be achieved by,

- Stressing equitable access to water, reflected in a strategy that is specifically designed to improve service delivery to the poor.
- Treating water as both an economic as well as a social good, and managing and pricing it accordingly.
- Balancing the management of losses and consumption with the development or expansion of supplies.
- Managing a change in organizational culture from being technology focused and supply driven, to one that puts people first and is demand responsive.

Brooks (2006) defined WDM as any method—whether technical, economic, administrative, financial or social—that will accomplish one (or more) of the following:

- Reduce the quantity or quality of water required to accomplish a specific task.
- Adjust the nature of a task or the way it is undertaken so that it can be accomplished with less water or with lower quality water.
- Reduce the loss in quantity or quality of water as it flow from source through use to disposal.
- Shift the timing of use from peak to off-peak periods.
- Increase the ability of a water system to continue to serve society during times when water is in short supply.

Stewart et al. (2010) suggested that WDM consists of five categories; (1) engineering, (2) economics, (3) enforcement, (4) encouragement, and (5) education. Thus, showing the multiple facetted nature of WDM, its' transdisciplinary characteristics and emphasizing that ultimately it is more behavioral than technical.

18.5.2 Effectiveness of Demand Management Interventions

The role of pricing and regulation in encouraging conservation in residential water consumption has been examined using criteria of effectiveness, efficiency and equity to compare pricing and regulatory approaches to water conservation (Barrett 2004). The study concluded that both approaches are important and that a pragmatic mix of policies is most likely to encourage residential water conservation.

Fielding et al. (2013) investigated the impact of a few strategies on water demand management. A set of households were divided into four groups; (1) control, (2) water saving information alone, (3) information plus a descriptive norm manipulation, and (4) information plus tailored end-user feedback and their water usages were monitored using smart water metering technology. The results indicated that the three intervention groups showed reduced levels of consumption during the course of the intervention and for some months afterwards. However, after a few months consumption has returned to pre-intervention levels.

The impact of household water savings from different WDM interventions was assessed by Bello-Dambatta et al. (2014) based on water-related energy use and cost, as well as impact on the supply/demand balance using a water distribution system of a European city. Sensitivity analysis for different population growth rates that are representative of different growth rates (either shrinking or growing) across the EU has been carried out. The results showed that different degrees of water, energy, and cost savings could be achieved depending on the type(s) and proportion of household micro-component appliances and fittings considered (water efficient household appliances, retrofit devices and fittings for household appliances). In all the intervention strategies considered, there were important trade-offs to be made between different performance indicators as not all interventions would result in water savings and/or reductions in water-related energy use and costs or have a positive impact on supply/demand balance.

Masia and Erasmus (2013) studied WC/WDM at large but with emphasis on smart metering technology. A smart meter is a flexible and interactive metering device enriched with electronics and digital features that always communicates with the environment through a digital interface. Smart metering increases the efficiency of billing systems. The municipalities have WC/WDM strategies in place but it seems that they are not being implemented or done on a small scale according to the survey results. There are no dedicated sections responsible for WC/WDM at most of the municipalities and a separate budget to implement WC/WDM. The dedicated WC/WDM group could be used to coordinate all the activities which are currently done by different sections. The participants indicated that their municipalities actively promote water conservation but it can be assumed to be ineffective as the non-revenue water (NRW) remains high.

Madebwe and Madebwe (2011) examined the role of WDM instruments to achieve domestic water use efficiency in Gweru, Zimbabwe. Household water consumption histories were reconstructed using monthly household water consumption records from 2005 to 2010. Background characteristics of household heads were taken into consideration when analyzing water consumption patterns. To manage water demand the city uses socioeconomic instruments like differential water rate structures, education and reduction in water releases to domestic consumers using mechanical devices. These measures are expected to impact domestic water consumption patterns by curtailing perceived non-essential uses of water. Results show that impact of these measures on household water consumption is diverse. There is a relationship between income and water consumption. Water consumption in high income residential areas is high due to presence of high water demanding indoor appliances and outdoor activities. Households in low income residential areas react to water price disincentives by restricting consumption to basic needs. To succeed water demand management strategies must be supported by robust institutional, legislative and regulatory frameworks for enforcement of the water demand management instruments.

18.5.3 Mechanisms for Regulating Water Demand

Mechanisms for regulating demand for water could be categorized as; (i) price mechanisms, and (ii) non-price mechanisms.

Price mechanisms include increasing block tariffs, fixed, volumetric, raw water, and conservancy charges, providing rebates, cross-subsidies, etc. Non-price mechanisms include management and regulatory mechanisms, technical and engineering solutions, public education and community involvement (Araral and Wang 2013).

Da-ping et al. (2011) said that if WDM is promoted and used, enormous economic, social and environmental benefits could be brought and in that effort water administrators, water operators as well as water users, need to participate actively in the implementation of WDM process and thereby alleviate the contradictions between water supply and demand, effectively. The proposed approach of WDM is as shown in Fig. 18.33.

Generally, it is true that higher prices will encourage better demand management. However, without the assistance of non-price measures the price increases may prove more significant in raising water-utility revenues than reducing water demand (Barrett 2004).

18.5.4 Price Mechanisms

Pricing is an efficient and effective method for managing the demand for water. This conclusion originates in the fact that,

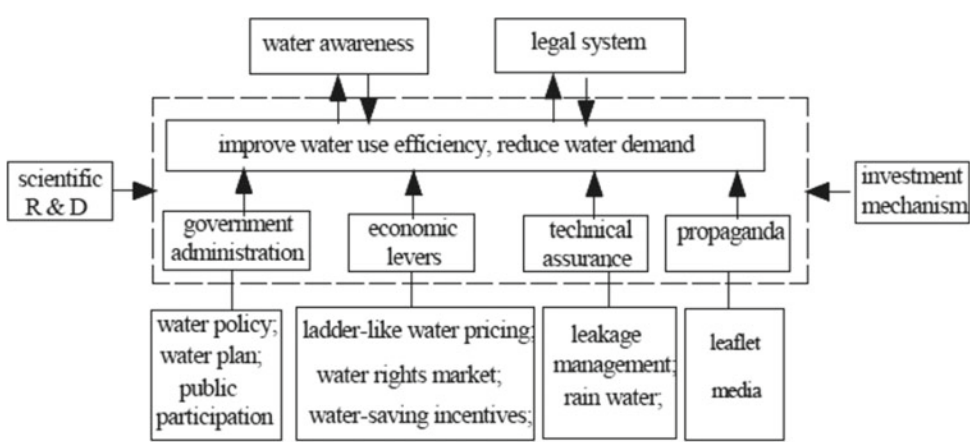


Fig. 18.33 Implementation mechanism of WDM (after Da-ping et al. 2011)

from the viewpoint for society, a properly operating price system will efficiently and optimally allocate goods and services (Millerd 1984).

18.5.4.1 Block Tariffs

It is the most common mechanism used for urban WDM. However, scholars and practitioners are often divided on the efficacy of this mechanism.

Block tariffs are volumetric charges. The prerequisite for setting a volumetric charge is that consumers have a metered connection to water services. Under a block tariff scheme, users pay different amounts for different consumption levels. Block tariffs have a step-wise structure. The water charge is set per unit (e.g., cubic meters) of water consumed and remains constant for a certain quantity of consumption (first block). As the water use increases, the tariff shifts to the next block of consumption and so on for each block of consumption until the highest one. Block tariffs can be differentiated among consumer categories (e.g. domestic and non-domestic) and are of two main types: increasing and decreasing.

Models have been developed to estimate expected water savings and the financial impacts of a change in water tariff as a WDM measure. Hoffman and Plessis (2013) presented a model that was developed for municipalities to calculate the predicted change in water use and the associated income. The model takes into account variation in price elasticity per tariff block.

This scheme divides water use into tiers, or blocks, where the price per unit of water increases with increased consumption. The price of water is the lowest for the amount in the first block. Once water usage hits the second block, the amount of water exceeding the first block will be paid at the second block's price, and so on. There are several defining features of an Increasing Block Tariff (IBT); the number of blocks, the volume of water used, and price for each block. Usually these are determined based on the water usage of a specified region.

18.5.4.2 Increasing Block Tariff

In IBT, the rate per unit of water increases as the volume of consumption increases as shown in Fig. 18.34. Consumers pay at a low rate up to the first block of consumption and pay a higher price up to the limit of the second block, and so on until the highest block of consumption. At the highest block, consumers can use as much water as they desire. IBTs are by far the most common charges for water services. They are used in countries, where water has been historically scarce such as in Spain and the Middle East and they are widespread in developing countries.

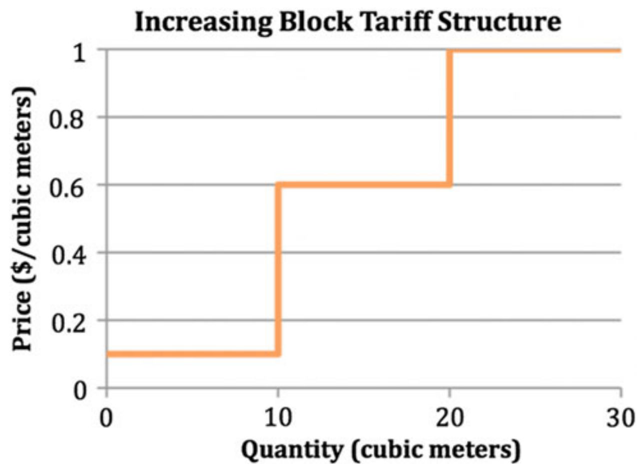


Fig. 18.34 Increasing block tariff

Water utilities and regulators in many countries are moving toward IBT pricing structure. Efficiency and equity are the two commonly stated justifications for using that pricing structure (Dahan and Nisan 2007). There are other arguments made in support of IBT such as discouraging wasteful use and promoting public health.

The IBTs are expected to assist low-income households and ensure an equitable allocation of the costs of water production and distribution. It is expected that low-income households use less water than high-income households as they have fewer water-using appliances and are less likely to have large lawns and gardens. Also the higher prices charged beyond the initial block discourage "extravagant" water use and promote water conservation.

IBTs, charging higher rates with increasing water consumption, can potentially reconcile cost recovery to finance the infrastructures with an equitable and affordable sharing of the cost burden. A firm understanding of the impacts of varying prices and socio-economic conditions on residential water demand is necessary for designing IBTs that promote these objectives. Consistently estimating water demand under an IBT requires a discrete/continuous choice (DCC) model. Klassert et al. (2018) applied a DCC model to estimate residential water demand under IBTs in the severely water-stressed country of Jordan, using 15,811 country-wide household-level observations from five years up to 2013. Under the estimated price elasticities, very few IBT designs achieve a full recovery of the financial costs of water provision, but a potential to improve cost recovery and affordability can still be identified.

Al-Saidi (2017) examined the viability of IBTs to achieve the right balance between efficiency, financial requirements and equity, and compared them to alternative pricing schemes. Using numerical examples, IBT structures of two water utilities in Yemen were analyzed. The main conclusion is that IBTs exhibit remnants of old thinking among policy makers to promote cheap water for people. In view of similar results from other regions, the current practice of IBTs in developing countries has significant deficiencies and could be replaced by simpler pricing schemes such as a uniform price with a rebate or a discount.

Monteiro and Roseta-Palma (2011) stated that IBT is frequently supported as a good tool for achieving the goals of equity, water conservation, and revenue neutrality but seldom has been grounded on efficiency justifications. In particular, existing literature on water pricing establishes that although efficient schedules will depend on demand and supply characteristics, IBT cannot usually be recommended. In their paper, they considered whether the explicit inclusion of scarcity considerations can strengthen the appeal of IBT. Results showed that when both demand and costs react to climate factors, increasing marginal prices may come about as a response to a combination of water scarcity and customer heterogeneity. They derived testable conditions and then illustrate their application through an estimation of Portuguese residential water demand. They showed that the recommended tariff schedule hinges crucially on the choice of functional form for demand.

Dahan and Nisan (2007) stated that each additional household member consumes the same water quantity regardless of household size, except for a single-person household. The study suggested that the IBT structure, which is indifferent to household size, has unintended consequences. Large households, which are also likely to be poor given the negative correlation between income and household size, are charged a higher price for water. The degree of economies of scale found here erodes the effectiveness of IBT price structure as a way to introduce an equity consideration. This implication is important in view of the global trend toward the use of IBT.

In practice, IBT is likely to promote inefficiency, unfairness and revenue instability, too, in developing countries (Boland and Whittington 2000). However, IBT may indeed increase equity but it depends on the size of the first block.

Most countries in South-East Asia rely on IBTs to manage demand for urban water. That is by employing increasing block tariffs while ensuring the affordability of water to low-income groups based on water-demand studies and charging full cost recovery to higher-income groups.

IBTs are only useful as an instrument of urban water demand management if accompanied by metering. Yepes and Dianderas (1996) suggested that the introduction of metering results in reduction in water consumption, regardless of the pricing structure used.

18.5.4.3 Decreasing Block Tariffs

In decreasing block tariffs, the rate per unit of water is high for the initial (lower) block of consumption and the rate decreases as the volume of consumption increases. Nevertheless, they penalize consumers with low level of consumption and provide a disincentive for reducing wastage of water.

This type of tariff structure was designed because “when raw water supplies are abundant, large industrial customers often impose lower average costs because they enable the utility to capture economies of scale in water source development, transmission, and treatment. Also, industrial users typically take their supplies from the larger trunk mains, and thus do not require the expansion of neighborhood distribution networks” (Whittington 2002).

Well-designed decreasing block tariffs allow utilities to recover costs. In order to design a decreasing block structure, as shown in Fig. 18.35, the number of blocks, volume of water use associated with each block, prices to be charged for water use within these blocks are needed to be decided.

However, there is a trend to move out of these kind of tariffs, essentially because water conservation has become interested by many governments and marginal costs of providing water are now relatively high in many countries. Decreasing block price scheme are still used in some communities of the USA and Canada, though in recent years other volumetric tariffs (e.g. uniform price and increasing block) are more frequently applied.

18.5.4.4 Water Rights

The pricing of water by a water distribution authority is an attempt to simulate what the price of water would be if it

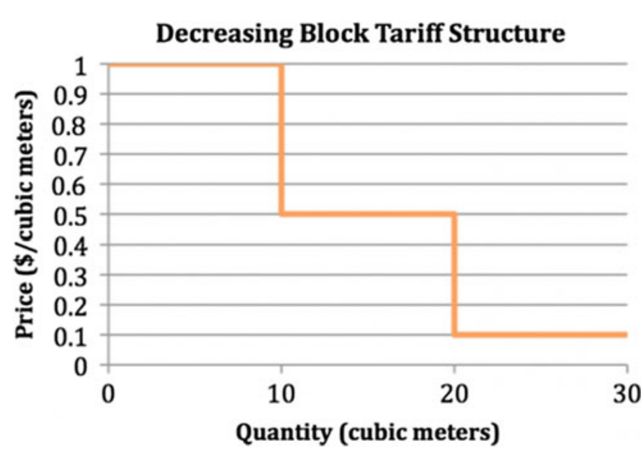


Fig. 18.35 Decreasing block tariff

were privately owned rather than publicly distributed (Millerd, 1984). With private ownership a market would develop and exchange at a market-clearing price would take place. Water rights are an attractive mechanism for efficiently conserving water. First, there is a definite upper limit on the amount of water consumed. No more water can be used than are rights. When conservation is pursued through price increases the future demand for water at higher prices can only be estimated. Second, if the rights are transferable, they will be automatically allocated in the most efficient manner, to the highest-valued use. Users willing to pay the most for the water will bid the rights away from lower-valued uses. Third, increasing demand for water is similarly automatically accommodated through price increases. With the quantity demanded being limited to the fixed supply, all adjustments take place through price increases.

18.5.4.5 Water Use Standards

Water use or plumbing standards are the most frequently suggested non-structural alternative to pricing for demand management (Millerd 1984). Standards are relatively easy to implement and administer. All users are required to behave in the same way and plumbing systems with particular specifications or characteristics are only allowed. In many cases the benefits of such requirements will exceed the costs for the vast majority of water users. Standards do not provide incentives to conserve beyond the standard and once the standard has been met there is no reward associated with additional conservation.

18.5.4.6 Rebates

Sibly and Tooth (2013) studied the impacts of adoption of IBTs to price urban water under the common constraints of scarce supply and cost recovery. The key tools used in IBTs are the volumetric rate in the low tier and the threshold level of that tier. Sibly and Tooth (2013) showed how variations in these tools influence (i) the fixed charge set, (ii) the dead weight loss from the IBT, and (iii) the bill paid by customers for particular levels of demand. Their analysis suggested that IBTs are neither fair nor efficient and they proposed a modification to IBTs that, while retaining their perception of fairness, results in the efficient allocation of urban water. The proposed modification involves providing a rebate to customers for water not used below the threshold.

18.5.4.7 Pricing

Singapore's water demand management strategy has had a strong emphasis on 'valuing' water and thus on pricing it (Tortajada and Joshi 2013). This philosophy is based on the responsible use of water where the underlying principle is that the next sources of water could cost much more than the current ones.

18.5.4.8 Rationing

Nyende-Byakika et al. (2012) analyzed the impact of demand on water supply service delivery and demonstrated that the higher the demand, the lower the pressure at which water can be supplied. It highlights the notion that water is a finite resource and many regions in the world have neither sufficient surface nor groundwater reserves to meet all competing demands for water. Moreover, there normally exist capacity constraints in available water infrastructure. In such cases, withdrawals from water distribution networks have got to be controlled if sustainable water supply is to be achieved. Thus, attention on water demand management should be accordingly increased. The study assessed the merits of rationing from a technical point of view and suggested that, if well managed, it stands out to be a viable water demand management strategy for water scarce areas. The study also suggests that water supply should be managed from an equity point of view rather than an equality point of view. Equity is achieved by treating everyone justly according to their circumstances.

18.5.5 Management and Regulatory Mechanisms

Use of water saving devices and kits is one possibility. For example, dual flush toilet cisterns, which cost no more than the single flush type, have the potential to conserve water. The Kingdom of Saudi Arabia provided water saving devices and kits among the consumers free of charge (Al-Zahrani et al. 2013).

Decentralized management is another common approach to urban water demand management. In some countries demand-management zones or territory-management approaches have been effectively employed as strategic approaches to managing non-revenue water (NRW). Likewise, the use of information technology such as geographic information systems and supervisory control and data acquisition (SCADA) technology are also extensively used. A *SCADA system* is essentially a distributed computer *system* that is used by operations and management for process (water transport, distribution, treatment, etc.) monitoring and automation.

A recent form of regulatory water use restriction is the imposition of specific water use technologies in building codes (Barrett 2004). For example, making all new homes to be fitted with dual flush toilets, using 6 or 3 litres per flush. This could be compared with the previous technology using 11 litres per flush. If these regulations are embodied in the water using technology, they will be very effective at reducing consumption. Regulatory approaches to water conservation are typically more effective than pricing approaches. Also, pricing will reduce equity while regulatory approaches may improve equity.

Integrating water, land use, and demographic data facilitates the identification of the driving factors for consumption, and establishment of metrics for comparison (Dziedzica and Karney 2014). It allows for a more holistic analysis of water use and is instrumental in integrated water demand management. Furthermore, it is a continuous process. Databases should be updated as frequently as new data is available or when the need arises, and can be expanded, with more information on the users, the water system, or even other infrastructure types. They facilitate internal and external communications, enabling conservation targeting as well as improvements to water rate structures, increasing the sustainability of the system.

Regulatory approaches to water conservation are more varied and their impacts (effectiveness) have been less studied than those for pricing (Barrett 2004). As reported, Australian water utilities clearly prefer regulations for restricting water use. Typically water-use restricting regulations in the form of bans on outside garden watering during periods of drought has proved very effective in reducing water consumption for limited periods.

18.5.5.1 Technical and Engineering Solutions

Technical and engineering measures play an important role on WDM. Engineering solutions such as introduction of pressure-reducing valves to manage water pressure, use of SCADA technology as the controlling and operating system, replacing ageing and leaking pipes could be useful in WDM.

Environmental and demographic pressures have led to the current importance of WDM, where the concepts of efficiency and sustainability now play a key role. Water must be conveyed to where it is needed, in the right quantity, at the required pressure, and at the right time using the fewest resources. Ponte et al. (2016) showed how modern Artificial Intelligence (AI) techniques can be applied on this issue from a holistic perspective. More specifically, the multi-agent methodology has been used in order to design an Intelligent Decision Support System (IDSS) for real-time WDM. It determines the optimal pumping quantity from the storage reservoirs to the points-of-consumption in an hourly basis. This application integrates advanced forecasting techniques, such as Artificial Neural Networks (ANNs), and other components within the overall aim of minimizing WDM costs.

18.5.5.2 Institutional and Regulatory Reforms

Institutional and regulatory reforms could be adopted to promote accountability of urban water utilities. For example, public water utilities could undergo a process of debt restructuring to make them more viable. Responsibility and accountability of the utilities could also be transferred to local governments. That is, defining the responsibilities of different levels of government—federal and state governments, provinces and districts, etc.

Public-private partnerships were instrumental in improving water service delivery. Successful private-sector participation requires, among other things, the alignment of corporate goals with social goals, as well an effective regulation. Regulatory reforms are introduced to separate service providers from regulators. Permitting and licensing system for groundwater extraction, but enforcement is challenging. Regulations for engineering and service standards are also important in managing urban water demand.

18.5.5.3 Leadership

Leadership plays an important role in improving the performance of urban water utilities, including WDM. A stable, competent and committed leadership can make a substantial difference in performance. The top leadership of these water utilities may have stayed with their jobs for no less than 10 years, overseeing the protracted processes of replacing ageing and leaking pipes, upgrading management and technology (including metering), and introducing tariff reforms, among others. Some attribute their success to corporate governance, financial management and operations management.

18.5.5.4 Public Education and Awareness

Educating consumers and capacity building initiatives are very useful in demand management. In order to sustain long-term benefits, education and awareness programmes need to be properly designed and well implemented. Such programmes should extend beyond the normal pamphlets and media presentations. For example, there are considerable opportunities provided through the billing system for effective communication with consumers. From a demand management viewpoint, it would be helpful if account forms could be designed to readily identify the total annual consumption.

Moral suasion (persuasion) or public education on water conservation is commonly used by utilities in South-East Asia to manage water demand, but with varying degrees of efficacy relative to other instruments. The most commonly used methods of moral suasion are communicating to consumers their marginal cost information, benchmarking their consumption with respect to national averages and highlighting block-tariff information. However, it is difficult to disentangle the effects of moral suasion from the effects of other instruments such as IBTs and the application of technical and management solutions.

Successful public education requires the achievement of the specific target of reduction in water consumption per capita (Tortajada and Joshi 2013). As such, the objective of public involvement strategies is to change the societal behavior towards greater conservation in daily water use by directly influencing their attitudes and behaviour.

18.5.5.5 Community Involvement

Interactive relationships with the community, based on information transfer and feedback, are very important in WDM. By developing an interactive relationship with the community, demand management can help keep water managers in tune with community needs and expectations. At the same time, the community would better understand the water industry and the complex issues involved in water resources planning.

In developing countries, which have to deal with large informal settlements, water utilities that have effectively reduced demand often have community-based water conservation programmes. For example, the large informal settlements in Metro Manila, which for years have been a major source of NRW due to leakage, theft, non-metering and non-billing, have been effectively organized into self-managed water districts, with each district connected to a bulk meter and provided with public taps (Araral and Wang 2013). The officers of these water user groups were responsible for collecting water bills and paying the water concessionaire. The water user associations were also responsible for monitoring and reporting theft and leakage.

Hamaideh et al. (2015) assessed the level of the consumers' participation in WDM and estimated their willingness to participate in WDM. The study is also aimed at determining the different socioeconomic factors associated with their willingness to participate in WDM. The willingness to participate in WDM was studied based on a standard questionnaire among a sample of 600 households in the Greater Amman area in Jordan. The results showed that the majority of the interviewed consumers were willing to participate in demand management and prefer more direct forms of participation. The results also showed that the willingness of the interviewed consumers was dependent mainly on their age and average income. The respondents are more responsive to penalties rather than rewards when it comes to taking measures aimed at reducing water consumption. When making policies, the policymakers need to take into consideration the measures the consumers are more responsive to.

In the case of public involvement strategies to achieve WDM goal, there has been a very strong emphasis on information and feed-backs, but not so much on policy-making (Tortajada and Joshi 2013). This is, active involvement of the public has not been in terms of development of plans or policies but rather on their implementation where they are able to become partly responsible for the outcomes. In daily life, members of the society are expected to participate actively by acting responsibly, adopting more efficient practices and changing their attitudes and behaviour.

Gilbertson (2011) found that significantly more people from a water-scarce location are supportive of water conservation behaviours than those living in a region with water surplus. The timing of community engagement programs and type of messaging is therefore critical to its success, and reframing messages from a focus on drought response to a focus on long-term water supply reliability may build continued support.

Community engagement is central to any demand management effort and there are many ways to communicate with communities about the value of water efficiency. While some organizations have traditionally used a one-way transfer of information to inform and educate the public and other stakeholders a shift to a broader spectrum of community engagement where relationships are built on shared visions and trust is occurring in many sectors. The shift indicates in part the radically different forms of communication organizations now need to embrace due to a fast pace of innovation compounded by increasing diversity, complexity and change in communities.

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Hans Peter Nachtnebel is a Professor Emeritus attached to the university of Natural Resources and Life Sciences, Vienna, Austria. His main areas of research are Hydrology, Water Resources Management, Environmental Risk Analysis and Management, Climate Change and the Water Cycle, Hydro-ecology, Water-Energy-Food Nexus, Multi-criterion Decision Making.

K. D. Wasantha Nandalal is a Senior Professor at the Department of Civil Engineering, University of Peradeniya, Sri Lanka. He received his Ph.D. in 1995 in the field of Water Resources Management from Wageningen Agricultural University in The Netherlands. His research interests are in the areas of application of soft computing techniques in water resources management, system dynamics modelling and flood modelling.

Part IV

Examples of Contexts and Scales: Facets of Water Resources Management and Use, Risks and Complex Systems

Examples of Water and Land Use Management

19

Bernhard Tischbein, Maksud Bekchanov, John P. A. Lamers, Navneet Kumar, Kai Schwärzel, Lulu Zhang, Tamara Avellán, Usman Khalid Awan, Fazlullah Akhtar, Anik Bhaduri, Janos J. Bogardi, Yanhui Wang, Pengtao Yu, Anh Bui, Mauricio Nevado Amell, Luana Tesch, Lúcia La Barca Pedrosa, Renato Mariano, Sanjana Balachandran, and Kurt Brüggemann

Abstract

This chapter is the collection of several examples, both in thematic and geographical sense, which manifest the need to address water and land management in an integrated way. It reviews irrigation and soil management techniques, performance assessment of irrigation as well as water delivery scheduling for irrigated agriculture. Water scarcity and drought may even jeopardize that irrigation

B. Tischbein · J. P. A. Lamers · N. Kumar · F. Akhtar
Center for Development Research (ZEF), University of Bonn, Bonn, Germany
e-mail: tischbein@uni-bonn.de

J. P. A. Lamers
e-mail: jlamers@uni-bonn.de

N. Kumar
e-mail: nkumar@uni-bonn.de

F. Akhtar
e-mail: fakhtar@uni-bonn.de

M. Bekchanov
Center for Earth System Research and Sustainability (CEN), University of Hamburg, Hamburg, Germany
e-mail: maksud.bekchanov@uni-hamburg.de; maksud.bekchanov@yahoo.com

K. Schwärzel
Thünen Institute of Forest Ecology, Eberswalde, Germany
e-mail: kai.schwaerzel@thuenen.de

L. Zhang
United Nations University, Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany
e-mail: lzhang@unu.edu

T. Avellán
Self-employed Expert in Participatory Water Resource Management, Dresden, Germany
e-mail: tamara.avellan@posteo.de

U. K. Awan
International Water Management Institute (IWMI), Lahore, Pakistan
e-mail: u.k.awan@cgiar.org

A. Bhaduri
Sustainable Water Future Programme, Griffith University, Brisbane, QLD, Australia
e-mail: a.bhaduri@waterfuture.org; a.bhaduri@griffith.edu.au

J. J. Bogardi (✉)
Center for Development Research (ZEF), University of Bonn and Institute of Advanced Studies Kőszeg (iASK), Kőszeg, Hungary
e-mail: jbogardi@uni-bonn.de

Y. Wang · P. Yu
Research Institute of Forest Ecology, Environment and Protection, Chinese Academy of Forestry, Beijing, China
e-mail: wangyh@caf.ac.cn

P. Yu
e-mail: yupt@caf.ac.cn

A. Bui
Department of Civil Engineering, Construction Management and Environmental Engineering, Northern Arizona University, Flagstaff, AZ, USA
e-mail: anhphibui023@gmail.com

M. Nevado Amell · L. Tesch · L. La Barca Pedrosa · R. Mariano · S. Balachandran · K. Brüggemann
TU Dresden, Dresden, Germany
e-mail: nevado_mau1@hotmail.com

L. Tesch
e-mail: luana_lt@hotmail.com

L. La Barca Pedrosa
e-mail: lucialabarcapedrosa@gmail.com

R. Mariano
e-mail: Renato.mariano@outlook.com

S. Balachandran
e-mail: Sanjana.b.nair@gmail.com

K. Brüggemann
e-mail: kurt.brueggemann@posteo.de

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infrastructure could be deployed to offset threatening economic losses. The chapter emphasizes the need for careful afforestation planning to avoid aggravating water shortage downstream. Finally, constructed wetlands are introduced as a low cost wastewater treatment technology with other positive spin off effects.

Keywords

Land and water management • Irrigation • Drainage • Drought loss assessment • Khorezm • Soil and water • Afforestation • Constructed wetlands

Abbreviations

CAP	Capillary Rise (from groundwater)
CR	Conveyance Ratio
CW	Constructed Wetland
DF	Depleted Fraction
DPR	Delivery Performance Ratio
DRAIN	Drainage Discharge Sum
E	Evaporation
ECe	Electrical Conductivity of the extract of a saturated soil paste
ESA	European Space Agency
ET	Evapotranspiration
ET_0	Reference Evapotranspiration
ETc	Crop Specific Evapotranspiration
ETa, ETpot	Actual and Potential Evapotranspiration
Ea, Eb, Ec, Ep	Irrigation Efficiency related to water application, farm ditch, conveyance, project (overall)
FAO	Food and Agriculture Organization of the United Nations
FAR	Field Application Ratio
FDR	Frequency-Domain-Reflectometry (soil moisture sensor)
GDP	Gross Domestic Product
GIS	Geographical Information System
GW	Groundwater
IWRM	Integrated Water Resources Management
IR	Infrared
Ky	Yield Response Factor
LANDSAT	Land-use satellite
LWP	Leaf Water Potential
MERRA	Modern-Era Retrospective analysis for Research and Applications
Mpa	Megapascals
Mha	Million hectares
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
OCR	Overall Consumed Ratio
Peff	Effective part of Precipitation
PER	Percolation below root zone (of an irrigated field)
RET	Relative Evapotranspiration
RUN	Surface Runoff (from irrigated field)
RWS	Reduced Water Supply (in deficit irrigation)
SEBAL	Surface Energy Balance Algorithm for Land
SENTINEL	Satellite Constellation of the Copernicus Program
SMAP	Soil Moisture Active Passive (mission)
Soilmoist	Soil Moisture
T	Transpiration
TDR	Time-Domain-Reflectometry
TV	Target Value
V	(Water) Volume
WCA	Water Consumers Association
Ya, Ypot	Actual or Potential Yield
Δ STORAGE	Storage Change (in soil moisture or water layer in an irrigated field)
t	Index Counting Days
Ha	Hectare
dS/m	Deci-Siemens per meter

19.1 Towards Integrated Water and Land Management

19.1.1 Introduction

The previous parts of this Handbook, whether from the viewpoint of the actual challenges (Chap. 3, Sect. 3.4), from the perspective of the different discourses and governance questions (Chaps. 7, 9, 12) or from the practical consideration of assessments (Chaps. 14, 15, 17) mention and analyze both the Integrated Water Resources Management (IWRM) and the nexus approach. While acknowledging the discrepancies which can be found between aims, claims and the practical applicability of these concepts, there can no doubt be left that the epoch, which was characterized by, what may be called "one dimensional water resources management", focusing on the availability and the delivery of the resource for the intended use, is definitely and irrevocably over.

While the complexities of socio-ecological systems (see Chap. 25), competing aspirations, constraints of governance, but also that of natural, human and financial resources would create varying scales and management contexts. The new water resource management era of integrated considerations, seeking consensus over synergies and tradeoffs, between upstream and downstream interests, monitoring the consequences of and revisiting decisions in an adaptive framework, is emerging.

Core of this integration is the "co-consideration" of the two key resources, water and land, and their interactions at different contexts and in frequently embedded scales.

In this chapter, five examples are presented. They highlight the importance and emphasize the message that the two, at global scale most abundant resources, water and land (soils), cannot and should not be managed separately.

19.1.2 Enhancing the Productivity of Land

Traditionally food production and agricultural activities in general are the largest users of both water and land resources. As Sect. 19.2 presents, enhancing water availability for food production through irrigation virtually doubles harvest compared to rainfed agriculture (at global scale). Irrespective of this "success story", irrigation did not become and cannot be the sole solution to increase crop productivity. Resource (mainly that of water) constraints, considerable financial investment demand and the need of technical prowess of irrigators, but also soil salinization, water quality deterioration and concerns of stakeholders located downstream of a potential irrigation perimeter can be mentioned as the most common reasons.

Section 19.2 introduces approaches for irrigation scheduling and different irrigation methods. It focuses on indices and their practical applicability to capture the performance of the whole, and components of an irrigation system. Especially through its excellent case study examples, Sect. 19.2 highlights the need to embed irrigation into a basin wide context, consider adequate drainage options and further issues, like land tenure, prices and market to be inducive for the adoption of water saving techniques and sustainability considerations.

Success and minimizing environmental impacts of irrigation depend as much on operational management (scheduling and distributing water deliveries within the system) as on a good design and state of irrigation infrastructure. Irrigation, while an integral part of water resources management, is ultimately an agricultural operation. Hence, the objectives and constraints of agriculture, such as land ownership, product choice, marketing, risk averse behavior of farmers must be accounted for and factored into the assessment of irrigation.

Section 19.2 is setting the stage for understanding and acknowledging the intertwined nature of land and water management. The case study examples are located along the Lower Amu Darya river basin in Central Asia. In this region reliable crop production can only be achieved with the help of irrigation. Historically this region can be called as one of the cradles of irrigated agriculture. Before the Mongol conquest of the Central Asian empire of Khorezm in 1219–1221 in the region 7-million-hectare land (comparable to the present extent) was under irrigation.

The following short Sect. 19.3 focuses on the soil–water management practices, thus dealing rather with agricultural techniques to improve infiltration, reduce evaporative losses from soils and to increase the soil water uptake by plants.

19.1.3 Water Conservation Under Drought Risk

Section 19.4 deals with recurrent droughts which are a serious threat to economic development and the sustainability of the livelihoods in arid and semi-arid environments, especially in downstream reaches of the rivers. In the presented case study economic losses of agricultural production due to reduced water supply are quantified. Various water-efficient measures intended to cope with future water shortages are analyzed. The example is again the Khorezm region located in the downstream reaches of the Amu Darya river in the Aral Sea Basin, Central Asia. According to a cost–benefit analysis, the magnitude of the shortage in water-scarce years was as low as 60% of the usual water consumption, leading to economic losses amounted to as high as 70% of the annual average agricultural profit level. Farmers would be better prepared to cope with future droughts through the implementation of simple and inexpensive measures (e.g., alternate dry furrows, short furrows, and double sided irrigation) in the pessimistic scenario that reduces overall water use by 15–18%. The sequential expansion of more advanced but more expensive techniques such as laser-guided land leveling and drip irrigation for limited area as assumed under the neutral scenario and for broader area under optimistic scenarios would reduce overall water use by 24–30% and 32–40%, respectively. Such kind of modernization of the irrigation system would be less costly than the damage costs of the drought. However, coping with the most severe droughts would require additional water supply improvement measures through improving conveyance efficiency and adopting a basin-wide coordination of water resources. Thus emphasizing that irrigation is ultimately not simply a farming activity, but very much piece and parcel of basin scale water resources management, including transboundary water or/and benefit sharing.

19.1.4 Afforestation and Constructed Wetlands: Examples of Water and Land Cover Change Management

Section 19.5 addresses the issue of balanced soil and water management in case of afforestation of drylands. Afforestation is certainly a very useful measure as it helps reducing soil losses due to erosion. It also improves the water retention capacity of the hitherto barren soil and so it can considerably reduce flood peaks downstream. In the international discourses afforestation enjoys, almost univocally, positive appraisals. In this one sided assessment the fact that forests can be Gargantuan water consumers frequently remains beyond consideration. They can lower water tables much below target and while their above mentioned retention capacity can be an asset for flood water management they ultimately reduce the water yield compared to that of an unforested watershed under similar hydroclimatic conditions.

Thus choosing the right sort of tree to be planted and the right portion of the catchment to be afforested are among the key questions to be answered in the integrated context of land and water management. In Sect. 19.5 these issues are discussed in connection with the afforestation of the Loess Plateau region in Northwest China.

Finally, Sect. 19.6 addresses an entirely different aspect of the integrated land water management nexus by looking beyond the traditional agricultural and silvicultural contexts.

By allocating land for constructed wetlands (CW) an nature-based solution version of the pollution control ecosystem service function of wetlands can be implemented. Irrespective that this technology is surprisingly underutilized, CWs have considerable potential, especially for developing countries. Constructed wetlands contribute to improve public health in human settlements. They offer a robust technology for the disposal and biological treatment of municipal waste water at low cost.

The closing segment of the municipal water cycle (treatment of wastewater) can thus be transformed to be an explicit component of land and water management. Constructed wetlands can hence be seen both as a nature-based solution, but also as a link to bridge the gap between urban and rural water resources management.

19.2 Irrigated Crop Production

19.2.1 Relevance of Irrigated Agriculture

Irrigation had, has and will have a high relevance directly for agriculture, but also going beyond as strongly influential to economy, ecology, health and even politics as proved in history. A look back in history shows, that irrigation played an important role in the developing of civilizations. The intention to establish and operate irrigation schemes at larger scale was a major reason for the development of ancient higher civilizations (with examples in: Mesopotamia, Egypt, Central Asia, Indus region, China). Under arid climate conditions, the relationship between (functioning) irrigation (and drainage) management and civilization is so close, that the term 'hydraulic' civilizations' (Wittfogel 1957) is justified: successful management of irrigation enhanced civilizations, whereas insufficient management contributed to declining and even collapse of civilizations.

Irrigated agriculture was and is expanding and intensifying. Some facts and figures are highlighted in the following to point out the current relevance in terms of achievements, but also without neglecting some problematic aspects.

- Irrigated agriculture practiced currently at around 300 Mha is by far the biggest water user being responsible for around 70% of withdrawals at global scale (compared to approximately 20% for industry and 10% for domestic purpose) (FAO 2020);
- Although accounting only for around 20% of agricultural area, irrigated lands produce about 40% of agricultural outputs at global level (UNESCO 2012);
- Yet, the production potential is adversely affected by salinization (around 20% of the irrigated area face severe salinization)—especially in case of insufficient consideration and integration of the salt management into irrigation concepts;
- Going beyond the irrigated area under consideration, irrigation exerts considerable impacts on the water availability and water quality of downstream water users. These impacts are often highly disadvantageous if irrigation is practiced without proper supplementary measures. As exemplified in the case of the Aral Sea Basin in Central Asia, tremendous irrigation developments upstream gradually led to the desiccation—or nearly disappearing—of once the fourth largest lake inducing extremely harmful and health threatening impacts on downstream ecosystems and the economy of the region.

Irrigation thus has both advantageous and disadvantageous aspects and is on a 'balancing-act': on the one hand irrigation is needed to realize food security and on the other hand irrigation is an intervention with far reaching—and often harmful impacts on the environment (and in turn on the health of the population). The future is even more challenging as an increasing demand (driven by population growth and changing nutrition behavior) is in contrast with available resources being already used today to a high degree at many locations across the world (in some parts even over-exploited) and expected to become more variable due to climate change. Furthermore, the competition for water is expected to sharpen in future due to higher (water) demands of an expanding industry, growing population and urgent need to consider—at least minimum—requirements of ecology (ensuring and enforcing environmental flow). Given this context, irrigation will continue to overtake an essential role in strategies for food security under increasingly complicated conditions. Yet, irrigation urgently has to become more targeted, efficient, effective, productive and impact-aware. These requirements are reflected in the structure of this section on 'Irrigated crop production' in a way that the sections (and their sequence) provide information to (re-)conceive irrigation management to meet future challenges. Section 19.2.2 will introduce irrigation and drainage using a systems approach. Performance assessment in Sect. 19.2.3 gives an overview on indicators for assessing current performance, detect reasons for eventual under-performance and provides the starting-point for conceiving promising and reason-oriented options towards improvement. Given the above-mentioned challenges, irrigation needs to be understood and conceived as a flexible intervention into the agricultural production system. Considering the temporal behaviors of water demand and supply as well as their matching while taking site-specific conditions into account enables to derive appropriate irrigation schedules, which are—together with approaches advancing the handling of and introduction of modern irrigation techniques—key components for raising efficiency and productivity (Sect. 19.2.4). In order to unfold this productivity potential through flexible irrigation scheduling, appropriate data collection and exchange (Sect. 19.2.5) are required. Moreover, the linked systems surface and (shallow) groundwater needs to be considered and jointly utilized and adaptive management should be implemented to re-act in an optimal way on an increasingly variable environment (Sect. 19.2.5). Complementing these rather 'internal' options (within the irrigation and drainage sphere) by embedding the irrigation systems and their operation into the hydrological basin and the socio-economical-institutional context (Sect. 19.2.5) can further advance the improvement of irrigation productivity and lower the environmental externalities.

19.2.2 Irrigation and Drainage Systems

Starting with a view on the purposes of irrigation, this section aims at providing an overview on the components of irrigation and drainage systems and their major features. The focus is on the technical system accompanied by an attempt to consider inter-linkages to the overall context.

Major purposes of irrigation consist in:

- *Fulfilling crop water requirement (full or supplemental to rainfall)*:
  by realizing a soil moisture level over time, which ensures no yield reduction by water stress (or minimizing the impact of water stress on yield in case of a non-avoidable under-supply—controlled deficit irrigation);
- *Leaching for salt management*:
  by limiting the rise of soil salinity below salt tolerance levels of crops via purposely over-irrigate from time to time in order to create percolation through the root zone leaching salts (which were accumulated from incoming salt in the irrigation water and eventually from capillary rise from shallow groundwater) below the root zone and via groundwater flow and/or a drainage system (as groundwater flow in most cases is insufficient) out of the irrigation scheme;
- *Protection of crops against freezing*:
  by running sprinkler systems to apply water which releases energy while freezing in order to compensate energy loss (outgoing radiation, wind) and keep crop temperature above zero degree;
- *Cooling of crops*:
  by applying water with sprinklers and use of energy needed for evaporation process to lower the temperature in crop stands;
- *Wastewater treatment/re-use*:
  by irrigating wastewater in order to close nutrient cycles.

As the last three purposes are rather specific and therefore limited to a few locations, we will focus in the following on irrigation to fulfill crop water requirements and salt management and will use the term crop irrigation.

Crop irrigation is an activity requiring a system consisting of components for supplying the water to the field or farm, applying the water into the root zone within the field and discharging surplus water (and salts) from the field and out of the scheme. In order to enable long-term successful operation, irrigation needs to be complemented by drainage facilities for managing salt and to control the groundwater table which might become too shallow due to recharge from irrigation water losses and eventual rainy periods. As a consequence, we consider the entire system of irrigation and drainage components.

Irrigation is impacting not only the location of the scheme under consideration, but in tendency exerts basin-wide effects. Given the multi-component structure of irrigation systems and the interlinked relationships of environmental media, scales and disciplines, the systems approach is a helpful tool and will be used in the following to structure the irrigation and drainage sphere.

In the following, the major components of the irrigation and drainage system and their main features (parameters to describe their function) are summarized. Figure 19.1 provides a sketch of these components.

- *Facilities to withdraw water from the source*:
  These facilities consist either in diversion from rivers with or without storage option in reservoirs or pumping

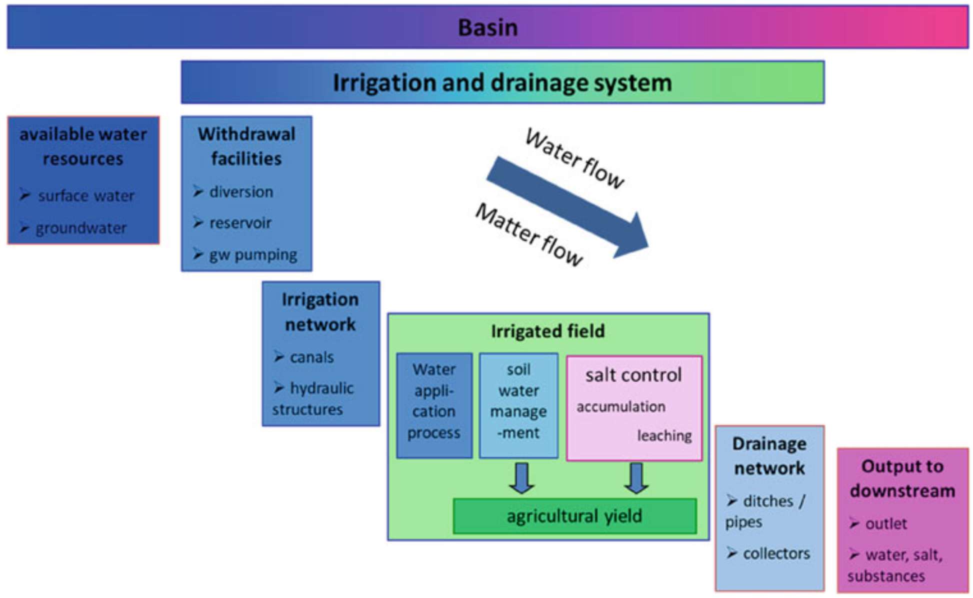


Fig. 19.1 Major components of irrigation and drainage systems

from groundwater. Issues related to groundwater management and conjunctive use as well as storage reservoir operations are discussed in detail in Chaps. 23 and 24 respectively. Furthermore, utilizing springs and water harvesting strategies can provide water supply. Withdrawal is quantified as a discharge over time and electrical conductivity as major water quality variable for salt management. The facilities are the link between the basin and the irrigation scheme.

- *Irrigation network (conveyance and distribution)*:
  Irrigation canals (in some cases pipelines) and hydraulic structures are major elements of the irrigation network to convey and distribute the irrigation water to and within the scheme. Depending on the size of the scheme, the network can be classified into several hierarchy level with the major ones serving for convey and the lower ones realizing the water distribution to the farms (and within the farms). Canals might be earthen or lined in order to reduce percolation and seepage dominating the irrigation water losses in the network. Main functions of hydraulic structures consist in: water level control, discharge measurement and dosage, flow dividing and supply provision to farms via outlets (and also providing an emergency link to the drainage system in case of discharges in the network exceeding the hydraulic capacity). As far as possible, the network is run by gravity; yet, depending on the topography, water lifting devices can be needed. Major variables to operate the network are discharge and water level with a spatial discretization according to hydraulic structures and a temporal resolution (day, hour).
- *Irrigation facilities at the field*:
  The task at field level consists in applying the appropriate amount of irrigation water at the right time (to fulfill crop water demand and leaching requirements) with highest possible uniformity and efficiency. To that end, structures for discharge dosage, bunds around the field, a uniform level or slope of the field and techniques for water distribution within the field (depending on the irrigation method) are used.
- *Drainage system*:
  In order to discharge surface runoff from the field (after heavy rainfall events, over-irrigation) and for managing the groundwater level (for salt control and cope with recharge by irrigation losses), drainage systems need to be installed. These systems consist of the outlet (operated by gravity or pumping), a hierarchy system of collectors and field ditches, which are complemented by drainage pipes (tiles) in case of too narrow spacing of open ditches hindering agricultural activities. Especially in case re-use of drainage water is envisaged, drainage pumping might be a further feasible option to manage groundwater level.
- *Outlet and downstream*:
  The outlet is linking the irrigation and drainage scheme to the basin via releasing discharge with potentially disadvantageously altered water quality (fertilizers, plant protective agents). Reduced flow (difference between withdrawals to and release form irrigation schemes) and water quality deterioration indicate the impact of irrigation on the downstream part of the basin (and especially its population).

The system introduced above reflects a rather technical view on water. Yet, irrigation is much more than handling water, as should be pointed out in the following by widening the perspective. Widening refers to two aspects: firstly, irrigation is an activity across the environmental media that means managing these media in combination, and secondly, the

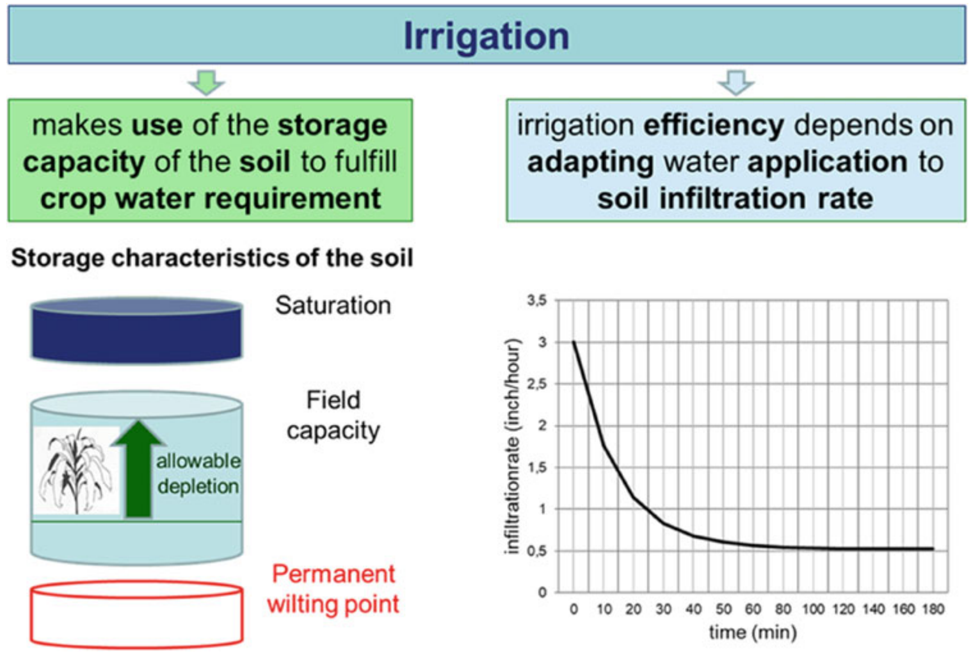


Fig. 19.2 Irrigation as management intervention across the environmental media (soil-water-atmosphere)

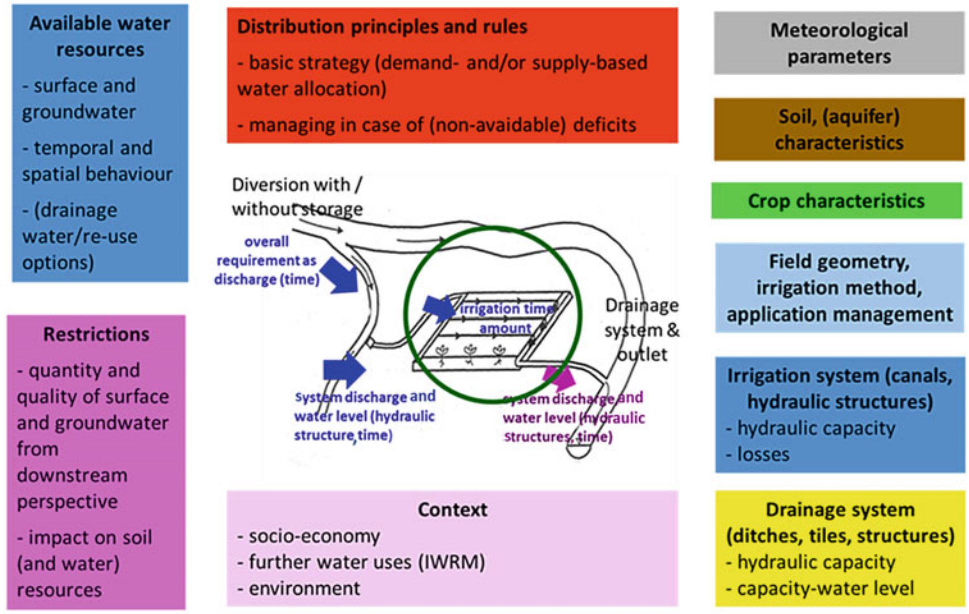
technical system needs to be embedded into the agricultural, socio-economic and institutional context.

The first step in broadening the view is to be aware that even within the bio-physical system, irrigation is a combined management of the media water, crop, atmosphere and soil. Variables of the atmosphere (temperature, air humidity, radiation, and wind speed) influence via the evapotranspiration the water demand of the crop. In order to achieve the full yield potential, irrigation meets that demand by utilizing the storage characteristics of the soil and provides appropriate soil moisture for agricultural production. Successful management across the above mentioned media needs an interdisciplinary approach. Figure 19.2 illustrates the linkage between water and soil: the amount of irrigation water to meet the crop water demand is utilizing the storage capacity of the soil (left part of Fig. 19.2) and the efficiency of irrigation strongly depends on an application rate, which is adapted to the infiltration rate (right part).

The second step towards widening the view consists in embedding the technical handling of irrigation within the bio-physical system into an overall context. As depicted in Fig. 19.3, the core of conceiving irrigation should start at the field by determining the amount and time of irrigation (demand oriented bottom-up approach). The demand is then translated into time-depending discharges to be realized in the irrigation network and summed-up to an overall water demand to be withdrawn from the water source. The arguments on the right side of Fig. 19.3 point out the information needed to estimate the water demand. The resulting demand needs to be contrasted to the available water resources (left part of Fig. 19.3) and checked, whether the resources (considering potential restriction from downstream) are sufficient to meet the demand. The technical handling is guided by institutional settings ('rules of the game': middle upper part of Fig. 19.3). These settings consist in the basic principle governing the water allocation and distribution (e.g.: demand driven versus allocating the available supply; water provision based on farm size or considering crops; rotational flow or flow on demand) and especially on the principles for managing deficits in water provision in critical times of non-avoidable under-supply becoming a future issue due to climate change and sharpening competition for water with further user-sectors (e.g.: proportional cutting of water allocated versus prioritizing crops). The arguments summarized in the middle-down part of Fig. 19.3 indicate the need to embed irrigation in the overall context. Within the agricultural system, irrigation in general targets to ensure full yield potential from water perspective and/or highest possible water productivity. Selection of crops and choice of irrigation techniques consider the socio-economic situation of the farmers being water end-user. In addition, impacts of irrigation in terms of reducing water availability and deteriorating water quality for people downstream and on the environment (environmental flow to sustain ecosystems and their service provision) should be assessed before implementation and balanced through considering irrigation in Integrated Water Resources Management (IWRM) concepts.

Given this system as framework, Sect. 19.2.4 will provide more detailed information on determining irrigation schedules and their implementation.

Fig. 19.3 Irrigation system and its embeddedness



19.2.3 Irrigation Performance Assessment

19.2.3.1 General considerations

Most of the countries around the globe have started relating water security to food security and even overall security and stability of these countries. In particular Chaps. 7, 8, 11, 12 and 17 provide insights into the different nexus connections and discourse implications. Irrigation performance assessment of large irrigation schemes is therefore now becoming a part of integral water policies of these countries (Sax 2000). Sets of irrigation performance assessment indicators were worked out and documented in guidelines (Bos et al. 2005) for both to monitor the strategic performance of the irrigation schemes as well as identifying flaws in monitoring the operational performance of these irrigation schemes. A further and next step consists in identifying the reasons for under-performance. As effective and long-term successful strategies to overcome current deficits in irrigation (dominating in terms of water quantities due to highest share of water withdrawals the entire sphere of water management) need to tackle the reasons for current problems, the results of irrigation performance assessment form the starting-point for guiding concepts towards improvements in irrigation and water management. Especially for coping with anticipated water scarcity, a major goal of irrigation consists in operating schemes with highest possible water productivity, which is the ratio of agricultural yield to gross water input. Maximizing that ratio by irrigation intervention can be achieved by contributing to reach a high yield with lowest possible gross water input. Maximizing agricultural yield by means of irrigation requires an irrigation scheduling, which is avoiding water stress or—in case of insufficient supply—minimizing the impact of water stress on the yield; that means irrigation needs to be appropriate. Lowering the gross water input without reducing the yield (that means ensuring net irrigation amounts high enough to maintain soil moisture levels sufficient for full yield potential) can be realized by irrigation with high efficiency and salt leaching with high effectiveness. Scaling-up to irrigation scheme operation, quality of performance can be expressed by smallest possible deviation between realized versus planned irrigation schedules (delivery performance ratio). Scaling-out to the agricultural system requires to embed irrigation scheduling into the provision of agricultural inputs (e.g. application of fertilizers) in a way, which is targeting the highest possible combined overall effect. Given that context, irrigation performance assessment can be structured (as a basic system) as depicted in Fig. 19.4 by indicators measuring: appropriateness of irrigation, efficiency of irrigation water distribution and application and effectiveness of salt management. Figure 19.4 provides basic information on these indicators (and link to water productivity).

The classical technical irrigation efficiencies (e.g., field application ratio, conveyance ratio, distribution ratio) are currently combined with modern sets of irrigation performance indicators (e.g., relative evapotranspiration, overall consumed ratio, depleted fraction) to evaluate the irrigation systems performance (Bos et al. 1994; Levine 1982; Small and Svendsen 1990). However, the main objective of the irrigation performance assessment is still classical i.e., it covers the key issues of appropriateness, efficiency, adequacy, equity and reliability of irrigation operation in irrigation schemes.

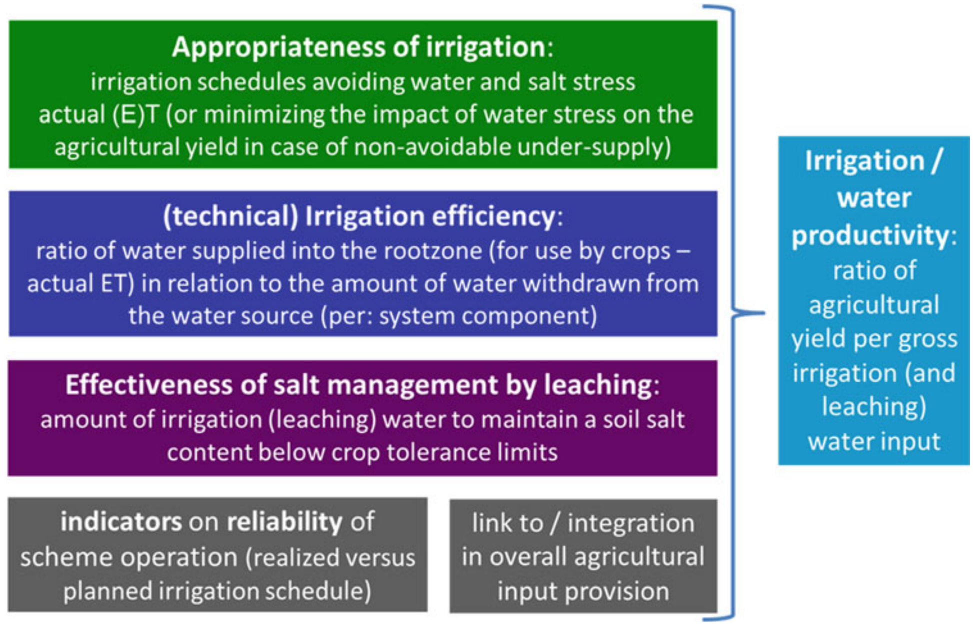


Fig. 19.4 Basic structure of irrigation performance assessment to support water productivity

19.2.3.2 Case study on irrigation performance in a Water Consumers Association in Khorezm, Uzbekistan

In the following, an analysis of irrigation performance in a Water Consumers Association (WCA) in the Khorezm irrigation and drainage system located at the lower reach of the Amu Darya River in Uzbekistan is presented as a case study. Around 80% of Uzbekistan's water supplies flow from neighboring countries via the Rivers Amu Darya and Syr Darya. Due to transboundary nature of the river basins in Uzbekistan and expected disadvantageous alterations of available water resources by climate change, enormous pressure on managing water resources in indispensable. Any intervention to manage surface water by upstream countries can influence the water- and in turn food security in Uzbekistan. Therefore, to secure the availability of water resources in a sustainable manner, assessing the current performance of the irrigation schemes in these river basins is of paramount importance. Irrigation performance assessment can identify the existing gaps, support to identify reasons for under-performance and guide to work out strategies to reduce these gaps in longer term. Water data in Uzbekistan is taken as a classified information at the highest level as water is considered as a strategic resource and any misinterpretation of this data can lead to conflict between water sharing countries as well as users within a country and even within irrigation schemes ('top versus tail-end problem').

We conducted a study in Amu Darya river basin with assistance of irrigation departments to monitor the current performance of a sub-unit of the Khorezm irrigation scheme. Shomokhulum Water Consumers Association (WCA) (Fig. 19.5) was considered as a case irrigation scheme to evaluate the adequacy, reliability and equity of water distribution on these schemes. A set of classical and modern irrigation performance indicators including relative evapotranspiration (RET), field application ratio (FAR), conveyance ratio (CR), drainage ratio (DR), depleted fraction (DF), overall consumed ratio (OCR) and delivery performance ratio (DPR) were employed in this study. RET relates actual to potential evapotranspiration and is therefore indicating the degree of water stress (in case RET < 1) and thereby assessing appropriateness of irrigation. FAR and CR are technical efficiencies with FAR enabling to assess the process of water application to the field (crop-specific evapotranspiration minus effective rainfall in relation to the water directed to the field) and CR indicating the water losses in the canal network (relation of discharges at the tail-end compared to those at the beginning of a canal). DR is the ratio of water drained from a scheme against the sum of inflow and effective rainfall. The actual evapotranspiration versus the sum of inflow and rainfall is the depleted fraction DF quantifying the overall losses in the system. DR and DF should complement to 1. OCR indicates whether crop water requirements are met and measures overall system efficiency. DPR is contrasting water actually delivered to a farm towards planned delivery and is therefore an indicator on operational performance of water distribution. More details in terms of definitions and equations are provided by Bos et al. (2005).

We combined remote sensing approaches and field measurements with collaboration of local departments to fill the data gaps at irrigation scheme level. For example, actual and potential evapotranspiration was estimated by the Surface Energy Balance Algorithm for Land (SEBAL)

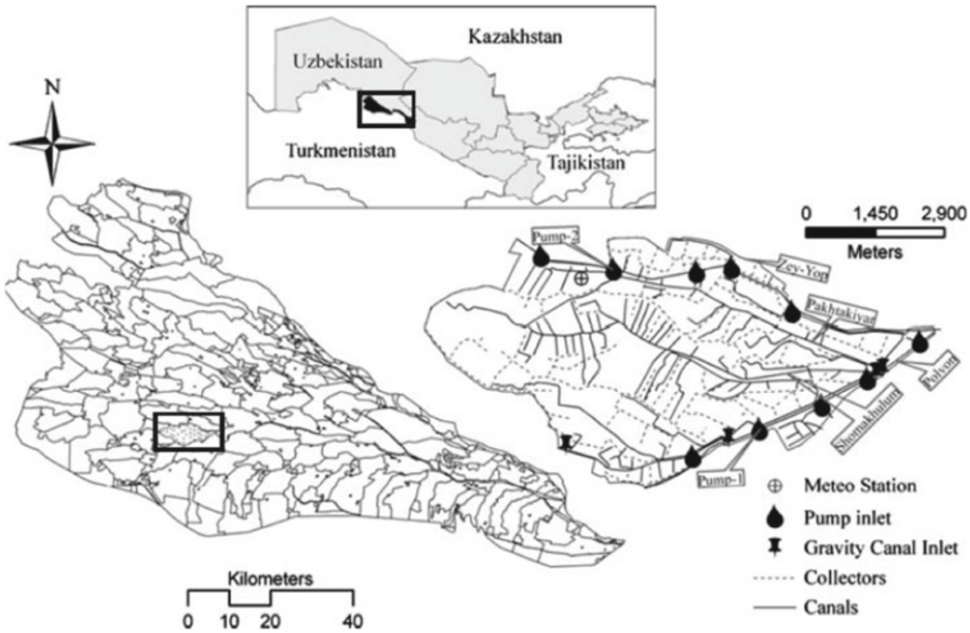


Fig. 19.5 Location of the Water Consumers Association Shomokhulun in Khorezm, Uzbekistan

(Bastiaanssen 1998) using MODIS satellite data. Gauge stations were installed to monitor irrigation and drainage water inflows and outflows. Losses in canals were estimated by ponding experiments and field water balances were established to estimate field application efficiency. Scientists have defined different target values for these indicators in different regions. Based on literature, we selected the target values of these indicators from the literature and evaluated the performance against these indicators.

Results of the study at irrigation scheme level show mixed results in terms of more or less acceptable RET (appropriateness of irrigation) and reveal deficits mainly in terms of efficiency and low depleted fraction. Figures 19.6 and 19.7 are depicting as an example the results of the relative evapotranspiration (RET) and depleted fraction (DF) with monthly resolution and aggregated for the season. Bandara (2006) suggested that DF is a good starting indicator as it evaluates crop water deficiency against the potential crop water requirements. When results of study for RET are compared with the target value of 0.75 on monthly basis, the crops meet the requirements for all the months except April and July which can be due to low water availability in the system (Fig. 19.6). The seasonal value of RET is also meeting the target value which shows that there is no water deficiency throughout the crop growing season.

Figure 19.7 is presenting the results of the DF which is below its target value (0.65) most of the season. The seasonal DF is 0.4 which is showing that around 60% of the water is lost in the irrigation system without any use. The DF is close to the target values only during the month of June and September.

Results of the other irrigation performance indicators also show that water delivered to the system is (much) more than the demand, which can also be evaluated from DPR which is over 1.0. Field application ratio was low ranging between 37 and 47% clearly below the target value of 67%. The seasonal DR of 0.55 is much higher than the target value of 0.1 showing that lot of water is being drained out from the system. The OCR is 0.82 against the target values of 0.75. It can be concluded from this study that there is no (big) water deficiency at field and irrigation scheme level. The losses in the system are due to non-functional water distribution mechanism whereas at the field are due to lack of awareness, insufficient facilities and incentives of farmers for water

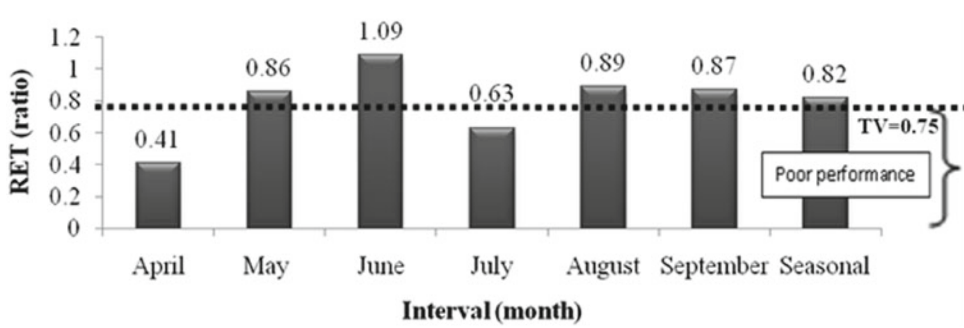


Fig. 19.6 Variation of relative evapotranspiration (RET) during different months in Shomokhulum WCA

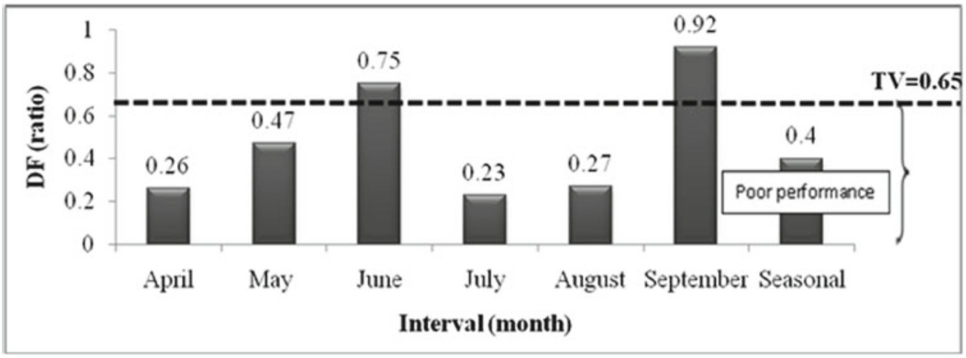


Fig. 19.7 Variation Depleted Fraction (DF) during different months in Shomokhulum WCA

saving. The results of the study can support policy makers in the region to opt the strategies for monitoring the performance of the irrigation systems, enhancing awareness for water saving among different stakeholders and facilitating reason-oriented measures to improve performance (guidelines, testing and demonstration sites).

19.2.4 Need for and Tools Towards Flexible Irrigation Scheduling

19.2.4.1 General aspects of irrigation scheduling

This Section aims to provide an overview on basic approaches for irrigation scheduling, point out the need for model-based flexible scheduling, summarize approaches to determine flexible schedules (for fulfilling crop water demand and salt control), deal with irrigation efficiency concept for stepping from net irrigation data (amount, timing) to gross variables (application discharge and system discharge) and highlight advantages of efficient irrigation going beyond water issues.

Irrigation scheduling is the procedure to establish plans which provide the information on when and how much to irrigate and when and by which amount to realize leaching, that means determining the timing of irrigation events and the water to be applied in order to enable full agricultural yield or optimal water productivity (as pointed out in Sect. 19.2.2). Basically, irrigation schedules can be estimated by following major approaches.

- Crop moisture status-based approaches by using sensors on leaf water potential and/or canopy temperature;
- Monitoring soil moisture conventionally by gravimetric approach and/or sensors (FDR/TDR, neutron probe, tensiometer, electrical resistance block)
- Water (and salt) balancing models ranging from storage concepts to flux models (with sophisticated approaches utilizing software packages).

Data provision is utilizing monitoring systems on the ground and becomes increasingly complemented by remote sensing techniques, especially while upscaling to larger areas. More details on the approaches and data needed as well as procedure to obtain the data are summarized in the first part of Sect. 19.2.5. In the following, the focus will be on water balancing approaches (which are used in combination with soil moisture monitoring for calibrating the models). The reasons for focusing on model-based water balancing consist in: (i) option to consider site-specific conditions and achieve high temporal resolution to react in a flexible way on diversifying and changing environments (daily resolution which is coinciding with the usual time-steps in implementing operation of irrigation systems), (ii) the capability of these approaches to run simulations (supporting farmers by running alternative schedules for pre-season crop- and irrigation planning and also for working out short-term options to cope with water deficits in the season), (iii) option to quantify the inter-linkage between soil moisture level and yield (optimizing water productivity), and (iv) less workload and cost than monitoring especially when considering a huge number of farms in large irrigation schemes.

Following trends and requirements call for an answer by flexible irrigation scheduling.

- An increasing variability of available water resources (and changing water quality) mainly as an impact by climate change and due to a sharpening competition with further water use sectors;
- Intensifying land use with diversifying cropping pattern resulting in diverse spatial demand and more variable requirements over time within irrigation schemes;
- Pressing need for an advanced coordination with further inputs in the agricultural system to raise overall productivity (FAO's 'More crop per drop-strategy') and to lower environmental impacts.

The core of flexible irrigation scheduling is water balancing with high methodological, spatial and temporal resolution. In terms of methodological resolution for estimating the components, physically-based approaches are most advantageous. Smallest spatial element is the irrigated field (in case of large fields—and in case data availability allows, an

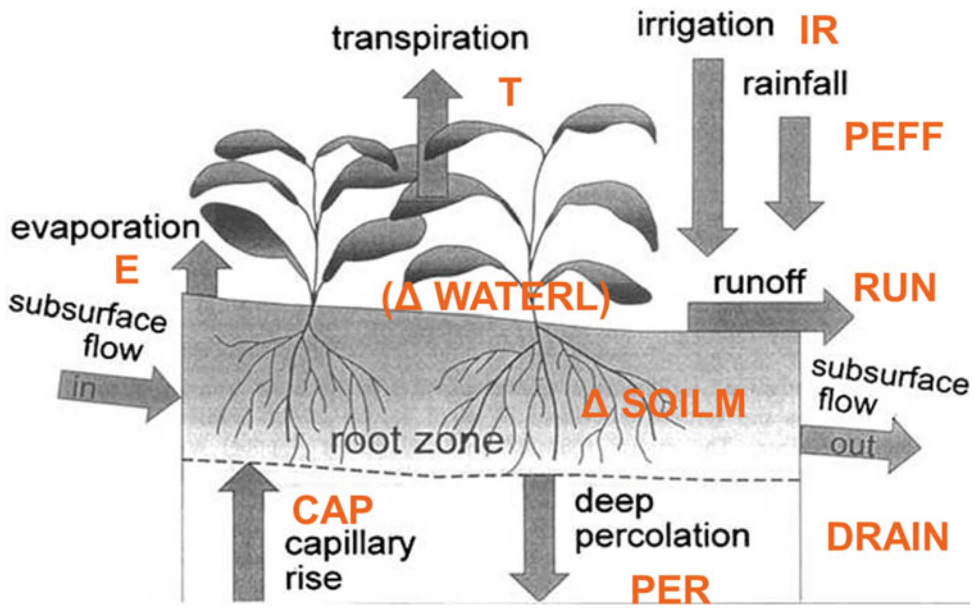


Fig. 19.8 Water balance of an irrigated field (modified from Allen et al. 1998)

$$IRR + PEFF + CAP = (E + T) + RUN + DRAIN + PER + \Delta STORAGE$$

Δ STORAGE as Δ SOILM (soil moisture change) and/or Δ WATERL (water layer, rice fields)

introduction of within-field compartments might be helpful). As typical resolution in implementing irrigations schedules are daily time-steps, establishing daily water balances is sufficient (with the operation in the system going to hourly resolution when considering several fields in the scheme).

Figure 19.8 illustrates the major components of a field water balance and is establishing the balance. As the water fluxes are the essential drivers of salt dynamics, a salt balance can be achieved in an analogous way by introducing the salt content of the components.

As mentioned above, the key-information from farmers' point of view comprise the time and the amount of irrigation to be applied to the field targeting full yield potential (no water stress) or—in case of non-avoidable under-supply—minimizing the impact of water stress on the yield. These basic irrigation scheduling data reflect the demand orientation with a bottom-up approach, which need to be checked at the irrigation scheme level against water availability and hydraulic capacity of the irrigation network. The procedure for deriving irrigation time and amount—and based on that scheme irrigation schedules—can be structured by major steps as pointed out in the following.

19.2.4.2 Establishing a soil water balance referring to the root zone

Relating the above water balance to the root zone, assuming that incoming subsurface flow (moisture exchange) equals outgoing and that groundwater effect is covered by capillary rise and considering surface runoff and percolation below the root zone implicitly by the irrigation efficiency concept, soil moisture can be balanced in daily steps (t):

$$soilmoist(t) = soilmoist(t-1) - ETc(t) + Peff(t) + Cap(t) \qquad (19.1)$$

ETc: crop-specific Evapotranspiration
Peff: effective part of precipitation (the share of rainfall reaching the root zone)
Cap: capillary rise from groundwater into the root zone.

Variables refer to average values per field with daily resolution in the unit (mm).

The crop-specific evapotranspiration can be estimated by modeling- and monitoring-based approaches. A widely used procedure follows the FAO concept (Allen et al. 1998) structured by steps: (i) calculating the reference evapotranspiration (ET_0) utilizing the Penman–Monteith equation, (ii) transforming the reference value into a crop-specific evapotranspiration with the help of crop coefficients which reflect the crop and the vegetation stage and enable a split into evaporation and transpiration, and (iii) applying reduction factors considering an eventual limitation by stress conditions. Further options for estimation of evapotranspiration are provided in Sect. 19.2.5.

The effective part of rainfall can be estimated either by empirically derived relationships (e.g. as provided by USDA Soil Conservation Service) quantifying initial losses (interception) and a limitation by soil moisture deficit.

Water flux models (e.g. Hydrus; Šimunek et al. 2013) are tools for quantifying the capillary rise. As these models are rather input-demanding, data bases established by these sophisticated models or even empirical relationships are used (e.g. in AquaCrop version 6.0, 2018; Raes et al. 2018).

For checking the balancing approach and supporting calibration of the methods used to estimate the balancing components (and to estimate application efficiency as described below), soil moisture measurements are needed. A straightforward approach is the gravimetric method enabling a rather high precision and therefore still used as reference method. Further approaches are introduced in Sect. 19.2.5.

19.2.4.3 Deriving the irrigation time and net amount at field level

The guiding target of crop irrigation is to avoid water stress or at least to minimize the impact of water stress on the yield. Basically, water stress occurs when actual evapotranspiration is reduced below potential level due to stomata closure as a reaction on crop roots hindered to uptake sufficient water caused by low soil water availability. According to FAO, reduction of actual evapotranspiration starts when the soil moisture drops below a limit, which is described by the allowable depletion. The allowable depletion is a share of the difference between field capacity and permanent wilting point and depends mainly on the crop. As long as soil moisture in the root zone is within the range of allowable depletion, actual evapotranspiration is at potential level. When the soil moisture drops below the allowable depletion limit, evapotranspiration is reduced and in turn, yield is lowered. Once the soil moisture reaches the permanent wilting point, evapotranspiration is completely hindered and yield lost. The magnitude of yield loss caused the degree of soil moisture below the allowable depletion is mainly depending on the crop as well as the vegetation stage and is either described as a function or as a set of 'response factors'.

The basic relationship is reflected by a water stress—yield response model provided by FAO (Steduto et al. 2012)

$$\left(1 - \frac{Ya}{Ypot}\right) = ky * \left(1 - \frac{ETa}{ETpot}\right) \qquad (19.2)$$

with: Ya and $Ypot$ actual and potential yield (maximum yield assuming with no limitation from a any factor besides water).

ETa and ETpot describe actual and potential evapotranspiration Ky is the yield response factor quantifying the strength a level of water stress is transformed into a yield reduction and depends on crop and vegetation stage.

Given that context, soil moisture is balanced according to Eq. (19.1). As long as the soil moisture is above the allowable depletion, no irrigation is needed (as no water stress). In case the soil moisture reaches the allowable depletion at a day t, irrigation is required and the scheduling data at field level are the day t for irrigation time and the difference between soil moisture and field capacity for the net irrigation amount. In general, soil moisture is refilled to field capacity as refilling to levels higher than field capacity would lead to percolation losses and lower levels would not fully utilize the storage capacity of soil. A refill level lower than field capacity could be considered in case of limited water supply or rainfall expected.

The approach on the yield model exemplified above represents a rather simple procedure. More detailed approaches in terms of estimating the yield (instead of a yield reduction) and splitting of evaporation and transpiration will be provided below when coming to an example on irrigation scheduling models.

19.2.4.4 Estimating irrigation efficiency and transforming net irrigation amount to gross irrigation in terms of application discharge over time

Realizing irrigation and operating the irrigation system requires to transform net irrigation water demand into a gross irrigation amount expressed as application discharge. Stepping from net to gross irrigation is performed by utilizing the irrigation efficiency concept and determining the discharge to be applied to the field is based on the irrigation method considering features of the irrigated field in order to optimize the application discharge given the hydraulic capacity of the irrigation network.

According to Fig. 19.9, irrigation efficiencies are considered as technical efficiencies (relation of water volumes or discharges at different locations in the system) and can be established as formulated in Fig. 19.9 for the components of the system (field application efficiency, farm ditch efficiency, conveyance efficiency) and accumulated to overall or project efficiency.

As the processes determining the losses at field and canal (network) level are different, following remarks on approaches to estimate the efficiency (covering the losses) are given with a differentiation into field and network level.

At field level, measuring and modeling approaches can be applied. The measuring approach consists in monitoring the soil moisture at several points in the field at different layers covering the root zone before and after irrigation (in general two days after reflecting the definition of field capacity), estimating the change in soil moisture by the irrigation event and relating that change to the monitored discharge sum directed to the field (sum of application discharge).

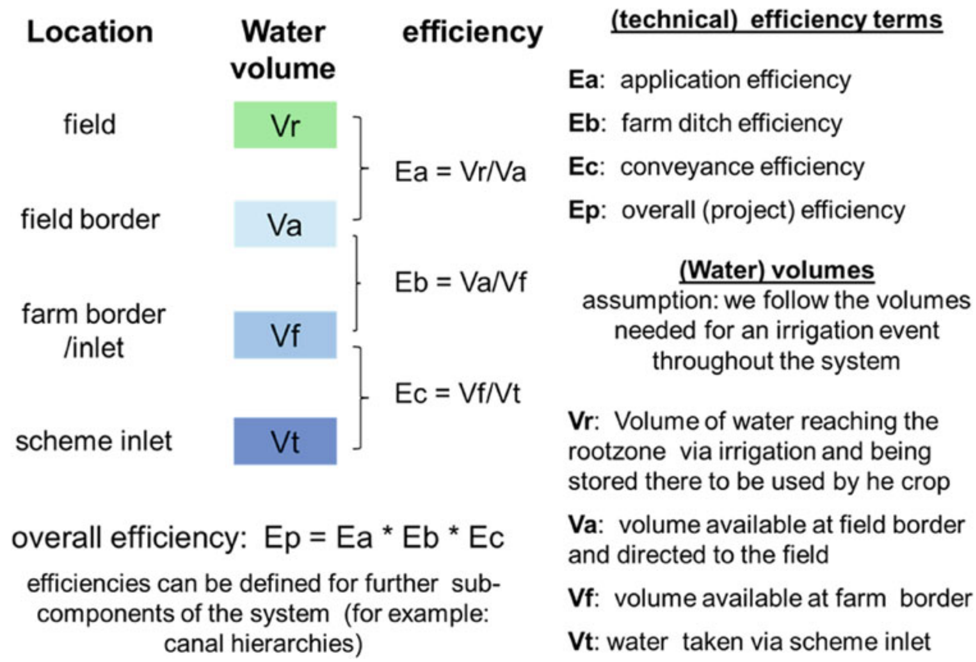


Fig. 19.9 Irrigation efficiencies (formulation, system components)

Modeling approaches are based on the application of models quantifying the soil water fluxes to estimate the change in soil moisture by the irrigation, which then is related to the monitored application discharge. The procedure to estimate the application efficiency needs replications taking into account the full range of factors influencing the efficiency (irrigation method, soil, field geometry, irrigation depths, crop and also factors going beyond technical issues like: farmers' skills in handling the method, water availability, water pricing).

Losses in the canals are mainly in terms of percolation and seepage (and to a smaller degree by evaporation). A straight-forward approach to estimate the losses in a canal reach consists in contrasting measured discharge reaching the end of the canal versus the discharge at the begin of the canal (and ensuring that no water is leaving the canal via outlets to other canals or fields). Yet, as discharge measurement is only possible with a limited precision (maximum 3 to 5% with flumes or measuring weirs), the outflow-inflow approach becomes questionable in case of canals with small losses (being in the range of the resolution by discharge measurements). An alternative is the ponding method, which consists in blocking the canal and monitoring the drop of water level in the blocked reach. Knowing the geometry of the canal, the change in water level can be transformed into a water volume quantifying the loss and can be related to the wetted area of the canal reach yielding in a loss in volume unit per time step and unit of wetted canal area. The ponding approach is limited to small canal slopes (as otherwise the reach to be blocked becomes too small). Besides necessary replications, the determination of canal losses needs to consider representative reaches (lined, unlined with different soil conditions, operational status (high initial losses in case of canals just filled versus lower losses in canals with continuous operation).

A major factor on application efficiency is the irrigation method, which can be grouped into surface irrigation methods, pressurized systems and sub-surface irrigation.

Surface methods consist in water application to and distribution within basins, borders and furrows covering the field. Given the soil conditions in a field (expressed by hydraulic conductivity), crops to be grown and irrigation depths to be applied, the application efficiency can be improved by selecting and realizing an optimal application discharge. Major processes during water application and distribution in the field are advancing, infiltration and recession of water. A typical disadvantage of surface irrigation methods is a non-uniformity of the contact time between water and soil (intake opportunity time, that means time for water to infiltrate) at the parts of the field close to field inlet versus the most far ones. Modeling advance, infiltration and recession of water along the basin, border or furrow provides the base to optimize application discharge. In general, an application discharge as high as possible without causing erosion leads to maximum efficiency because in that case above mentioned non-uniformity can be minimized. Further interventions to raise efficiency under the constraints of a given field comprise sub-division of the field in smaller units (easing to lower non-uniformity) and laser-guided leveling to realize a uniform slope in the field to avoid under- and over-irrigation at higher or lower spots in the field (can be seen as an intervention towards 'creating an enabling environment' for surface irrigation methods). Especially for the furrow irrigation, refinements have been developed in terms of blocking furrow ends, surge irrigation (intermittent handling of application discharge enhancing uniformity of intake opportunity time), alternate furrow, raised-bed planting). Numbers on efficiencies of surface irrigation methods show a high range mainly depending on how well the method is adapted to field conditions and to what degree the options for optimization are used. Typical levels are in the range of 50–60%; yet, with refined approaches 70% range is achievable.

Sprinklers (stationary/permanently installed systems, hand-moved, self-movable sprinkler machines, center pivot, micro-sprinkler systems) and drip techniques have the potential to reach rather high levels of efficiency (90–95% for drip and 80–85% in case of sprinklers). Especially drip irrigation can mobilize synergisms in terms of high efficiency as well as uniformity, targeted and frequent irrigation and option to combine with fertilizer application resulting in high water productivity; yet, high investment cost are still hindering expansion of drip technology.

Sub-surface irrigation comprises management of groundwater level (via the drainage system) to enhance capillary rise, reversed tile drainage systems or even introducing water via sub-surface lines into the soil. Yet, sub-surface irrigation needs large plain area and is prone to salinization (due to comparatively higher salt content in groundwater and lacking opportunity to perform salt leaching).

19.2.4.5 Salt balancing for determining the leaching requirement

Water used for irrigation contains to some degree salts and therefore supplying irrigation water leads to salt input into the root zone. The amount of soil salinity in the root zone of irrigated fields is a result of salt inputs and outputs mainly driven by water fluxes. Input of salt consist in the amount as well as salt content of the irrigation water, a possible capillary rise in case of shallow groundwater, fertilization, and to a very small extent precipitation. Percolation below the root zone, surface runoff, lateral water exchange and removing biomass during harvest, drive output of salts. Differences between input and output over time either cause an increase (salt accumulation) or decrease (leaching of salts) in soil salt content in the balancing period (e.g. vegetation period).

Due to easier measurement, salt content of water is quantified by electrical conductivity and salinity of soil is standardized by the electrical conductivity in the saturation extract ECe. Salt management aims to keep ECe below plant tolerance limits, which would lead to salt stress reducing crop yields once reached or exceeded. Conceiving salinity control by water management builds on consideration of two major processes: (i) estimating the salt accumulation from the balance of the above components, and (ii) determining leaching water quantities, which compensate and discharge the salt input by a corresponding output.

Assessing the magnitude of salt in- and output components reveals that precipitation does not lead to any significant salt input and contribution by fertilization is rather small; surface runoff on irrigated fields is largely avoided, lateral exchange is low and salt output with harvested biomass is numerically not high. In case of deep groundwater (no capillary rise), salt input is driven by irrigation water amount (and its salt content) and salt output depends on the water percolating below the root zone and its salt content. In order to keep salt content in the root zone below crop salt tolerance limits, salt output via water percolating below the root zone must balance the input by irrigation water. The share of the percolation water in relation to the irrigation water input is the leaching fraction equaling in the above formulated simplified case the relation between salt content of irrigation water and percolation water (assumed to be in the range of drainage water in case of an artificial drainage system. Based on that balancing approach, FAO (Ayers and Westcot 1985) is suggesting an empirical equation to estimate the leaching fraction LR:

$$LR = ECw/(5 * ECeTol - ECw) \tag{19.3}$$

ECw: electrical conductivity of water used for irrigation (and of capillary rise in case of shallow groundwater) in deci-Siemens per meter (dS/m).
ECeTol: tolerance of the crop against salinity expressed as electrical conductivity of the saturation extract in dS/m.

More sophisticated approaches for quantifying the processes of salt accumulation and salt leaching can be derived by physically based models on soil water fluxes and linked matter flow (e.g. Hydrus model).

In order to realize leaching, following processes need to be implemented: (i) irrigation refilling soil moisture above field capacity, which (ii) is creating percolation through the root zone taking—at least a part of—accumulated salts. The amount of percolation water is the above-mentioned leaching fraction (related to irrigation water input in the respective balancing period). A further condition to effectively perform leaching (process iii) consists in discharging the leaching water after percolating through the root zone and reaching and recharging groundwater out of the irrigation scheme. As in most cases natural groundwater flow is not sufficient to realize that outflow, an artificial drainage system needs to be installed.

19.2.4.6 Establishing scheme irrigation schedules (from field to overall system)

The gross irrigation demand at field level is expressed by a time-dependent discharge. With a discretization of the irrigation network by canal reaches and hydraulic structures and a temporal resolution by hours, the field discharges are summed-up considering the network structure. While summing-up, the losses in the canals (expressed as efficiency) and the translation time (or in case possible taking retention behavior into account) need to be considered. Furthermore, the estimated (demanded) discharges must be checked against the hydraulic capacity of the canal reaches (and hydraulic structures) and the overall discharge summed-up at the withdrawal facility must be contrasted to the available water resources ('reality check' of demand). In case of demanded discharges exceed hydraulic capacity and/or the overall summed discharge is higher than the available resources, either options to raise efficiency or measures to lower the demand must be considered in order to avoid and overcome a situation overloading the system and/or the available resources.

Model-based tools for supporting irrigation scheduling range from rather simple approaches (e.g.: FAO CROPWAT (FAO 2020)) to sophisticated Crop-Water-Atmosphere-Soil models (e.g.: APSIM; Holzworth et al. 2018). Application of first mentioned models lack a reliable estimation of the yield, whereas sophisticated models are highly input demanding and therefore their application is limited to well monitored sites and hindered for scheduling of irrigation schemes consisting of a high number of diversified fields. FAO AquaCrop is an option due to its capability to estimate the yield and based on a rather detailed quantification of water as well as salt balancing (splitting evaporation and transpiration; estimating capillary rise).

As depicted by Fig. 19.10, the core of the AquaCrop model is a water productivity module estimating the biomass (and the yield with help of an harvesting index) driven by the transpiration. The model can be used for establishing irrigation schedules and estimating the yield by linking the atmosphere, soil, water and cop components to a system. Going beyond that task, a further option consists in bringing scientists and practitioners from different disciplines together and thereby facilitating interdisciplinary approaches.

Complementing this section, Fig. 19.11 is summarizing beneficial impacts from raising irrigation efficiency going for beyond water issues ('win–win-situation'). Saving irrigation water leads to less water to be withdrawn from the hydrological cycle and lowers therefore the pressure on the cycle in terms of quantity and quality (blue balloons). Agricultural yield formation is enhanced (dark green balloons) and environmental impacts reduced, energy saved (light green),

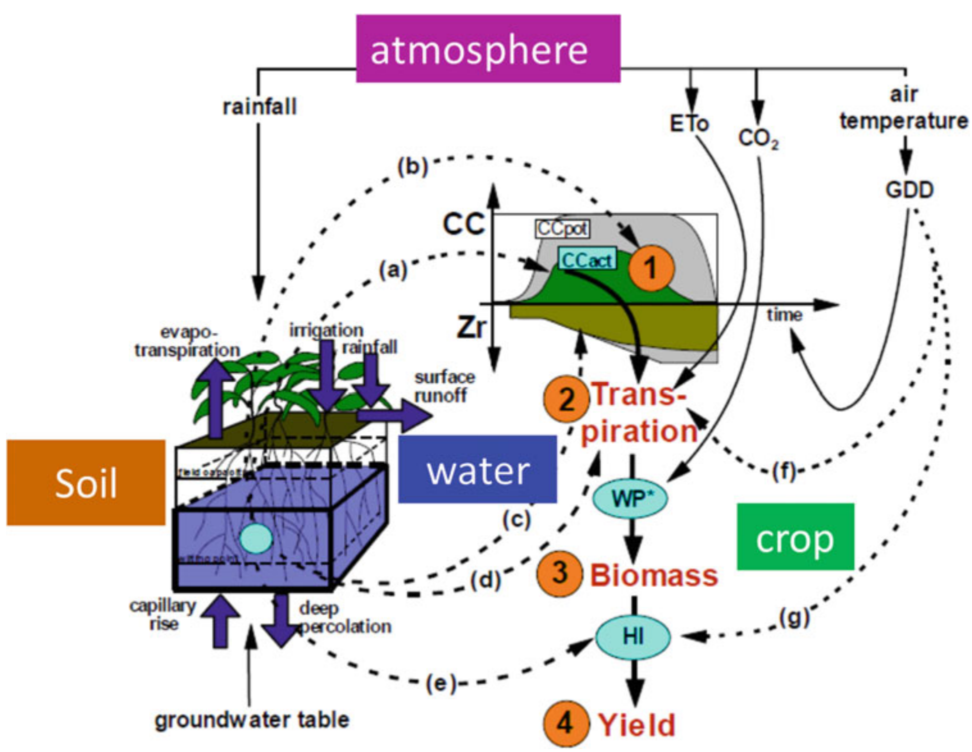


Fig. 19.10 FAO AquaCrop model linking crop-water-atmosphere-soil **a**–**e** indicate processes potentially impacted by water stress and **f**–**g** by temperature stress (*Source* Raes et al. 2018)

CCpot and CCact stand for potential and actual canopy cover, Zr for rooting depth, WP* for Normalized Crop Water Productivity, HI for Harvesting Index, GDD for Growing Degree Days

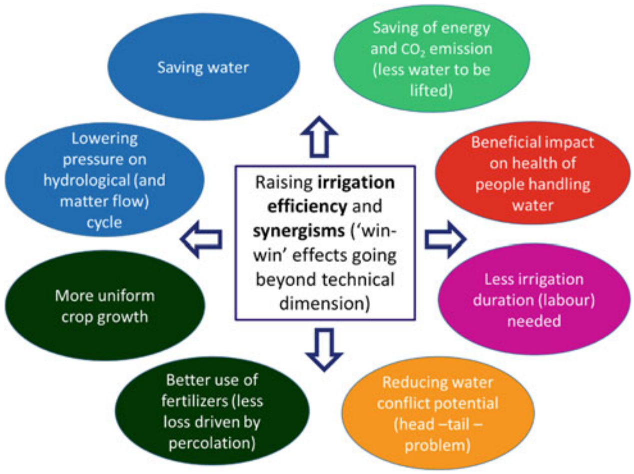


Fig. 19.11 Beneficial impacts of water saving

health situation improved (red), labor savings can be achieved as a consequence of less gross irrigation water to be applied (pink), and lower withdrawals have the potential to relax conflicts within irrigation schemes (top-tail) and at larger scale even going to transboundary level (orange).

19.2.5 Improving Performance/Productivity (Including Case Studies)

19.2.5.1 Data for irrigation scheduling

As described in Sect. 19.2.4, flexible irrigation scheduling aims to consider site-specific conditions and time-dependency of relevant processes. Therefore, flexible and proper irrigation scheduling requires an understanding of the movement and storage of water in the root zone of the crop (soil moisture) and the rate of water use by the crop (evapotranspiration). To that end, appropriate modeling approaches (as mentioned in Sect. 19.2.4) need to be fed by sufficient data. As a consequence, the full potential of benefits from proper irrigation scheduling can be mobilized consisting in:

- Efficient use of water, energy and other production inputs such as fertilizers
- Improved crop yield and quality
- Reduced production cost and maximize farm profit
- Lowered burden on the environment (controls: runoff, waterlogging, soil salinization, land degradation and helps: in reducing the quantity of fertilizers and pesticides application and potential contamination of soil and groundwater due to checks over irrigation and seepage losses).

Implementing proper irrigation scheduling has to tackle some constraints–as for example:

- Water is cheap (no or rather low water fee) and if available easily then people generally do not bother about using it efficiently.
- Lack of awareness about the benefits of proper irrigation scheduling.
- It requires efforts in understanding the soil water movements, soil moisture fluctuations and crop water demand over time.
- Benefits of proper irrigation scheduling are not immediately visible.

The main purpose of this sub section is to give an overview on data needs and options for data acquisition to enable model-based, flexible and proper irrigation scheduling.

19.2.5.2 Factors affecting the irrigation scheduling

As described in previous sections, irrigation scheduling is a process to estimate and apply the right amount of water, at the right time, and in the right way to the target crops based on their actual water requirements. Correct balance of water and air in root zone is essential for optimum growth and development of plants. Hence, both water logged and water scarce conditions in root zones with reference to a particular crop can reduce their yield and quality.

Soil type, crop characteristics and climatic conditions are the main factors that determine the amount and time of water application in a given irrigated land.

(i) *Soil characteristics*

Soil physical properties such as water holding capacity (soil moisture at field capacity and at permanent wilting point) and hydraulic conductivity of soil determine the amount of water available for crop growth.

(ii) *Crop characteristics*

Root growth: The water intake of crops depends at the rate the roots extend vertically below the surface to tap the soil moisture reserves deep down in the soil profile. Root type also affects the soil water intake by the crops. Root growth depends on the crop type.

Rate of crop water use (evapotranspiration rate): The combination of evaporation from soil surface and transpiration from a plant is termed as Evapotranspiration. It is often difficult to distinguish between the two processes. The main factors that affect evapotranspiration are: climate parameters (solar radiation, air temperature, air humidity and wind speed), crop characteristics (crop genetics and crop phenology), management practices and environmental aspects.

High evapotranspiration by a crop requires more irrigation (if rainfall is a limiting factor) to meet the crop water demand. The crop water requirement varies with the crop type and variety and also changes with the different stages of crop development. Hence, an accurate estimation of evapotranspiration over a regular interval of time is one of the key information in irrigation scheduling.

Stage of Crop Growth: During the vegetation period, as the crop grows the rooting system also develops and the soil water reservoir accessible to the crops increases that leads to depletion of soil water storage over time. Hence, a proper irrigation amount at a particular interval of time is required in order to ensure that the crops are not stressed at their particular growth stage (especially at their critical growth stage).

Crop water stress tolerance and sensitivity: Different crop types (based on their genetic structure) have different levels of tolerance and sensitivity against similar water stress conditions.

(iii) *Climate conditions*

Climate conditions of a location affect the potential evapotranspiration. Low relative humidity (dry conditions), high wind speed and high temperature result in high potential evapotranspiration and lead to more crop water demand. Under such conditions irrigation scheduling should be closely monitored in order to avoid unnecessary crop water stress. Occurrence of rainfall needs to be monitored with high spatio-temporal resolution due to strong influence contributing to meet the crop water demand and thus on irrigation scheduling.

(iv) *Other factors*

Apart from the above mentioned factors, irrigation scheduling is also affected by human factors such as farmer's personal preference to irrigate (e.g., Irrigation at fixed interval of time: even or odd days), labor constraints, availability of water and irrigation infrastructure (e.g. canal system). Irrigation scheduling can also be influence by the factors such as religious, cultural and social obligation aspects of the farmers.

19.2.5.3 Data and methods depending on the type of irrigation scheduling

There are several methods of irrigation scheduling. A successful method needs to consider the above listed factors of influence and it should be based on the scientific, economic and environmental aspects.

Any irrigation scheduling method consists of irrigation criteria that trigger irrigation and an irrigation strategy that estimates an exact amount of water application for a particular crop. Irrigation scheduling methods differ by the irrigation criteria or by the method used to estimate or measure these criteria. Common and widely used irrigation criteria are based on soil moisture status and the crop water demand (evapotranspiration).

According to Sect. 19.2.4, irrigation scheduling can be guided basically by crop moisture status, soil moisture monitoring and soil water balancing. Based on these principles, following categories will be used to summarize data needs and steps to acquire the data:

- Crop moisture status
- Crop water demand
- Soil water (moisture) status
- Water budget method
- Computer models
- Remote sensing based approaches

19.2.5.4 Crop moisture status

Evapotranspiration plays a major role in estimating the crop water extraction. However, there are also other factors such as soil moisture status, presence of nematodes, herbicides, compacted soil layers and soil salinity that also affect the amount of water actually transpired.

Crop moisture status measurements using crop based sensors consider all factors (plant-soil-weather complex) together in estimating the actual amount of water transpired. This concept is emerging and subject to recent research area in the field of irrigation scheduling. Some of the crop moisture status measurement methods are listed below:

(i) *Leaf Water Potential (LWP):* It indicates the crop moisture status. The leaf water potential indicates the negative pressure or tension in plant leaves measured in megapascals (MPa). A well-watered crop has higher LWP compared to a crop under water stress conditions. The pressure chamber (also referred as pressure bomb) is a device that measures the leaf water potential of a crop. However, the device is expensive and can be used during the certain period of a day that limits its wider use.

(ii) *Canopy temperature:* Crops cool themselves via transpiration and thus the air temperature under crop canopy is cooler than the surrounding. Infrared (IR) thermometer sensors can be used to continuously measure the canopy temperature. If the soil moisture status gets drier and transpiration decreases, then the canopy temperature will get warmer and indicates a need for irrigation. Limitation of this method includes the regular maintenance of IR thermometers, cloud free atmosphere and the presence of full canopy cover.

19.2.5.5 Crop water demand

Crops responds to the soil water deficit and the visual appearance of crops during water stress phase can indicate the time when crop needs irrigation. However, the amount of irrigation application cannot be estimated based on visual appearance. The crop water demand mainly depends on crop evapotranspiration rates and varies with the stages of crop development, which is crop specific. Hence, measurement and monitoring of crop water demand (evapotranspiration) at regular interval of time is required and considered as an important aspect in irrigation scheduling. Several methods are used in estimation of evapotranspiration and some of them are listed below:

(i) *Penman Monteith equation*: A widely used method that is derived based on the combination of energy balance method with the mass transfer method to compute the evaporation from an open water surface and extended to cropped surfaces by introducing the crop coefficients curves.
(ii) *Lysimeter*: a closed container equipment fixed below the earth surface enabling to measure the soil moisture (by weighting or pressure sensors) and monitor percolation. In combination with a climate station providing data on rainfall, evaporation and variables to estimate evapotranspiration (and avoiding surface runoff), lysimeter data allow to establish a closed water balances, from which actual evapotranspiration can be derived with high precision, yet as point data.
(iii) *Surface energy balance algorithm*: The estimation of evapotranspiration is based on net radiation, soil heat flux and sensible heat flux.
(iv) *Eddy covariance (also known as eddy correlation and eddy flux)*: It directly estimates the transfer of water vapor (evapotranspiration) from the land (or canopy) surface to the atmosphere

19.2.5.6 Soil water status

Soil water content (soil moisture) within the root zone is the main source that can provide the required water to meet the crop water demand. In nature, soil moisture content is highly fluctuating and depends on the rainfall amount and intensity. In addition, the crop water requirement (demand) also changes with time based on the different stages of crop development. Often there is a mismatch between the soil water supply and crop water demand especially in the areas where rainfall is a limiting factor for agriculture. The deficit water demand of crops can be generally fulfilled by irrigation water (via surface and/or groundwater sources). Hence, an effective irrigation scheduling requires measuring and monitoring the soil water content over time and then comparing to a pre-determined lower or minimum water content ('allowable depletion') or tension level for a particular crop. If the soil moisture level goes below the minimum level, then irrigation should be triggered to maintain it above the minimum limit.

There are several methods (listed below) that can be used for soil moisture content measurement.

(i) *Soil Feel and Appearance*: This method is based on human experience to judge the soil water content based on soil appearance or feel. The results vary with personal experience and capabilities. This method can find when to irrigate; however, the amount of irrigation is difficult to estimate.
(ii) *Gravimetric Method*: By this method, soil moisture content is determined by drying the soil sample to a constant weight and measuring the soil sample mass after and before drying. It gives high accuracy in soil moisture measurement and is therefore still used to calibrate the other approaches. However, it is labor intensive, time consuming to handle and gives the result with a delay due to sampling and drying time.
(iii) *Frequency-Domain Reflectometer (FDR) and Time-Domain Reflectometer (TDR) sensors*: utilizing the inter-dependency between dielectric constant and soil moisture, these sensors enable in-situ measurements, which can be used to monitor soil moisture at several locations and depths in irrigation fields.
(iv) *Neutron Probe*: It is a device that can be used easily and rapidly to measure the quantity of water that exists in soil. It can penetrate into the soil layer and can measure the moisture contents in depth. However, neutron probe contains radioactive element and hence it is risky to use, unless the necessary precaution has been taken.
(v) *Tensiometer*: A device that measures the soil water tension that can be further related to the soil water content for specific soils. They are easy to use once the calibration has been done (based on pF-curves) and also allow measurement at different soil depths in the field. However, they are limited to use in coarse textured soils in situations like high frequency irrigation regimes where soil moisture maintains at higher levels. The other limitation is its routine maintenance.

(vi) *Electrical Resistance Blocks*: This device can also measure soil water tension and is based on the electric resistance to current flow between electrodes. The electrical resistance of the electrodes varies with its water content. As the soil dries, the electrode loses water and the electrical resistance increases. This device is not sensitive to low tensions and affected by soil salinity.

19.2.5.7 Water budget method

Water budgeting is a widely used method of irrigation scheduling. As described in Sect. 19.4, this method involves in estimating the changes in soil water content for an agriculture land based on the difference between the additions of water (irrigation and rainfall) and losses of water (actual evapotranspiration, runoff and percolation).

19.2.5.8 Computer models

Especially application of sophisticated approaches and considering irrigation schemes consisting of many fields and going for high temporal resolution, computer models are increasingly used. Due to the capability to simulate scenarios for operation, computer models can be useful in supporting decision-making. However, the quality of input data—to a great extent—decides the quality of output estimated by the computer models and hence the quality aspects of input data is of high importance. Computer models are being developed, updated and refined in close intervals. Simple models can do "checkbook" type record keeping. More sophisticated models require weather data inputs (one can supply these inputs manually or some programs record the data directly from an in-field weather station). Computer models can be very useful in decision making. However, the statement "Garbage in—Garbage out" is very applicable for computer models. It needs to be carefully ensured that the model is applicable to a geographical area under consideration and that the input data fed into the models are valid; otherwise, the results could be misleading. The applicability and performance of model in the area of interest should to be checked via appropriate monitoring (supported by sensitivity analyses).

19.2.5.9 Remote sensing based approaches

Soil moisture content and crop evapotranspiration rates (major inputs for irrigation scheduling) are estimated at specific point locations using different equipment and conventional methods discussed above. However, farmers need to irrigate their field as a spatial unit which might show non-uniformities in case of large fields with irregular micro-topography (e.g. in soil moisture). In addition, the soil moisture content and actual evapotranspiration are highly variable in nature. Hence, sufficient number of point measurements should be taken to represent the whole agriculture area. Also to monitor the fluctuations in soil water content and evapotranspiration rates, the point measurements should be taken on a regular basis, which is time-consuming, labor extensive and expensive.

Due to current limitations in ground-based monitoring (especially in terms of spatial coverage as well as spatio-temporal resolution), Remote sensing based techniques have been used. Remote sensing is an emerging and promising tool that provides exhaustive time series multispectral imageries for estimating and monitoring the cropped areas, crop water demand (evapotranspiration) and soil moisture content at different spatial resolutions: LANDSAT 8 (30-100 m); SENTINEL-2 (10–60 m); MODIS (250-1000 m) etc. and at different temporal resolutions. These remote sensing products are freely available and can be used with the application of developed algorithms and climate data to estimate evapotranspiration and soil moisture content. Thus, the total cost of information derived from remote sensing products are quite cheaper and available at regular interval of time as compared to the conventional methods. In addition, several agencies (such as NASA, MERRA, ESA, etc.) are also providing the ready to use derived soil moisture content (e.g. Soil Moisture Active Passive (SMAP)) and evapotranspiration products that can be freely downloadable from the internet.

Several researchers have advocated the use of remote sensing derived information in irrigation scheduling (Calera et al. 2017; Droogers et al. 2010).

Geographical Information System (GIS) is a computer assisted program that is designed to capture, store, use, combine, update, analyze and manage different types of spatial (remote sensing satellite imageries) data and display the analysis on maps. GIS has tremendous application in irrigation water management. The spatial distribution of irrigated and non-irrigated areas, evapotranspiration and soil moisture extents can be easily delineated and visualized in the form of spatial maps using GIS technology. The spatial maps serves as an effective tool for supporting decision-making.

19.2.5.10 Conjunctive use of surface- and groundwater resources for fulfilling on-farm water needs and supporting adaptive management

Most irrigated areas of the world are facing spatial and temporal water scarcity due to either human induced actions or otherwise impacts of climate change. Growth in human population and changes in the human food consumption behavior add up to strong effect towards enhancing water demand creating the need for innovative approaches to meet the global food security standards. In most of the developing countries, the existing infrastructure and traditional knowledge does not support farmers enough to sustainably manage water shortages and as a result, it halts the sustainable food production and in addition negatively affects the ecosystems and their deliverable services. Especially in conditions featuring shallow groundwater table—as in many conventional irrigation schemes in South and Central Asia, irrigation water consumption involves directly (via withdrawals) and indirectly (via capillary rise from groundwater) supply both from surface and groundwater resources respectively). Yet, during water distribution and allocation, the share of groundwater contribution to crop root-zone (i.e. capillary rise) is mostly ignored due to lacking or insufficient information on the magnitude of capillary rise.

In order to quantify the share of groundwater contribution through capillary rise in the conjunctive use of water, a study was conducted in the Khorezm region of Uzbekistan located in the lower reaches of the Amu Darya river basin where the groundwater levels are shallow and fluctuating between 0.9 m (pre-seasonal leaching period, peak irrigation season) and 2.0 m (winter season without irrigation) (Akhtar et al. 2013). In this area, earthen canals are dug while farmers pump out water from the main canals which are diverted from the Amu Darya River and feed the tertiary canals which then convey water through gravity for irrigating the crops. Although huge amounts of water are withdrawn from the Amu Darya river (around 4.4 km^3 for irrigating 275000 ha in Khorezm (Tischbein et al. 2011)) and directed to the irrigation sub-schemes (Water Consumers Associations) to the end-users, but farmers still complain about water scarcity at their farms to meet their requirements as per their own understanding. This discrepancy is due to deficits or even collapse of infrastructure (e.g. farmers' pumping stations are not functional, canals are unlined, low investment for the rehabilitation and maintenance) leading to high irrigation losses in the canal network. In addition, current farmer water management leads to considerable application losses (large field, insufficient knowledge on irrigation scheduling, tendency towards over-irrigation favored in a situation with unreliable water supplied in the canal system). This is even more severe for farmers at the downstream reaches of the canals ('tail-end problem'), especially, during the peak demand periods; and in the tail-end reaches of the irrigation system, farmers are under considerable pressure to increase the available water supply and therefore practice local blockage of drains to rise the water level in the drainage system and as a consequence, raise groundwater level in order to enhance groundwater contribution to meet crop water requirements via capillary rise; furthermore, pumping of drainage water for re-use in irrigation is eased by 'drainage blocking'. Yet, these practices, on increasing water supply, are accompanied by a higher risk of salt accumulation in the root zone due to comparatively higher salt content in the drainage system as well as in the groundwater. Therefore, managing groundwater level as a part of conjunctive water use strategies needs to be handled with care. Reliable knowledge on the amount of capillary rise is a prerequisite for utilizing this option. Yet, often there is not enough information on the amount of capillary rise contribution from shallow groundwater, since it depends on manifold, highly spatio-temporarily variable and interdepending factors (soil texture, soil moisture, hydraulic conductivity, spatio-temporal groundwater level, root depth as well as development, etc.).

For the quantification of the capillary rise to the cotton root-zone, Hydrus—1D model was used at two different fields (namely A and B) which were selected in the Khorezm irrigation scheme located in lower part of the Amu Darya River basin where the mean groundwater levels during the cotton growth period were 0.97 m and 1.20 m respectively (Fig. 19.12).

Soil types of the fields A and B are sandy loam and silt loam respectively while rest of the biophysical information for both the fields were almost the same. Investigations at the study site A showed a 194 mm contribution to the root-zone through capillary rise which accounts for about 31% of the overall crop evapotranspiration (Fig. 19.13). Similarly, at the study site B, under the silt loam soil texture, the mean groundwater table throughout the cropping season was 1.20 m which contributed 153 mm of water through capillary rise and hence accounts for 24% of the overall crop evapotranspiration at this site.

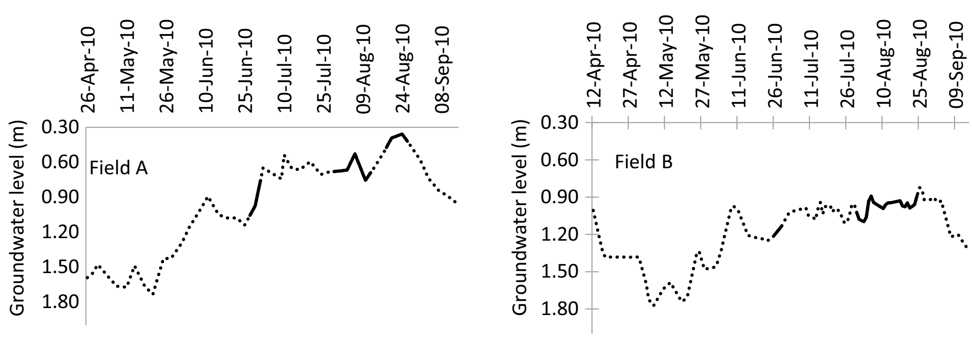


Fig. 19.12 Groundwater fluctuation in fields A and B (the bold lines are influenced by irrigation events which contribute to rise in the groundwater level)

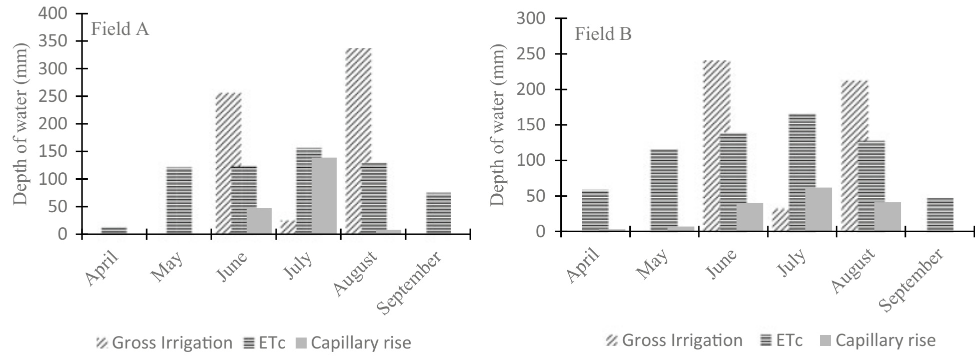


Fig. 19.13 Water balance components at Field A and Field B

As a follow-up strategy, two options for adaptive management were suggested to farmers in case of and to cope with the water scarcity.

The first approach suggested as an adaptive option was to use the surface water and groundwater in conjunction thereby considering the potential share of capillary rise contribution alongside the surface water supplies to fulfill the net crop water requirements. The Hydrus-1D based approach provides reliable information on the magnitude of capillary rise depending on soil characteristics and groundwater level, which can be utilized to adapt the irrigation amounts and timing. Going further, the model can be used to simulate a groundwater level which enables a substantial contribution to meet crop water requirements via capillary rise and does not lead to non-acceptable increase in soil salinity level ('optimal capillary rise'). Information on an optimal capillary rise and the respective groundwater level under the site-specific soil and crop conditions can be used to conceive interventions in the drainage system for managing the groundwater level (in a sub-scheme of the irrigation and drainage system) to target the optimal capillary rise.

The second adaptive approach suggested was to apply deficit irrigation by applying proportionally reduced water supply (RWS) (i.e. of the optimum schedule derived from the simulations of the AquaCrop model) of 20%, 40%, 50% and 60% at both fields A and B (Tables 19.1 and 19.2).

Results from the simulations for fields A and B show that with a 20% of deficit irrigation application throughout the crop growth-period, the yield increased by 2% while biomass was reduced in the range of 8%–12%, this increased the Water Use Efficiency (Yield/Evapotranspiration) from 0.89 to 0.95 kg/m^3. By irrigating proportionally 20% less, the water stress at the start of the season results in reduced canopy growth, hence less transpiration and a more optimal irrigation regime is achieved which give slightly higher yield. Similarly, by irrigating 40% proportionally less, biomass reduction was in the range of 25%–39% while yield reduction was in the range of 14%-29% in both the cotton fields. The third approach suggested was to introduce deficit irrigation at a certain crop growth-stage that mimic the natural water shortage conditions. Therefore, a deliberate stress at different crop growth stages was introduced by skipping an irrigation event and keeping rest of the schedule (i.e. optimum) as such without altering the irrigation water amount as suggested by the AquaCrop model. The main idea of stress introduction into specific crop growth stage is to identify and knock out those irrigation events which have the least impact on crop yield and biomass (periods of least sensitivity of crop against water stress). The results show that water stress at the early crop development stage is risky by causing failure to seed germination, at this stage a RWS of 8% to 9% resulted in yield loss of 17% to 18% in fields A and B respectively. During stress at this stage, biomass reduced in the range of 13%–15%. The simulation further showed that during stress at the late vegetative stage, 12% to 13% water could be saved together with 7% to 8% yield increment compared to the optimal conditions. In general, stress introduced during late vegetative and early boll formation stages in cotton provides adequate and feasible irrigation options for smallest yield reductions with limited supplies of irrigation water.

19.2.5.11 Simulation of Groundwater dynamics under different irrigation efficiency scenarios in Khorezm region

This case study is meant to exemplify the irrigation-drainage interlinkage by analyzing the impact of raising irrigation efficiency (accompanied by lower percolation and in turn groundwater recharge) on the groundwater level. In case of integrating the groundwater contribution via capillary rise estimation into irrigation scheduling (as in the situation of Khorezm with shallow groundwater as described above), it is an advantage to anticipate changes in groundwater level.

At the study region, for analyzing the groundwater dynamics under different irrigation efficiency scenarios, groundwater levels were simulated through FEFLOW-3D model (Mike 2016) while considering four improved irrigation efficiency scenarios. These scenarios were as given below:

Table 19.1 Proposed deficit irrigation schedule for cotton at field A

Days after sowing	100% optimum irrigation supply (mm)	20% RWS (mm)	40% RWS (mm)	50% RWS (mm)	60% RWS (mm)
21	26	21	16	13	10
43	30	24	18	15	12
52	31	25	19	16	13
58	33	26	20	17	13
65	38	30	23	19	15
104	48	38	29	24	19
118	48	38	29	24	19
113	45	36	27	23	18
Total	298	239	179	149	119

Table 19.2 Proposed deficit irrigation schedule for cotton at field B

Days after sowing	100% optimum irrigation supply (mm)	20% RWS (mm)	40% RWS (mm)	50% RWS (mm)	60% RWS (mm)
25	32	26	19	16	13
46	38	30	23	19	15
61	44	35	26	22	18
69	46	37	28	23	18
76	43	34	26	22	17
85	46	37	27	23	18
105	51	41	31	26	20
134	56	45	34	28	23
Total	356	284	213	178	142

(a) Current Irrigation Efficiency (S-A baseline) which is based on the results of Awan et al. (2013)
(b) Improved Conveyance Efficiency (S-B)
(c) Increased Field Application Efficiency (S-C)
(d) Improved Conveyance and Application Efficiency (S-D)

Based on the simulations of these scenarios—depicted in Fig. 19.14 - the monthly trend was found to be identical for the first two scenarios (i.e. S-A and S-B) while almost opposite for the last two. In the first two scenarios, irrigation efficiency was quite low, whereas irrigation efficiency is comparatively much higher in S-C and S-D. The trend differences can be explained by taking into account the groundwater levels for the months of April and August. For S-A scenario, the groundwater levels are 30 cm less shallow in the month of April than in August, whereas this difference reduces to 19 cm for the scenario S-B. Conversely, the S-C and S-D scenarios depicted groundwater level drop in the months of April-August. The results of S-C scenario show a 5 cm higher groundwater level in April compared to that of August while for the S-D scenarios, the difference is rather higher i.e. 10 cm. The results of this study further indicate that the existing drainage system in scenarios S-A and S-B lead to drainage of higher recharge whereas, in scenarios S-C and S-D the drainage can lead to over drainage by reducing groundwater levels from the start of the season.

The overall comparison of the simulations of groundwater level in the months of April—August shows a continuous decline in groundwater table; for example, the groundwater level for the scenarios S-C and S-D is lower in the month of August than the groundwater level in the month of April. The reason for that decline consist in lower groundwater recharge rates due an increase in irrigation efficiency. As a consequence of declining groundwater table, the capillary rise contribution is lowered which needs to be compensated by higher irrigation amounts. As smaller capillary rise in tendency leads to lower salt accumulation, leaching water application is reduced. The above-mentioned Hydrus model can help to find a trade off in terms of overall effect on water saving.

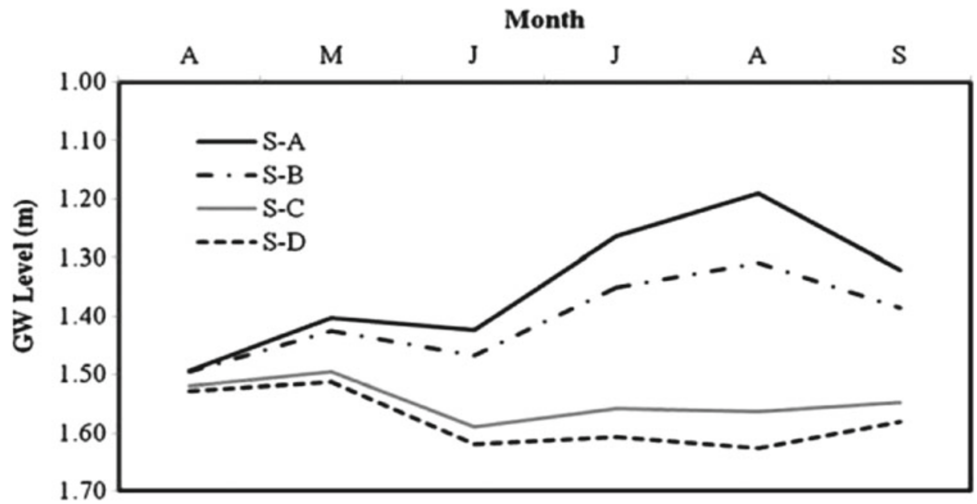


Fig. 19.14 Simulated mean monthly groundwater levels for 4 improved irrigation efficiency scenarios

19.2.5.12 Embedding Irrigation Into The Hydrological Context (basin management): irrigation and basin modeling/management (towards integration)

The largest consumer of fresh water resources on earth is agriculture sector. Globally around 70% of fresh water withdrawals from rivers, lakes and groundwater is used for irrigation purpose only reaching even more than 90% in arid regions. Although Irrigated agriculture constitutes only 20% of the total cultivated land but it produces 40% of the total global food (Siebert and Döll 2010), which reflects the significant role of irrigation in food production worldwide. Productivity and especially the potential to rise productivity by irrigation is a major reason for doubling of irrigated area in the last 50 years. In the view of rising population growth and food demand, a future expansion of irrigated areas and related increase in water consumption is highly expected (Neumann et al. 2011). However, the scope for expansion of cultivated land is limited and therefore sustainable intensification in agriculture with a special focus on irrigation is urgently needed. Whereas, water scarcity and uneven distribution of water resources across the globe can hinder the intensification of irrigated areas. Climate change on the other hand has reported to impact a significant decline with high uncertainty in water availability and likely to exacerbate irrigation water demand from different parts of the world (Strzepek and Boehlert 2010; Leng et al. 2015). In addition, there are other major constraints such as low irrigation efficiency in commonly used irrigation techniques i.e. flood irrigation (Evans and Sadler 2008); over-exploitation and unsustainable pumping of groundwater resources for irrigation (Kumar et al. 2018) and the changing river regimes (Döll and Schmied 2012) that further emphasize the urgent need for a transformation towards more efficient, productive and sustainable use of water in irrigation.

The prerequisite for sustainable and efficient water use in agriculture requires information on spatial distribution of water availability, extent and identification of irrigated areas, types of crop grown, spatial crop water demand and supply, spatial variation in soil moisture status, etc. Hence, a spatial database on irrigation (infrastructure, source, availability and amount) is of prime importance for policy and decision makers for framing strategies for efficient utilization of regional water resources and enhancement of food security.

Due to the high quantities of water withdrawn for irrigation schemes from the hydrological cycle and considerable amounts of harmful substances released into the hydrological cycle, irrigation exerts in many cases a substantial basin-wide impact. This creates the need to embed irrigation into overall water management concepts of the basins. To that end, reliable information with appropriate spatio-temporal resolution covering the basin with a focus in irrigated schemes is a prerequisite. Data provision by remote sensing and hydrological modeling are the major tools to provide that information.

19.2.5.13 Irrigation and remote sensing

Global data on irrigation is usually in coarse resolution. There is huge uncertainty in the actual area irrigated, the location of irrigated areas, and the irrigation strategies (water sources, timing and intensity of use), which leads to uncertainties in estimates of actual water use by irrigation and in turn contributes to mis-management of water resources. However, advancement in satellite remote sensing offers a tremendous potential for continuous monitoring and mapping of irrigated areas due to the availability of satellite imageries at different spatio-temporal scales (Alexandridis et al. 2008; Thenkabail et al. 2009).

Featuring a huge extension as a well as a distinct intensification of irrigation mainly driven by the need to fulfil the rising food demand of a quickly growing population, undergoing a tremendous increase of withdrawals from groundwater and facing an advancing processes of urbanization and industrialization. The mapping of spatio-temporal dynamics of irrigated areas (based on irrigation sources) using remote sensing satellite imageries is a key to understand the drivers of change and spatially identify and locate the 'hotspot' regions at high risk of over-exploitation due to extensive and unsustainable groundwater irrigation. Moreover, the mapping of canal infrastructure explores the areas where the potential benefits of canal system are still not reached and also reveals the gaps or bottlenecks in the irrigation systems.

Several basins especially in developing countries face the contrast between an urgent need for action in terms of water management (strategies, infrastructure) and the non-availability of sufficient data on water use as well as on demand. In order to contribute to mitigate this challenging situation, an approach which can combine the information from different sources at different scales (official statistics, remote sensing, field surveys, expert knowledge) on (i) extension of irrigated areas, (ii) intensification of irrigation, (iii) water source used (canal vs. groundwater), and (iv) water applied referring to seasons and crops is highly required. This approach also enables to detect important trends with respect to dynamic development of irrigated areas and water sources used.

19.2.5.14 Irrigation data and hydrological models

The large-scale irrigation has a considerable potential to directly and substantially affect the terrestrial water cycle via considerable withdrawals of irrigation water and release of drainage water with lowered water quality (as pointed out in Sect. 19.2.2). The effect of irrigation basically depends on irrigation amount, source and method of application e.g. flood irrigation applies large volume of water in short duration of time that results in larger impacts on surface runoff and groundwater depth compared to drip and sprinkler irrigation (Leng et al. 2017). Irrigation also leads to increase soil moisture and hence triggers increase of actual ET (Sacks et al. 2009; Ozdogan et al. 2010). Understanding the complex interactions and impact of different irrigation practices (scenarios) on water cycle components can be investigated using hydrological models. Moreover, hydrological models can also simulate the impact of environmental changes (e.g. climate and land-use change) on crop water availability and crop water demand (evapotranspiration) that further guides in irrigation scheduling and management of water resources.

The appropriateness of water management measures depends on the reliability of the output gained by the modeling tools, which in turn is highly determined by the capability of the models and the quality of model inputs (Shrestha et al. 2006). Thus, the quality aspects of model input data (such as irrigation data source and amount) should be considered during data acquisition. Despite the importance of hydrological modelling, hydrological impacts of irrigated croplands are poorly understood (Ozdogan et al. 2010). Several studies reported the limitation of regional quality datasets especially for catchment scale study that may severely affect the accuracy in hydrological model simulation (e.g., Shrestha et al. 2006; Burlando and Rosso 2002). The need for acquisition of high quality input data develops an approach that combines remote sensing techniques, official statistics, field visits, and expert interviews enabled to detect irrigation dynamics in detail. As a consequence, the quality of highly influential input to the hydrological model and the model results could be clearly improved.

Combining remote sensing techniques and hydrological modeling enabled to detect hotspot sites, which are characterized by severe changes in land-use impacting strongly the water balance components. These areas could be seen as priority sites for refined modeling and monitoring in order to conceive options to counterbalance disadvantageous impacts on the water balance. Yet, these sites should not be considered in isolation, but as a part of an integrated concept for basin-wide coordination of water management activities. Key interventions of such a concept can be derived from the model-based simulations.

Modeling results help in working out options to lower gross water withdrawals by improving irrigation schedules in terms of site-specific irrigation strategies matching the time-depending demand and combining canal and groundwater irrigation (conjunctive use options).

As detailed and direct information on water quantities used in the irrigation schemes is missing, information on the spatio-temporal development of irrigated areas can be used as a starting-point towards more comprehensive modeling and assessment of (irrigation) water balances. Based on the spatio-temporal dynamics of irrigated areas, extensive groundwater irrigated area with less recharge from percolation losses in irrigation canals can also be identified. Remote sensing approach can be useful for: (i) enhancing the understanding of usage of canal and groundwater for irrigation in terms of spatio-temporal trends, (ii) detecting eventual 'hotspot areas' (sites with a high risk towards groundwater-overexploitation), (iii) providing input into surface water and groundwater modeling. Thus, a contribution towards facilitating appropriate, adaptive and integrated land and water resources management.

19.2.5.15 Embedding Irrigation In The Socio-Economical-Institutional Context: identifying barriers and creating incentives for raising performance

The role of irrigation for higher crop yields and agricultural income as well as improved food security and rural livelihoods are well-documented (Schade and Pimentel 2010; Cassman 2016). In particular, in dry regions or in regions with fluctuating rainfall over seasons, irrigation is a key to reduce water stress in dry periods and enhance crop yields. The advancement of improved water lifting technologies and better access to energy also allows for irrigated area expansions. Carefully designed drainage systems permit to control soil salinity related with irrigation water application. Extension of irrigated areas creates massive employment opportunities especially for people from rural areas. Increased agricultural outputs contribute to food, fiber and energy security.

Given its lower labor and capital productivity compared to the industrial and services sectors, development policies in the last few decades often ignored the agricultural role for economic prosperity (Szirmai 2012). Consequently, there have not been sufficient investments in improving irrigation and drainage canals, and maintaining water regulation facilities (Dethier and Effenberger 2012). Sky-rocketing food prices during 2008–2009 disproved the arguments against agriculture's importance for better livelihoods. Indeed, better food access for the poor, increased job opportunities and poverty reduction in rural areas directly depend on the performance of the irrigation systems (Byerlee et al. 2009; Haggblade et al. 2010; Mellor 2017).

Industrial growth, urbanization and need for improved environmental flows intensify tensions over allocating scarce resource (Rosegrant et al. 2009). As a main consumer of water all over the world, potentials of water saving is substantial in the irrigated agriculture. Various irrigation technologies such as drip or sprinkler irrigation as well as improved water application processes such as short furrows and alternate dry furrows allow for reducing considerable amount of water consumption (Bekchanov et al. 2010). Indeed, because of the reduced return flows following the water conservation technology adoptions the basin-scale water use reduction effects of improved irrigation technologies can be much lower than their field level effect (Grafton et al. 2018). Yet, there are other financial and institutional barriers to be tackled for a wider implementation of the water-wise technologies.

19.2.5.16 Barriers to irrigation technologies

Main financial barrier is high cost of advanced irrigation technologies such as drip irrigation. Overall, inverse relationship is observed between the water use reduction effect and the costs of the implementing the water conservation technology (Bekchanov et al. 2010). Poor households or farmers producing low income crops can barely afford expensive irrigation technologies. Government control of the agricultural production system and consequent low procurement prices for harvest also limit the implementation of expensive technologies. Indirect taxation of the agricultural system through full control of upstream and downstream value chains leaves little space for producers to make any technological change. Furthermore, underdevelopment of banking system and low access to credit facilities also limit the technology adoptions.

Institutional barriers to wide-scale adoption of irrigation technologies include poor governance, lack of land tenure, non-transparency of water rights, frequent changes in policies and laws. Short-term rights to use land while neglecting the delegation of ownership rights does not create any incentive to implement soil reclamation or water use reduction measures. Since farmers are well aware of losing their rights to use the land after a few years, they are more eager to get maximum benefit in a short time while ignoring soil nutrition depletion and water overuse in their fields. Since irrigation technologies such as drip irrigation require investments that can be recovered in long time period, farmers with a short-term tenure and goals lack of interest in such technologies.

Non-transparent water rights and intermittent water supply also create inequalities in water distribution. Farmers located near to the main canal can get as much as water they want and even overuse scarce water resources while farmers located at the tail-ends of the irrigation canal face inadequate supply of water. In this situation upstream farmer do not see any incentive to save water since water is always abundantly available. Meantime, inadequate and intermittent supply of water for downstream users may increase water stress in dry periods at a level that cannot be even addressed with advanced irrigation technologies.

Unstable policies and regulatory framework increase the risks in agricultural production. Therefore, risk-averse farmers limit the implementation of productivity change measures that can bear fruits in the long-term. In addition to land privatization and consolidation policies, changes in input supply channels and prices also have impact on farm profitability. Similarly, changes in policies regulating the output markets and prices also play important role in farm decisions on technology adoptions. For instance, liberalization of industry sector while strict state control of agricultural production may lead to low prices for agricultural outputs while increasing input supplies from industry, consequently diminishing farming incomes.

19.2.5.17 Incentives to implement irrigation technologies

A wider implementation of the irrigation technologies requires parallel improvements in governance, institutions, regulatory framework and investment allocations. Main measures should aim, first of all, at improving the recognition of water and land use rights. Second, the real value of water that depends on its location, uses and time period should be recognized. Third, access to good quality and affordable irrigation technologies should be maintained. Fourth, output markets should be secure and allow gaining in considerable incomes to farmers.

Improved land tenure and delegating land use rights over long period create incentives for improved land management practices and investments that bring benefits over long time. Long-term use of land by a single farmer also allows for utilizing benefits from crop diversity and improved rotations that appear over time (Bobojonov et al. 2013). Farmers, being aware of the consequences of the current water and land management practices, attempt to reduce soil-salt accumulation and eliminate soil nutrient depletions. Given the long-period duration of their land use rights, farmers also will have incentive to implement advanced irrigation technologies such as drip irrigation that can be beneficial only when used over long-period. Recognizing water use rights is important to improve water supply and eliminate inequalities and injustice in water allocation. Entitling water use rights and monitoring the water allocation reduce water overuse by upstream users while improving water access by downstream users, eventually improving system-wide efficiency of water uses.

Recognizing value of water is important for reducing wasteful uses of water especially under growing water scarcity. Water pricing while considering the location, season and quality of water may serve for improving water use productivity. Progressive rates of water fees that mean increasing water fees per unit of water use exceeding thresholds prevents water overuses. Following the recognition of water value and entitlement of water use rights, more advanced schemes water reallocation, for instance, water market mechanisms, can be introduced (Bekchanov et al. 2015; Li et al. 2017). Chapter 10 discusses in some detail the pre-requisites and success chances of water markets. Yet, basin-wide accounting of water and proper institutional settings are required for adequate functioning of such systems (Wheeler et al. 2017, Zhu et al. 2019).

Water pricing and water rights trading create also incentives for a wider adoption of irrigation technologies. Domestication of producing irrigation technologies can make them more affordable to farmers since transportation costs and customs fees may increase their prices. In case of possibility to improve environmental flows due to water conservation, state may consider subsidizing irrigation technologies as it may have positive environmental externalities. Yet, since advanced irrigation technologies require enormous amount of energy, their adverse effects due to increased carbon emissions should weigh against their positive externality. Improved energy access is also important for implementing and operating advanced irrigation facilities. The nexus triangle between water-, food-, and energy security can be traced even at the scale of a single irrigation plot.

Farmers should have adequate incomes to afford the implementation costs of irrigation technologies. Liberalization of agricultural markets for allowing farmers to get market price for their product may improve farming incomes. Furthermore, market channels that lead to global markets should be improved through reducing taxation and easing to obtain trade permissions. Reducing the post harvest losses through using proper transportation and storage systems also improve farming incomes.

19.2.6 Summary and Outlook

Irrigated agriculture is facing the challenge to enhance the contribution to food security under conditions becoming more difficult in future. Increasing variability of and a sharpening competition for water resources due to climate change impacts and driven by population growth complicate the future supply provision for irrigation. In order to rise agricultural production and to lower the impact on the environment with only rather limited potential for exploring further water resources, crop irrigation needs to become more targeted, efficient and productive (as expressed by FAO's 'More crop per drop Strategy'). Advancing productivity requires to improve water use within the irrigation sphere and to realize a better integration of irrigation into the overall system of agricultural inputs and procedures.

Applying a system approach eases to understand and improve the operation of irrigation schemes and to embed irrigation into the hydrological cycle, institutional, socio-economic and environmental context. Assessing appropriateness, efficiency, productivity, reliability of supply provision and detecting the underlying reasons for an eventual under-performance (by irrigation performance assessment) enables to conceive promising strategies for improved operation and concepts for re-design irrigation and drainage infrastructure. Flexible irrigation scheduling in combination with advancing irrigation techniques form an intervention with strong impact on the water productivity. Modelling water fluxes for balancing soil moisture as well as salinity provides the base to work out irrigation schedules, which are guided by crop-water-soil-atmosphere relationships in order to avoid water as well as salt stress or at least to minimize the impact of water stress on the yield (in case of non-avoidable under-supply). Advancing techniques comprise to optimize handling of conventional surface irrigation methods ('optimal application discharge'), refining these methods (surge flow, alternate furrow, raised-bed) in combination with improved land preparation (laser-guided field levelling) and—in case upgrading of current systems does not enable to reach the necessary rise in productivity—to change technologies (sprinkler, drip).

In Sect. 19.2, we provided information on sources as well as approaches to acquire the data needed for flexible irrigation scheduling, assessing the performance, combining surface and groundwater resources for conjunctive use strategies, utilizing controlled deficit irrigation and option towards adaptive management steps and for integrating irrigation into the hydrological system of the basin. Coming back to the overall socio-economic context and putting the focus on implementation of advanced irrigation strategies and concepts, we point out the need for and steps towards identifying barriers hindering implementation and options as well as steps to overcome these barriers by creating enabling environments and incentive systems.

19.3 Soil Water Management Practices

19.3.1 Soil Water Balance

One of the main aims of soil water management is to revise the water balance to improve plant growth conditions. The mean annual soil water balance of sites with deep groundwater level is:

$$S = P - E - T - I - D - R \tag{19.4}$$

The S stands for plant available soil water pool, P for rainfall, E for evaporation from soil surface, T for transpiration via stomata (equal to the root water uptake), I for evaporation of water which was intercepted by the canopy during rainfall, D for subsoil drainage (equal to the downward movement of water through the soil beyond the root zone), and R for surface runoff (which leads to soil erosion by water). The deep groundwater condition implies no capillary rise of water from the aquifer to the root zone. At such sites, rainfall is the only source for the replenishment of depleted soil water pools.

Management of soil water for improving plant production seeks to ensure a high level of water supply while preventing unproductive water losses. In this regard, best soil water management practices promote the infiltration of rainwater into the soil, control evaporation, increase the ability of soils to retain water, and enhance the rootability of soils for making water retained in subsoils accessible for root uptake. Soil water management is, besides crop management and breeding for yield and water use, the key for increasing the water use efficiency in plant production. In the following sections, main principles of management practices for increasing plant available soil water pools are briefly discussed. Drainage of soils and irrigation is not part of this discussion.

19.3.2 Controlling Infiltration

The soil surface conditions control the partitioning of rainfall into surface runoff and infiltration. The latter is the intake of rainwater by soils, while the rate of inflow is called infiltrability. Soil surface manipulations by tillage, residue management or mulching ensure roughness and openness at the soil surface as a basis for high infiltrability. Roughness describes the soil surface microrelief; it is generated by soil aggregates, formed and exposed at the soil surface (Ehlers and Goss 2016). Aggregates are formed mechanically by tillage or biologically by soil fauna (e.g. earthworms or termites) and soil microorganism (e.g. bacteria or fungi). Biologically formed aggregates are generally more stable than the mechanically formed ones. Openness describes the degree of hydraulic connection between the soil surface and underlying topsoil through large soil pores between individual soil peds or aggregates (Ehlers and Goss 2016). The presence of such large, well-connected soil pores enables the soils intake of rainwater at a high rate. Thus, soil water management aims not only to promote the formation of aggregates but also to stabilize them. In Table 19.3, various measures for preservation of roughness and openness are compiled. Moreover, the effects of these measures on soil properties are described.

19.3.3 Controlling Evaporation From the Soil

At given meteorological conditions as net radiation, vapour pressure deficit and wind velocity, evaporation of water from soils is governed by the unsaturated hydraulic conductivity of the topsoil. Soil management for controlling evaporation from soils needs thus to manipulate the near-saturated and unsaturated hydraulic conductivity of the soil surface. The

Table 19.3 Soil management measures for controlling infiltration

Measure	Effect
Loosening soil	Creates pores and cavities between soil aggregates
Mulching with any material	Reduces splash erosion, minimizes aggregate slaking
Mulching with plant litter	Reduces splash erosion, minimizes aggregate slaking, and promotes the formation of aggregates by soil organism
Stubble tillage	Makes the soil surface rough and open
Liming of soils or adding gypsum	Stabilizes soil surface aggregates
Application of stable humus in the form of organic manure or compost	Stabilizes soil surface aggregates
Proper timing of tillage on clay soils: consider the narrow moisture range for good tillage	Avoids soil compaction
Reduce traffic on arable land	Avoids soil compaction
Deep ripping	Breaking up of compacted soil layers (e.g. plough pans or traffic pans)
Minimum or conservation tillage for maximizing crop residues at the soil surface	Increases aggregate stability, reduces splash erosion, minimizes aggregate slaking, promotes biologically aggregate formation
Furrow diking	Allows more time for infiltration of rainwater through improving soil surface storage
Converting sloped farmland into terraces	Decreases surface runoff while increasing infiltration due to increasing time for infiltration of rainwater

concept of roughness and openness of the topsoil is—as in the case of infiltration control—applicable to control evaporation from soils. Roughness and openness at the soil surface promote infiltration of water as discussed above. But when such rough and open top layer becomes dry, there is an additional role of the soil surface in the soil hydrologic cycle. The surface layer acts then as a kind of capillary barrier by resisting water passage from the underlying wet soil to the top-layer. The reason for it is that the pore size of the rough and open top layer is larger than that of the underlying soil. Resulting is a capillary break effect at the interface between dry top soil layer and the underlying soil. Vegetative mulches, stubble tillage, or loosening of soils are measures to create such structures (see Table 19.3). In addition to the measures listed in Table 19.3, plastic mulches are commonly used for crops with high cash values to reduce water losses via evaporation from soils.

19.3.4 Increasing the Amount of Extractable Soil Water

The amount of soil water, extractable by plant roots, depends on the ability of soil to retain infiltrating water and the rooting depth. However, not all of the retained soil water is extractable by plant roots. The extractable soil water, usually called plant available soil water, is the difference between the field capacity, which is the maximum amount of water the soil can hold, and the permanent wilting point, where the plant can no longer extract water from the soil (it corresponds—per definition—to a soil pressure head of 1.5 MPa). The water content at field capacity is a point at which water moves slowly after a rainfall or irrigation event (usually 1 or 2 days after the event). At this point, the downward movement of water is so slow that the daily soil water content changes are insignificant. The water content at field capacity and at permanent wilting point depends on soil texture and the amount of organic matter. Increasing the amount of soil organic matter or enrichment of sandy soils with silt or clay is a way to increase the amount of extractable soil water. How much water is taken up depends on the rooting intensity and rooting depth. Removing any barrier that restricts vertical root penetration makes soil water stored in deeper layers accessible for root water uptake. Some examples for increasing the amount of extractable soil water are compiled in Table 19.4. Increasing the amount of extractable soil water will also contribute to control of subsoil drainage and minimize seepage loss.

Table 19.4 Soil management practices for increasing the amount of plant available soil water

Reasons for interventions	Example	Measure	Effect
Soil layering or soil type	Sand over loam	Deep mixing/ ploughing	Increases rooting depth Increases plant available water of the subsoil
	Podzol with iron pan	Deep loosening Deep mixing/ ploughing	Increases rooting depth
Low water holding capacity	Sandy soils	Adding organic or fine textured material	Increases plant available water of the topsoil horizon
Soil compaction or high bulk density in the subsoil	Plow pan	Loosening	Increases rooting depth
	Clay pan	Deep loosening	Increases rooting depth and plant available water of the soil profile

19.4 Cost-Effective Water Conservation Interventions for Drought Hotspots in Central Asia

19.4.1 Introduction

Current and expected water shortages are major threats to agricultural sustainability, food security, and economic stability. Water shortages severely impact on the livelihoods in arid and semi-arid regions as well as in downstream areas of massive river basins. At present, about 20% of the global population live already under water-scarce conditions and their share is expected to increase to one third until 2025 (UN WATER 2007). Major conflicts in this century are predicted to happen over water resources because of increased demand for this resource under limited supply (Serageldin 2009). Water scarcity therefore challenges countries throughout the world to implement mitigation measures. Measures of providing secure water availability for food and drinking needs are essential, particularly achieving the Millennium and followed Sustainable Development Goals of decreasing malnutrition, eradicating poverty, and providing better sanitary conditions (UN 2000; von Braun et al. 2003, 2009).

Consent has been reached that mitigation measures should increase water use efficiency especially in the agricultural sector, which is globally the main water user, requiring more than 70% of total water use in the world (World Resources Institute 2005). This is particularly true for the irrigated areas in the world which increased from around 50 million ha (Mha) at the onset of the 1900s to about 280 Mha one century later. Nowadays employed on almost 20% of the global share of arable land, irrigated agriculture is responsible for about 40% of global food production (UNESCO-WWAP 2006). The challenges associated with the expansion in irrigated croplands are particularly evident in Central Asia, covering the countries Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. This dryland region enlarged its irrigated area from ca. 2 Mha to ca. 8 Mha in less than four decades during the Soviet period (FAO/WFP 2000; Cai et al. 2003) and became one of the largest irrigated zones in the world. Irrigation extension in Central Asia diverting the river flows reduced downstream inflows and led to a gradual shrinkage of the Aral Sea, once the fourth largest lake in the world. The desiccation of the Sea is acknowledged as one of the worst man-made ecological catastrophes in the world (UN 2010). Moreover, several other environmental problems such as waterlogging, soil salinization, river flow contamination, and public health degradation due to irrigation water overuse, increased drainage flow, and inadequate water governance have been threatening regional livelihoods. Water scarcity has been growing in the region with increasing population and rising demand for food and hydro-electricity generation, while water use efficiency remains too low. To this end, improving water use efficiency of irrigation systems would help not only to deal with increased water demands and frequent droughts but also reduce the threats on the environment (Lamers et al. 2011; Tischbein et al. 2012).

Worldwide, many innovations have been examined as means to fight water scarcity, for example changing crop patterns towards less water-consuming crops, adopting technologies to increase soil moisture, e.g. applying hydrogel or organic manure, leveling the land to reduce irrigation water needs, introducing drip irrigation to reduce water application, and improving field-level irrigation through furrow management. The question is often raised why those technologies, if available, are not widely employed. However, for the successful introduction of water-wise technologies it is crucial to assess the financial trade-offs which can be important barriers to application. Moreover, regionally specific conditions may favor or limit adoption rates of the technologies.

It has been suggested that the "water-wise" innovations would suit land users (farmers) and land managers (the public sector) also in the irrigated areas of Khorezm, a region located at the lower reaches of the Amu Darya River in the Aral Sea basin, Central Asia. With a cropping area of around 230,000 hectares (Conrad et al. 2012), the region is representative of not only the ca. 8 Mha irrigated lands in Central Asia but also other dry and semi-dry or downstream oases of the world. Frequent droughts in the region are seriously threatening the rural livelihoods which mainly rely on irrigated agriculture (Müller 2006). Whereas various studies have tried quantifying the dynamics of water supply to the Khorezm region (e.g. Müller 2006, Bobojonov 2009 etc.), little research has addressed the socio-economic impact of reduced water supply and the magnitude of water-wise options to deal with the observed water shortages.

With respect to the level and impact of reduced water availability, probability of sufficient water supply to Khorezm was discussed by Müller (2006. Impact of water scarcity on different crop yields across the administrative districts in the region was analyzed by Bekchanov et al. (2010a). However, level of the shortage in comparison with the required regional demand and irrigation benefit losses due to the scarcity was not addressed.

Potential water use reduction rates under different water-wise options such as cropping paddy rice under aerobic conditions (Devkota 2011), double furrow (Poluasheva 2005), laser guided land levelling (Egamberdiev et al. 2008), and drip irrigation (Ibragimov et al. 2007) was investigated based on experimental studies. Bekchanov et al. (2010b) and Lamers et al. (2011) summarized water use reduction of different water-wise options based on the results of the experiments and additionally evaluated their costs and benefits. However, regional overall water use potential of adopting the technologies considering their adoption rates (areas) were remained unanswered.

Therefore, this section aims to assess the level and economic impact of reduced water supply on one hand and the overall water use reduction potentials and costs of implementing water-wise technologies on the other hand to examine the question if the magnitude and costs of the drought are preventable through the irrigation improvements. Thus, at first, we here assess drought levels and costs over the years. Changes in water withdrawal to the Khorezm region after independence period are also compared to test the impact of main political event on water distribution. Then, we estimate the overall water use reduction potentials and the economic feasibility of various water-wise measures to cover the water supply and demand gap in the Khorezm region using an additive approach of implementing the measures under different adoption rate scenarios (pessimistic, neutral, and optimistic). Scenarios consider one-time change from the initial state to the ultimate state.

19.4.2 Methods

19.4.2.1 Study area

Khorezm is the western region in Uzbekistan and located 250 km away from the shores of the desiccating Aral Sea (Fig. 19.15). The other two downstream regions in the Amu Darya basin are Dashauz (in Turkmenistan) and Karakalpakstan (in Uzbekistan) which together with Khorezm rely on Tuyamuyun reservoir for water supply. With more than 3 million inhabitants, the Khorezm region is one of the most densely populated regions in Uzbekistan. Of these people, 70% are rural. Irrigated agriculture has been practiced in Khorezm since ancient times (Tolstov 2005) and is the backbone of the regional economy even at present. The sector provides 60% of the regional income and more than 95% of the regional export revenues (Rudenko et al. 2009. If food crops, fruits, grapes, and fodder crops (clover) dominated the agricultural production by twentieth century the crop portfolio is currently dominated by cotton, wheat and rice and fodder crops (Fig. 19.16). There are various reasons for this shift: (1) the Soviet administration imposed a cotton self-sufficiency policy during the twentieth century which is followed up by the Uzbek government aftermath of independence (in 1991); (2) a wheat self-sufficiency policy was imposed by the Uzbek government starting from the early 1990s (Rudenko et al. 2012), and the wheat area quickly expanded to now more than 50.000 ha or 20% of the total cropland area in Khorezm; (3) rice is a preferred food option in Uzbekistan and a profitable crop, in spite of its high water use intensity; and (4) cotton needs to be grown in rotation with other crops including clover to maintain yield levels. Cotton and wheat production is scrutinized by the government to keep stable export revenues and maintain food self-sufficiency but state procurement prices paid to the farmers are lower than world market prices (e.g. Djanibekov et al. 2012a).

The agriculture is a main user of water resources and accounts for about 85% of total regional water withdrawal which amounts to about 5 km^3 in average in years with normal water supply. However, risks of water availability and thus the vulnerability of the downstream water users are increasing over the years due to climate change and extension of upstream water diversions (Müller 2006). Considering low payment rates for cotton—a dominant crop- in the region and the poverty rate of over 30% in the region even without droughts, it can be easily guessed how harsh can be

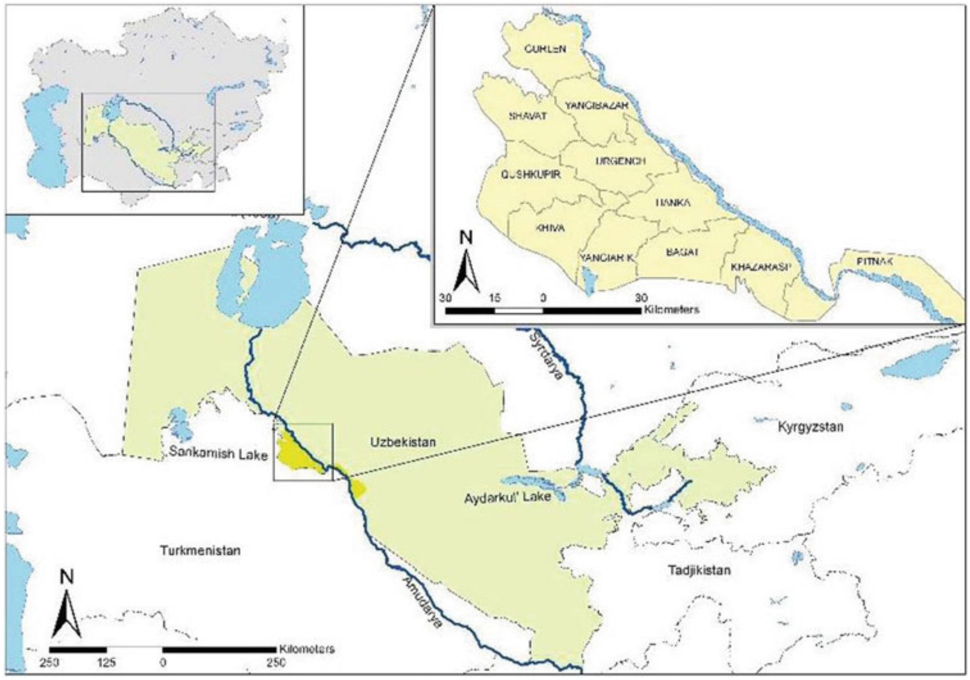


Fig. 19.15 Location of the Khorezm region. *Source* GIS Laboratory of ZEF/UNESCO Project

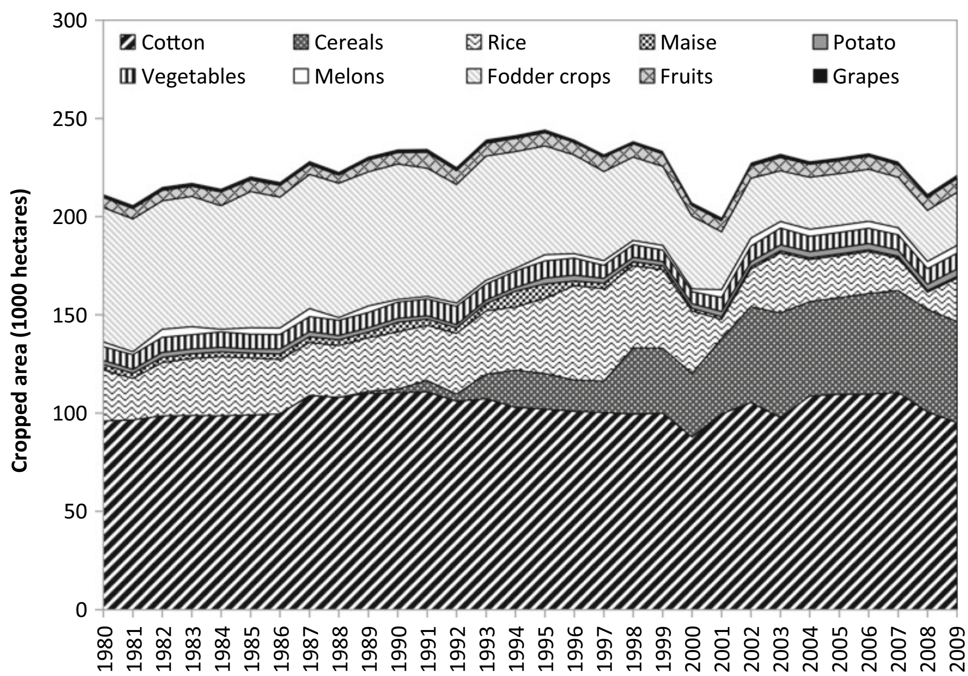


Fig. 19.16 Crop pattern in Khorezm (1982–2008). *Source* SIC-ICWC 2011, OblStat 2011

even small reduction in water supply to the regional livelihoods. Unfortunately, the region is not well equipped with advanced irrigation technologies to be able to cope with the consequences of sudden drought. Since water application is mainly based on furrow and basin irrigation, water application efficiency is about 40% (Bekchanov et al. 2010b). Therefore, there is an urgent need and huge potential for irrigation management improvements.

19.4.2.2 Indicators of drought and drought vulnerability

Analyses of water availability and drought costs in this study are based on long term observations of water supply and consumption in the Khorezm region. Non-linear declining trend of water supply was estimated based on long-term annual inflows to the Tuyamuyun reservoir. Data on inflows to the reservoir was obtained from UzHydroMet (2009).

Water diversion to the Khorezm region over the years and its variability were analyzed to compare the water use situation before and aftermath of independence. Therefore, average values and standard deviations of water diversion during the period before and after 1991 were assessed and compared. Data on water use in the region was provided by SIC-ICWC (2011) and UzHydroMet (2008).

For estimating level of regional water scarcity, among many possible indicators, we used the one which is defined by the share of the water deficit in total water use requirement (Mishra and Singh 2010). Water scarcity indexes (*WSI*) were estimated using data on actual water use (*WA*) and required water use (*WR*) from regional water management organizations (OblSelVodKhoz 2011), as follows:

$$WSI = \left(1 - \frac{WA}{WR}\right) \cdot 100\% \qquad (19.5)$$

Irrigation profit reductions due to water scarcity at year t were accepted as drought costs (DC_t). Drought costs were estimated as the difference between actual level of agricultural profit (AP_t) and the average agricultural profit in normal water supply years (*AAP*), as proposed by Dziegielewski (2003):

$$DC_t = AP_t - AAP \qquad (19.6)$$

This calculation considers only the direct costs of drought. Eventual indirect costs caused by subsequent unemployment, reduced health and education quality, decreased living standards, and social damages due to poverty were not considered and could add substantially to the total drought costs. Agricultural profits (AP_t) in Eq. 19.6 were calculated as the difference between revenues and production costs:

$$AP_t = \sum_c P_c Q_{c,t} - \sum_c VC_c A_{c,t} \qquad (19.7)$$

Production revenue is the product of crop price (P_c) and production volumes ($Q_{c,t}$). Production cost is the product of per hectare cost (VC_c) and the area ($A_{c,t}$) for each crop (c). Data on crop prices is from Bobojonov (2009) and data on production levels is from OblStat (2011). For estimating annual profits over the period 1982–2010, the crop prices and per hectare production costs of 2005 were kept constant for all years to provide comparability of yield changes due to water availability change across the years.

19.4.2.3 Indicators of water use reduction

Opportunities for reducing water use were estimated to cope with the costs of sudden droughts. Estimations of water use reduction potential and economic feasibility of introducing different water-wise technologies under different scenarios are based on three calculation steps:

(1) Evaluating water use reduction rates of each technology per hectare;
(2) Assessing yield and profit changes under these technologies, also per hectare;
(3) Estimating potentially suitable areas for scaling up the adoption of each technology.

19.4.2.4 Water use reduction rates under different water-wise options

Since the rather inefficient furrow and basin irrigation methods dominate the irrigation practice in Khorezm (Tischbein et al. 2012) adaptation of different water-wise options can lead to substantial regional water use reduction if their implementation is economically feasible. Based on their technical suitability under the agro-climatic conditions of the region and the mode to enhance water use efficiency, four groups of water-wise options were analyzed: A—crop alternatives and diversification; B—methods that increase soil moisture duration; C—technologies to provide adequate and uniform water supply to the crop root zone; and D—furrow irrigation improvement (Bekchanov et al. 2010b).

Crop diversification aims at replacing water demanding crops with less water-intensive crops, e.g. replacing paddy rice with maize or aerobic (upland) rice management that demands less water (Devkota 2011). Soil moisture can be preserved by introducing hydrogel or organic fertilizer (manuring) in cotton, wheat, and potato fields. We assume manuring to be applied only to these three crops due to its limited supply and high yield impact when applied to cultivate these crops. Two options are considered to increase water use uniformity: drip irrigation—potentially suitable in cotton, potato, vegetable, melons, grapes, and fruit; and laser-guided land leveling before cotton and wheat seeding—on leveled land the water distributes more evenly, reducing the amount of water needed to reach all parts of the field. Furrow irrigation improvement techniques consist of surge flow, double furrow, alternate dry furrow, and shorter furrows for irrigating cotton. In surge flow, water is delivered intermittently establishing a fine layer in the previously wetted parts of the furrows which reduces filtration losses in the next rounds of water delivery. In double furrow, water is applied from both sides of the furrow providing better uniformity of the applied water along the furrow and less losses to infiltration. In alternate dry furrow, only every second furrow is flooded and thus less water is required to irrigate the field. Shorter furrows reduce percolation losses and decrease irrigation duration.

Water use reduction rates have been estimated as the percentage of reduced water use assuming that the option is implemented compared to the conventional irrigation methods (Table 19.5). The efficiencies of water-wise options differ with crops and some technologies are unsuitable for some crops. Based on the different sources, ranges (minimum and maximum values) rather than point values for water use reduction rates were estimated. Only for the option replacing paddy rice to maize (A1), which has one of the highest water use reduction rates, minimum and maximum water use reduction rates are considered to be similar. According to Mamatov (2009), drip irrigation has a substantially higher water consumption reduction potential in vegetables, fruits, and grapes than in cotton.

19.4.2.5 Yield and profit changes under different water-wise options

Similarly, the yield range (minimum and maximum values) and changes under different water-wise options compared to conventional irrigation practices were estimated from experimental results, secondary sources and expert opinions (Table 19.6) suggesting that potential yield increases of vegetables may range from 50 to 80% and of fruits from 20 to 40% under drip irrigation. Despite enhancing water use improvement options, surge flow and alternate dry furrow could reduce yields by 10 to 15% (Horst et al. 2007).

Combining the data sets on traditional (*0*) and technology based (*k*) yield ($y_{c,0}$ and $y_{c,k}$, respectively) and water use

Table 19.5 Potential water use reduction rates under different water-wise options

		Water use reduction rate		
Groups	Options	Minimal (%)	Maximal (%)	Source
A1	Rice to maize	82	82	Bobojonov (2009)
A2	Aerobic rice	30	50	Devkota (2011)
B1	Hydrogel:			
(a)	Cotton (H)	20	40	I. Abdullaev (personal communication)
(b)	Wheat (H)	20	40	Timirova and Salokhitdinov (2002)
B2	Manuring:			
(a)	Cotton (M)	20	30	J. Ruzimov (personal communication)
(b)	Wheat (M)	20	30	J. Ruzimov (personal communication)
(c)	Potato (M)	20	30	J. Ruzimov (personal communication)
C1	Laser leveling:			
(a)	Cotton (L)	25	30	Egamberdiev et al. (2008)
(b)	Wheat (L)	25	30	Egamberdiev et al. (2008)
C2	Drip irrigation:			
(a)	Cotton (D)	20	40	Ibragimov et al. (2007)
(b)	Potato (D)	45	60	Mamatov (2009)
(c)	Vegetable (D)	45	60	Mamatov (2009)
(d)	Melons (D)	45	60	Mamatov (2009)
(e)	Fruits (D)	45	60	Mamatov (2009)
(f)	Grapes (D)	45	60	Mamatov (2009)
D1	Surge flow: cotton	18	22	Horst et al. (2007), authors' estimation
D2	Double furrow: cotton	10	20	Poluasheva (2005)
D3	Alternate dry furrow: cotton	28	32	Horst et al. (2007), authors' estimation
D4	Shorter furrows: cotton	5	10	Assumed based on Poluasheva (2005)

Source modified after Bekchanov et al. (2010b); efficiency values and sources are updated

Table 19.6 Potential yield change under different water-wise options

Groups	Options	Yield change		Source
		Minimal (%)	Maximal (%)	
A1	Rice to maize	n.a	n.a	
A2	Aerobic rice	−40	−30	Devkota (2011)
B1	Hydrogel:			
(a)	Cotton (H)	10	15	I. Abdullaev (personal communication)
(b)	Wheat (H)	10	15	Timirova and Salohitdinov (2002)
B2	Manuring:			
(a)	Cotton (M)	25	30	J. Ruzimov (personal communication)
(b)	Wheat (M)	15	25	J. Ruzimov (personal communication)
(c)	Potato (M)	25	30	J. Ruzimov (personal communication)
C1	Laser leveling:			
(a)	Cotton (L)	20	30	Egamberdiev et al. (2008)
(b)	Wheat (L)	20	30	Egamberdiev et al. (2008)
C2	Drip irrigation:			
(a)	Cotton (D)	15	25	Nerozin (2005)
(b)	Potato (D)	50	80	Mamatov (2009)
(c)	Vegetable (D)	50	80	Mamatov (2009)
(d)	Melons (D)	50	80	Mamatov (2009)
(e)	Fruits (D)	20	40	Mamatov (2009)
(f)	Grapes (D)	20	40	Mamatov (2009)
D1	Surge flow: cotton	−15	−10	Horst et al. (2007)
D2	Double furrow: cotton	5	10	Assumed based on Poluasheva (2005)
D3	Alternate dry furrow: cotton	−15	−10	Horst et al. (2007)
D4	Shorter furrows: cotton	5	10	Assumed based on Poluasheva (2005)

Source modified after Bekchanov et al. (2010b); yield change values and sources are updated

($w_{c,0}$ and $w_{c,k}$, respectively) by crops (c), with crop production budgets and technology costs, total cost changes ($\Delta TC_{c,k}$) and profit changes per hectare ($\Delta\pi_{c,k}$) under each option were calculated as:

$$\Delta TC_{c,k} = TC_{c,k} - TC_{c,0} \quad (19.8)$$

$$\Delta\pi_{c,k} = P_c\left(y_{c,k} - y_{c,0}\right) - \Delta TC_{c,k} \quad (19.9)$$

Crop budgets and costs of innovations were estimated using the database of various sources (Bobojonov 2009, Djalalov 2005, Bekchanov et al. 2010b).

Assumptions on technology adoption areas

For estimating a system-wide impact of water use reduction potential and costs of each water-wise option, the potential areas of adoption were estimated under pessimistic, neutral, and optimistic scenarios (Table 19.7). It was assumed that under the pessimistic scenario, farmers would have limited capability to adopt advanced irrigation technologies such as laser-guided land leveling and drip irrigation and thus be able mainly to implement low-cost technologies such as surge flow, double flow, alternate dry furrow, and short furrows which have in general lower efficiencies than others. Neutral scenario considers partial reduction of the implementation of the above-mentioned less efficient options but increased replacements of water intensive crops to less water demanding crops as well as moderate expansion of advanced irrigation methods. We assume that under the optimistic scenario the land users would have opportunities to broadly adopt advanced technologies such as laser-guided land leveling and drip irrigation,

Table 19.7 System effects of introducing water-wise options: Initial areas of crops and assumed changes (as % of the basic (initial) level cropland area) by adopting water-wise options under pessimistic, neutral, and optimistic scenarios

Groups	Options	Basic level of cropland area without technology (1000 ha)	Technologically changed share of the cropland area		
			Pessimistic scenario (%)	Neutral scenario (%)	Optimistic scenario (%)
A1	Rice to maize	21.3	30	50	60
A2	Aerobic rice	21.3	10	20	30
B1	Hydrogel:				
(a)	Cotton (H)	109.6	5	10	10
(b)	Wheat (H)	49.2	5	10	20
B2	Manuring:				
(a)	Cotton (M)	109.6	10	20	20
(b)	Wheat (M)	49.2	10	20	40
(c)	Potato (M)	3.2	20	50	50
C1	Laser leveling:				
(a)	Cotton (L)	109.6	5	20	50
(b)	Wheat (L)	49.2	5	20	40
C2	Drip irrigation:				
(a)	Cotton (D)	109.6	5	10	20
(b)	Potato (D)	3.2	5	20	50
(c)	Vegetable (D)	7.8	5	20	50
(d)	Melons (D)	3.6	5	20	50
(e)	Fruits (D)	6.6	20	50	100
(f)	Grapes (D)	1.5	20	50	100
D1	Surge flow: cotton		5	10	0
D2	Double furrow: cotton	109.6	20	10	0
D3	Alternate dry furrow: cotton	109.6	20	10	0
D4	Shorter furrows: cotton	109.6	20	10	0

concurrently decreasing the use of the less efficient options. For instance, considering the high water productivity potential of drip irrigation in orchards and gardens, we assumed high adoption rates for drip irrigation in the production systems with potato, vegetables, and melons, and even more optimistic rates with fruits and grapes.

Crop pattern changes have been done all the times, hence are in principle acceptable for farmers (Fig. 19.16). Under conditions of increased water scarcity, replacing high water consuming crops with low water use intensive crops is justifiable (Table 19.7). Considering high demand for fodder crops in the region, under the optimistic scenario it is assumed up to 60% of areas under rice can be transformed to produce maize which demands 5–6 times less water than rice. In addition, up to 30% of rice production was assumed to be done under aerobic conditions, e.g. applying a lower amount of water which is up to 40% less than the normally required amount. Since hydrogel may require special soil conditions, only up to 10% and 20% of wheat and cotton areas, respectively, were assumed to be available for this technology. Manuring is limited due to the livestock number in the region; it was assumed that up to 20% and 40% of the cotton and wheat areas, respectively, can be manured regularly. Since income returns from manuring in potato production is substantially high, up to 50% of potato can be produced by manuring under the neutral and optimistic scenarios. Adoption of laser-guided land leveling can be as high as 50% and 40% of the cotton and wheat areas, respectively, as it substantially reduces water consumption due to the more even distribution of irrigation water applied (Egamberdiev et al. 2008). Due to the low profitability of cotton farming, only up to 20% of the cotton area was assumed to become equipped with drip irrigation system. Higher adoption rates up to 50% were assumed for potato, vegetables, and melons, considering the much higher income rate from these crops. Full transformation of the gardens and vineyards into drip equipped production systems was assumed under the optimistic scenario. Improved furrow irrigation technologies were assumed to be applied on up to 20% of the cotton area under the pessimistic scenario due to their lower adoption costs, but shall be fully replaced by modern irrigation technologies, manuring, and hydrogel under the optimistic scenario.

19.4.3 Results of Water Scarcity and its Impact on Crop Patterns and Production Revenues

Analysis of water inflow to the Tuyamuyun reservoir showed decreasing trend of water availability to downstream reaches in the Amu Darya (Fig. 19.17). Upstream and midstream irrigation expansions over years led to reducing downstream supply. River runoff reduced also because of climate change effects. Upstream reservoir release changes to increase hydropower benefits also might be caused instability of downstream water supply. The graph also shows that water supply levels between 2002 and 2006 were higher than average trend. Thus, adequate water diversions for irrigation and other needs can be assumed in these years.

However, higher demand in upstream regions accompanied by reductions in natural water supply particularly in 2000, 2001, and 2008 worsened the situation. Water flow measured at the Tuyamuyun gauging station in these years did not exceed 7 km^3 within the vegetation period compared to more than 20 km^3 in normal years of water supply (UzHydromet 2009). These water supply reductions severely damaged the local economies in downstream regions Khorezm, Dashauz and Karakalpakstan (Froebich et al. 2007).

The long-term analyses also demonstrate that the annual average amount of total annual water intake to the Khorezm region decreased after 1991 and from then on the availability became less secure due to increased fluctuations (Fig. 19.18). For instance, in 2001, the year with the severest drought on record, the region used only 2.5 km^3 water. Although water shortages had been observed also before 1991, regional water consumption was only slightly impacted (Figs. 19.16 and 19.17). Possibly, before 1991 the adverse effects were cushioned by the centralized authority which was an administration unit responsible for water management in the entire Amu Darya basin. However, since the collapse of this overarching coordination system after independence combined with an increasing demand of upstream regions for water due to population growth and hydro-power production, less water became available for the downstream regions (Manschadi et al. 2010). This is expected to be reduced even more in the future as evidenced in the increasing frequency and scope of shortages after 1991 (Müller 2006).

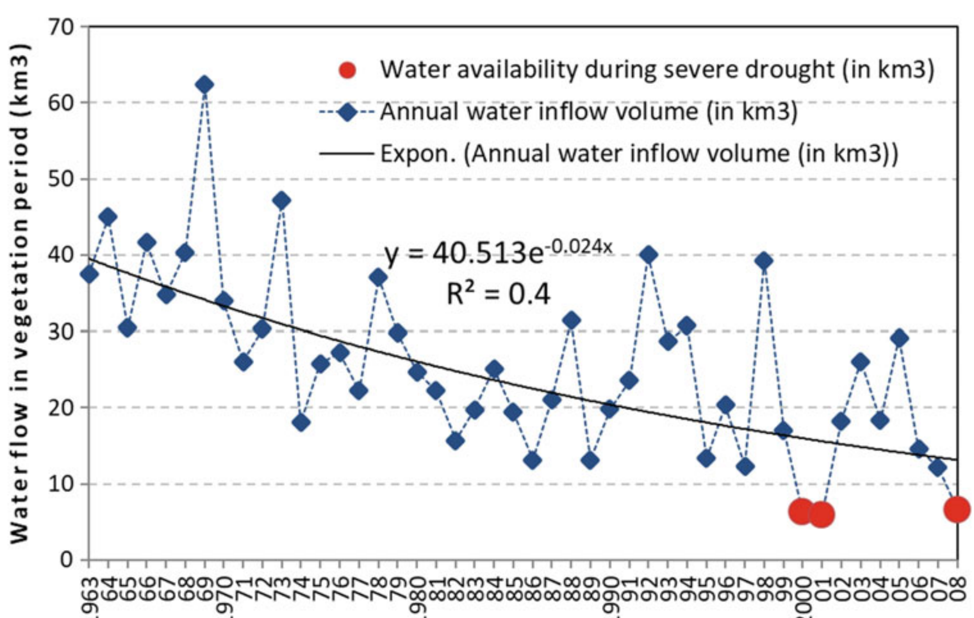


Fig. 19.17 Annual water flow volume to the Tuyamuyun reservoir during the vegetation period (1963–2008). *Source* UzHydromet (2009), authors' calculation

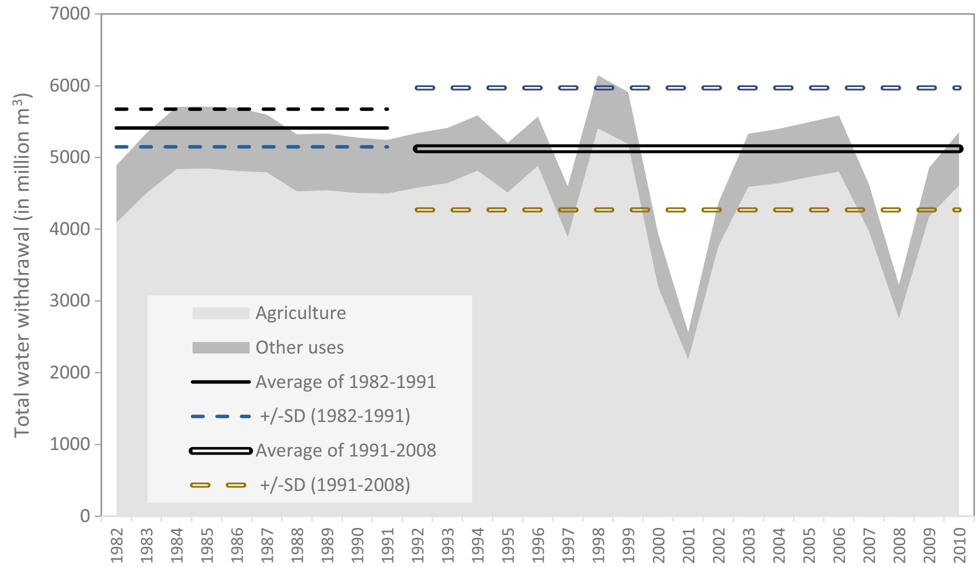


Fig. 19.18 Total and sector-specific annual water withdrawals in Khorezm (1982–2008). *Source* SIC-ICWC (2011), UzHydromet (2008), authors' calculation

Due to the recurrent shortages, water users in Khorezm need to learn at least dealing with reduced water availability which could be as low as 60% of the water resources required (at river node), meaning a 40% (=100–60%) water-scarcity level (Fig. 19.19). The water-scarcity level can be even more severe as in 2001, reaching 60% and leading to damage on irrigation based agricultural production.

The monitored droughts that especially occurred for the past decade substantially reduced agricultural profit because of both lower production per area and crop areas per se (Fig. 19.20). For instance, profits from crop production declined from USD 91 million in 1999 to USD 14 and 16 million in the drought years 2000 and 2001, respectively. To assess the economic losses due to drought, we used profit level under water abundance conditions in the most recent year as a reference point. The most recent year when there was no water scarcity was 2005. In 2005, irrigation profit was USD 65 million. When considering the reduced profits compared to the reference level (USD 65 million) as direct drought costs, these costs amounted to USD 51 and 49 million in 2000 and 2001 or 78% and 76% of the average annual profit, respectively.

Frequent water shortages severely impact on the living conditions by increasing poverty, food insufficiency, and subsequent health risks. Since poverty levels already exceed 30% even outside drought conditions (WFM 2008) there is an urgent demand for reducing risk from water shortages. Meanwhile, because of the dominance of the unlined open canals the average conveyance efficiency is 55%, meaning huge percolation losses in water delivery process (Conrad 2006). Considering that furrow and basin irrigation with an

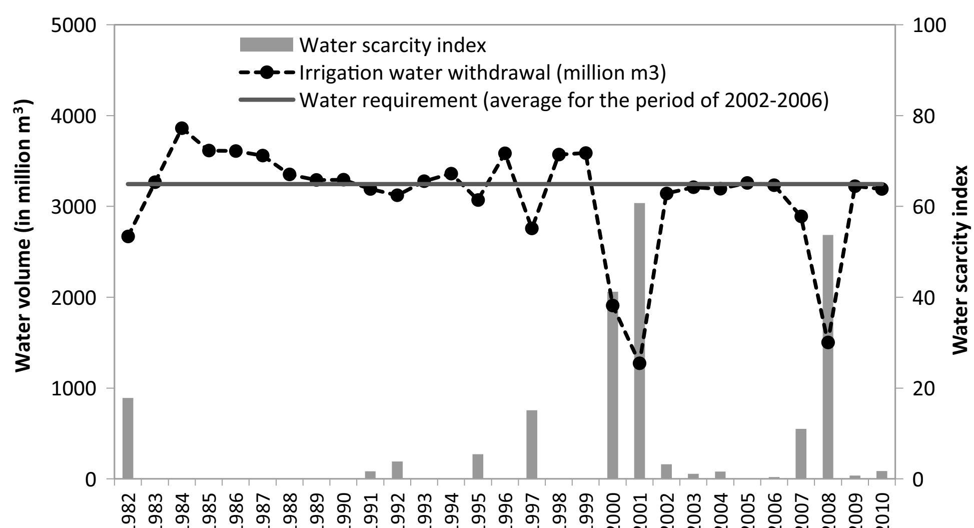


Fig. 19.19 Water diversion and water scarcity (1997–2009). *Source* OblStat (2011), OblSelVodKhoz (2011), authors' calculation

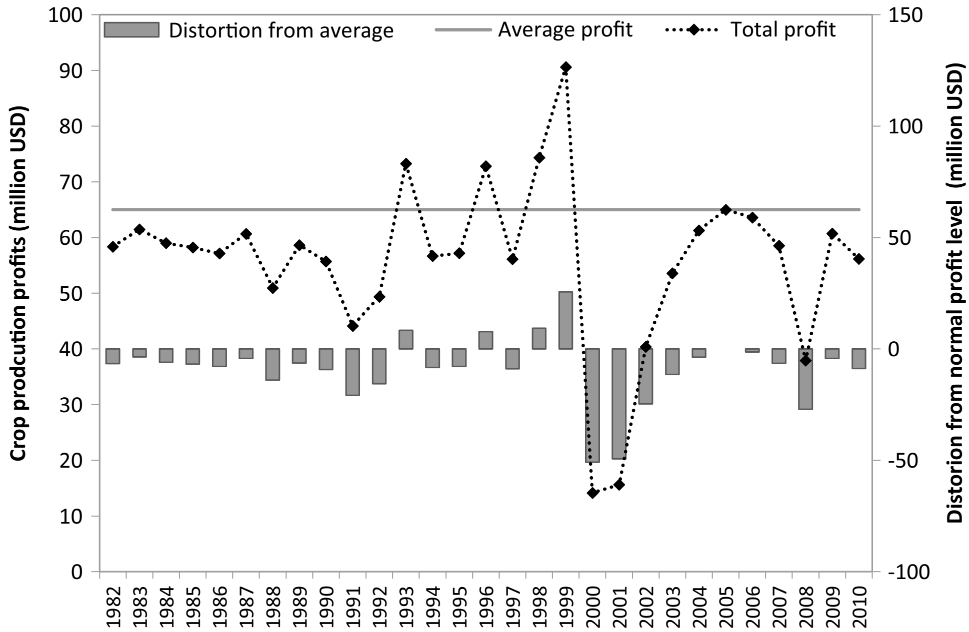


Fig. 19.20 Crop production profits and profit losses due to drought during 1982–2009 (based on prices of 2005). *Source* SIC-ICWC (2011), OblStat (2011), authors' calculation

irrigation efficiency of less than 65% are the main practices of irrigation water use in the region (Martius et al. 2009, Bekchanov et al. 2010b), water losses at the field level also very high. Therefore, there is a huge need and substantial scope for implementing a diverse set of innovative water-wise options that could trigger substantial reductions in water use, stabilize agricultural production and reduce the environmental impact of irrigation.

19.4.4 Water Use Reduction Rates Under Different Water-Wise Options

When all the assumed strategies are applied, overall water use could be reduced by 15–18% under the pessimistic scenario, 24–30% in the neutral scenario, and 32–40% under the optimistic scenario (Table 19.8). The single most significant reduction in water demand would be achieved by replacing paddy rice with maize. Under the pessimistic scenario, it outweighs all other options together. Under the neutral scenario, water use reduction potentials of replacing paddy rice with maize and introducing aerobic-cropped rice conditions for anaerobic varieties, hydrogel application, and manuring would almost double, whereas for drip irrigation this would be tripled, and for laser-guided land leveling it would be quadrupled. Under the optimistic scenario, substantial water use reduction can be expected from innovations such as laser-guided land leveling and drip irrigation in addition to replacing paddy rice with alternative crops.

19.4.5 Estimated Economic Efficiency of Water-Wise Options

19.4.5.1 General considerations

Considering the present low profitability of cotton and wheat farming (Djanibekov 2008) which occupies together more than 70% of irrigated lands in the Khorezm region (Fig. 19.16), financial assessments of gains and costs of water-wise innovations should be of high interest to both farmers and the State's water managers. Positive and considerable profit changes can occur under drip irrigation when applied to potato, vegetables, melons, fruits and grapes according to our assessments (Table 19.9). Manuring potato, double sided irrigation for most crops and short furrows for cotton production, showed to be highly profitable as well. Laser-guided land leveling has much water use reduction potential when implemented in particular to cotton and wheat. Since these crops are state ordered and thus to a certain level underpaid for by the state (Rudenko et al. 2009), profit changes due to laser leveling are expected to be negligible for these crops.

However, since water delivery costs is heavily subsidized by the government reduced water demand in cotton and wheat production due to increased use of laser-guided land leveling may decrease government expenditures for water conveyance and thus can make this option more attractive for public investors. Most of the options such as replacing rice with alternative crops, applying hydrogel, adopting surge flow, and implementing alternate dry furrow would

Table 19.8 Total water use reduction (in million m^3) by adopting water-wise-options under pessimistic, neutral, and optimistic scenarios

Options	**Pessimistic scenario**		**Neutral scenario**		**Optimistic scenario**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
Paddy rice to maize	149.0	149.0	248.4	248.4	298.1	298.1
Paddy to aerobic rice	18.2	30.4	36.5	60.8	54.7	91.1
Hydrogel	8.7	17.4	17.4	34.9	22.2	44.3
Manuring	18.7	28.0	37.9	56.9	47.4	71.0
Laser leveling	10.9	13.1	43.6	52.3	103.1	123.7
Drip irrigation	12.8	21.3	32.9	52.3	71.2	112.0
Surge flow	5.7	7.0	11.4	14.0	0.0	0.0
Double furrow	12.7	25.4	6.4	12.7	0.0	0.0
Alternate Dry Furrow	35.6	40.7	17.8	20.3	0.0	0.0
Short furrow	6.4	12.7	3.2	6.4	0.0	0.0
Total:	**278.7**	**345.0**	**455.4**	**558.9**	**596.6**	**740.2**
As a percentage of annually required water (at field) during the vegetation (in normal year):	*15%*	*18%*	*24%*	*30%*	*32%*	*40%*

Table 19.9 Per hectare profit change under different water-wise technologies and crops

Groups	Options	Basic profit (USD ha^{-1})	Profit change	
			Minimal (%)	Maximal (%)
A1	Rice to maize	1096	−77	−77
A2	Aerobic rice	1096	−65	−47
B1	Hydrogel:			
(a)	Cotton (H)	67	−60	−14
(b)	Wheat (H)	285	−14	−4
B2	Manuring:			
(a)	Cotton (M)	67	−44	1
(b)	Wheat (M)	285	−31	−11
(c)	Potato (M)	1270	22	29
C1	Laser leveling:			
(a)	Cotton (L)	67	−41	46
(b)	Wheat (L)	285	−10	10
C2	Drip irrigation:			
(a)	Cotton (D)	67	−9	81
(b)	Potato (D)	1270	94	144
(c)	Vegetable (D)	934	67	119
(d)	Melons (D)	1358	56	98
(e)	Fruits (D)	511	21	66
(f)	Grapes (D)	700	27	66
D1	Surge flow: cotton	67	−141	−97
D2	Double furrow: cotton	67	36	81
D3	Alternate dry furrow: cotton	67	−125	−82
D4	Shorter furrows: cotton	67	26	70

Table 19.10 Expected profit change (in million USD) under different water-wise technologies and adoption rate scenarios

Options	Pessimistic scenario		Neutral scenario		Optimistic scenario	
	Min	Max	Min	Max	Min	Max
Paddy rice to maize	−5.4	−5.4	−9.0	−9.0	−10.8	−10.8
Paddy to aerobic rice	−1.5	−1.1	−3.0	−2.2	-4.5	−3.3
Hydrogel	−0.3	−0.1	−0.6	−0.2	−0.8	−0.2
Manuring	−0.6	0.1	−1.1	0.3	−2.0	0.0
Laser leveling	−0.2	0.2	−0.9	1.0	−2.1	2.2
Drip irrigation	0.7	1.8	2.7	5.9	6.5	13.7
Surge flow	−0.5	−0.4	−1.0	−0.7	0.0	0.0
Double furrow	0.5	1.2	0.3	0.6	0.0	0.0
Alternate Dry Furrow	−1.8	−1.2	−0.9	−0.6	0.0	0.0
Short furrow	0.4	1.0	0.2	0.5	0.0	0.0
Total:	**−8.7**	**−3.7**	**−13.4**	**−4.4**	**−13.7**	**1.7**
As a percentage of current total profit level:	*−13.0%*	*−5.6%*	*−20.0%*	*−6.5%*	*−20.4%*	*2.5%*

decrease the current levels of revenue. Despite their low investment costs, implementing these water-wise innovations would likely reduce basic profit or would even cause economic losses. Relatively high revenue losses, which could be seen as adoption costs, were estimated for surge flow and alternate dry furrow for cotton and altering irrigation practices for paddy rice to maize and rice under aerobic conditions.

19.4.5.2 Overall Additional Profits (losses) of adopting water-wise options

Based on the per-hectare profit change and adoption areas, the overall costs or gains from introducing different water-wise options can be estimated. Despite its highest potential for overall water use reduction, replacing rice with other crops would substantially decrease agricultural revenues (Table 19.10) since rice is one of the most marketable crops (Djanibekov et al. 2012a) gaining high prices on local markets. The expected profits when adopting drip irrigation could partly cover losses from reduced rice production under the pessimistic scenario. Only under the optimistic scenario, if the maximum water reducing potential of drip irrigation technology is attained, revenues of drip adoption can compensate directly for the losses from decreased rice production.

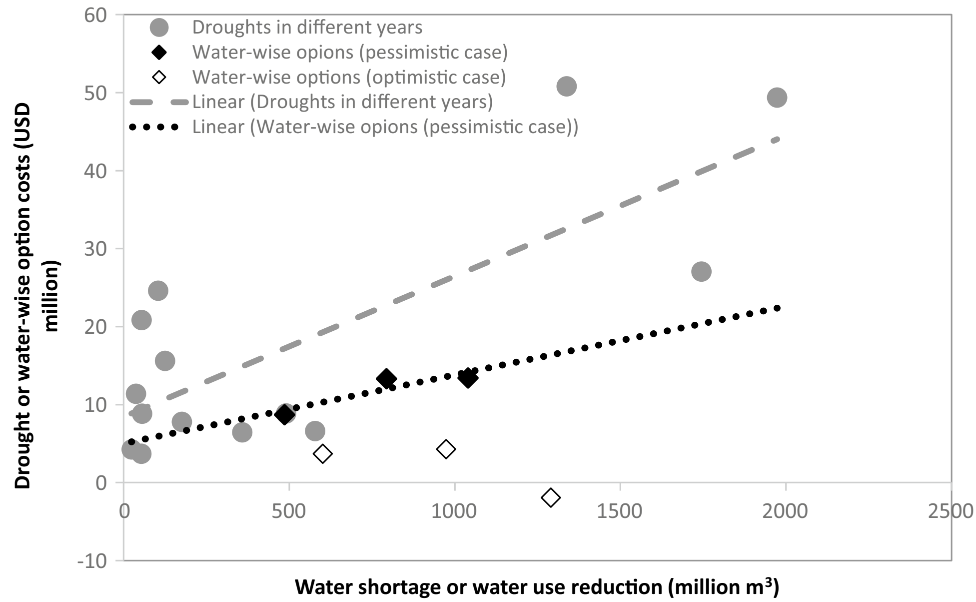
19.4.5.3 Comparing the drought damage and water-wise options adoption costs

The comparison of water-wise options implementation costs with drought costs indicated the economic feasibility of the action to cope with drought (Fig. 19.21). Plotting drought induced costs against the level of water shortage resulted in increasing damage costs of drought at higher levels of water shortage. Higher water demand reduction is also coming at higher costs. Yet, even under pessimistic scenario when higher costs per unit of reduce water demand is assumed adoption costs are much lower than drought damage costs, implying advisability of applying the discussed water-wise options in Khorezm. However, although these options are adequate to cope with low or medium level water shortages they can only partially reduce the effect of the most severe droughts as observed in 2000, 2001, and 2008. In addition to demand management measures water supply enhancement through improving conveyance efficiency (Bekchanov et al. 2014) and basin-wide cooperation and coordination of the resources and infrastructure are necessary for nullifying drought damage costs. Transaction costs of the supply enhancement measures can be sufficiently high particularly with the consideration of transboundary nature of water management in the Amu Darya basin.

19.4.6 Discussion

Our results confirmed the previous studies (Müller 2006, Bobojonov 2009) that stated reduced water availability to the needs of downstream regions of the Amu Darya Basin over the years. Particularly, in the Khorezm region, average water withdrawals reduced in the period after 1991. The disintegration of the countries in Central Asia after the collapse of the Soviet Union complicated the coordination of water resources in the basin increasing the frequency of downstream water shortages. On one hand, collapse of the political system gave freedom for the riparian states to make

Fig. 19.21 Water use reduction potential and adoption costs of water-wise options to cope with water supply reduction and production damage costs of drought



decisions over their fates themselves rather than following the orders of the center. On the other hand, the emergence of several independent states with conflicting interests raises tensions over sharing common water resources and related infrastructure. Downstream irrigated areas took the main burden of these conflicts and reduction in natural river runoff.

This situation requires downstream regions seek ways of reducing water demand through the implementation of water-wise options. Our results demonstrate that wide implementation of low-cost, low-efficiency innovations such as replacing paddy rice with maize and rice grown under aerobic conditions, surge flow, double furrows, alternate dry furrows, short furrows while limiting adoption of the modern drip and laser-guided leveling technologies as assumed under the pessimistic scenario can reduce water demand moderately. In contrast, the optimistic approach through wider adoption of modern drip irrigation technologies in orchards and gardens, of laser-guided land leveling on cotton and wheat fields, and of increased manuring in potato and wheat production can considerably reduce irrigation water requirements. Although replacing paddy rice with maize and rice grown under aerobic conditions can be an instant measure which can be implemented during droughts, water use reduction and revenue return potential are higher for the drip irrigation and laser-guided land leveling despite the need for multi-annual planning and substantial initial investments.

What are current constraints for the adoption of these water-wise approaches? Because of low procurement prices for the cotton and wheat crops that dominate the agricultural production under the state order (e.g. Djanibekov et al. 2012a), farmers can hardly afford high initial investments of water use reduction at present (Bekchanov et al. 2010b). Thus, the public sector should take the lead in investing in expensive laser-guided land leveling equipment (Abdullaev et al. 2007). The public sector should have an interest in promoting the wider adoption of leveling as it currently pays for the water supply in a form of subsidy. Recent results from the Indo-Gangetic Plains (IGP), which experience similar agro-ecological conditions to the Khorezm region, confirmed that laser-guided land leveling improves yields and reduces water consumption in the irrigated production systems (Gupta and Seth 2007). There, the adoption of laser leveling technologies gained momentum since the late 90 s when the technology became rapidly available to farmers at affordable, subsidized prices.

Alternatively, the liberalization of cotton and wheat prices would allow farmers to make independent decisions over land and water resource use. Since liberalized crop prices are higher than the state order prices, with time, farmers would build up the necessary funds to invest in efficient irrigation technologies. Improved infrastructure and legal-institutional framework maintained by the government create chances for increased incomes. Although liberalization of cotton and wheat production system meantime also means reduced or eliminated government subsidies, higher benefits from the liberalization is expected than continuing overregulated production system since farming incomes are substantially taxed through the government quota system (Müller 2006).

The high potential profitability of drip irrigation in orchards and gardens may increase its adoption once farmers' awareness about this technology is increased. Adoption of drip irrigation technologies currently depends on expensive imports. Investment costs can be substantially lowered by establishing domestic production of these technologies

(Djanibekov et al. 2012a). The human, technologic, and material resources are available in Uzbekistan to establish domestic drip irrigation technologies.

Insecure land tenure in Uzbekistan is also often considered to constrain farmers' investments in new technologies (e.g., Djanibekov et al. 2012b). On the other hand, the lack of adoption of soil and land conservation practices by farmers in Kyrgyzstan who have private ownership over their cropland, illustrates that land ownership alone does not guarantee the adoption of agricultural innovations (Kienzler et al. 2012). Thus, secure land rights should be accepted as necessary but not sufficient condition for creating incentives for efficient resource management in crop production systems. Infrastructural improvements, institutional renovations, and human capacity development must be the remaining conditions for developing modern, efficient, and sustainable irrigation system in Khorezm. Developed markets for irrigation technologies and crop production system outputs, fast and less risky transportation, and strong cooperation with international partners are main components of infrastructural development. Institutional improvements targeted free-market relationships should not only provide more freedom and tax facilities to the producers but also should boost healthy competition and create incentives for adopting modern production technologies. Indeed, training producers to act in the new market-based economic environment and raising their awareness on frontier technologies in efficient water management is important for the successful realization of modernization reforms.

The comparison of potential water use reduction rates and profit changes due to irrigation management improvement and water shortage level and damage costs under drought also revealed that the costs of adoption is considerably higher than the costs of inaction (e.g. drought damage). However, even under the wide-scale adoption of modern technologies as assumed in optimistic scenario the most severe water shortages in Khorezm can be only partially addressed. Elimination of the drought effect would may additionally require water supply enhancement costs through conveyance efficiency improvements and basin-wide water coordination to reduce downstream water availability.

Though not comprehensively analyzed here, since all water users in a river basin are highly interdependent (e.g., Keller et al. 1996, Rosegrant et al. 2000, Ringler 2001) basin-wide water management (Dukhovny and Sokolov 2003) based on cooperation among the riparian countries undoubtedly would improve water management in the basin and would provide more stable water supply to the downstream region. Incentives for cooperation to gain optimal river basin profits, for instance, can be created by introducing water market that imposes transfer of water use rights to more water productive regions while compensating the reduced profits of lower productive regions (Bekchanov et al. 2015, Ringler 2001, Dinar et al. 1997, Howitt 1994; Rosegrant and Binswanger 1994). Alternatively, decreasing the reliance on irrigated agriculture by expanding manufacturing (agro-processing, machinery) and services (tourism, information technologies) sectors also works for improved incomes yet at lower water consumption levels (Rudenko et al. 2013).

19.4.7 Conclusions

Water shortages can severely impact on the livelihoods in downstream regions under irrigated agriculture such as the Khorezm region in Uzbekistan. Water uses in the region in dry years can be as low as 40% of the water intake under normal water supply. Crop production profit losses due to the drought conditions can reach up to US$ 50 million in dry years which means the loss of almost 80% of the potential regional profit. Water managers in downstream regions may employ internal resources to cope with increased frequency of droughts. Once water-wise options are put into place, the potential negative economic and ecological impacts of droughts can be considerably cushioned. Frequent annual water scarcity, reducing the water supplies by up to 40–50%, could however be addressed through long-term water management strategies and by regularly upgrading and maintaining technologies. Particularly, despite considerable revenue losses, replacing paddy rice with less water consuming maize production can greatly reduce water demand and lower farming income risks under drought. While a wide adoption of less costly water-wise measures such as surge flow, double furrow, alternate dry furrow, and short furrow for cotton cultivation only partially reduce the impact of water scarcity, more advanced technologies such as laser-guided land leveling in cotton and wheat cultivation and drip irrigation technologies in potato, vegetables, melons, fruits, and grapes cultivation can effectively deal with water scarcity. Implementing long-term water management measures through adopting advanced irrigation technologies is also economically justifiable as the costs of drought prevention measures are substantially lower than the damage costs of the drought. Considering high investment costs of drip irrigation and laser-guided land leveling, state support through subsidies or increased prices for cotton and wheat are needed for wide adoption of these technologies. Domestication of the production of these technologies would substantially decrease their investment costs and thus increase their adoption rate. Secure land rights, institutional and infrastructural improvements, and increased awareness of the water users and managers on advanced water management technologies are essential for the success of the technological change reforms. Coping with the most severe droughts as observed in 2000, 2001, and 2008 however in addition to demand management options may require the adoption of water supply management measures by increasing conveyance efficiency and improving downstream water availability by improving basin wide coordination.

19.5 Balancing Soil and Water Management in Afforestation in Drylands

19.5.1 Introduction

Drylands are defined by the scarcity of water, including arid, semi-arid and dry semi-humid areas. They account for almost 50% of the global land surface and are often vulnerable and prone to changes because of limited water availability and extreme temporal variability in rainfall. Land degradation is one of the fundamental environmental problems in drylands that limit social and economic development, particularly due to its negative impacts on the potential capability of soil and land to produce goods and services. Therefore, control, improve or even reverse land degradation become a key issue to improve the environmental quality of drylands.

The Loess Plateau region in Northwest China is one of such regions. Centuries of intensified use and improper management of land caused degeneration of ecosystems and severe soil erosion, and thus a decline in local economy. To control soil erosion, the Chinese government implemented the world's largest afforestation programmes: The Three North Shelterbelt (or known as the Great Green Wall) and the Grain for Green programme. These programmes were successful in terms of soil conservation or reducing soil erosion, but led to a number of other environmental problems, including low survival rate of young plantation, low forest quality, loss of biodiversity, and increasing water shortage (Sun et al. 2006; Zhang et al. 2015). The main reasons behind these problems are that forest consumes a much higher quantity of water than other land covers (e.g., grass and shrubs) and almost no proper forest management is applied. Therefore, the future forest development in the Loess Plateau region needs to be revised.

19.5.2 Methods of Planning and Management

In drylands, large-scale afforestation or uncontrolled development of existing forest may result in exacerbated water shortage threatening water supply security. For this reason, forest planning and management in dryland areas need to consider the causality between forest cover increment and water yield decline. A number of methods are suggested to control excessive water use by tree plantation, to alleviate the negative impacts on water resources and to make afforestation in dryland more sustainable (Wang et al. 2017). The key requirements are to determine a feasible forest cover ratio and control the water use by forests.

19.5.2.1 Determine a feasible or acceptable forest cover ratio

To afforest catchments or regions, a maximum possible forest cover ratio has to be specified in a first step based on water availability needed for the establishment of stable forest stands. There are several ways to estimate this forest coverage. One of these estimations is based on the water limitation, namely how much forest cover can be supported by the annually received rainfall. In this way, the maximum possible forest cover of a catchment or region can be estimated. Yet, a feasible (acceptable) forest cover ratio, which is smaller or much smaller than the maximum forest coverage, is more important in drylands, as a given amount of water supply (e.g., river discharge, baseflow and groundwater formation) has to be safeguarded for local and downstream water users. The feasible forest cover ratio can be explored using the relationships between forest cover and river discharge at catchment scale. A meta-analysis using long-term observation records of forest cover and water supply (e.g., annual runoff) across various spatial scales can give a simple but plausible estimation of suitable forest coverage for decision making (Box 19.1). However, seasonal rainfall variations, climatic extremes or the impact of relief on water fluxes is ignored in such an approach. A more accurate way to estimate a feasible forest cover ratio is to use ecohydrological models. With such models, the impact of varying forest cover on seasonal and annual water cycle in watershed under current and future climate can be estimated and assessed.

Box 19.1: Acceptable forest cover determination for the Loess Plateau in China

Based on a meta-analysis of the long-term annual data from 57 catchments of the Loess Plateau, the results showed that with an assumption of the average annual precipitation of 600 mm, the acceptable forest cover should not exceed 23% to ensure an annual runoff of 40 mm for the downstream users. Afforestation should be particularly cautious in drier catchments. To meet the demand of the same amount of water supply, afforestation should cover not more than 10% of the area in dry catchments with an average annual precipitation of 500 mm (Wang et al. 2011). It thus can be concluded that unregulated increase of forest cover can damage the water security in dryland regions such as the Loess Plateau in China

19.5.2.2 Control the water use by forest

In water cycle, soil evaporation, canopy interception and tree/vegetation transpiration formulate a water flux that is commonly referred as evapotranspiration. Evapotranspiration is a flow of vapour to atmosphere, thus not available for water users. In water limited regions, it is vital to reduce the water loss through evapotranspiration and make more water available for human use. In contrast to tropical forests, soil evaporation is normally low and sometimes negligible under the dryland forest ecosystem with the presence of litter or mulch (Magliano et al. 2017; Villegas et al. 2010), thus will be not discussed in this section. The following sections mainly focus on how to reduce tree transpiration and increase water yield through a range of forest management measures.

- Select site specific tree species to reduce tree transpiration

Appropriate tree species are essential and have to be selected with the consideration of climate (e.g., rainfall), topography (e.g., elevation and slope orientation), and soil (e.g., texture and thickness) conditions. Fast-growing exotic tree species consume generally more water in comparison to indigenous vegetation or native tree species and thus reduce the amount of deep percolation. Suited tree species for afforestation have to be selected taking into account site specific water availability as well as soil and relief conditions. In addition, drought-resistant capacity of trees is vital for forest survival and stability in dryland. Parameters, such as the osmotic potential at incipient plasmolysis, can be used as a suitable index for decision on suitable tree species (Wang et al. 2017).

- Manage the forest stand structure to enhance water yield

Evapotranspiration of forests in water-limited regions is relatively high in proportion to local precipitation, thus the water yield is low (Mátyás and Sun 2014). To ensure a given amount of water supply, ideal forest stand structure needs to be determined based on tree species composition, forest and canopy density, tree height to diameter at breast height (H/DBH) ratio, understory natural vegetation, etc. They are key indicators to regulate, manage and improve the functions of forests. For example, maintain a certain degree of canopy density can regulate the understory regeneration and growth. By doing so, it can reach a rational coverage of ground for promoting water infiltration and prevent massive invasion of weeds and shrubs for reducing understory vegetation water consumption. In addition, a rational forest density can reduce snow damage, increase forest stability, lower the evapotranspiration to increase water yield, and promote the growth of large trees to enhance the forest quality (Box 19.2 and Box 19.3).

Box 19.2: A sparse forest on sunny slope with thin soil vs. a dense forest on slope with fertile soil

Thin soil on sunny slope denotes low productivity and weak drought-resistant capacity. Afforestation on such sites is expected to maintain a rational land cover (including grasses and shrubs) that consumes less water and provides as much runoff water as possible with a pre-condition of no soil erosion. The suitable stand structure on this site is to maintain a sparse forest with enough high ground vegetation cover to prevent soil erosion. There is no need to grow more trees or prune them, and disturbance of land surface should be avoided to trigger soil erosion

Afforestation on slope with fertile soil is expected to regulate water cycle, supply water, and produce timber with a precondition of no soil erosion. Due to the abundant water and nutrients, the understory coverage is usually good while the trees are dense, thin and vulnerable to weather extremes. To increase the forest quality, the proper measures of management are to select target trees for timber production, to do selective cutting with a low frequency (e.g., 2–3 times with an interval of 3 years) to reduce the competition between trees, and maintain a given canopy density to regulate natural regeneration and understory growth

Box 19.3: Case on suitable forest stand structure of the Larix Principis-Rupprechtii plantation

The fast-growing tree species of *Larix Principis-Rupprechtii* has been selected to afforest in the Xiangshuihe watershed of the Liupan Mountain—one of the water source areas on the Loess Plateau in northwest China - with a main purpose of timber production and soil erosion control. Study of a 26-year stand showed that to meet the increasing demands on various forest services and to improve the stand stability and quality, an ideal stand structure should be (i) a ground coverage $\geq$ 0.7 to control soil erosion on the forest floor, (ii) a canopy density between 0.6 and 0.8 to maintain a natural regeneration but prevent the over-dense understory shrub/grass growth to avoid understory water use, (iii) a ratio of tree height to diameter at breath height (H/DBH) $\leq$ 0.7 to reduce the vulnerability to snow damage. All these requirements can be realized by regulating the stand density at 1000–1200 trees/ha under the given site and tree age, meanwhile it can promote the growth of large trees and the formation of high quality forest with a multitude of balanced ecosystem services required locally (Wang et al. 2017)

19.6 Overcoming Implementation and Research Focus Biases in Nature-Based Solutions to Achieve Sustainable (Waste)Water Management

19.6.1 The Potential of Constructed Wetlands

Clean water is necessary for both human and environmental health. Over 80% of the world's wastewater—and over 95% in some least developed countries—is discharged into the environment without any treatment (UN Water 2017). Potable water is still limited for a large amount of the world's population. As of 2015, the World Health Organization (WHO) reports that 842,000 annual deaths in low and middle-income countries are caused by inadequate water supply, sanitation, and hygiene (WHO 2015). A combination of lack of access for human waste disposal, and inadequate facilities to treat municipal wastewater causes major diseases, including diarrhea, intestinal worms, and cholera.

Constructed wetlands (CW) are a nature-based solution for pollution control and a viable solution to reduce the proportion of untreated wastewater and increase potential reuse. Most untreated wastewater, primarily municipal and agricultural wastewater, contains a high concentration of macronutrients. The nutrient content can, if desired and needed, be recovered from the effluent; application of the treated effluent in irrigation could reduce freshwater supplies for watering (Marecos and Albuquerque 2010). Nitrogen is one principal constituent of wastewater. Nitrogen influent to wastewater often results from excess agricultural fertilizer and human and animal waste: Ammonia (NH_4-N), Nitrite (NO_2-N), Nitrate (NO_3-N). Total Kjeldahl Nitrogen (TKN) and Total Nitrogen (TN; the sum of Org-N, NH_3-N, NH_4-N, NO_3-N, and NO_2-N) are the principal forms of nitrogen. NH_4-N is responsible for the growth of algal blooms in wastewater, which will ultimately reduce the amount of freshwater supplies; the poor water quality consists of toxins that are harmful to human health if consumed (United States Environmental Protection Agency 2017). More than 10 mg/L of NO_3-N in drinking water is toxic for infants because it prevents oxygen from being released to the body's tissues (Reddy and DeLaune 2008). Reduction of nitrogen is vital to sustain both human and environmental health.

Potentially, using CW in developing countries can be useful for protecting watersheds, lakes, and rivers.

However, CW are barely reported for developing countries. As Bui (2018) showed in a literature review of 110 selected CW that assessed nitrogen removal efficiency most were reported on in areas with lower temperatures (Fig. 19.22). North America, Europe, and East Asia have the highest density of reported CW. Countries in Africa and Latin America have only a few CW studies.

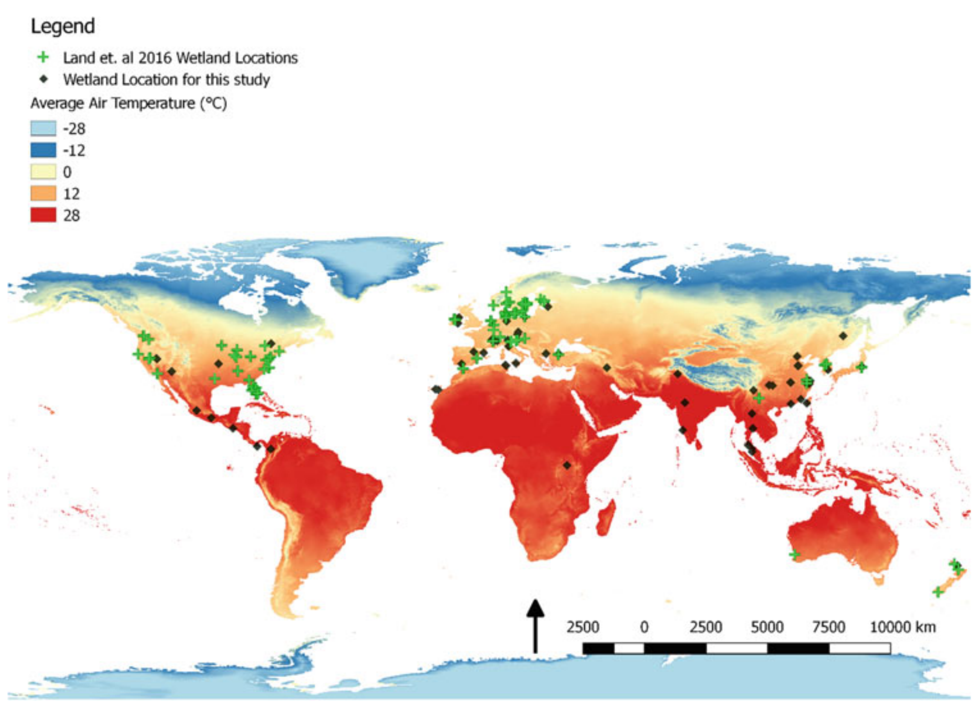


Fig. 19.22 Overview of the geographic location of constructed wetlands assessed in peer-reviewed journal articles that included nitrogen removal efficiency (reproduced from Bui 2018)

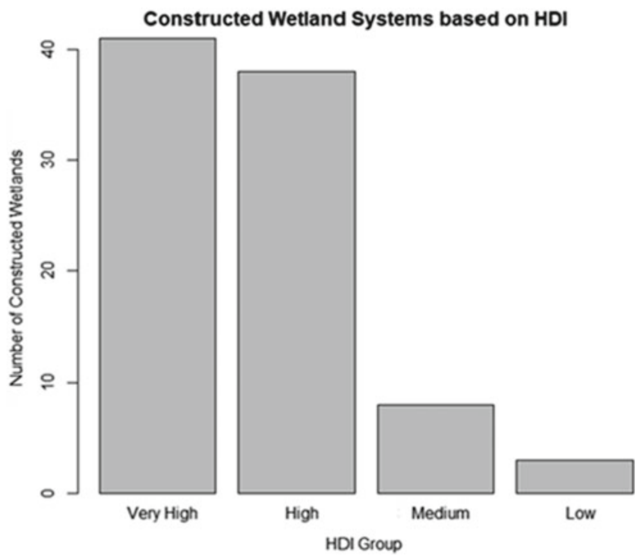


Fig. 19.23 Countries with Very High, High, Medium, and Low Human development have 41, 38, 8, and 3 CW systems respectively

Bui (2018) further showed that according to the World Development Report of 2017, 54 countries or 30% of the countries are categorized as Low Development. However, countries with a higher Human Development Index (HDI) have more published CW studies for municipal wastewater treatment than countries with lower HDI. Therefore, although nitrogen removal is a common pollutant for wastewater analysis, few studies are conducted in countries with low HDI. Figure 19.23 shows the total amount of CW systems evaluated in this study based on HDI.

19.6.2 Towards Developing and Disseminating Constructed Wetland Design Criteria

Nonetheless, application of CW in developing countries is possible. Ali et al. (2018) indicate that their study is the first assessment of a CW in Pakistan for macronutrient removal. With an HDI value of 0.55, Pakistan is categorized as a country with low Human Development. Ali et al. (2018) ability to conduct their study indicates the possibility of publishing more CW studies from developing countries. In a similar vein, a study project conducted by Balachandran et al. (2019) showed that the performance of CW in Brazil yielded a total of 63 peer-reviewed journal articles in Portuguese and English. According to the articles reviewed Southern and Southeast regions of Brazil witness majority of the CW. According to Machado et al. (2017), the majority of the studies had started in the 1980′s and continued until 2014 were conducted specifically in the states of Minas Gerais (MG), Santa Catarina (SC) and São Paulo (SP). This new research shows that the majority of the CWs continue being developed in the states of Minas Gerais and Santa Catarina but also in new states such as Paraíba (PB) and Rio Grande do Sul (RS). The location of the CWs showcases the influence of economic factors on the development of regions, since regions with a higher amount of CWs are considered to be the more developed parts of Brazil (Machado et al. 2017).

In all cases, data quality issues are a main concern. Similar as to what Bui (2018) showed in the global study, Brazil's CW are developed at a pilot scale since most systems are being developed for research purposes at universities and research institutes. In many cases, water quality assessments for CW had not been applied long-term (i.e. more than 1 year) in the systems assessed in developing countries. Bui (2018) also showed that authors used different methods to report and average nitrogen removal efficiencies rarely reporting the raw data, making reproduction of the results virtually impossible. Therefore, the lack of homogenous studies throughout the globe prevent arriving at significant results and thus long-term wetland research is recommended for developing countries to propose CW as a possible treatment solution.

The Constructed Wetlands Knowledge Platform, originally developed by UNU-FLORES and now being developed further by the Leibniz University Hanover (https://cwetlandsdata.com), intends to overcome some of these challenges by providing a one-stop solution for quality controlled contextual and operational data on constructed wetlands around the globe. The ambition of this platform is to provide practitioners benchmarks for design principles and decision-makers with examples of successful implementations as well as failures to look out for. In particular, design principles for climates as well as operation and maintenance conditions that are different from the global North are currently lacking. Nevado (2020) assessed currently available design handbooks of CWs and categorized and optimized them for biological oxygen demand (Fig. 19.24). He clearly showed that there is no one-size-fits-all solution and that care in selecting for a guideline as well as clarifying the desired target state early on is critical.

In order for CWs to become and be an effective nature-based solution for wastewater treatment, including the various co-benefits that they can bring (Avellán and Gremillion 2019) researchers and practitioners need to start adhering to a set of clear design and measurement criteria. This can help overcome the knowledge divide that seems to exist when looking at the actual implementation between the global north and the global south. Some recommendations include:

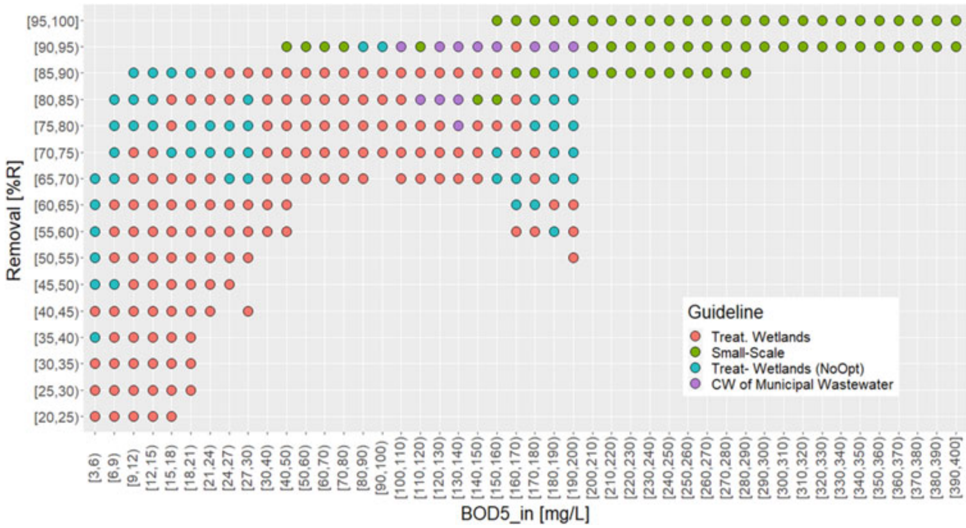


Fig. 19.24 Overview of the type of guideline (colored dots) that would work best given inflow concentrations of Biological Oxygen Demand (x-axis) vs. desired removal rates (y-axis) (from Nevado 2020) (Treat. Wetlands: Optimized formula as per results from Nevado 2020 based on Treatment Wetlands (Robert H. Kadlec and Scott Wallace 2008); Small Scale: As per Small-Scale Constructed Wetland Treatment Systems Feasibility, Design Criteria, and O&M Requirements (Wallace and Knight 2006); Treat. Wetlands (NoOpt): Use of original formula from Treatment Wetlands (Robert H. Kadlec and Scott Wallace 2008); CW of Municipal Wastewater: As per Constructed Wetlands Treatment of Municipal Wastewater (EPA 2000))

– Provide exact measurements instead of estimated values, comprehensive supplemental resources, and a clear description of the calculation, measurement, and assessment methods;
– Account for NO_3-N removal in addition to NH_4-N removal;
– Indicate the sampling frequency, sampling location and the sampling period.

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Bernhard Tischbein got his Ph.D from the Agricultural Faculty of University of Bonn (Topic: Planning of irrigation systems) and works as a Senior Researcher at the Center for Development Research / University of Bonn on hydrological and water management topics (Irrigation, Drainage, Basin-wide management of surface and groundwater resources, Flood management, Impact Assessment). A focus of his research is on deriving irrigation and drainage management strategies and design concepts taking the environmental, economic and institutional context into account. These concepts aim at assessing the performance of the irrigation and drainage systems and deriving options towards rising efficiency of irrigation, enhancing effectiveness of salt management and raising water productivity considering impacts on the environment. He contributed to several ZEF-

projects in Asia and Africa (Algeria, Benin, Burkina Faso, China, Egypt, Ghana, India, Indonesia, Mali, Niger, Pakistan, Uzbekistan, Yemen) covering the range from full to supplemental irrigation, hydrological modeling of surface and groundwater resources (including matter flow approaches), adaptive, impact aware and integrated water management.

Maksud Bekchanov is a Research Associate at the Center for Earth System Research and Sustainability (CEN) of the University of Hamburg and a former Senior Researcher—Agricultural Economist at Center for Development Research (ZEF) in Bonn, Germany. His main research areas are water, land and energy resources management and economics. Dr. Bekchanov is interested in economic modeling analyses, system-wide economic-environmental assessments, and sustainable development futures. His research addressed various issues including irrigation versus hydropower, optimal irrigation efficiency improvements, water rights trading and pricing, wastewater recycling, water and soil ecosystem services, economic instruments along waste-to-asset value chain, deforestation prevention, and hunger eradication across Central and South Asia, South America, and Africa.

Johannes Petrus Agnus Lamers (Dr. Ir.), studies in agronomy and plant nutrition at the Agricultural University of Wageningen, The Netherlands, and in agro-economics (Ph.D grade magna cum laude) at the Institute of Agricultural Economics and Social Sciences in the Tropics and Subtropics at the University of Hohenheim, Germany. More than 15 years of professional experience in long-term and short-term missions in Africa as researcher, government advisor, development worker and consultant. Work experience with international agricultural research institutes, NARS, national extension systems, NGOs and farmers' organizations. Since 1997, started to work in countries of the former Soviet Union such as Georgia, Azerbaijan, Tajikistan and Uzbekistan. The main focus of these assignments was on land and water management, food security, agricultural extension, group development and institutional development and human capital building.

Navneet Kumar (Dr.-Ing.) works as a Senior Researcher and Disciplinary Course Coordinator for the Doctoral Program at Center for Development Research (ZEF), University of Bonn in Germany. He earned his Ph.D in Engineering from University of Bonn. His main research themes are water and natural resources management and geoinformatics. Particular topics include hydrological modelling, flood management, climate change, risk and impact assessment, irrigation, remote sensing and GIS applications in water management and agriculture.Dr. Kumar has contributed to several research and developement projects in Africa and Asia (Algeria, Ethiopia, India, Mali, Niger and Uzbekistan). In addition, Dr. Kumar has been involved in capacity and network building project with PAUWES: Pan African University—Institute of Water and Energy Sciences in Algeria and recently involved in global classroom program with partner institutions from USA and Brazil. He has contributed to the development of e-Learning courses on spatial planning in water management in urban settings and conducted several lectures, summer schools and workshops in Africa, Asia and Germany. Dr Kumar has presented his work at several international conferences and published his researches in peer-reviewed journals. He is a reviewer for several peer reviewed journals and research grant proposals.

Kai Schwärzel's research focuses on a better understanding of how environmental resources interact under the conditions of global changes, and how—based on the outcome of his research—a more sustainable management of water, soil, and forests can be implemented. Dr. Schwärzel did his Ph.D at Technische Universität Berlin in the field of Soil Physics and Wetland Hydrology and holds a venia legendi in Ecohydrology and Soil Science (Technische Universität Dresden). As Head of the Programme Co-ordinating Centre of ICP Forests he is employed at the Thünen Institute of Forest Ecology.

Lulu Zhang got her Ph.D (Dr. rer. nat.) from the Technische Universität Dresden (TU Dresden), Germany in 2015. She specializes in forest and agricultural ecosystem assessment and management, as well as multifunctional landscape and land-use system. Her work also focuses on nature conservation and climate change mitigation/adaptation, as well as science-policy interface and payment for ecosystem services.

Tamara Avellán's research focuses on the overarching understanding of the bio-physical inter-linkages between the natural resources with a particular focus on water, and on the interlinkages of these resources with social, economic and institutional spaces. Dr. Avellán's career has shown her the world of academic research and its implementation in the service to member states through the United Nations in Latin America and the Caribbean, Small Island Developing States and West Africa. Working at this interface, learning and applying inter- and transdisciplinary methods have been crucial.

Usman Khalid Awan (Dr.-Ing.) is an experienced Water Resources Engineer, 18-plus years of experience (more than 10 years post Ph.D) ranging from academia, research, and research for development. Worked in and led research components of multi-million U.S$ in five major river basins including Amu Darya, Syr Darya river basins in Central Asia, Indus river basin Pakistan, and Nile river basin Egypt. Exposed to water resources management issues in Murray Darling river basin, Australia that is often used as a model basin management system globally due to its innovative approaches in managing and allocating water resource sustainably cross economic sectors. Excellent track record of research project design, fundraising, project management, for multi-partner, multi-country water scarcity initiatives, including demonstrated experience of monitoring and evaluation in five major river basins of the world. Reputation for bringing innovation and problem solving. Highly developed state-of-the-art computer modeling, GIS and remote sensing skills for water resources management. Excellent communication skills at all levels. Currently working at IWMI/Office Lahore-Pakistan and contributing to the knowledge creation and dissemination related to water management.

Fazlullah Akhtar (Dr.-Ing.) is an Afghan scientist, currently working as a Sustainable Development Goal Fellow (SDG-Fellow) at the Center for Development Research (ZEF) in Bonn. He studied B.Sc (Agricultural Engineering) from the University of Agriculture Faisalabad Pakistan (2002–2006), M.Sc. (Agricultural Science and Resource Management in the Tropics and Subtropics-ARTS) with major in land and water management (2009–2011) and Ph.D (Engineering) (2013–2017) both from the University of Bonn (Germany). During his M.Sc and Ph.D, Dr. Akhtar worked on the quantification of the groundwater contribution to the crop root zone through capillary rise in the Khorezm region of Uzbekistan as well as analyzed water availability and demand in the Kabul River Basin of Afghanistan. He is the author/co-author of several peer reviewed publications, articles and book chapters in the field of water management and hydrological modelling. Dr. Akhtar is also member of the peer reviewers' group of several international scientific journals in the field of hydrology, water management, climate change, remote sensing and agriculture etc. Beside his academic efforts, Dr. Akhtar has extensive experience of working with UNFAO, Deutsche Welthungerhilfe, USAID and some prestigious governmental entities including the office of the President of the I.R. of Afghanistan.

Anik Bhaduri is an accomplished leader in the field of water economics, global water policy and water governance with over 20 years of experience. Dr. Bhaduri is the Director of the Sustainable Water Future Programme (Water Future) of Future Earth. Water Future is a global platform facilitating international scientific collaboration to drive solutions to the world's water problems.

Anik is also an Associate Professor within the Australian Rivers Institute, Griffith University. Previously, he served as Executive Officer of the Global Water System Project (GWSP). With a background in environment and natural resource economics, Anik has specialised in water resource management. He has worked on several topics and projects, ranging from transboundary water sharing to adaptive water management under climate change. Anik also serves as a senior fellow at the Centre of Development Research, University of Bonn, Germany.

Janos J. Bogardi is senior fellow of the Center for Development Research of the University Bonn. where he is also professor for water resources management. He is senior scientific advisor of the Institute of Advanced Studies Köszeg (iASK) in Hungary and fellow of the Stellenbosch Institute of Advanced Study (STIAS), South Africa. Since 2014 Distinguished Adjunct Professor of the Asian Institute of Technology (AIT, Bangkok). He was executive officer of the GWSP (2009–2012). He served till his retirement from the UN as director of the United Nations University (UNU) Institute for Environment and Human Security 2003–2009 and as Vice Rector a. i. in Europe 2007–2009. He was Chief of Section in the Division of Water Science in UNESCO, Paris (1995–2003) and chair professor of hydrology, hydraulics and quantitative water resources management at the Wageningen Agricultural University in the Netherlands 1989–1995. He was associate professor at AIT between 1985–1988. Between 1969 and 1985 he had research and consulting appointments in Europe and in Africa. He graduated in civil engineering at the University of Technology Budapest in 1969. He holds a doctorate in water resources engineering (Dr.-Ing.) from Karlsruhe University 1979 and three Dr. honoris causa distinctions from universities in Poland, Hungary and Russia.

Yanhui Wang studied in the Beijing Forestry University in P.R. China during 1978–1982 for his bachelor degree and 1982–1985 for his master degree. Professor Wang studied in the University Göttingen in Germany during 1991–1996 for his Ph.D degree. He is working at the Chinese Academy of Forestry as a leading professor on forest ecohydrology. He is also working in the field of multifunctional forestry.

Pengtao Yu studied in Peking University in P.R. China during 1988–1992 for her bachelor degree and 1993–1996 for her master degree. She studied in the Chinese Academy of Forestry in P. R. China during 1998–2001 for her Ph.D degree.Dr. Prof Yu is working at the Chinese Academy of Forestry as a leading professor on forest ecohydrology.

Anh Bui worked from 2017–2018 at the United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), in Dresden, Germany. She holds a B.Sc. in Biosystems Engineering from Michigan State University and a M.Sc. in Environmental Engineering from Northern Arizona University. Currently, she is conducting her Ph.D. research at the Helmholtz Institute Centre for Environmental Research (UFZ) under the Environmental Biotechnology department in Leipzig, Germany. Dr Bui's research focuses on the use of constructed wetlands to treat greywater from informal urban settlements. The Water JPI project, Accessible Greywater Solutions for Urban Informal Townships in South Africa (URBWAT) aims to explore microbial degradation of organic pollutants in water and flow behavior.

Mauricio Nevado Amell is a Civil Engineer graduated from the Universidad del Norte, Columbia and the Technische Universität Dresden (M.Sc. in Hydro Science and Engineering). He gained experience in Constructed Wetlands (CWs) during his time as an intern and research assistant at UNU-FLORES. Here, he supported the further development of the 'Constructed Wetlands Knowledge Platform' and carried out his M.Sc. thesis on the optimization of the design of horizontal flow CWs for municipal wastewater treatment.

Luana Tesch is a Brazilian Civil Engineer pursuing a Master degree in Hydro Science Engineering at Technische Universität Dresden. Currently, she is a Research Assistant at Leibniz-Institut für ökologische Raumentwicklung.

Lucia La Barca Pedrosa is a Geological Engineer currently studying for her master at TU Dresden. She is specializing in Hydro Sciences and Engineering to analyze and manage efficiently the scarcest and important resource of them all: Water.

Renato Mariano is a Brazilian Civil Engineer currently pursuing a Master degree in Hydro Science and Engineering at Technical University of Dresden. He participated in the expansion of the CWetlands platform.

Sanjana Balachandran is currently working towards a masters' degree in Hydroscience and Engineering at Technical University of Dresden, Germany. She holds a bachelors' degree in Chemical Engineering, majoring in water treatment using nanoparticles. The subject of water treatment and the sustainable use of water have always been of utmost interest to her. She has been able to actively explore this field of research while working on a project regarding constructed wetlands in Brazil and while interning at a major water treatment company in the Sultanate of Oman, during the course of her graduate degree.

Kurt Brüggemann is currently a project officer at the Environmental Office of the City of Dresden working on heat-resilient urban development. His work focuses on the implementation of climate change adaptation measures. Before joining administration, Mr Brüggemann did his master degree in "Hydro Science and Engineering" at Technische Universität Dresden. During this time, he interned at UNU-FLORES and later acted as a consultant, carrying out research on nature-based solutions, water resources management and development of knowledge platforms.

Water and Energy

20

Nikos Mamassis, Andreas Efstratiadis, Panayiotis Dimitriadis,
Theano Iliopoulou, Romanos Ioannidis, and Demetris Koutsoyiannis

Abstract

The fundamental concepts in the field of water-energy systems and their historical evolution with emphasis on recent developments are reviewed. Initially, a brief history of the relation of water and energy is presented, and the concept of the water-energy nexus in the 21th century is introduced. The investigation of the relationship between water and energy shows that this relationship comprises both conflicting and synergistic elements. Hydropower is identified as the major industry of the sector and its role in addressing modern energy challenges by means of integrated water-energy management is highlighted. Thus, the modelling steps of designing and operating a hydropower system are reviewed, followed by an analysis of theory and physics behind energy hydraulics. The key concept of uncertainty, which characterises all types of renewable energy, is also presented in the context of the design and management of water-energy systems. Subsequently, environmental considerations and impacts of using water for energy generation are discussed, followed by a summary of the developments in the emerging field of maritime energy. Finally, present challenges and possible future directions are presented.

N. Mamassis (✉) · A. Efstratiadis · P. Dimitriadis · T. Iliopoulou · R. Ioannidis · D. Koutsoyiannis
School of Civil Engineering, National Technical University of Athens, Athens, Greece
e-mail: nikos@itia.ntua.gr

A. Efstratiadis
e-mail: andreas@ntua.gr

P. Dimitriadis
e-mail: pandim@itia.ntua.gr

T. Iliopoulou
e-mail: theano_any@hotmail.com

R. Ioannidis
e-mail: romanos.ioannidis@gmail.com

D. Koutsoyiannis
e-mail: dk@itia.ntua.gr

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20.1 Introduction

20.1.1 A Brief History of Water and Energy

From the dawn of humanity, people had to ensure access to water and food for their survival. Solar energy was nourishing the Earth, triggering the hydrologic cycle, supporting the production of vegetation via photosynthesis and offering humans light and warmth during sunny days. At these early periods humans were mainly gatherers, as they collected water from its natural sources (rivers, lakes and springs) and consumed raw fruits gathered from local flora. Gradually, they utilized stone, wood and animal's bones to make tools and weapons that improved the efficiency of hunting. As they were yet unable to produce energy from other sources, they used the energy of their own bodies and muscles, acquired from food and water via metabolism, for all their activities.

Exploitation of natural resources to control the energy production, where term "production" is used as shorthand for transformation to a usable form or release from a stored form, was essential for humankind throughout its existence. Although water and food were the two basic requirements for survival, energy was essential to (a) ensure the supply of water and production of food and (b) support domestic, manufacturing and transportation activities of developing human societies.

When humans controlled fire (about 70 000–100 000 years ago), they had managed to exploit fuels for energy production for the first time. Wood was the first fuel

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used and, practically, remained the main one until the twentieth century, despite the increased use of coal from the eighteenth century. Fire changed the style and quality of life, as it provided warmth, light, a better diet (cooked or grilled meals) and protection from wild animals. Fire also triggered human development, as people gained a small amount of control over nature and extended their activities. They could now harden primitive wooden tools and weapons, work during nights, inhabit dark places (caves) and finally migrate from Eastern Africa to areas with colder climates as Europe and Asia.

At some point during the late Neolithic period, a new human activity emerged, agriculture. People shifted from gathering and hunting activities, characterized by high insecurity, to agriculture in stable fields that improved food safety. This change, known as the Neolithic Revolution (McClellan and Dorn 2015), started at about the 10th millennium BC. Somewhere around this period groups of people concentrated in a zone of hills extended from what is today Syria to the foot of Taurus and Zagros mountains, an area known as the Fertile Crescent. In this area the winter rainfalls favoured the natural growth of wild cereals, such as barley and wheat. These early communities organized cultivations, developed the first agricultural methods, domesticated animals, and constructed the first small scale hydraulic works for water exploitation. During the 8th to 5th millennium BC, the population began to increase and spread to the nearby river alluvial valleys (Nile, Tigris, Euphrates, Indus and Yellow river). The growth of agricultural activity at the new areas caused a significant increase of the water needs. However, the water was abundant and ensured by the nearby large rivers. These were the valleys where the first cities rose during the period known as Urban Revolution, offering a more civilized life to these early societies. Domestic water use, irrigation for food production and flood protection became essential for these developing civilizations. Large scale hydraulic works were constructed for collecting, transferring and storing water, as well as for urban and rural drainage (Angelakis et al. 2012; Bazza 2007). The main source of energy that supported this extended agricultural activity (planting and ploughing, transporting crops, manufacturing, lifting water from wells or rivers) remained the chemical energy utilized through human and animal muscles. The first device for lifting water was shaduf, a long wooden pole that operates like a seesaw. Its use is widespread in Mesopotamia and Egypt from 5th millennium BC until today.

As civilizations developed, a new energy source came into use, the wind. Sails on boats were possibly used for the first time around 10th millennium BC, but as the technology was improved, marine transportation expanded further to support commerce. As the use of continental roads for the transportation of goods and people was hard, ships with sails opened up new maritime trade routes. On the other hand, sailors could not control wind energy to sail against the wind and thus they also had to paddle. The technology to sail into the wind was optimized and spread several centuries later.

As metallurgical activity expanded, energy needs were substantially increased. Although Neolithic societies used soft metals such as gold, silver, lead and copper, gradually they discovered harder metals or alloys to produce tougher tools and weapons. For example, the production around the 3th millennium BC of bronze, a hard alloy of copper and tin, improved the metal industry significantly. The melting of metals consumed large amounts of thermal energy produced exclusively from wood burning. During the Iron Age around the 3th millennium BC, the need to melt harder metals, such as iron, led to production of charcoal, a partially new and artificial fuel that is widely used even today. Charcoal was made by burning wood in a low oxygen environment, a process that lasted a few days. As charcoal contains more carbon, it produces higher and steadier temperatures, than wood.

Coal, oil, natural gas and their calorific attributes were known in antiquity, but their use as fuels was quite limited. Coal was used as a fuel in a consistent way from 4th millennium BC in modern day Mongolia and China (Dodson et al. 2014). It is also mentioned by Theophrastus (4th century BC) in his treatise *On Stones*. He says that “anthrax” (Greek word for coal) was excavated from the ground, was burned like charcoal and was used for heating by copper workers. Coal was also used extensively in Roman Britain, where several exposed coalfields were exploited. It was transported to distant sites, such as London, although wood and charcoal remained the main fuels (Dearne and Branigan 1995).

Petroleum is mentioned by Herodotus (5th century BC) and Plutarch (1th century AD). Herodotus (Book 6, 119) describes wells near Susa (today central Turkey) which were used to extract “oil”; it was black with strong smell and was stored in vessels. From the same wells asphalt was extracted. In another Herodotus’ book (Book 4,185) the presence of asphalt in the Island of Zakynthos is described. Plutarch (*Parallel Lives, Life of Alexander, 35*) describes a chasm of fire at Ecbatana (today Iran) that streamed as a spring, while the abundant liquid *naphtha* was stored nearby. He mentions that naphtha was like asphalt but more flammable. Also, Plutarch narrates that “barbarians” impressed Alexander the Great by lighting the road that led to his lodging. Generally, the use of petroleum as fuel in antiquity was rare. On the other hand, the use of asphalt was widespread in almost all civilizations as waterproof material, mainly in vessels but also as mortar in buildings and pottery.

In several ancient sources, seeps from which gas escapes are mentioned. Several oil and natural gas seeps, especially in the Mediterranean area, are cited by Pliny the Elder (1th century AD) in his treatise *History of Nature*. The temple of Hephaestus, the Greek god of fire, was built next to such a burning gas seep in Chimaera, in modern day Turkey (Etiope 2015).

From the Iron Age to the Industrial revolution during the 18th century AD, most things related to water and energy management, remained almost stagnant. Wood, charcoal and wind were the main energy sources, and surface and ground water were the main water resources. As water and energy management followed the ups and downs of civilizations, few essential developments were achieved as summarized below:

(a) *Devices and mechanisms for lifting water*. Several devices were used throughout history for lifting water, as comprehensively reviewed by Yannopoulos et al. (2015). The most important, Archimedes' screw and Noria, were invented around 3th century BC. Archimedes' screw was the predecessor of the modern pump, and it was powered by human or animal force. The modern version of this device, powered by thermal or electric energy, is used in many contemporary water projects. Noria is also a very important invention, as the machine worked with hydraulic power. It is a wooden waterwheel, powered by flowing water and fitted with buckets that lifted water to another collector out of the river. Finally, it is worth to mention that the inverted siphon technology was achieved at a rather large scale in some ancient aqueducts starting from the Hellenistic period, even though this is not actually lifting of water.

(b) *Construction of hydraulic works.* All civilizations constructed extensive hydraulic works to manage water, such as aqueducts, cisterns, qanats, tunnels and dams (Angelakis et al. 2006, 2013; Feo et al. 2013). Other kinds of hydraulic works were also built with the purpose of draining cultivation areas, flood protection and river navigation. Especially, Mediterranean civilizations, that flourished in an environment of water scarcity, exploited available water resources extensively and built admirable hydraulic works.

(c) *Water use for energy production*. During the 1th millennium BC, water mills were invented to grind the grain and olives for flour and olive oil production, respectively. Olive oil became the main fuel for home lighting for several centuries and was used in most civilizations (in specific areas animal fat was used instead). Around the 7th century AD wind mills were invented in Persia, and they were used until the twentieth century all over the world to grind cereal, pump water and even drain land, like, for example, in the Netherlands.

(d) *Birth of science for understanding and control of natural powers*. As societies became more and more dependent on the natural resources, early scientists tried to understand the relevant environmental processes and describe their laws. Nature was now more predictable and hence more controllable. The first scientific theories of natural phenomena were formulated around the 6th century BC by Greek philosophers from Ionia (Koutsoyiannis et al. 2007). During the next centuries Greeks advanced the existing knowledge and defined the scientific method. Aristotle (4th century BC) codified the existing information for several natural sciences. Also he defined the way to understand nature, introduced the formal study of logic and, in particular, the methods of deduction and induction. It is worth mentioning that Aristotle first distinguished the terms energy (ενέργεια) and power (or "potential"; δύναμις) with the former being the existence of something and the latter is the potential to be something (Metaphysics Book 9, 1048a). Thus, in the context of the Aristotelian philosophy, energy is regarded as the action needed to materialize a potentiality. During this period there was significant progress in mathematics, physics, astronomy and technology. A fascinating technological achievement was the use of steam for production of mechanical motion that was discovered during 2th century BC by Heron in Alexandria. Although the invention was applied in the construction of a few amusing mechanisms, it was more than 2000 years later that the reinvented stream engine would start to play an important role in human development.

At the beginning of the 18th century, societies remained rural, and the majority of the population was involved in agriculture. The manufacturing activity was limited to small factories, cottages and urban craft shops. At the middle of the 18th century, a transition from manual labour manufacture to centralized, standardized and organized production was made. The Industrial Revolution began in England and spread to the rest of Europe and North America. In about one century, the factory system was developed, machines and tools were invented, and iron, chemical, shipping and textile industries were blooming. As wood and charcoal were the main fuels used in these developments, large quantities of wood were consumed very quickly and forests were depleted. A new fuel was used to replace wood, coal and its processed form, coke (charred coal). As coal consumption increased, surface deposits were exhausted, and deep mines were constructed. Deep galleries were flooded by groundwater, which was a big problem. The problem was resolved by an engine, called the "Miner's Friend", which replaced traditional animal-driven pumps. This pump was a great invention as it used thermal energy to convert water to steam, which under pressure produced mechanical work to remove water from mines. Later in 18th century more advanced steam engines were produced and were used in several industrial applications. However, the most important application of steam engines was in the transportation sector. During this period trains and ships moved using coal and wood as fuels.

Also, during the Industrial Revolution, the use of hydropower for industrial activities begun. Iron waterwheels were built, and water powered devices operated a variety of industrial applications, mainly in the textile industry.

At the end of the 19th century internal combustion engines which used petroleum and gas were invented. During the 20th century most human activities expanded thanks to these engines. The transportation sector in particular boomed, as cars, aircrafts and boats were now used extensively to transport people and goods. Petroleum and its derivatives, such as gasoline, kerosene and, diesel, were the main fuels for this activity, while natural gas was also available but less frequently used. During the early 20th century, the gas that was released during petroleum mining was usually burned at the fields, as it was considered very expensive to transport or to store for later use. Very soon, devices were invented to exploit gas, e.g., for heating and cooking in the domestic sector. At the end of the 20th century natural gas was already exploited extensively. Finally, the liquefied natural gas (LNG) is another common method used to facilitate conveyance.

While phenomena connected with electricity had been known since antiquity, in the 19th century a steady stream of inventions led to a multitude of practical applications, and by the end of that century electricity had transformed the world. Electricity could now be stored, transported, and transformed into other types of energy with relative ease. This led to rapid growth of the type and number of everyday life applications. During the 20th century electricity transmission networks were installed all over the Earth. In 1980 the electrical energy corresponded to 30% of the total energy consumed, and in 2015 this percentage was about 40%. Water power was one of the first resources (alongside coal and petroleum) that were used for electricity production. As electric energy needs expanded, hydropower became of great importance, and thousands of hydroelectric power plants were constructed all over the world. Their reservoirs were not only used to manage energy production but also to provide irrigation water, domestic water supply, and flood protection. In the 1950s, when the controversial nuclear technology emerged, it began to be used extensively for electricity production, using radioactive fuels such as uranium and plutonium. After the oil crisis of 1970s, societies started to explore renewable resources for electric energy generation. At the beginning of the 21th century, wind, geothermic fields, biomass, and solar energy began to be used more extensively for electricity generation.

The 20th century is also characterized by the improvement of water facilities and new related technologies, as well as the introduction of environmental protection in water management. Hydraulic works were constructed mainly for (a) collecting, transferring and distributing water from sources to end users, (b) storing water for later use, (c) cleaning potable water and managing waste waters, (d) exploiting hydropower for electricity, (e) protecting from floods, and (f) ensuring river navigation. At the end of the century, desalination plants were constructed in coastal areas, and the terms “waste water recycling” and “environmental flow” were introduced.

Table 20.1 lists some of the most important historical events that influenced water and energy management.

20.1.2 Water and Energy at the Beginning of the 21th Century

At the beginning of the 21th century, the world population exceeded 6 billion (while in 2019 it exceeded 7.7 billion) distributed among about 200 countries. In 2014 and 2015 the mean annual water consumption and energy production per capita were estimated to about 550 m^3 and 25 MWh, respectively. During the 20th century enormous infrastructures were constructed to ensure access to water, energy and sanitation to the majority of the world population. The progress of science and technology improved the design, operation and management of hydraulic works and power plants. On the other hand, many developing countries still lack these basic facilities. In Fig. 20.1 the percentage of the population that has access to potable water, electricity, and sanitation in the years 2000 and 2014 is depicted for each country.

From Fig. 20.1a-left, referring to the access to potable water in 2000, it is evident that in several countries all over the world a significant (more than 10%) percentage of the population had no access to potable water. The problem was more severe in some African countries where the majority of the population had no access to water. Regarding access to electricity (Fig. 20.1b-left) and sanitation facilities (Fig. 20.1c-left), the situation seems even worse. It is evident that several African and Asian countries had serious difficulties in covering these basic needs.

From the right panels of Fig. 20.1, which refer to 2014, it becomes obvious that during 21th century the living standards in many of these countries did not change drastically. Some improvement is visible in potable water access, but better access to electricity would help with both potable water and sanitation, overall there is a long way ahead for humanity to ensure decent living conditions for all.

Table 20.1 Milestones of water–energy use

Time (approximately)	Era	Inventions	Energy sources	Water management
100th millennium BC	Palaeolithic	Fire control	Wood	Use from sources
10th millennium BC	Neolithic revolution	Agriculture, Animal domestication, Sailing	Wind	Water transfer, Water storage
5th millennium BC	Urban revolution			Urban water supply
1th millennium BC	Iron age	Charcoal production	Charcoal	Recreational use, Advanced hydraulic works
5th century BC		Pumping devices, Water mills	Water	Water lift, Scientific explanations for geophysical processes
7th century AD		Wind mills	Wind	River navigation
18th century	Industrial revolution	Steam engine	Coal	Industrial water uses
19th century	Scientific revolution	Internal combustion engine	Petroleum, Natural Gas	
20th century		Electricity, Nuclear Energy	Water, Nuclear fuels, Geothermic, Solar, Marine	Desalination, Recycling, Environmental flow

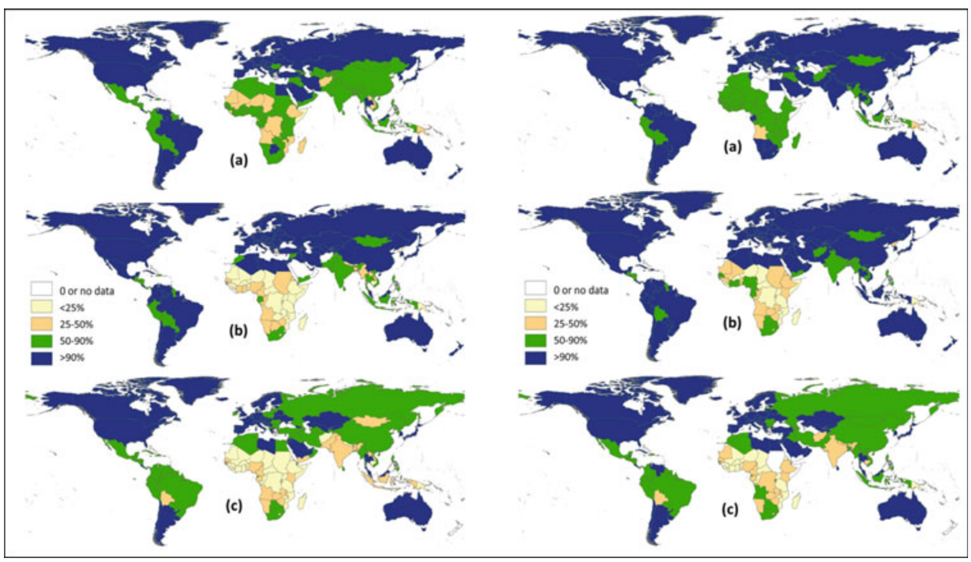


Fig. 20.1 Access to **a** potable water, **b** electricity and **c** sanitation (% of the population of each county) in the year 2000 (**left**) and 2014 (**right**) (constructed from data of World Bank; https://data.worldbank.org/)

20.1.2.1 Water Use

According to World Bank data for 2014, the world's annual water consumption was estimated to about 4000 km^3; this corresponds to about 550 m^3 per person. Five countries (India, China, USA, Pakistan and Indonesia), whose population amounts to 30% of the global, were responsible for more than 60% of the total global water consumption. From the total amount, 70% was used for irrigation, 19% for industrial, and 11% for domestic use (a mean value of 170 L/d per person). These uses are classified as consumptive, as water is removed from its initial environment or its quality degrades to a state that it requires treatment for reuse. The water consumption quantities are estimated on a country basis based on data from free web databases maintained by organizations such as the Food Agricultural Organization (FAO; https://www.fao.org/nr/water/aquastat/data/query/index.html) and the World Bank (https://data.worldbank.org/indicator).

Irrigation refers to water used to assist in growing crops, to protect plants against frost or to remove salts from the crop root zone. Industrial use refers to water used in industries for purposes such as processing, cleaning, diluting and cooling. Domestic use refers to water that is used in households for everyday needs, such as drinking water, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering gardens. In addition to the main three water uses mentioned above, there are a few more specific consumptive water uses, including (a) commercial (water for hotels, office buildings, and other commercial facilities), (b) livestock (water for stock animals, dairies, fish farms, and other nonfarm needs), and (c) mining (water for the extraction of minerals such as coal and ores, crude petroleum, and natural gas).

On the other hand, there are several non-consumptive uses, where the water remains in the natural environment. The main non-consumptive water uses are: (a) hydroelectric energy production, (b) river navigation, (c) recreational activities (fishing, sailing, swimming), and (d) preservation of the environment. The latter use includes mainly water releases from reservoirs in order to (a) help fish reproduction, (b) restore natural river flow regime, and (c) provide water to wetlands to protect their ecosystems.

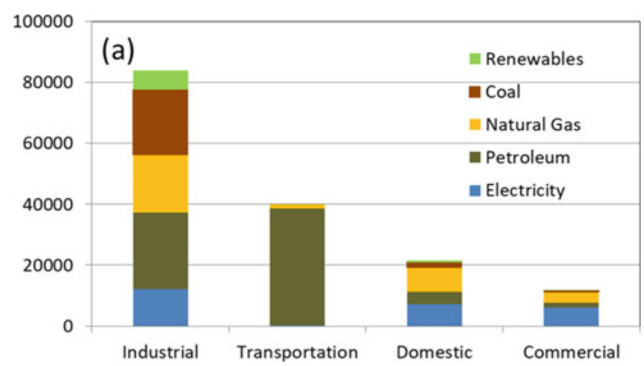
To cover all these water demands, a large amount of available water resources has to be exploited by constructing the appropriate hydraulic works. Potentially, water can be found in the (a) ground (aquifers), (b) surface of the earth (rivers, lakes), (c) atmosphere (rain, water vapour) and, (d) sea (after desalination). Alternative sources could be the transfer of water from other areas or reusing the outflows of drainage networks or waste water treatment plants. The atmospheric water is exploited as a source only on a small scale mainly by harvesting rain water and humidity condensation installations such as fog collectors.

20.1.2.2 Energy Use

According to the United States Energy Information Administration data (EIA 2017) the total world primary energy production in 2017 was about 14 000 Mtoe (million tons of oil equivalent). Here one toe is the quantity of energy that is released from the combustion with 100% efficiency of a ton of crude oil; this corresponds to 41.9 GJ or 11.6 MWh. The world primary energy was mainly produced from coal, petroleum and natural gas and consumed in the industrial, transportation, domestic, and commercial sectors. The distribution of primary energy (TWh) by source and use in 2017 is shown in Fig. 20.2a. Some of the electricity used by the different sectors was originally generated from fossil fuels. Hydropower and nuclear power have a significant share in electrical energy production as well. Apart from hydropower, other renewable energy sources such as wind, (direct) solar radiation, biomass and biofuels, geothermal, and marine energy (waves, tides, currents) have a small but increasing share. Biomass and geothermal energy are widely used as thermal energy sources, especially in the industrial and domestic sectors. Notably, the conversion efficiency of fossil fuels for electricity production is generally low (35% for coal to 55% for natural gas) when compared to the conversion efficiency of hydropower (more than 85%).

The total electricity produced globally in 2017 was about 25 500 TWh (2200 Mtoe) and the consumed fuels (mostly fossil) were about 6000 Mtoe. The world electric energy mix for 2017 is presented in Fig. 20.2b. From the end of the 20th century the fear of exhausting fuel reserves combined with environmental concerns triggered an effort to increase the share of renewable energy sources in electricity production (Fig. 20.2b). Also, the technique of coproduction of thermal energy from electric power plants was widely used and increased the efficiency of the systems to more than 70%.

The industrial sector consumed 53% of the total global energy production and was proportionally fed by petroleum, coal, natural gas and electricity. The transportation sector consumed 25% of the total energy and was almost exclusively fed by petroleum. Finally, domestic and commercial



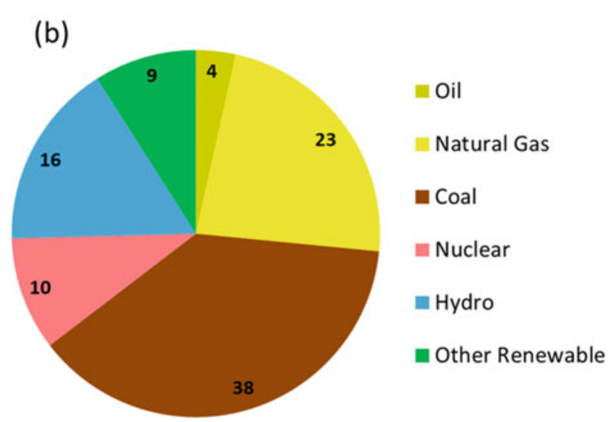


Fig. 20.2 **a** Distribution of primary energy (TWh) by source and use (constructed from data from EIA); **b** World electric energy mix for 2017 (constructed from data from BP British Petroleum 2018)

sectors consumed the 22%, and were mainly fed by electricity, natural gas and petroleum.

Fossil fuels (petroleum, natural gas and coal) produced 65% of electrical energy, while hydropower and nuclear energy were also very important for power generation as they were responsible for 26% of electrical energy production.

20.2 Water-Energy Nexus

Water and energy systems interrelate in multiple ways that are both complex and dynamic. For example, energy is used for abstracting, purifying, distributing and disposing water, while water is indispensable for various energy production phases, including, among other processes, oil drilling, biofuel production, thermal plant cooling and hydropower. Accordingly, problems with one may directly or indirectly affect the other, e.g. water shortage having negative knock-on effects on energy production. These close relationships belong to the so-called 'water-energy nexus', a term coined to describe the multiple interactions between the two systems. Some of the earliest attempts to investigate water-energy interdependencies in the economy and water sector, thus introducing a joint approach into policy planning, were made in the United States in 2006 (US DoE 2006). Langhamer et al. (2010) discussed the scientific and technological aspects of water and energy and explored related research challenges. During the first two decades of the 21th century, a growing body of research acknowledged the water-energy nexus complications and its relevance to the economy. However, the identification of these relationships and their impact remains a field largely underexplored till now.

20.2.1 Water Used for Energy Production

According to Spang et al. (2014), approximately 52 km^3 of freshwater are consumed annually for energy production, excluding hydropower (which in fact does not consume water). Yet this number is an approximate estimate coming from countries with greatly diverse economies and energy sectors. In the United States the energy sector is regarded to be the biggest consumer of water resources (Carter 2010). The U.S. is also the most important consumer on a global scale, followed by China, while for instance, northern Africa has a minimal contribution to the global amount of water used in the energy domain. Apparently, these statistics should be viewed with caution as the assumptions behind them may vary substantially, while also they are changing over the years due to reforms in the energy sector and emergence of more water-efficient technologies that reduce the pressure on regional water resources.

To trace the water used for energy production in a more systematic way, Hoekstra and Hung (2002) introduced the concept of the 'water footprint' of a country, i.e. "the volume of water needed for the production of goods and services consumed by the inhabitants of the country". The water-footprint has been further specified to denote three distinct types of water use: 'blue water', referring to consumption of groundwater and surface water; 'green water', denoting the amount of rainwater required for a product, e.g. rain-fed agriculture; and 'grey water', representing the amount of freshwater required to dilute pollutants to maintain water quality according to certain standards (Hoekstra and Chapagain 2006). This concept has also been used in energy production and supply in order to identify impact of trading relationships on water resources. For example, petroleum products heavily contribute to the water footprint for energy production in Thailand, but very little to the water footprint for energy supply, since related energy is mostly exported, while the opposite is true for the country's crude oil water footprint (Okadera et al. 2014).

It is also useful to differentiate between two types of water use for energy, i.e. 'water withdrawal' and 'water consumption'. The first denotes the amount of water removed or diverted from a source for use. The second is a part of the first and denotes the water withdrawn that is evaporated, transpired, incorporated into products or crops, or otherwise permanently removed from the immediate water environment (Kenny et al. 2009). Most relevant studies focus on water consumption.

The following sub-sections refer to operational uses of water excluding indirect uses of the life-cycle, for instance, water used in energy stations auxiliary facilities, e.g. sanitary facilities.

20.2.1.1 Fossil Fuel

Crude oil production requires water for processes including onshore oil exploration, onshore oil extraction and production, enhanced oil recovery, water injection (water-flooding), thermal steam injection, oil refining, and other plant operations. The amount of water required is regionally varied, mainly according to the combination oil recovery techniques used in each case. For example, primary oil recovery, by means of the natural pressure of the well, is much less water-intensive than secondary oil recovery, including water-flooding, whereas varied estimates are reported for enhanced oil recovery techniques such as CO_2 injection (Wu et al. 2008). Excluding enhanced oil recovery, median values of 0.081 m^3/GJ and 0.040 m^3/GJ are reported (Spang et al. 2014; Wu et al. 2008) for conventional oil extraction and refining, respectively. These estimates differ, in general, for less common crude oil production, such as oil sands and shale oil, though altogether tend to decrease over the years as energy technologies become more water efficient and employ other sources than freshwater, e.g. saline or brackish water (Wu et al. 2008).

Coal consumes water for surface or underground mining, beneficiation, slurry pipelines, and other plant operations, while natural gas requires water for the processes of onshore exploration, onshore extraction, natural gas processing, gas pipeline operation, and other plant operations. Shale gas is even more water intensive requiring water for the process of hydraulic fracturing (fracking) with estimates ranging in the United States from 1136 m^3 per well to 34 069 m^3 per well in 2012 (Meldrum et al. 2013). Reported median global estimates are 0.043 m^3/GJ, 0.004 m^3/GJ and 0.017 m^3/GJ, for coal, natural gas and shale gas production, respectively (Meldrum et al. 2013; Spang et al. 2014).

In the fossil fuel industry, water consumption is globally dominated by the oil industry where water is used for crude oil extraction and refinement processes, except for China, India, Indonesia and Australia, where coal is the greater consumer of water among the fossil fuels (Spang et al. 2014). The natural gas industry has a minor contribution in water consumption worldwide, with Russia and the United States being the major contributors.

20.2.1.2 Nuclear Fuel

Water is required for many processes involved in the production of nuclear fuel, including uranium mining, milling, conversion, enrichment, fabrication, and reprocessing phases. A median water consumption estimate of 0.105 m^3/GJ is reported for these processes (Meldrum et al. 2013; Spang et al. 2014).

On a global level, water requirements for nuclear fuel production are estimated an order of magnitude lower than that of fossil fuels (Spang et al. 2014), which is both a result of the limited availability of uranium deposits and the restricted nuclear fuel production worldwide.

20.2.1.3 Biomass Production and Processing

Biomass may refer to (a) food crops, such as sugarcane and rapeseed, (b) energy crops as poplar and miscanthus, as well as (c) various types of organic waste from agriculture processes, e.g. manure and crop-residues (Gerbens-Leenes et al. 2009). Biomass is often subsequently processed to biofuels such as biodiesel, ethanol, and biogas. For example, the United States and China produce maize-based ethanol, India uses rapeseed to produce biodiesel, and Brazil depends on sugarcane to produce ethanol. Water for biofuels relates both to the water required for the cultivation of biomass, in the case of crops, and to water required for its processing. Biofuels are mainly first-generation, including biodiesel, ethanol, and biogas, and second-generation, including energy crops and waste products.

In case of first-generation biofuel, water is primarily required for cultivation of biomass. This type of biomass production is generally considered the most water-intensive energy production process due to its dependence on irrigation. Relevant estimates are highly regionally varied and uncertain, since they heavily rely on the crop type, irrigation system, and climatic conditions (Mielke et al. 2010). Subsequently, ethanol production from biomass requires water associated to grinding, liquefaction, fermentation, separation, and drying processes (Wu et al. 2009).

Second-generation biofuels require water mostly for conversion of cellulosic ethanol to ethanol through biochemical or thermochemical processing (Naik et al. 2010). In general, second-generation biofuels do not require incremental irrigation if grown in their native ground, and water use estimates are usually omitted, though some energy crops may need additional irrigation (Wu et al. 2009).

In 2016, biofuels yielded only a small amount of the total energy production (957 TWh), according to data from BP Statistical Review of World Energy (British Petroleum 2017); however, they are a growing energy pathway (Berndes 2008). For instance, in Thailand energy from biofuels had already reached 18% of total energy supply in 2010 (Okadera et al. 2014).

20.2.1.4 Electricity

Electricity has the most diverse profile of water consumption owing to the variety of pathways for electricity production in terms of fuel, generator type, and cooling type. Spang et al. (2014) classify these in eight major categories: coal-based steam turbine (ST), gas- and oil-powered ST, nuclear ST, biomass and waste heat ST, geothermal ST, solar ST, combined cycle, and gas turbine. The majority of water used in the production of electricity refers to water used for thermoelectricity processes, i.e. freshwater used for cooling the steam after exiting the turbine generator. The cooling water that is needed by thermal power plants is estimated to be around 76–190 m^3/MWh (Kohli and Frenken 2011). Geothermal technologies differ in the usage of water due to differences in technology configurations and regional characteristics (Clark et al. 2010), and may require further water usage for generation of electricity (Macknick et al. 2012).

Hydroelectricity provides 16% of the total world electric energy production, which corresponds to 80% of renewable sources. For some countries (Albania, Norway, Paraguay and Congo), it is almost the only resource in their electric energy mix. During the twentieth century, the extensive use of hydroelectricity revealed issues of great importance to the operation of water-energy systems. Hydroelectric energy is produced by the falling of a water volume from a certain height. The main method to exploit the hydropower of a river is to build a dam that forms an upstream reservoir, which regulates river flow. At certain time periods, water is released under pressure to produce electric energy. However, allocation of water consumption for hydropower is generally avoided in the literature, since water is not actually consumed. Hydroelectric dams are usually multi-purpose works, serving simultaneously flood control and water supply purposes, so assigning, for instance, evaporation losses solely to hydropower is ambiguous and misleading.

For other electricity technologies such as photovoltaic (PV) plants and wind power production, water is mostly associated with occasional life-cycle requirements of washing PV panels and wind turbine blades. Thus these present the lowest withdrawal and consumption rates (Macknick et al. 2012), and also rank low on the global scale of water use in the energy sector (Spang et al. 2014).

20.2.2 Energy Intensity of Water Sector

At the start of the 21th century and considered on a global scale, water is an important input for nearly all forms of energy (International Energy Agency 2016). Although the water sector is not yet a significant user of energy on a global level, in light of energy reforms towards a 'greener' economy and increasing use of desalination plants, this is likely to change. Recent important developments involving the use of novel desalination methods, such as nanoporous graphene sheets as well as capacitive deionization, which are much more energy efficient compared to the reverse osmosis method, could further increase the spread of desalination plants (Aghigh et al. 2015; Copeland and Carter 2014; International Energy Agency 2016). According to the International Energy Agency (2016), the global energy consumption in the water sector reached approximately 5×10^9 GJ (1390 TWh) of energy in 2014, about 60% of which is in the form of electricity.

In the United States, past analysis has shown that over 3% of the national electricity consumption is used for water-related purposes (Cohen et al. 2004). However, these aggregate estimates do not show the large variability of the energy-intensity on the regional scale, e.g. California uses 19% of its electricity and 32% of its natural gas resources for services related to the water sector (Klein et al. 2005; Stokes and Horvath 2009).

Energy for the water supply sector has been classified into 'physical energy' (the amount of energy applied to produce and transport water supplies to meet demand within each hydrological region) and 'embedded energy' (the actual amount of energy needed in other regions to produce and deliver water that is consumed within that region). Specifically, the energy embedded in water is defined as "*the amount of energy that is used to collect, convey, treat, and distribute a unit of water to end users, and the amount of energy that is used to collect and transport used water for treatment prior to safe discharge of the effluent in accordance with regulatory rules*" (Park and Bennett 2010). The term 'energy intensity' refers to the average amount of energy used for these processes on a per unit basis.

20.2.2.1 Urban Water and Wastewater

Energy estimation for the urban water cycle can be segmented into the phases of supply, conveyance, treatment and distribution of water, and waste water treatment (Park and Bennett 2010).

The supply phase may include surface water, groundwater, desalinated water, and recycled water. Due to their increasing importance, desalination plants are examined separately below. Relevant energy consumed in the supply process is driven by the type of the source water, the technology used in each case, and the regional regulatory standards. In essence, exploitation of groundwater requires a supply of energy determined by the pumping method and efficiency, the depth of the well, and the volume of the pumped water. About 800 TWh (3% of the total world electric energy production) are required to pump water from deep aquifers (e.g. 80 m). For example, in Greece, a country where groundwater is extensively used for irrigation, 5% of total electricity was consumed in water pumping. In some agricultural regions, in which deep wells are used, this percentage is up to 15%. Recycled water's energy intensity is driven by the wastewater discharge standards and the level of additional treatment that is required in order to bring the water into an acceptable quality for the specific purpose of interest. The extraction of surface water and groundwater generally accounts for the 40% of the electricity used in the water sector (International Energy Agency 2016).

Energy intensity of water conveyance and distribution by means of pumping depends on the topography, the geometric and hydraulic properties of the pipe system, and the requirements of consumers in terms of discharge and pressure.

Energy intensity of water treatment is subject to the type of treatment technologies used, the water quality standards, the initial quality of the raw water, as well as the treatment plant configurations. For example, energy-intensive methods include reverse-osmosis, ozonation, and ultraviolet light rays.

Finally, the energy consumed in the waste water treatment plants is determined by the plant capacity, the level of treatment, the technology used, the wastewater influent quality, and the discharge standards (primary, secondary or tertiary). In 2014, it was estimated that a quarter of the electricity consumed by the water sector was used for waste water collection and treatment. This electricity demand is projected to increase by 60% or even more up to 2040, as more wastewater will be collected and treated (International Energy Agency 2016). Yet, in some cases, the use of the produced biomass from waste covers a significant part of the thermal and electric energy needed for treatment.

20.2.2.2 Agricultural Uses and Irrigation

Irrigation is a dominant consumer of energy. Energy required depends on (a) the type of source water used (surface water or pumped groundwater), (b) the type of irrigation methods (surface, drips, sprinklers), and (c) the water requirements of the crop. In South Asia, and particularly in India, irrigation heavily depends on groundwater pumping and is energy-intensive to such a degree that it is frequently described by the term the 'energy-irrigation nexus' (Shah et al. 2004).

In the first decades of the 21th century, alternative sources to produce electricity for irrigation have been explored. For instance, renewable resources, especially photovoltaic panels, are used to produce energy for pumping (Chandel et al. 2015).

20.2.2.3 Desalination Plants

Desalination refers to the process of converting non-usable water resources into usable by removing excess salts and minerals. The energy intensity depends on the volume of water being desalinated, the quality of the source water, and the specific desalination technology. For example, processing brackish water, containing moderate amounts of salts and minerals, is not as energy-intensive as processing sea water, containing very high quantities of salts and minerals. Desalination technologies utilize either thermal energy, e.g. in multi-stage flash systems, or mechanical energy as in reverse osmosis, the most commonly installed technology (International Energy Agency 2016). The reduction of energy-intensity of water desalination technologies is a very active research field with reverse-osmosis desalination plants showing the most growth and concentrating engineering focus worldwide (Peñate and García-Rodríguez 2011), while new graphene-based technologies also have a great potential (Aghigh et al. 2015). It is highly likely that in the future desalination will be a viable alternative to mitigate water scarcity due to limited water resources or during drought periods. Although desalination is a very energy consuming process (3.5–5 kWh/m^3 for reverse osmosis), the resulting world energy demand is low. The desalination plants have a global annual water production of about 6 km^3 and consume about 30 TWh of energy, a value that corresponds to the 0.1% of total electricity production (see FAO database mentioned above). Desalination processes accounted for roughly 5% of the electricity used in the water sector in 2014 (International Energy Agency 2016), and it is projected to rise to more than 20% in 2040.

20.2.3 Synergies and Trade-offs

The various interdependencies of the water-energy systems often lead to competitive uses of the naturally constrained resources, thus rendering the management of these systems challenging. The competitive nature of the resources may have detrimental effects on the economy and water sector if ignored in the management strategy, while, on the other hand, an integrated approach creates opportunities for mutually beneficial situations.

McCornick et al. (2008) reviewed interesting case studies; among them the case of Ethiopia. In spite of water abundance and great hydropower potential, Ethiopia lacks relevant infrastructure and is very dependent on unsustainable biomass growth, leading to poverty, water insecurity, energy deficiency and destruction of forests, among others. The use of hydropower dams as a means for integrated management of water-energy systems has long been advocated (Koutsoyiannis et al. 2003, 2009; Nalbantis and Koutsoyiannis 1997) with an emphasis on the necessity of large scale projects to increase energy-efficiency and enable reliable multi-purpose operation (Koutsoyiannis 2011a; Koutsoyiannis et al. 2003; Nalbantis and Koutsoyiannis 1997).

At the beginning of the 21th century, environmental or climate concerns and efforts to reduce economy's dependence on fossil fuels engendered an increase in the use of renewable resources, including biomass. However, these policies, being highly dependent on existing water and land resources, have sometimes been criticized of disregarding the latter, placing pressures on stressed water resources and leading to land degradation, and thus having opposite effects to the ones intended (Pittock 2011). Concerns about the shift towards biomass have also been expressed due to substitution of water and land resources from food production to energy production, i.e. a 'water for food' versus a 'water for energy' competition (Dalla Marta et al. 2011; Gerbens-Leenes et al. 2009).

Eventually, we should be able to increase efficiency in both sectors and achieve water and energy security by better informed integrated policies together with technological innovations. An important reflection on the regional nature of the water-energy stresses and on the limits of future progress is provided by Bazilian et al. (2010, 2011). The study notes that arising inequalities in terms of present and future access to water and energy should be examined in political terms as well as in terms of environmental and technological constraints, and therefore, political prioritization is also required.

20.3 Energy Hydraulics

20.3.1 Governing Equations

In order to extract energy from water or to add energy to water, we use *hydrodynamic machines* called *turbines* and *pumps*, respectively.

The governing equation for electric power production via transformation of the dynamic and kinetic energy of water is

$$P = \eta\, \rho\, g\, Q\, H_n \tag{20.1}$$

where ρ is the water density with a typical value for clean water of 1000 kg/m^3; g is the gravity acceleration with a typical value of 9.81 m/s^2; Q is the discharge; H_{n} is the *net* or *effective head*, i.e. the dynamic energy, expressed as elevation difference, after subtracting the hydraulic losses across the water transferred to the turbine, which depend on Q; and η is the turbine efficiency that changes with Q, according to a function which is a characteristic of the turbine. Both H_{n} and Q may vary in time, and therefore so does P. By applying the SI units for Q (m^3/s) and H_n (m), the power P is expressed in Joules per second (J/s) or Watts (W).

Similarly, the governing equation for estimating the power consumed by lifting water at head H_{m} through pumping is given by

$$P = \rho g Q H_{\mathrm{m}} / \eta \tag{20.2}$$

where H_{m} is the so-called *manometric head*, and η is the pump efficiency, which is a function of Q that is a characteristic of the pump. The manometric head is the sum of the elevation difference Δz plus the hydraulic losses across the pipeline system, where $\Delta z = z_2 - z_1$, with z_1 and z_2 being water elevations before and after the pump (typically $z_1 < z_2$).

The energy produced or consumed during a time interval [t_1, t_2] is the integral of P, i.e.

$$E = \int_{t_1}^{t_2} P(t)dt \tag{20.3}$$

After simplifications, we get the following formula, expressing the average energy produced over a specific time interval

$$E = \rho\, g\, V \overline{H}_{\mathrm{n}} \overline{\eta} \tag{20.4}$$

where V is the water volume that passes through the turbines during the time interval [t_1, t_2], and $\overline{H}_{\mathrm{n}}$ and $\overline{\eta}$ are the net head and efficiency during this period, respectively, averaged over time.

Similarly, the consumed energy over a specific time interval due to pumping is approximated by

$$E = \rho\, g\, V \overline{H}_{\mathrm{m}} / \overline{\eta} \tag{20.5}$$

where the symbols have the same meaning as above.

20.3.2 Key Concepts of Hydropower Technology

Hydropower is generally produced either through *hydroelectric dams* or *run-of-river plants*. The former take advantage of the height difference that is artificially generated due to the rise of the river level upstream of the dam, and they also take advantage of the regulation capacity of the reservoir, which allows for storing the surplus flows and releasing them according to the time-schedule imposed by the reservoir management policy. On the other hand, run-of-river plants do not have significant storage capacity, and thus they operate with the available natural flow, which is irregularly varying. There are also other types of hydropower plants which make use of wave and tidal energy, but they are based on the same energy transformation laws.

Figure 20.3 illustrates a sketch of a conventional hydroelectric work, comprising the *dam*, the *intake* system, the conveyance pipe, called *penstock*, the turbine station, the outflow pipe, called *draft tube*, and the channel conveying water to the river, called *tailrace*. The dynamic energy of water is expressed by means of the so-called *gross head*, which is determined by the reservoir level upstream z_1, and the outflow level downstream z_2, i.e. $H = z_1 - z_2$. The reservoir level ranges between a minimum and a maximum value, i.e. the intake level and the spill level, respectively. The outflow level may also vary (e.g., outflow to a river), yet its fluctuation is generally very small, if compared to the variability of the upstream level, thus it is usually neglected in computations.

As the flow is conveyed from upstream to downstream, the available dynamic energy is decreased due to frictional and local energy losses that occur along the flow conveyance from the intake to the turbine. Therefore, the available energy to be converted, expressed by means of kinetic and pressure energy, is reduced by the quantity of losses ($\Delta H = H - H_n$), while the amount of mechanical energy that is finally available as electric power is further reduced by the factor $1-\eta$.

Key design objective is to minimize the hydraulic losses and maximize the turbine efficiency in order to exploit as much of the gross head as possible. The overall design of the hydropower system is in fact a challenging optimization problem, involving the construction and maintenance costs of hydraulic and power infrastructures, and the benefits of energy production. Typically, conventional large-scale hydropower systems exploit 80–85% of the gross head, where 3–10% of head reduction is due to hydraulic losses and about 10% to conversion losses.

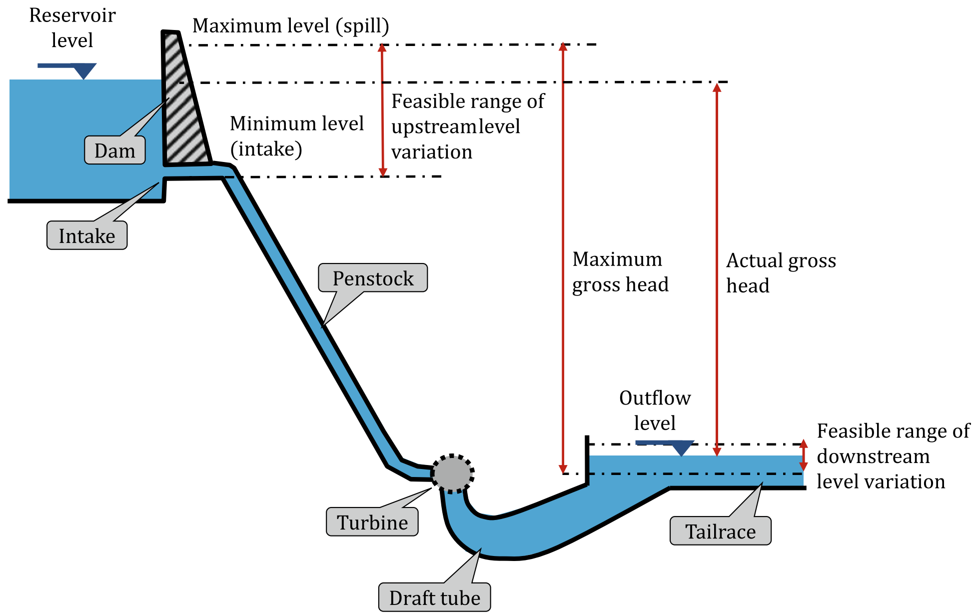


Fig. 20.3 Sketch of a conventional hydropower system

20.3.3 Hydraulic Losses

Frictional losses across the penstock as well as local energy losses that occur due to the changes in the flow geometry contribute to gross head reduction.

For given discharge Q and pipe diameter D, the flow velocity is given by

$$V = \frac{4Q}{\pi D^2} \tag{20.6}$$

For the above flow characteristics, the energy gradient J across the pipe is typically estimated by the so-called Darcy-Weisbach formula

$$J = f\frac{1}{D}\frac{V^2}{2g} \tag{20.7}$$

where f is a (dimensionless) friction factor. The latter is given by the Colebrook–White equation

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \tag{20.8}$$

where $\mathrm{Re} \coloneqq V\,D/\nu$ is the *Reynolds number* and ε/D is the *relative roughness*, both dimensionless, whereas ε is the absolute (surface) roughness of the specific pipe and ν is the kinematic viscosity of water, which is function of temperature; e.g., for T = 15 °C, $\nu = 1.1 \times 10^{-6}$ m^2/s.

For a pipe of length L *and diameter* D, assuming steady uniform flow with discharge Q, the *friction losses* h_f, which are the main component of the total hydraulic losses, are given by

$$h_f = fL\frac{8Q^2}{\pi g D^5} \tag{20.9}$$

Due to the complexity of friction loss calculations based on (20.6), a number of simplified formulas have been developed in the literature (e.g., the Hazen-Williams expression), which are however noticeably less accurate than the Darcy-Weisbach equation. A more consistent and accurate approximation is offered by the so-called *generalized Manning equation*, introduced by Koutsoyiannis (2008):

$$J = \left(\frac{4^{3+\beta}\mathrm{N}^2Q^2}{\pi^2 D^{5+\beta}}\right)^{1/(1+\gamma)} \tag{20.10}$$

where β, γ and N are coefficients depending on roughness, for which Koutsoyiannis (2008) provides analytical expressions that are valid for specific velocity and diameter ranges. In particular, for the large diameters (i.e., $D > 1$ m) and velocities (i.e., $V > 1$ m/s) that are typically applied in hydropower systems, we get:

$$\beta = 0.25 + 0.0006\varepsilon_* + \frac{0.024}{1+7.2\varepsilon_*}, \gamma = \frac{0.083}{1+0.42\varepsilon_*}, \\ \mathrm{N} = 0.00757(1+2.47\varepsilon_*)^{0.14} \tag{20.11}$$

where $\varepsilon_* := \varepsilon_0$ is the so-called normalized roughness and $\varepsilon_0 := (\nu^2/g)^{1/3}$ = 0.05 mm, for temperature 15 °C.

The roughness coefficient ε is a characteristic hydraulic property of the pipe, mainly depending on the pipe material and age, where aging is mainly associated with pipe erosion due to the presence of sediments. For design purposes, it is recommended to apply quite large roughness values, e.g. $\varepsilon = 1$ mm, in order to account for all above factors at the end of time life of the penstock. For the above value, we get ε_*= 1/0.05 = 20, and thus $\beta = 0.262$, $\gamma = 0.009$, and $N = 0.0131$.

On the other hand, local losses, also referred to as *minor hydraulic losses*, are occurring at every change of geometry and thus change of the flow conditions (e.g. flow entrance through the intake, change of diameter, flow split, elbow, etc.). Each individual loss is generally estimated by

$$h_L = k\frac{V^2}{2g} \tag{20.12}$$

where k is a dimensionless coefficient, depending on geometry. Classical hydraulic engineering handbooks (e.g., Roberson et al. 1998) provide analytical relationships, empirical formulas and nomographs for estimating k as function of local geometrical characteristics (e.g., ratio of upstream to downstream diameter). Typical values that are applied in hydroelectrical system components moving from upstream to downstream are:

- $k = 0.04$ for intakes;
- $k = 0.10$–0.15 for grates;
- $k = 0.08$ for contractions;
- $k = 0.10$ for elbows;
- $k = 0.10$–0.20 for fully open valves;
- $k = 1$ for outflow to the tailrace.

In preliminary design studies, local loss calculations are generally omitted, since the geometrical details are not yet specified, or they are roughly estimated, by considering an aggregate value of k for all types of local losses.

20.3.4 Turbines

A hydraulic turbine (from the Latin *turba*, meaning vortex, transliteration of the Greek *τύρβη*, meaning turbulence) is a rotary mechanical structure that converts the available kinetic and pressure energy of water (i.e. the net head) into mechanical work, which is next used for generating electrical power, when combined with a *generator*. Early turbine examples are waterwheels and windmills.

In large hydroelectric systems, turbines are generally classified into two categories, namely *impulse* and *reaction* (Fig. 20.4). In an impulse turbine, a jet of water passing from a contracting *nozzle* enters the curved (double) *buckets* of the turbine wheel to produce energy as the runner rotates. After impinging the buckets, the water outflows freely (i.e. under atmospheric pressure) to the downstream channel (Fig. 20.4, left). Since the jet flow is not axisymmetric, and only part of the runner is activated (typically only two or three out of a total of about 20 buckets are simultaneously hit), impulse turbines are also referred to as *partial admission*. They are also called *Pelton wheels*, in honour of the American engineer Lester Allan Pelton, who invented this machine in the 1870s (apparently by streamlining the traditional windmill technology). As shown in Fig. 20.4 (left), the objective is to convert the available dynamic energy (net head) into kinetic energy by substantially increasing the flow velocity from V_1 to V_2, where V_1 is the velocity through the penstock with diameter D_1, and V_2 is the velocity through the nozzle with diameter $D_2 << D_1$. If Q is the discharge, then from the continuity equation we get

$$Q = V_1\pi D_1^2/4 = V_2\pi D_2^2/4 \Rightarrow V_2 = V_1(D_1/D_2)^2 \tag{20.13}$$

Generally, V_1 ranges from 4 to 6 m/s, while V_2 may exceed 100 m/s. Impulse turbines are applied in the case of significant heads ($H > 250$ m) and relatively small discharge. Large units may have multiple impinging at different locations of the wheel.

There also exist other types of impulse turbines that are applied for low heads and large discharges, e.g. the Turgo turbine, which uses single instead of double buckets on the wheel that are shallower than the Pelton ones, and where the jet is horizontal. Another example is the cross-flow turbine (Fig. 20.5, right), in which the water passes through the turbine transversely or across the turbine blades, and after passing to the inside of the runner, it exits on the opposite side. Passing through the runner twice provides additional efficiency, and also allows for self-cleaning from small debris, leaves etc. Another advantage of cross-flow turbines is the practically flat efficiency curve under varying loads, which makes them ideal for run-of-river plants.

In contrast to impulse turbines, which operate under atmospheric pressure, in reaction turbines, the flow is under pressure, since the chamber of the runner remains completely filled by water. In this case, the runner consists of several guide vanes, which change the direction of flow, thus producing forces due to change of momentum, which in turn make the runner rotate. After leaving the runner, the water enters the draft tube, before being extracted to the tailrace. The objective of the draft tube is to convert the mechanical (hydraulic) energy into rotational energy of runner-generator system, while reducing the flow velocity and hence the kinetic energy at the outflow section, i.e. the tailrace. As shown in Fig. 20.4 (right), this energy is subtracted from the gross head, thus it is a hydraulic loss in the system.

There are two main types of reaction turbines, the so-called Francis machine, which is suitable for a wide range

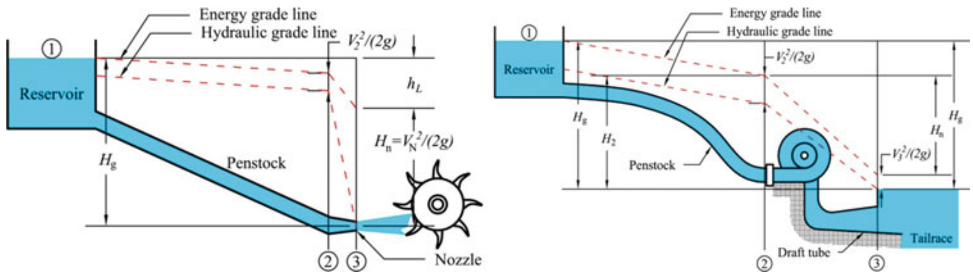


Fig. 20.4 Sketches of impulse (left) and reaction (right) turbines (adapted from Leon and Zhu (2014))

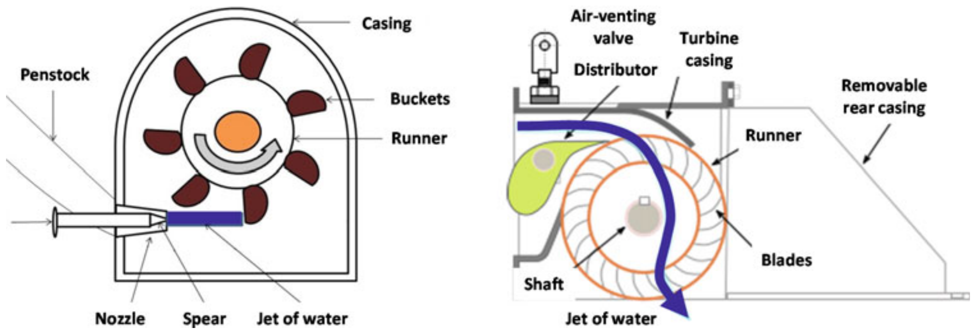


Fig. 20.5 Sketches of Pelton (left) and cross-flow (right) turbines (adapted from Wikipedia)

of discharge and head conditions (and thus applied in the majority of hydroelectric dams, worldwide), and the propeller (also known as Kaplan) turbine, which is employed in cases of high-flow and low-head power production, e.g. tidal stations.

Turbines are also classified according to the main direction of flow in the runner as tangential-flow (Pelton), radial-flow (Francis), mixed-flow (cross-flow) and axial-flow (Kaplan). The selection of the turbine type is driven by the available head and discharge. Within preliminary investigations, we may refer to nomographs, such as in Fig. 20.6. Actually, the overall design of a large-scale turbine system is a very challenging task, also requiring laboratory experiments to identify the geometrical details and assess the hydraulic performance of the specific machine. One of the most important issues to account for within design is cavitation, affecting runners in reaction turbines, in which the relative pressure at the discharge ends of the blades is negative (Novak et al. 2006).

Since the flow conditions differ across different turbine types (e.g., atmospheric pressure for impulse turbines, pressurized flow for reaction turbines) and their geometrical details also differ, the turbine characteristics affect the net head estimations and, consequently, the determination of the optimal diameter of the penstock (Leon and Zhu 2014).

20.3.5 Efficiency of Hydroelectric Systems

The total efficiency (or simply efficiency) η of a hydroelectric plant for a given head and load is the ratio of the electric energy, which is provided to the electricity grid, to the hydraulic energy, i.e. the available net head. The value of η depends on scale (expressed in terms of discharge, since higher discharges ensure larger efficiencies) and the type of the turbine. Very large installations may reach efficiencies up to 95%, while small plants, with output power less than 5 MW, may have efficiencies between 80 and 85%, which again are quite high compared to other types of energy converters (see Sect. 20.1.2.2).

The total efficiency may be considered as the product of four individual components

$$\eta = \eta_T \eta_G \eta_{TR} \eta_E \qquad (20.14)$$

where η_T is the efficiency of the turbines; η_G is the efficiency of the generator; η_{TR} is the efficiency of the transformer, and η_E is the efficiency of the transmission lines. Typical values for the latter three are 0.96, 0.98 and 0.98, respectively.

The turbine efficiency is defined as the ratio of the mechanical energy provided by the turbine to the net head. The difference between the two energy quantities is due to:

- *Hydraulic losses*, which refer to friction losses of the fluid layers in motion, friction losses due to water crash on blades, local losses due to changes of tube section, etc.;
- *Volumetric losses*, which are only occuring in case of impulse turbines, and they are due to small amounts of water that are extracted to the atmosphere, without crashing on the blades;

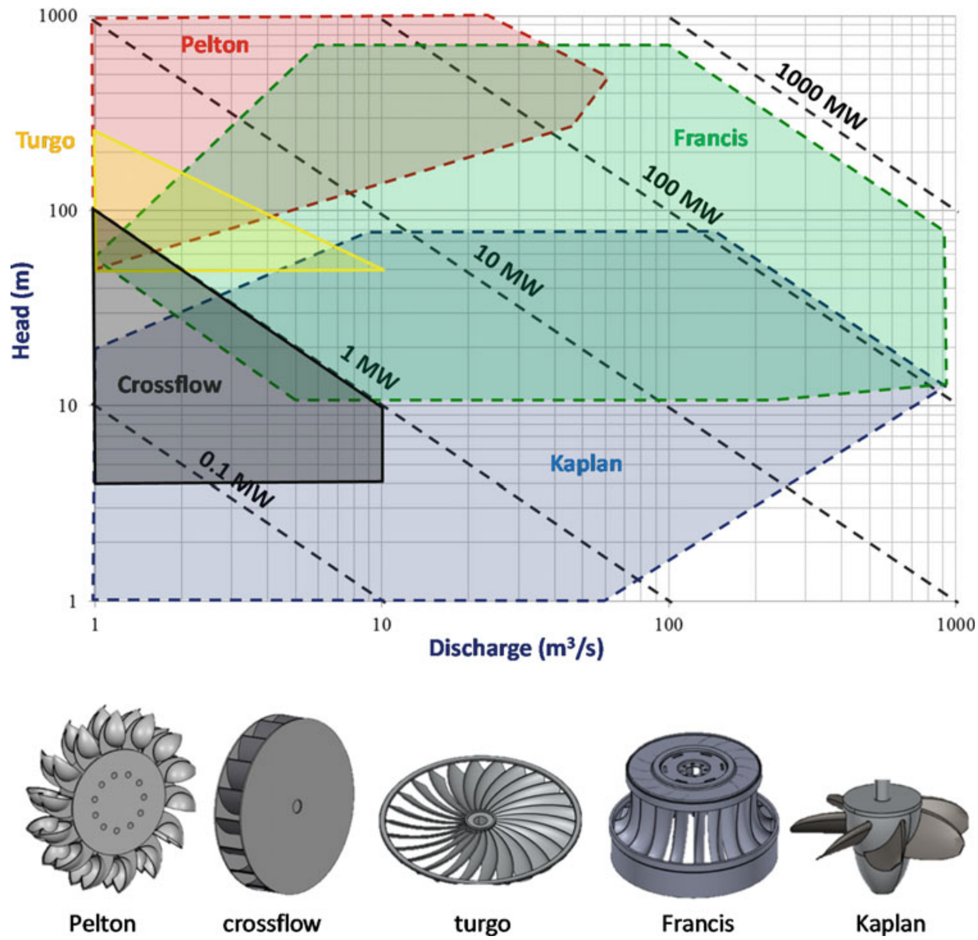


Fig. 20.6 Recommended ranges of application of different turbine types

- *Mechanical losses* that are developed in the rotating parts of the turbine.

Therefore, η_T is also derived as the product of three components, i.e. hydraulic, volumetric, and mechanical efficiency, with typical values 0.90–0.96, 0.97–0.98 (only for impulse turbines) and 0.97–0.99, respectively.

Although in preliminary design and common management studies the efficiency is considered constant, it is actually a complex function of head and load. In real-world conditions, e.g. in case of large hydroelectric dams, the two aforementioned quantities are varying in time, since they depend on the reservoir level and the discharge, which are also evidently varying. As shown in Fig. 20.7, the variation of efficiency against head and discharge for different gate opening ratios is typically expressed by means of nomographs, which are experimentally derived and provided by the manufacturer of the turbine. For a specific turbine, there exists a theoretically optimal efficiency that is achieved for a specific combination of head and discharge. However, the actual optimum may differ, since the operation of the turbine is determined by the head-discharge relationship of the penstock, i.e. $H_n = H - h(Q)$ (where $h = h_f + h_L$), dictating the feasible operation range. Since across this range the efficiency may differ significantly, also taking quite low values, a key design objective is to ensure that the turbines will mostly operate as close to the optimal efficiency value as possible. In hydroelectric reservoirs, this is achieved by properly tuning the opening of turbine gates, thus adapting the outflow to the given head conditions.

20.3.6 Pumps and Pumping Systems

Pumps convert mechanical energy to hydraulic energy, thus allowing to lift water from a lower to a higher elevation or to increase the discharge capacity across a water-transportation system (or even to boost water conveyance from a higher to a lower elevation by adding energy for the increased frictional losses). Pumps are classified into two categories, namely *positive displacement* pumps, which deliver a fixed amount of water with each revolution of the rotor, and *rotodynamic* or *kinetic* pumps, which apply energy to the water by accelerating it through the action of a rotating impeller. Archimedes' screw pumps (see Sect. 20.1.1) are also another category, still in use, but it is not examined here.

Rotodynamic pumps are the most usual type used in water resource systems (Chin 2006). The pipe upstream and downstream of a pumping system are called *suction* and *delivery* pipes, respectively, conveying water from an upstream level z_1 (water source) to a downstream level z_2 (destination tank).

As shown in Fig. 20.8, the total energy head provided by the pump, called *manometric head*, is the sum of the following components

$$H_m = z_2 - z_1 + h_L + h_f + V^2/2g \quad (20.15)$$

where h_L are local head losses at the pump; h_f are friction losses across the suction and delivery pipes, which are estimated by Eq. (20.9) as function of the diameter, roughness and discharge, and $V^2/2g$ is the kinetic energy at the downstream end, e.g. the destination tank (which is another local head loss). Equation (20.15) represents the hydraulic operation of the pipeline system, expressing the manometric head H_m as function of the discharge Q.

Each pump also has a *characteristic curve* or *performance curve*, showing the relationship between the manometric head H_m and the discharge Q. Thus, a combination of a specific pump with a specific pipeline has a unique operation point, which is determined by the intersection of the two curves (Fig. 20.9).

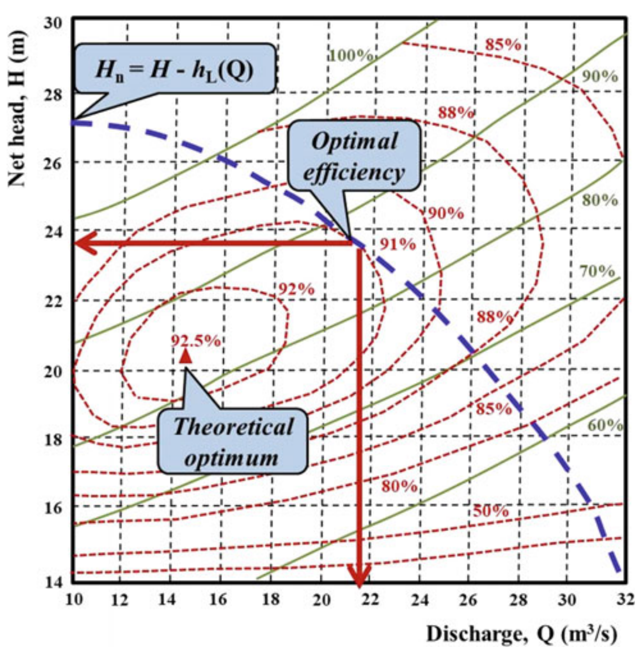


Fig. 20.7 Example of performance curves of a specific hypothetical combination of turbine and penstock, showing efficiency values for different head, discharge and gate opening ratios, along with a plot of the head-discharge relationship

Usually, a pumping station comprises a set of pumps that are put either in series (multistage pumps) or in parallel. In multistage pumps two or more impellers are arranged in series with the discharge from the first impeller entering the eye of the next one and so on. This layout is preferred when large heads are required, e.g. in a case of deep underground abstractions. In that case, considering N similar pumps, the total head is divided by N, while the total flow is conveyed through all individual pumps. On the other hand, in the parallel configuration, the discharge is divided by N, where the total manometric head is estimated by summing each of all individual pumps. We remark that whenever a pump in series or in parallel is added to the system, the operation point of the pumping system changes accordingly.

20.3.7 Reversible Turbines

Reversible turbines are specific types of hydrodynamic machines that can operate both as turbines and pumps. Such systems are typically installed in pumped-storage plants, which allow to pump water to an upstream location by consuming the available excess of electric energy (or low-price energy, e.g. during night), so to be retrieved later as hydropower. The importance of these systems has increased significantly due to the great expansion of renewable energy sources, such as solar and wind energy, which are highly-uncertain as the energy generation depends each time on current meteorological conditions (Koutsoyiannis et al. 2009). In this context, pumped-storage systems are essential to regulate the excesses and deficits of energy production through renewable sources, as discussed further in following sections.

20.4 Design and Operation of Hydroelectric Systems

20.4.1 Classification of Hydroelectric Systems

Hydroelectric systems comprise a wide range of layouts, from large-scale reservoirs to minor run-of-river plants, which take advantage of the available dynamic and kinetic energy of water across rivers and streams. These may be classified into categories (a) to (g), according to a number of criteria that are listed below, which also dictate the design and management of such systems.

(a) Based on their *installed capacity*:
- Large hydro plants for $P > 15$ MW;
- Small hydro plants for $P < 15$ MW;
- Micro hydro plants for $P = 5$ to 100 kW;
- Pico hydro plants, for $P < 5$ kW.

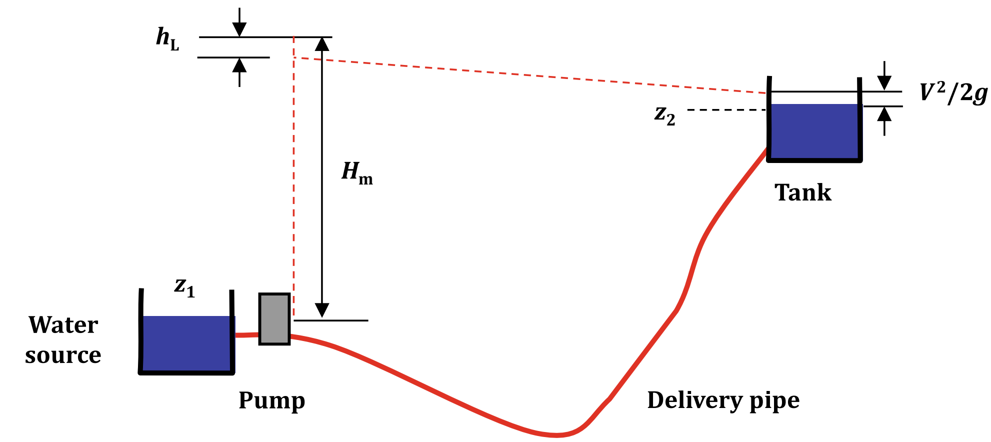


Fig. 20.8 Sketch of a typical pumping system

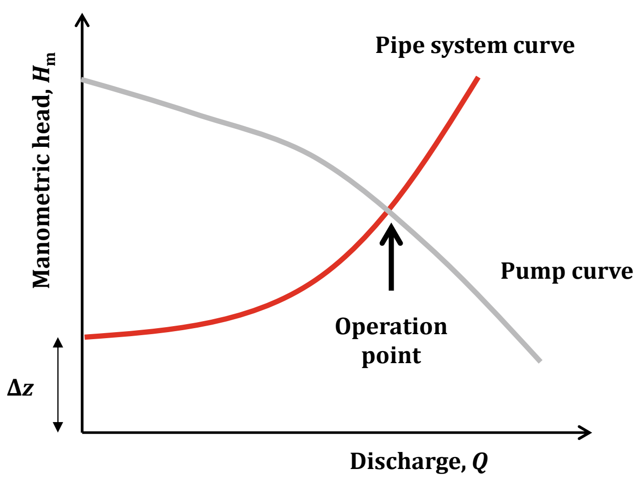


Fig. 20.9 Definition of operation point of a pumping system

The thresholds used may differ worldwide; for instance, the threshold for large and small plants typically ranges from 5 to 20 MW. Usually, but not exclusively, large plants are installed downstream of dams, to take advantage of the regulating capacity of the reservoir. Small plants may or may not have storage capacity, while micro and pico hydro plants only capture the kinetic energy of small streams to provide electricity to isolated homes or small communities.

(b) Based on their *head*:
- Large head for $H > 200$ m;
- Medium head for $H = 30$ to 200 m;
- Small head for $H < 30$ m.

As explained in previous section, the available head combined with discharge determines the selection of the turbine type.

(c) Based on the *location of the power station*:
- Power stations installed close to the dam;
- Power stations installed at a significant distance downstream of the dam;
- Power stations installed at an adjacent river basin (interbasin water transfer).

The typical case is the first, thus involving a penstock of relatively small length, in order to minimize the friction losses and the environmental impacts. Yet, there are cases where it is more advantageous to construct the power plant at a downstream location in order to increase the available head. Apparently, such a layout is economically efficient only when the river slope is large, so that the gains from elevation difference exceed the hydraulic losses due to the water being transferred at a long distance. An important issue to account for is the environmental impacts, since the water does not return to the river just downstream of the dam, as happens in typical configurations where the power station is located close to the foot of the dam.

Another case is the installation of the power station in a neighbouring basin, where the water is transferred through a pipeline connecting the two basins. This layout is preferred when there is a significant elevation difference between the upstream catchment, in which the water is gathered, to the one downstream, where the power station is installed. Typically, in large-scale interbasin systems, Pelton type turbines are used, as this option becomes economically efficient when the head is large enough. However, if the transfer is implemented for other reasons (e.g. if the principal objective is the transfer of water per se), then the head may be small.

(d) Based on the type of the *hydrodynamic machine*:
- Action turbines;
- Reaction turbines;
- Reversible turbines.

As already explained, action turbines are applied only in case of relatively small discharges and large heads, while reaction turbines are employed in any other case. Reversible turbines are applied within pumped storage systems, which require a cascade of two storage components, one upstream and one downstream. Although any combination of storage systems is generally valid, the most usual case is when a large hydroelectric reservoir (typically called head reservoir) is located upstream to implement long-term flow regulations, and a small-one downstream. Another widely used scheme comprises a reservoir, installed across the river, connected with a run-of-river tank, installed at a relatively small distance but at a higher elevation.

(e) Based on the *reservoir scale*:
- Large-scale reservoirs, having storage capacity larger than the mean annual inflow, thus ensuring multiannual regulation of the river flows;
- Medium-scale reservoirs, providing seasonal regulation of inflows;
- Small-scale reservoirs that are constructed to create an artificial head, but have minimal regulation capacity;
- Run-of-river plants without storage capacity.

(f) Based on the *time-schedule of turbine operation*:
- Continuous (or almost continuous) operation to provide base-load electricity;
- Intermittent operation to provide peak-load electricity;
- Pumped-storage operation to regulate energy production excesses and deficits from other sources.

It is well-known that a major advantage of (hydro) turbines is their almost immediate response, as they can be activated very quickly to adapt to changing energy demands. In this context, hydroelectric works are the most flexible source of electricity. In particular, large and medium-scale reservoirs may provide both base and peak load, since they offer enough storage capacity to operate independently of the inflows. However, in the current energy scene, comprising multiple energy sources, the typical operation of such works is for fulfilling peak energy demands by releasing water only during a few hours per day (a tactic called *hydropeaking*).

Small hydroelectric works with minimal or negligible storage capacity do not offer the opportunity to regulate outflows and they may also have intermittent operation. Actually, the energy production follows the variability of input process (in this case, streamflow), similarly to other renewables such as solar, wind and wave plants.

(g) Based on the *water uses* served by the reservoir:
- Single-purpose use, i.e. exclusively for hydropower generation;
- Multiple-purpose use.

Often, hydroelectric reservoirs serve additional water uses, such as water supply and irrigation, and also provide flood control. Environmental constraints are also imposed to the operation of existing and new dams, typically by means of releasing a constant (or sometimes varying) flow rate downstream of the dam to maintain riverine ecosystems. Such uses do not allow fully exploiting the hydrodynamic potential of the reservoir system, because water abstractions, water level regulations or water release schedules differ from the ones maximizing power production. In many hydroelectric reservoirs worldwide, recreation activities and associated touristic infrastructures have been developed as result of the generation of an artificial landscape and ecosystem of important aesthetic and environmental value, thus introducing additional constraints to the primary water use, which is energy production. Nevertheless, as multipurpose hydroelectric reservoirs are by definition subject to complex and generally contradictory objectives, a rational management policy is essential to ensure an optimal balancing of the associated conflicts (Christofides et al. 2005; Efstratiadis and Hadjibiros 2011).

20.4.2 Hydrological Analysis

For an assessment of an existing or planned hydroelectric system, it is essential to estimate the available water yield from the upstream catchment, as well as its variability, at multiple temporal scales. The surface runoff produced by the catchment is either directly available, by means of flow observations at the site of interest, or estimated indirectly, through a hydrological model. In the literature, numerous modelling approaches are available, of different levels of complexity.

The time scale of hydrological analysis depends on the scope of the study, but also depends on characteristic scales of the hydroelectric system. For the simulation of large reservoirs, a monthly time scale is typically adopted, while for small hydroelectric works the recommended temporal scale of hydrological analysis is daily. However, other aspects of the overall design and management may require another temporal resolution, for example, hourly or finer for flood analysis purposes, and daily for environmental flow assessment.

There are two ways of expressing the variation in river flow over the time period of interest, namely the hydrograph and the so-called *flow duration curve* (FDC), which is none other than the empirical exceedance probability plot (EEPP) of observed flows. The hydrograph (flow time series) depicts the evolution of flow for a specific time scale (annual, monthly, daily, hourly) over a specific time period. In case of hydroelectric works with non-negligible storage capacity, the sequence of flows plays a crucial role on the energy production, as it determines the required flow regulation by the reservoir.

The FDC (EEPP) is constructed by sorting the flow data in descending order and assigning an empirical exceedance probability based on the order of each value. Thus, the vertical axis represents the flow value and the horizontal axis the percentage of the time that the flow exceeds the given flow value. As the FDC (EEPP) expresses the distribution of flow values over a time period, a flatter curve corresponds to a more even spread of the annual inflow over the year. On the empirical probability distribution function, a proper theoretical model can be fitted using the typical probabilistic methodology. In this respect, the FDC (EEPP) of the river inflow at a specific site can be mathematically modelled as

$$P(Q) = 1 - F(Q) \quad (20.16)$$

where Q is the discharge; P is the exceedance probability of the value Q (also thought of as the fraction of time in which Q is exceeded), and F is the probability distribution function.

Figure 20.10a illustrates the hydrograph of 21 years of daily flow data. Based on it, one can recognize the seasonal variability of flows and the sequence of wet and dry periods. Figure 20.10b depicts the FDC (EEPP) constructed from the same data. As an example, from the FDC we easily see that the flow rate that is available for at least 30% of the time period is about 1.0 m^3/s; likewise, a flow rate exceeding 2.0 m^3/s is available in 15% of the time period.

20.4.3 Hydroelectric Reservoirs

Planning and management of hydroelectric reservoirs, often stated as an optimal control problem, remains a challenging issue, although a plethora of methods and software tools are available worldwide (e.g., Celeste and Billib 2009, Labadie 2004, Nicklow et al. 2009). At the start of the twenty-first century, the growing share of renewable sources with intermittent delivery created a need for novel means for energy regulation and storage. Classical system-based methods, i.e. linear, nonlinear, dynamic or stochastic dynamic programming as well as more advanced concepts and tools, such as fuzzy logic and neural networks, fail to provide the essential holistic approach with regard to the various complexities of the problem. Problems arise due to the large number of variables, the nonlinearities of system dynamics (e.g. the dependence of energy production on the reservoir level), the inherent uncertainty of future conditions (inflows, demands), as well as the multiple and often conflicting water uses and constraints that are involved in the operation of such systems.

Simulation allows for a detailed and faithful representation of reservoir systems and the evaluation of their performance, since it accounts for all technical (e.g., storage and flow capacities) and operational (e.g., desirable storage and flow ranges) constraints that are involved in the actual operation of such systems. In a following section we will see that the simulation can be performed within stochastics (Monte Carlo simulation) and can further be incorporated in an optimization framework, thus providing a powerful methodology for optimal design and management of complex hydrosystems.

Within a simulation context, the reservoir dynamics is described through the water balance equation, expressed in discrete-time form, i.e.

$$s_{t+1} = s_t + i_t - r_t - w_t \quad (20.17)$$

where s_t is the reservoir storage at time step t; i_t is the accumulated net inflow within time interval [t, t + 1], i.e. runoff produced over the upstream catchment and precipitation falling over the reservoir surface minus water losses due to evaporation and possibly leakage (inflows may also include water diverted from adjacent catchments); r_t are the controlled water releases through the intakes, and w_t are (occasional) overflows through the spillway. For a given storage at the beginning of simulation s_0, a given sequence of inflows i_t (either projected or synthetically generated), and given a demand, Eq. (20.17) can be explicitly solved to provide the unknown quantities, i.e. storage, release and spill, at each time step. In particular, for a specific demand d_t, the actual release will be the minimum between the available water and the desirable release to meet this demand, i.e.

$$r_t = \min\,(s_t + i_t - s_{\min}, d_t) \quad (20.18)$$

where $s_{\min}$ is the reservoir storage at the minimum operation level, i.e. up to the intake (Fig. 20.3).

On the other hand, if the remaining storage after implementing releases exceeds the reservoir capacity $s_{\max}$, the surplus quantity is considered water loss due to spill, i.e.

$$w_t = \max\,(0, s_t + i_t - r_t - s_{\max}) \quad (20.19)$$

In the case of hydroelectric reservoirs, where a desirable energy production target is assigned, the demand at each time step is estimated on the basis of both the energy target, E, and the available head, $\overline{H}_{\mathrm{n}}$, by solving Eq. (20.4) for the volume, i.e.

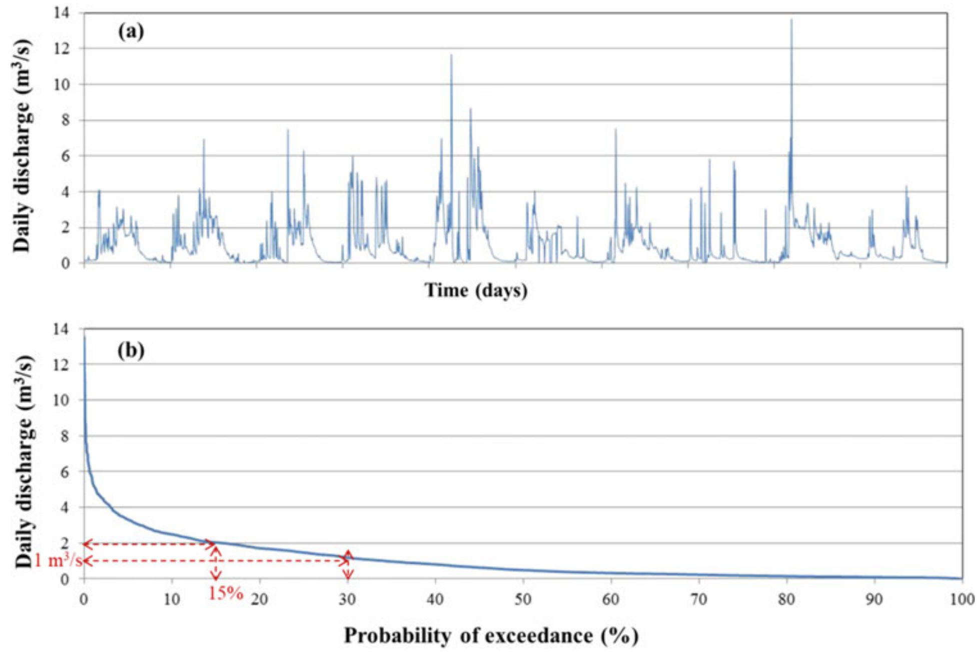


Fig. 20.10 **a** Daily hydrograph of a 21-year period, **b** Flow duration curve (empirical exceedence probability plot)

$$d_t = \frac{E}{\rho g \overline{H}_{\mathrm{n}} \overline{\eta}} \quad (20.20)$$

In Eq. (20.20), the average head $\overline{H}_{\mathrm{n}}$ is a function of the discharge and the reservoir level over the time interval. These are actually unknown. In order to provide an explicit solution in the simulation, the varying reservoir level is approximated as constant and equal to the level at the beginning of the time step. This approximation introduces some error in simulations, which requires adopting an appropriately small time interval in order to ensure relatively small fluctuations of the reservoir level within a time step.

Another key characteristic of hydroelectric reservoirs is the occasional generation of the so-called *secondary energy* by passing surplus flow through the turbines in order to avoid or minimize spill losses, thus releasing more water than the one imposed by the associated firm energy target. The price of secondary energy is lower than the firm one, as its production is unpredictable and not dictated by a systematic release policy. Actually, this resembles energy produced by other renewables, including small hydroelectric works, where the lack of storage capacity makes the energy production follow the pattern of randomly varying inflows instead that of the demand.

Figure 20.11 shows the output time series from a simulation example, involving the monthly operation of a hydroelectric reservoir at Central Greece, where a hypothetical constant energy target of 18 GWh per month is assigned. The total capacity of the reservoir is 361 hm^3 (cubic hectometres, that is, million cubic meters) and the net capacity is 286 hm^3. The last diagram in Fig. 20.11 depicts the time series of monthly energy production. The target of 18 GWh is fulfilled in 554 out of 558 of simulated steps, thus the firm (reliable) energy is ensured with reliability up to 554/558 = 94% on a monthly basis. Moreover, in 50 out of 558 steps, the energy production exceeds the target, thus this surplus is considered secondary energy. In this example, there seems to be a clustering of wet years, resulting in water losses due to spill and generation of secondary energy, and another clustering of dry years, resulting in energy deficits. This phenomenon is known as *long-term persistence* and is associated with the changing hydroclimatic behaviour, the so-called Hurst-Kolmogorov dynamics. As explained in Sect. 20.8.3, this natural behaviour influences greatly the design and management of water-energy systems (Koutsoyiannis 2011b).

The simulation procedure can be generalized to include additional reservoirs as well as other hydrosystem components. Moreover, it can be easily combined with a stochastic model to generate synthetic inflows for long simulation horizons, which should essentially reproduce the long-term persistence, and an optimization model to derive a release policy that ensures the optimal performance of the system. Optimization is substantially facilitated if the entire representation is parsimonious, i.e. if the number of control variables is kept as small as possible. This is ensured through a suitable system parameterization, in terms of parametric expressions of operation rules for the major system controls (e.g. reservoirs, power plants). The above scheme is also referred to as *parameterization-simulation–optimization* framework, which is a generalized Monte Carlo methodology for modelling hydrosystems of any complexity (Koutsoyiannis and Economou 2003; Koutsoyiannis et al. 2002). This approach also allows for evaluating the system operation, constraints and objectives in probabilistic terms and also expressing firm (or better named *reliable*) energy in terms of *reliability*.

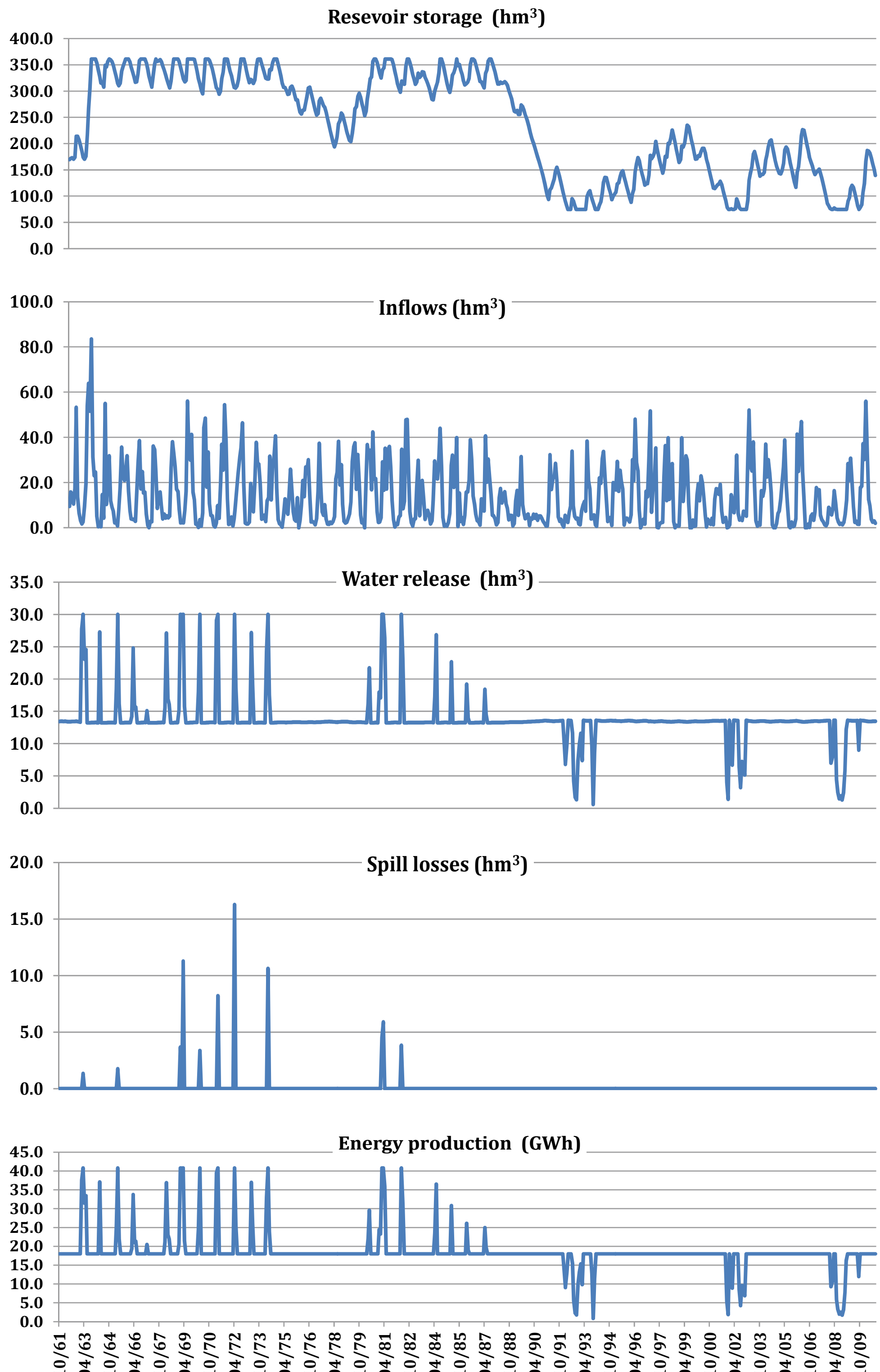


Fig. 20.11 Example of monthly simulation of Plastiras reservoir, Central Greece, considering the observed inflows of years 1961–2010, and by assigning a constant energy demand of 18 GWh per month (adapted from Efstratiadis and Hadjibiros 2011)

20.4.4 Small Hydroelectric Works

As already mentioned, a hydroelectric plant is typically classified as small or large by considering a threshold on its installed capacity. This threshold varies considerably around the world, but values between 5 to 20 MW are the most common. Generally, most of such systems have negligible storage capacity, thus their design aims at maximizing the power production by capturing as much of the available runoff as possible.

Figure 20.12 illustrates a sketch of the most characteristic type of a small hydroelectric work, referred to as run-of-river plant. The main elements of the system are: (a) a weir with a water intake that controls the amount of river flow to be used for hydroelectricity, (b) a channel that conveys the water to forebay tank, (c) the penstock, (d) the power station, and (e) a tailrace that conveys the water back to the river. In the typical layout of Fig. 20.12, the power station is located far away from the intake to ensure an economically effective elevation difference between the forebay tank and the power station, but the case that it is embodied in the intake is also common.

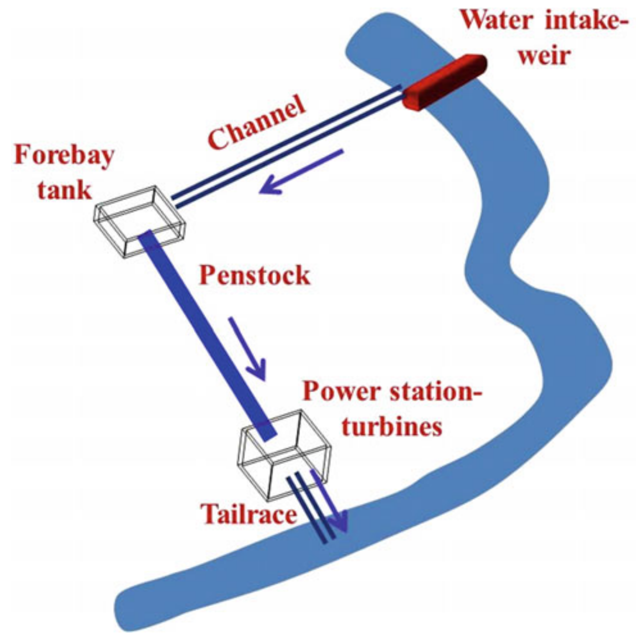


Fig. 20.12 Main components of a small hydroelectric work

For a given installed power capacity P and hydraulic head H, the turbines produce energy for a certain range of discharges and associated efficiency values. Except for very large flow values, the relationship between the discharge and the efficiency is monotonically increasing. The discharge ensuring the maximum power production is referred to as *nominal discharge*. For smaller discharge values, the turbine operates at lower power, while below a threshold equal to 10–20% of the nominal discharge, the turbines do not produce electric energy. In this respect, the turbines operate within a specific flow range [Q_{min}, Q_{max}].

The nominal discharge is a key element of the overall system design, since it also dictates the capacity of the water intake, the channel, and the forebay tank. Typically, the latter has very limited regulation capacity, because its objective is preserving a practically constant upstream head. Under this premise, the water intake is designed to capture up to the nominal discharge of the turbines Q_{max}, while the surplus amount overflows from the weir to the river. During periods that the river flow is lower than Q_{min}, the power station stops its operation. At all intermediate flow ranges, all available water is used for energy production, which depends on the actual discharge and associated efficiency of the system. The key difference of the above configuration with a typical large hydroelectric work is the lack of the regulation capacity offered by the reservoir. The lack of water storage makes impossible to exploit flows that are out of the operational range [Q_{min}, Q_{max}]. In contrast, a hydroelectric reservoir not only can take advantage of any flow, but also ensures a scheduled energy production under optimal flow and efficiency conditions. For as the storage capacity increases, the reliability of the energy production also increases, since it absorbs the fluctuations of inflows at the seasonal and the over year scales. The higher the variability of inflows, the larger the reservoir capacity should be to minimize losses due to spills or deficits due to long-term droughts.

Due to the lack of a storage component, run-of-river hydroelectric plants can exploit only part of the potential hydrodynamic energy. In this respect, key objective of their design is to maximize the long-term energy production via a proper selection of a turbine mix that ensures a large enough flow range [Q_{min}, Q_{max}] and as high as possible efficiency rates. Usually, this problem is examined by considering the flow-duration curve at the site of interest, which allows defining on a mean annual basis (a) the percentage of the exploited water volume by aggregating the flow-time curve within the range of operational discharges and (b) the corresponding time of turbines operation. A numerical example is given in Sect. 20.10 at the end of the chapter.

20.5 Energy-Mix and Hybrid Water-Energy Systems

20.5.1 Energy Systems Design

In order to satisfy energy demand on a national scale, each country uses a combination of various energy sources, which is typically referred to as “energy mix”. Although some types of fuels are strongly preferred for some needs, for example, petroleum for transportation, in the case of electricity production, there is a high degree of flexibility in configuring the existing energy mix. Isolated areas, such as remote islands not connected to the national grid, may have their autonomous mix. Remote stand-alone power systems that implement renewable energy technologies, by mixing two or more renewable energy sources, have been known as hybrid renewable energy systems. Hydropower is the most important component of such systems, as it provides increased system efficiency as well as greater balance in energy supply.

The main factors that influence the energy mix of a country are the following:

- The quantity and type of energy demand to be satisfied.
- The available energy resources (and their potential), such as availability of fossil fuels, existence of hydropower, wind and solar radiation potential and geothermal fields.
- Political conditions in the wider area that are related to fuel and energy transfer.
- Construction, maintenance and operation costs, i.e. life-cycle cost of energy works.
- Social acceptance of environmental issues associated with, for example, nuclear energy use, CO_2 production, or the influence of energy production on fauna and flora.

In general, electrical grids suffer from the critical limitation that they must be continuously fed with the same amount of energy that is consumed. As the electric energy demand is, practically, uncontrollable, the electric energy production must be continuously adapted to follow the demand that changes irregularly. The long-term statistical characteristics of energy consumption time series in an electrical grid, e.g. year-long, determine the design of the grid and the composition of the energy mix. The most important statistics are the maximum and minimum electric energy demand at fine time scales, e.g. hourly or less.

The minimum electric energy demand (base load) determines the threshold of energy that must be continuously produced while, the maximum demand (peak load) determines the minimum installed power capacity of the electrical system.

The ability of a power plant to contribute to synchronization of production and demand in an electrical grid that uses various energy resources depends on three important issues:

- *Control and predictability of energy production.* In thermal power plants the energy production is under the control of the operators, but it is not easily adaptable to changes; it depends only on fuel availability and operational readiness. However, for renewable energy resources the amount of control of the operators over the process depends strongly on the type of resource. For some resources energy production is completely controlled (e.g., biomass, geothermal), for others there are limits on control, but those limits can be reliably predicted (e.g., tide). Finally, there are resources that depend on unpredictable natural processes (e.g., wind speed, solar radiation, water flow, waves). In these cases, the energy production has poor predictability and cannot offer reliability to electric energy grids. This is a great weakness, making them more difficult to fit into an energy mix than more conventional sources. To promote them, states have prioritized the modification of their energy grids to allow absorption of the electricity produced from this type of renewables. Controllability and predictability of hydropower tend to be high when water is stored in large hydroelectric reservoirs; in that case the system is vulnerable only during long-term droughts.
- *Time that is required to adjust the energy production.* The time that is needed to change the energy production to follow demand depends on the type of power plant. This time ranges from several hours (or even days) for coal and nuclear stations to a few hours for natural gas thermal stations, and to a few minutes for hydroelectric stations. The adaptation time of power plants determines their role in electrical systems. Peak loads are covered mainly by hydroelectric stations and base load mainly by coal and nuclear stations.
- *Ability to store energy.* The issue of electric energy storage is very important, especially in cases that renewable energy sources represent a considerable share in the energy mix. In fossil and nuclear fuels, the energy is stored inside the material, and the total amount is measurable and expressed by local and global reserves. The installed capacity of thermal power plants is designed based on the desired degree of exploitation of the available (local or regional) reserves. Considering the renewable resources, opportunity of storage is only offered by hydropower (using reservoirs) and biomass. Additionally, for geothermal fields, the total "stored" energy can be estimated, while tidal energy is reliably predicted. Surplus energy by other renewable sources could be stored through pumped-storage schemes or in batteries. From the start of the twenty-first century extensive research and development on batteries is in progress, but at that point in time batteries were considered an option suitable only for smaller scale systems.

20.5.2 The Concept of Capacity Factor

The ability of electric energy production by a power plant that has a specific installed power is expressed by the capacity factor (CF). CF over a time period is defined as the fraction of the actual electric energy produced from a power plant to the electric energy that could be produced considering continuous operation of the plant at the maximum installed power. For a specific power plant, the potential electric energy that can be produced is a structural characteristic, calculated by multiplying the installed power by the time period length. Thus, the CF always depends on the quantity of electric energy that is actually produced by the plant.

The CF expresses different characteristics in various electric power plants. In thermal power plants, the installed power is determined taking into account economical and operational parameters, such as the energy demand, the availability of fuels, as well as socioeconomic and operational parameters. Energy production is controlled, except in emergency situations such as accidents, lack of fuels, etc. The CF of a time period can be scheduled taking into account the desired operation time and the active power used. Theoretically, a thermal power plant for a given time period may have a unit CF, if it is operated continuously at maximum power.

In wind and solar power plants, the energy production is uncontrollable as it depends on a meteorological process (wind speed, solar radiation). The installed power of a specific plant is exploited only for time periods that the associated input takes on values within a specific range. Otherwise, the power plant produces less energy or remains inactive. For example, contemporary wind turbines produce the energy that corresponds to the installed (nominal) power, when wind velocities are between 12 and 25 m/s. For lower velocities (typically, 3–12 m/s) turbines produce only a fraction of its maximum output. For wind velocities outside the range of 3–25 m/s turbines cease to operate. As a result, it is impossible for a wind turbine to have annual CF approaching 1, and values of about 0.3–0.4 are common. In solar power plants, the CF is limited by the sunshine hours. As the potential sunshine hours are, on average, half of the total, there is a physical limit of 0.5 to CF in solar power plants. Yet, less or even no energy is produced when sun is located low on the horizon or the weather is cloudy. For these reasons annual CFs of about 0.2–0.3 are common in solar power plants.

20.5.3 Combined Management of Water Energy Systems

Water and energy are vital goods for human societies and must be provided in a sustainable, reliable, cost-effective and environmentally friendly way. Therefore, the design, operation and management of water-energy systems are very important issues.

Water and renewable energy sources are sustainable by nature (Koutsoyiannis and Efstratiadis 2012). The unexhausted solar energy drives the eternal hydrological cycle that feeds the natural system with water. Solar energy also drives the processes of wind, sunshine, waves, and vegetation, supporting the water-food-energy production. Additionally, the astronomical motion controls tidal energy. However, the concept of water-energy sustainability in societies is related to ensuring satisfaction of the various demands, not only in the present but also in the future. Water and renewable energy sources must be synchronized with various demands in space and time, and therefore, storage and conveying works are necessary. Water and energy storage are essential to water-energy systems.

Key concepts of uncertainty, reliability and optimality should be taken into account in order to ensure rational and sustainable solutions to the design and management of highly complex water-energy systems. As discussed herein, uncertainty is an inherent property of hydro-meteorological processes that are related to water and renewable energy sources. As predictions of future water and energy production using deterministic methods are impossible, the statistical behaviour of the associated natural processes is studied, and stochastic modelling is performed for uncertainty quantification. The uncertainty of water-energy resources availability strongly affects the reliability of water-energy systems. The latter is typically expressed either as a constraint, imposed by the system manager, or as an objective to maximize, which is equivalent to minimizing the risk of water-energy shortage. Nevertheless, optimal design and management of water-energy systems should ensure both minimization of construction and operational costs and maximization of their long-term performance in terms of safe yield, mean economic benefit, firm energy, etc. In water-energy system optimization, there are several hard issues to handle such as the large number of variables and constraints, nonlinearity of system dynamics, uncertainty of future supplies and demands, and competitive or conflicting objectives.

20.5.4 Suitability of Hydroelectric Reservoirs for Integrated Water-Energy Management

Several characteristics make hydroelectric reservoirs essential for water-energy systems:

- In contrast to other renewable sources, hydropower produced by large reservoirs is almost fully controllable. While streamflow is a stochastic process, when stored in the reservoir, its variability is regulated which allows for scheduled energy production in the long run. As the storage capacity of a reservoir increases, the reliability of energy production also increases. This is because the ability to store water smooths out the natural fluctuation of inflows during drought and flood periods and ensures that electric energy is produced according to schedule.
- They can serve more than one purpose. The release of water for energy production can be combined with local water uses (irrigation, domestic), flood protection and recreational activities in the reservoir area.
- Hydroelectric reservoirs store the electric energy production of other energy sources (mostly renewables) using mainly pumped storage systems. These systems pump water to a higher location, when there is excess of energy in the grid (e.g. during night hours or even during sunshine hours in the case that the solar energy is a substantial component of the energy mix), and later, when lack of energy occurs, retrieve the water to generate hydropower. The efficiency of pumped storage systems is very high (more than 80% for large-scale systems). Today several wind farms store the produced electric energy in nearby pumped storage projects.
- Hydropower is a flexible source for electricity management, since the produced energy can be increased or decreased very quickly to follow changing energy consumption in the grid. The start-up of hydro-turbines is in the order of few minutes, much shorter than for other types of power plants.
- Hydropower offers sustainability as it ensures enough energy to satisfy various demands now and in the future. As fossil fuels are limited in quantity and expendable, while most renewable energy sources are unpredictable and uncontrollable, hydropower can support sustainability in the electric grids.
- While the installation cost of hydroelectric reservoirs is relatively high, hydroelectric stations have long economic lives (50–100 years) and low operational and maintenance costs.

The main disadvantages of hydroelectric power plants are related to their environmental impacts. The main ones that are referred to the literature are: (a) inundation of large areas of land and possible displacement of local population, (b) changes to water and sediment regime of the river, (c) block of fish migration, and (d) failure risks for downstream settlements and infrastructures. These issues are analysed in more detail in Sect. 20.7.1.

20.5.5 An Illustrative Example of Renewable Resources Management

On islands that are not connected to the electric grid, the electric energy is mainly produced by oil-fuelled power plants, whose unit cost is high due to oil import cost. Therefore, the integration of renewable resources in the energy mix is essential for reducing the financial and environmental cost. A pilot investigation of how various energy resources (renewable and fossil fuels) can be evaluated using technical, environmental and economic criteria in order to create the appropriate electric energy mix for a non-connected island can be seen in Chalakatevaki et al. (2017). Particularly, six basic renewable resources are examined (solar, wind, marine, hydropower, biomass and geothermal) for the energy mix in a non-connected island at the Aegean Sea (Astypalea, Greece). Table 20.2 summarizes the outcomes from two case scenarios, based on a preliminary (but indicative) analysis where each source has to be harvested according to the energy demand (Mavroyeoryos et al. 2017) and economic analysis (Karakatsanis et al. 2017) for the selected case. Therefore, a separate stochastic and cost analysis was first employed for solar energy (Koudouris et al. 2017), wind and marine energy (Moschos et al. 2017), hydropower with a pumped storage system (Papoulakos et al. 2017), biomass and geothermal energy (Chalakatevaki et al. 2017). The second case that was finally selected includes two wind turbines of 75 m height, 3800 m^2 of photovoltaic panels, two wave converter installations, addition of a small hydro turbine to the existing dam, a biomass facility fed with 180 t/year of cultivated biomass, and a pumped storage system that includes a reservoir with storage capacity of 0.5 hm^3, a 2 km penstock and a hydro turbine installation. The total installed power of the proposed solution is 4.8 MW (with a peak demand of 2.6 MW) with a total cost of more than 10 M€.

20.6 Marine Energy

Marine energy can be considered as the most widely spread, reliable and efficient nearshore renewable energy resource with a theoretical annual potential of approximately 400 EJ or 10^5 TWh. However, while the technology for harnessing other renewable resources, such as wind and solar, is continuously evolving, marine energy is expected to make a

Table 20.2 Analysis of two selected scenarios for a small non-connected island

Source	Estimated cost (M€/MW)	Power (MW)	
		Case 1	Case 2
Wind turbine	1.5–2	1	1
Solar panels	2–3	0.5	0.5
Hydroelectric dam	1	0.08	0.08
Wave energy converters	3–4	0.3	0.6
Geothermal power station	1–2	0.5	–
Pumped storage system	1.5–2	–	1
Biomass power station	2–3	2.1	1.6
Total		4.5	4.8

Source Chalakatevaki et al. (2019)

significant contribution in the twenty-first century due to its nascent stage of development (Edenhofer et al. 2011). A promising technology is the exploitation of waves and tides for which there are some wide-scale industrial applications (de Falcao 2010) and has the largest expected future cost reduction among all renewable resources (Magagna and Uihlein 2015).

The ocean energy sources can be divided into two main groups (see Table 20.3): the ones generated by gravitational forces (waves, tides, currents) and those that harvest the oceans chemical or heat potential (temperature and salinity differences).

Specifically, there are three main ocean energy resources mostly related to the fluid properties of the ocean water. The first is the energy present in the waves generated by the wind passing over the surface of the ocean. The largest wave heights occur at high latitudes (greater than 40º from the equator), where the trade winds blow across large stretches of open ocean and transfer power to the sea swells (OES-IEA 2012). Waves are considered as a promising resource with a rising technology on energy control (de Falcao 2010, Falcão and Henriques 2016, Roberts et al. 2016 and references therein), however still facing considerable barriers due to the high cost for energy absorption, relatively to the other renewable resources (Uihlein 2016, and references therein). Additionally, the environmental impacts on the coastline can be significant, and great caution is required for the estimation of the optimum location and orientation of the devices. Nevertheless, wave energy is highly sustainable with a significant absorption density of 2–3 kW/m^2 compared to solar 0.1–0.2 kW/m^2 and wind 0.4–0.6 kW/m^2 densities (López et al. 2013). Also, the operating time of the wave energy projects is even up to 90%, a very high value compared to the 20–30% of the solar and wind energy (Pelc and Fujita 2002)

The second is tidal energy (range and currents), which is one of the most reliable renewable resources due to its high predictability, when compared to solar and wind resources as well as the other ocean resources. Since tides depend almost exclusively on the relative position of the Earth, the Sun, and the Moon (the rest of planets have minor effects), the tidal period and amplitude in oceans can be predicted very accurately for many years, assuming that there are no significant changes (e.g. anthropogenic and geological) in the coastlines. Tides have several periodic cycles (Schureman 1963) with the most important one for energy production being the diurnal (and semi-diurnal). The height difference between successive high and low tides varies from 0.6 m in mid-ocean to more than 15 m at a few continental locations (Sleiti 2017; Twidell and Weir 2015). Tidal power can be efficiently harvested only in relatively shallow waters and coastal regions, and so technical potential is likely to be significantly less than theoretical potential (Edenhofer et al. 2011).

A third energy source, closely related to the above, originates from the ocean currents which are generated

Table 20.3 Ocean energy sources along with an indicative potential energy production in a global or local scale

Source	Indicative potential energy production
Wave energy (wind-driven)	30 000 TWh/year (theoretical potential)
Tidal range (rise and fall)	10 000 to 30 000 TWh/year (theoretical potential)
Tidal currents (in coastal regions)	e.g. 100 TWh/year (Europe and China)
Ocean currents (wind-driven and thermohaline ocean circulation)	e.g. 0.2 TWh/year (Florida Current, Gulf Stream, North America)
Ocean thermal energy conversion (OTEC)	45 000 TWh/year (theoretical potential)
Salinity gradients (osmotic power)	1 500 TWh/year (theoretical potential)

Source Edenhofer et al. (2011)

mostly by the Coriolis effect as well as temperature and salinity differences (Edenhofer et al. 2011). Similar to the above two sources, the kinetic energy of these currents can be efficiently harnessed nearshore, particularly where there are constrictions, such as straits, islands and passes (OES-IEA 2012).

Two other main ocean energy resources mostly relate to differences in the physicochemical properties of the ocean waters and, in particular, temperature and salinity differences. One is the osmotic pressure created by the salinity differences between fresh and sea water at river mouths, but it has a low potential energy status due to its limited exploitation (Edenhofer et al. 2011); the other is the ocean thermal energy. The latter is regarded as a candidate marine energy resource (Nihous 2007) since the temperature in deep ocean water tends to be relatively constant (around 4 °C), and thus, the heat exchange between warmer surface waters can be quite significant for a wide range of locations and for a large portion of the year (OES-IEA 2012).

20.7 Environmental Impacts

The population boost and the steep increase of energy demand per capita during the twentieth and twenty-first centuries have dramatically increased the water and energy needs. In this respect, water-energy infrastructures have expanded massively and impacted vast areas in previously undeveloped lands, causing major changes to the landscape at a global scale. Indicatively, there are approximately 58 000 large dams in the world today (this is a total number of dams, including those used for irrigation, water supply, etc.) (Tanchev 2014), and several countries have exploited more than 80% of their economically feasible hydro potential (Leckscheidt and Tjaroko 2003).

Criticism on dams over their environmental impacts has been harsh, and legislation in many countries considers the energy produced from hydroelectric dams to be non-renewable (Koutsoyiannis et al. 2009) due to their impacts on the riverine systems. However, these environmental impacts can be managed, to an extent, through optimized siting with the use of environmental impact assessment regulation as well as through the utilization of various technologies that have been developed for their mitigation, such as fish passes (DVWK 2002), sediment management techniques (Annandale et al. 2016), etc. Thus, the irreversibility of environmental impacts of dams has been questioned, and their importance for water storage and renewable energy generation is considered to justify their further expansion with adequate environmental planning (Klemeš 2007; Koutsoyiannis 2011a).

Below we compile the major and commonly cited environmental impacts of hydroelectric power plants combined with brief references on methods that can be utilized to reduce or avert them, when such methods exist. Not all of the examples and cases presented refer to dams used solely for hydroelectricity, since most impacts are common to all dams. Moreover, a brief reference to other environmental problems related to the use of water for energy, for example, use of water for cooling in thermoelectric plants, is also made.

20.7.1 Hydroelectricity

20.7.1.1 Water

Among the impacts of hydroelectric dams to the environment, the most evident is on river dynamics. A dam changes the spatio-temporal route of water transforming a riverine system into an artificial lake. In particular, a dam blocks the flow of water from upstream collecting it in the reservoir and transfers the temporal and quantitative control of the hydraulic supply from nature to man.

The transition of the hydrological system from riverine to lacustrine (referring to lake) causes changes to both the physical and chemical characteristics of water. Initially, in relation to the temperature of the water, it is observed that the water, becoming almost stagnant, ceases to present the significant variation in temperature that is usual for the water of a river throughout a year. It ends up fluctuating with significantly reduced variation around a higher average temperature (Maheu et al. 2016), and very often, in reservoirs, stable temperature zones appear with temperature decreasing with increasing depth. In some cases, the lower layers of water develop temperatures much lower than those of natural rivers, and when water from these layers is released, it may affect downstream ecosystems. Releasing water from the surface layers is an easy solution to this problem provided suitable outlet pipes have been designed.

The chemical characteristics of water are also prone to alterations as a result of the impoundment, especially when trees and flora are not removed from the reservoir area prior to the inundation. The density of pre-existing vegetation is also a significant determinant of the emergence of such phenomena. If large amounts of organic matter were present in the reservoir area, the dissolved oxygen concentration in the water can be noticeably reduced even for more than twenty years after the inundation of the reservoir (McCartney et al. 2000).

Finally, there are effects on the type and amount of aquatic biota present in the reservoir, where one can find plankton, aquatic plants, seaweeds that surround submerged objects and floating plants, which grow mainly in tropical zones.

20.7.1.2 Geology–Geomorphology

Hydroelectric plants are complex engineering projects consisting of many separate elements and supporting engineering works like road works for access to the dam area, excavations for slope stability in the abutments of the dam and various other types of earthworks. These alter the geomorphology of the dam area, and the geological impact of the dam is also extended to distant downstream areas due to the significant amounts of sediment trapped. Less often, hydroelectric dams are associated with several geological effects such as landslides in the reservoir area, erosion of the river bank downstream of the dam, as water released through the dam is clear of sediments (Collier et al. 1998), or triggering of earthquakes (Dixon et al. 1989)

Nevertheless, as far as the geological impacts of the dam are concerned, the main and most cited effects are related to the trapping of sediment. Dams retain a large proportion of the materials that rivers would normally carry away downstream, especially, when there are no plans for removing deposits. Notably, based on Hay (1994), the sediment flow of Turkey's Black Sea rivers has decreased from 70×10^6 t/year to 28×10^6 t/year due to the operation of hydroelectric dams. According to the study of Walling and Fang (2003), the sediment loads of 145 more rivers have been significantly reduced after the construction of dams, as reported by UNESCO Office in Beijing, IRTCES (2011)

All these phenomena depend on many different factors varying from random events, like earthquakes or landslides, to the quality of the design of the plant (e.g., the design of the dam can include measures to reduce sediment trapping) and do not appear in every dam. In terms of sediment trapping, many different reservoir sedimentation measures have been developed, taken both in the reservoir area and at the dam site. For example, these include dredging with mechanical equipment, flushing from the bottom outlets of the dam or sluicing when floods with heavy sediment load are expected (Schleiss and Oehy 2002). Even though relevant research continues, new methods are developed and the older ones are improved, with early twenty-first century state of the art, sediment trapping cannot be completely avoided (Morris and Fan 1998).

20.7.1.3 Atmosphere and Microclimate

The effects of the dam on the microclimate of the reservoir area can be divided into short-term and long-term. Short-term effects are related to the construction of the dam and its appurtenant structures, a process that usually lasts several years, and they include vibrations, dust and noise pollution. Long-term effects include an increase in the humidity in the periphery of the reservoir due to the evaporation of water and the intensification of storms, as reported in Mediterranean and arid areas (Degu et al. 2011).

Regarding the impact of hydroelectric dams to the atmosphere, the main phenomenon observed is increased gas emissions. The phenomenon is intensified when the area of the reservoir has not been cleaned from biomass prior to the inundation and is apparent mainly in tropical areas (Fearnside and Pueyo 2012) due to more abundant vegetation. The main gas produced in these cases is methane, which is a result of the decomposition of the biomass inside reservoir. The exact type of biomass that triggers the phenomenon is soft biomass, from leaves and branches (McCartney et al. 2000).

20.7.1.4 Fauna

The effects of dams on ecosystems are many and complex. They concern the fauna and flora of the reservoir area, as well as the people living there and people who use the power produced by the hydroelectric power plant. In relation to the fauna of the area of the dam, both negative and positive effects from dams have been observed (Bardach and Dussart 1973). In literature, negative impacts have been studied more thoroughly. These include, for example, the inundation of animal habitats by the reservoir with various examples from different countries, in some cases even habitats of endangered species have been affected. Moreover, the effects of the dam on aquatic fauna are also significant, as the continuity of the river is interrupted, therefore its flow changes and the type of ecosystem changes from riverine to lentic. All of the above are causes of problems for fish populations with impacts being more significant on migratory species (e.g. salmon, sturgeon etc.), which can end up being threatened with extinction, especially when fish ladders for free movement of fish from upstream to downstream and vice versa are not built.

However, cases of reservoirs that helped enrich and improve the life of their ecosystems have also been reported. In the study of Bergkamp et al. (2000), 66 dams were examined, regarding their impact on the biodiversity of fish in the ecosystem, and 27% of the dams showed increase in biodiversity and 73% decline. Similar conclusions about artificial lakes that have been evolved to wetlands of high biodiversity were drawn for hydroelectric reservoirs in Greece (Tzitzi 2008).

Nevertheless, hydroelectric projects are certainly major interventions on the environment that may even affect the fauna of areas relatively far from their location. A typical example is the case of the Aswan Dam in Egypt, where the containment of sediment from the dam caused a significant reduction in the sardine population in the delta of Nile region (Biswas and Tortajada 2012), which is approximately 850 km away from the dam. This population was an important factor in the income of the fishers of the area, and the decrease observed in the volume of fish caught in the first years of operation of the dam was spectacular: from 18 000 to 400–600 t within five years. Remarkably, the population returned to fairly high levels after approximately 20 years (El-Sayed and Dijken 1995).

20.7.1.5 Flora

The most significant impact on flora by a dam and its reservoir is the loss of forest areas and natural vegetation in general. These areas include the site of the reservoir itself, where the vegetation is either flooded or removed, but also all other areas that are affected from the construction of the dam's appurtenant structures. It is worth noting that efforts have been made to preserve some of this vegetation, especially, in cases where rare or endangered plants grow in the reservoir area. Such an example is the Three Gorges dam, China, where more than 200 plant species, including 37 endangered species, were transplanted to other locations (Zhang and Lou 2011).

During the dam operation, the development of lakeside vegetation that normally grows in natural lakes is usually restricted by variations of the reservoir level. This is due to the fact that this type of vegetation is particularly sensitive to small changes in the ecosystem, let alone the intense variation in the level of an artificial lake. Thus, it is common that instead of lakeside vegetation, the creation of a dead-zone around the shore of the reservoirs is observed (Christofides et al. 2005).

The effects of reservoirs on the flora also extend to areas downstream of the dam as a result of the alteration of the physical variation of the water flow. The outflows through the dam are controlled by various structures, in terms of volume and timing of the flow released, and also typically have different physicochemical characteristics from the water of the natural river system. Consequently, when the water characteristics (chemical, physical, hydrological, etc.) are greatly modified, there is a risk for species that live downstream of the dam and are dependent on them (Kingsford 2000). As far as the variability of flow is concerned, there have been numerous studies proposing methods for maintaining an ecological flow similar to the natural, which may also require adapting the operation strategy of the hydroelectric plant (e.g., Efstratiadis et al. 2014b, Koutsoyiannis and Ioannidis 2017).

Again, the management of water resources by man through dams and reservoirs also has a positive side for the development of ecosystems and vegetation in particular. Through multipurpose reservoirs combining irrigation and water supply with electrical energy production, freshwater that would outflow to the sea can now be used for organized agricultural use as well as a source of life for all kinds of vegetation that people cultivate in their homes and their cities.

20.7.1.6 Human Societies

The thousands of large dams built globally over the course of the twentieth century are responsible for the displacement and resettlement of tens of millions of human population (Scudder 2012). An extreme case is the Three Gorges Dam (China), which caused the displacement of more than one million people (Jackson and Sleigh 2000). Massive displacements are common in countries like China or India (Fernandes and Paranjpye 1997), but there have also been cases, where displacements caused by a major project, were moderate such as, for example, in Itaipu dam (Brazil), the second biggest hydroelectric project of the world, where 59 000 people were displaced (Ledec and Quintero 2003).

Regarding the effect of the dam on the health of people in the area, cases of stagnant water have been reported to contribute to increases in diseases such as typhoid fever, malaria and cholera in developing countries (Goldsmith and Hildyard 1984), due to the fact that vectors find favourable conditions in the relatively stagnant water of the reservoir. At the same time, dams have been a source of highly reliable energy and clean drinking water, thus helping to develop health infrastructure, increase life expectancy, avoid illnesses associated with poor water quality, often eliminating water scarcity and ensuring a better standard of living overall (Koutsoyiannis 2011a). The positive effects of dams are commonly and mainly utilized by people who live hundreds of kilometres away from its location, significantly exceeding the range of direct environmental impacts. For those people, dams translate into drinking water, cheap and non-intermittent electricity, agricultural products, etc.

The same applies to the inhabitants of the area of the reservoir, but with an important difference. Almost all of the environmental impacts reported are more apparent to them and affect their lives more directly. Overall, depending on how large the impacts of the dam are on the environment and how much the inhabitants of the dam area are culturally connected with it, its construction can be a cause of significant changes in the people's culture itself (Wijesundara and Dayawansa 2011). Yet such changes are not exclusively negative as various cases have been reported internationally in which hydroelectric dams boosted growth, attracting tourism and recreational activities in general, for example, in Spain, Norway, Greece, and the United States (Christofides et al. 2005; Nynäs 2013; Pérez et al. 2013; Smardon 1988). Such cases are abundant and can be found in most countries with hydroelectric infrastructure (Ioannidis and Koutsoyiannis 2017a).

20.7.1.7 Natural and Human History and Landscapes

The process of selecting a suitable site for a dam is challenging and affects the final design in many ways. This is largely guided by economical and technical limitations and can lead to very limited alternatives for the sitting of the dam. In some cases, the final choice might be one that necessitates the inundation of areas of natural and human heritage by the reservoir. In relation to cultural heritage, there are examples of loss of important cultural objects, buildings, archaeological finds, and entire sites that are related to human cultures (Brandt and Hassan 2000). Likewise, many reservoirs have inundated scenic landscapes or places of particular geological value (Tahmiscioğlu et al. 2007).

Nevertheless, in the context of a future where almost all of the energy produced comes from renewable sources, dams are the only type of renewable energy that can create new landscapes without causing industrialization and degradation (Ioannidis and Koutsoyiannis 2017b), which are common problems with solar and wind farms (Frolova et al. 2015; Stremke and Dobbelsteen 2012). In literature related to dams, landscape impact is not considered important, and in fact, dams have both qualitatively and quantitatively less impact on landscapes (Ioannidis and Koutsoyiannis 2017a; Koutsoyiannis and Ioannidis 2017), attract touristic and recreational activities, as mentioned in the previous subsection, and are also considered to create new sites of cultural heritage (Nynäs 2013; Rodriguez 2012).

20.7.1.8 Uncommon Impacts

The focus so far was to report the most common and adequately cited effects of dams on the environment. Nevertheless, it is important to emphasize that dams, as projects that are built all over the globe under different climatic, geographic and cultural conditions, do not have fully predefined and universally identical impacts. Actually, their impacts depend on the design, management and maintenance of the dam as well as on, sometimes unexpected, reactions from nature. Such a case is, for example, the Brokopondo artificial lake (Suriname) whose surface was covered by more than 50% with hyacinths in less than three years (Farnworth and Golley 2013), resulting in increased water evaporation and adverse conditions for fish. Another example of a particular impact from the construction of a dam is the case of the natural lake Urmia (Iran) which almost dried up as the dams upstream of its site were used to divert water for agricultural use (Joudi and Eiraji 2013) without proper water management for the maintenance of the natural lake downstream.

20.7.2 Thermal Power Plants

Thermal power plants use several different resources for energy production, ranging from fossil fuels to nuclear energy. In any case, the turbines use steam to produce mechanical work and thus need water that turns into steam to drive the steam cycle heat transfer. Water is also needed, in much larger quantities, to lower the temperature of steam that remains in the steam circuit after passing through the turbines and condense it back to fluid form. The relatively low energy efficiency figures for thermal plants (Sect. 20.1.2) means that much of the energy produced in the boiler remains in the steam, which explains the large volume of water needed for cooling.

The most important environmental impacts of thermoelectric plants are related to the cooling process and its efficiency. Two major techniques are commonly used in thermoelectric power plants, and they have different, but significant environmental impacts. The first one is called once-through cooling and is described as simply running water through the condensers for one time and then discharging it from the facility (Shuster 2008). This technique is the cause of thermal pollution, as the sudden temperature changes or semi-permanent rise of temperature creates significant problems for aquatic life downstream of the station, which may either be susceptible to sudden changes (thermal shock) or may need certain low temperatures to survive (Pokale 2012).

The second major technique reduces thermal pollution significantly but has the disadvantage of evaporating a percentage of approximately 5% of the water used, thus increasing the water consumption of the plant (Rogers et al. 2013). This is called recirculating or indirect cooling, and its main feature is the use of a so-called cooling tower that dissolves the water into droplets and uses air to lower their temperature. The water drained from the tower is then recirculated in the steam circuit. Another impact is that of carryover salt and other contaminants in the water passing from the cooling tower. To a lesser extent groundwater is also used for the cooling process of thermal plants (Averyt et al. 2011) reducing the reserves and influencing groundwater temperature (in case of reuse).

20.7.3 Marine Energy

As mentioned, marine energy includes various different types such as tidal energy, wave energy and salinity gradient power (osmotic power), and thus several different devices and technologies have been developed to exploit them. In 2020, most of these devices were still considered experimental or pilot, and had not been fully incorporated to national energy generation systems yet (Hamelinck et al. 2012). As a result, the discussion on the environmental impacts of marine energy at that time was based on only a small amount of data on existing marine energy plants and mostly on predicting possible impacts (Frid et al. 2012).

Most of expected impacts are not related to the devices themselves but stem from their manufacturing progress and the auxiliary works. For example, according to Uihlein (2016), the most important impact is from the foundation and mooring works, processes that produce large amounts of CO_2 emission, but also interfere with aquatic life (Langhamer et al. 2010). Additionally, significant CO_2 quantities are also emitted from the manufacturing progress of the devices. As far as the impact of marine energy devices on marine ecosystems is concerned, several possible hazards have been observed during the operation of these devices. These range from direct impact from turbine blades on fish (Hammar et al. 2015) to disorientation and alteration in the behaviour of several species from noise and electromagnetic waves created from the devices.

Meanwhile, several potential impacts of marine energy devices, which have been theoretically considered as important, have not yet been tested on the field, as no large projects of marine energy have been built to provide adequate data. For example, the impact from the alteration of hydrodynamics and kinetic energy in the marine environment (Shields et al. 2011) or the unknown impacts that marine energy devices could possibly have for migrating fish and marine mammal populations (Langhamer et al. 2010), which are similar to the problems that offshore wind farms cause to migrating birds.

20.8 Handling Uncertainty in Water-Energy Systems

20.8.1 Uncertainty Issues in Water-Energy Systems

All aforementioned water-based electric power sources, i.e. hydroelectricity, either as an individual component or integrated within hybrid renewable schemes, as well as wave energy, are driven by randomly varying process across all scales. This irregular behaviour introduces a remarkable degree of uncertainty to the water-related power systems, thus resulting in limited predictability of the natural drivers of energy production. The energy demand is also highly unpredictable (particularly in the long run), as it is strongly influenced by broader socio-economical and geopolitical factors. In this respect, uncertainty is a major element of water-energy systems, which strongly affects their planning, design and management, as well as the cost and sustainability of associated investments.

Typical measures of uncertainty, which are widely used in water resource systems analyses, are reliability and failure probability (sometimes referred to as risk, but the notion of risk has a broader meaning). Reliability is defined to be the probability that a system will deliver a desired performance for a specified period of time, under stated conditions, while the probability of failure is its complement (Koutsoyiannis 2005). Both these probabilistic metrics are associated with a specific desirable performance of the system. For instance, in the case of hydroelectric reservoirs, this is usually expressed in terms of a long-term target energy to be produced at a constant rate throughout a large (theoretically infinite) time horizon, also referred to as firm or reliable energy (Koutsoyiannis and Economou 2003). In a more general context, the target energy is time-varying, thus the system performance, and the underlying uncertainty, are evaluated by contrasting the produced energy against the associated demand.

Nevertheless, in water-energy systems, the analytical determination of reliability and risk through typical statistical approaches (i.e. inference from data, by fitting either an empirical or theoretical distribution), is practically impossible. This has two major reasons. First, such systems are driven by processes exhibiting multiple peculiarities such as periodic change of statistical properties across seasons and auto-dependencies across all temporal scales, which do not allow for applying the major hypotheses of statistical inference (stationarity, independence). Second, the concept of reliability is applied to the system output, i.e. the energy production, not the input. Particularly in hydroelectricity, this output is a highly complex and nonlinear transformation of the input process, i.e. inflow, where a key component of nonlinearity is the regulation of inflows via the storage capacity offered by reservoirs. Additional complexities arise when multiple energy sources are involved (e.g., in case of multireservoir systems as well as hybrid schemes), in which the system's performance is also subject to multiple and conflicting constraints, objectives and human decisions (Koutsoyiannis et al. 2002).

20.8.2 The Stochastic Simulation Paradigm

The well-established approach for evaluating the performance of complex systems is through simulation, generally defined as the representation of a system's dynamics through a computer model. The model is fed with a sequence of inputs to mimic the operation of the system (expressed in discrete time), and produce hypothetical yet realistic outputs, based on which one can evaluate the system's performance by assigning appropriate metrics. In this respect, the reliability of an energy system is easily quantified by counting the number of time steps when the produced energy fulfils the associated demand and dividing by the total length of data.

It is widely accepted that in the context of simulation, the use of synthetic inputs instead of historical records is favoured, because it provides sufficiently large samples (e.g., with length of hundreds or thousands of years) or ensembles of different time series of the same process, to allow the evaluation of a wide range of possible outcomes of the system in study (Efstratiadis et al. 2014a). This is the core of the stochastic (also known as Monte Carlo) simulation paradigm, in which long synthetic series of inputs (e.g. reservoir inflows) are generated from an appropriate stochastic model and then transformed, through the operation model, into synthetic outputs. The use of long synthesized data series allows representation of all aspects of variability of the associated processes (with emphasis to the long-term scaling behaviour as explained below), and proper description of their statistical dependencies in space and time. It also ensures accuracy in the estimation of the desirable statistical quantities, i.e. reliability and risk, in contrast to usually short historical samples. Furthermore, stochastic simulation can be easily combined with optimization, thus offering a robust and generic method for modelling complex systems under uncertainty (Koutsoyiannis and Economou 2003).

Hydrologists and water engineers have long appreciated the usefulness of stochastic simulation–optimization approaches and have applied them in a wide range of water resources applications, including the design and operation of hydroelectric systems (e.g., Pereira et al. 1984, Tsoukalas and Makropoulos 2015, Ubeda and Allan 1994). However, the application of such approaches in hybrid renewable energy systems is rather limited, maybe because the essentially fine temporal resolution of simulations (typically hourly) in addition to the complexity of such systems, introduces significant computational barriers to simulations.

It is worth mentioning that the stochastic simulation paradigm is not restricted to the generation of inputs but can be extended to the energy demand and also captures several other uncertainty issues in water-energy modelling. In fact, uncertainty spans over all aspects of the energy production cycle, which is a sequence of highly complex nonlinear conversions, e.g. rainfall to runoff, wind energy to wave energy, hydraulic energy to mechanical and hence to electrical energy. The associated processes are typically represented through simplified approaches, i.e. models, which are subject to structural and parametric uncertainties. In particular, the internal energy conversion processes are expressed by means of a sole input property, i.e. efficiency, which is a major source of uncertainty. For instance, the efficiency curves of hydro turbines are typically extracted from laboratory models, and they are next adjusted to fit the prototype, by employing empirical corrections; next they are prone to damages and aging of the equipment over time, thus their actual value is by definition uncertain (Paish 2002; Sakki et al. 2020). Nevertheless, a generalized stochastic simulation framework should describe both process and model uncertainties, as is done in a case study of a hypothetical system by Papoulakos et al. (2017).

20.8.3 Insights into Stochastics and Their Application in Water-Energy Problems

The stochastic approach allows for developing a unified perception for all natural phenomena and expelling common dichotomies, such as randomness vs. determinism, or, equivalently, unpredictability vs. predictability. In fact, both randomness and predictability coexist and are intrinsic to natural systems which can be deterministic and random at the same time, depending on the prediction horizon and the time scale. Specifically, the line distinguishing whether determinism or randomness dominates is related to the scale (or length) of the time-window within which the future state deviates from a deterministic prediction by some error threshold ε, and for errors smaller than ε, we assume that the system is predictable only within this time-window (Dimitriadis et al. 2016).

As already mentioned, stochastic approaches enable the generation of (theoretically infinite) ensembles of realizations, while observation of the given natural system can only produce a single observed time series. The literature offers a plethora of models that allow for representing important statistical characteristics of the process of interest, such as its marginal distribution structure and its second (and higher) order dependence structure. By robustly simulating both structures, several important behaviours of the process of interest can be preserved, such as the marginal distribution function along with the diurnal and seasonal periodicities, for example, through marginal transformations (Deligiannis et al. 2016), entropic transformations (Dimitriadis and Koutsoyiannis 2015), or copula-based schemes preserving different distribution functions and autocorrelation structures across seasons and scales (Tsoukalas et al. 2019), as well as the intermittency and the persistence on a wide range of scales (Dimitriadis and Koutsoyiannis 2018).

Depending on the problem of interest, one may focus on different aspects of the processes and put emphasis on the representation of specific characteristics at specific temporal scales. For instance, although the short-term variability is of interest in renewable energy resources (due to its link to intermittency effects and short-term predictions), the long-term variability is more significant in energy management and system sustainability. In fact, all geophysical processes, and apparently the processes that are related to water-energy systems, seem to exhibit high unpredictability at all scales, from the large hydrometeorological to the small turbulent one due to the clustering of events. Interestingly, this clustering behaviour has been first identified in nature by Hurst (1951), while analysing water records from the Nile within the design of projects for the Nile development. However, the mathematical description and analysis of this behaviour through a power-law autocorrelation function is attributed to Kolmogorov (1940).

A recent extensive analysis of a massive number of measurements around the globe of the most vital hydrometeorological processes (Dimitriadis 2017) has shown that all exhibit an intermittent behaviour at small scales quantified by a fractal parameter, and the so-called Hurst phenomenon at large scales, or else Hurst-Kolmogorov dynamics, abbreviated as HK (Koutsoyiannis 2011b). The HK behaviour is characterized by long-term variability (the autocorrelation function decays as a strong power-law and not exponentially; see also O'Connell et al. 2016, and references therein). Therefore, two simple yet robust measures of the inherent short- and long-term uncertainty or variability of a process may be quantified by the fractal and Hurst parameters, which can be both robustly estimated through the climacogram or other climacogram-related metrics (Koutsoyiannis 2019).

20.9 Future Challenges and Directions

Overall, to address the complexity of the water-energy nexus and to pursue a sustainable future in terms of water and energy security, the following research and technology activities will play key roles:

- Addressing the policy fragmentation issue between the two sectors (Hussey and Pittock 2012).
- Pursuing technological innovations and reforms to reduce the water intensity of the energy sector to improve the energy efficiency of the water sector and minimize related environmental impacts.
- Dealing with the lack of water and energy infrastructure and relevant under-investment issues, particularly present in the developing world (Bazilian et al. 2010; Koutsoyiannis 2011a; McCornick et al. 2008).
- Engaging in the design and implementation of large-scale multi-purpose water-energy projects exploiting the available renewable energy resources potential and aiming for reliability and sustainability (Koutsoyiannis 2011a).
- Advancing the understanding of the conflicting and synergistic relationships of the water and energy systems and of the ways they are likely to evolve in the future.
- Extending the data availability to more regions of the world, as in present they are mostly US-dominated (Spang et al. 2014), and strengthening the efforts for systematic data collection and observation platforms (Liu et al. 2017).
- Adopting an integrated modelling approach or a systems approach (Bazilian et al. 2011; Koutsoyiannis 2011a; Newell et al. 2011) dealing with uncertainty, which dominates the natural resources involved (Langhamer et al. 2010); stochastic methods are of great utility in this respect.

Water and energy sources are part of the processes forming the hydrological cycle, and thus, they should entail the same complexity or else the same uncertainty. It is rather crucial then to treat them with similar methods as the stochastic ones implemented for precipitation, wind, and temperature. Furthermore, it is expected that they carry the same degree of unpredictability, and therefore, systems that require management of a large number of such sources (like the hybrid ones) should be optimized through an integrated stochastic simulation–optimization framework. Such an integrated framework, where water, wind, and solar radiation are the sources of energy with water in an additional integrative and regulating role, is highly desirable, given that the exploitation of renewable energy resources should be necessarily combined with large-scale pumped-storage technologies.

20.10 An Example for the Design of a Small Hydroelectric Power Plant

A small hydroelectric power plant is scheduled to exploit the flows of a river. The exceedance probability of the river inflow (Fig. 20.13a) is modelled by the generalized Pareto distribution:

$$P(Q) = 1 - F(Q) = (1 + Q/10)^{-5} \tag{20.21}$$

where Q is the discharge (m^3/s); P is the exceedance probability of the value Q, and F is the probability distribution function. The hydraulic head of the system is $H = 400$ m, and the overall efficiency is $n = 0.85$. For simplicity, both quantities are considered constant (i.e., independent of flow conditions). Using the above data, estimate:

1. The total water volume (hm^3) and the corresponding annual potential electric energy (GWh).
2. The water volume (hm^3) used from a single turbine with power capacity 16.7 MW and the produced annual electric energy (GWh).
3. The water volume (hm^3) used from a system of two turbines with power capacity 13.3 and 2.7 MW, respectively, and the produced annual electric energy (GWh).

The exceedance probability can be converted to average time by multiplying with a given time interval T. In order to express all quantities of interest on annual basis, we employ $T = 31.56 \times 10^6$ s. We also remark that the inverse of Eq. (20.21) is

$$Q(P) = 10\left(P^{-0.2} - 1\right) \tag{20.22}$$

and its indefinite integral over P is

$$\mathrm{IQ}(P) := \int Q(P)\mathrm{d}P = 12.5P^{0.8} - 10P \tag{20.23}$$

This gives the average inflow as

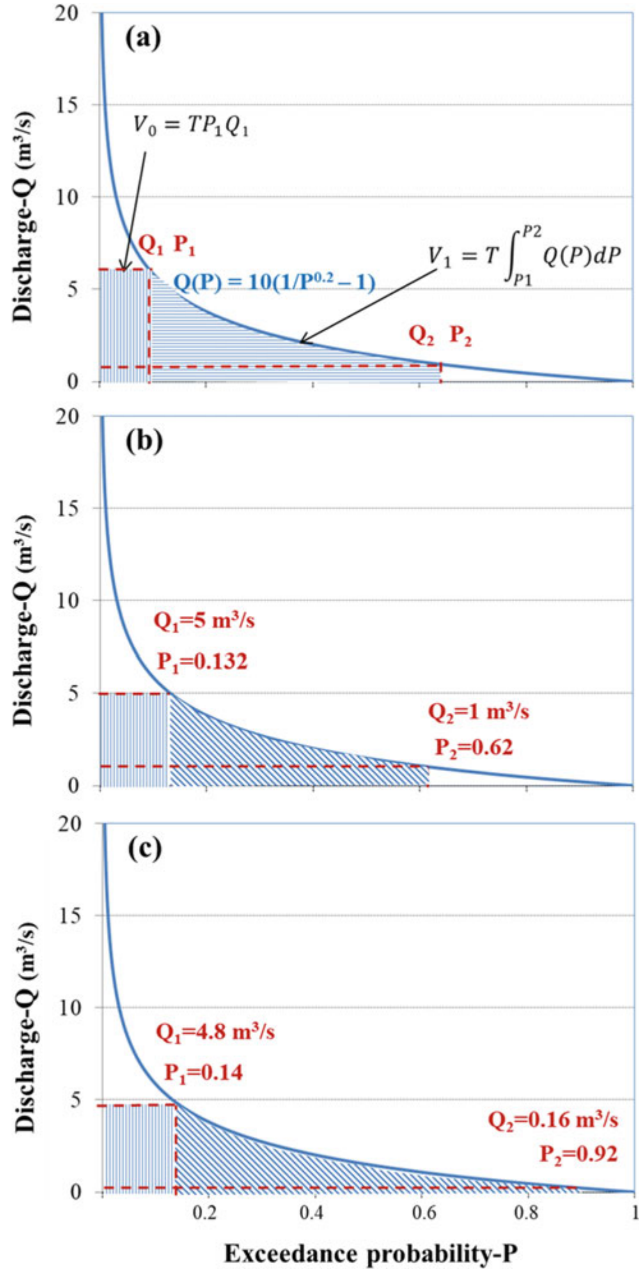


Fig. 20.13 **a** Discharge vs. exceedance probability water volume used in a flow range Q_1−Q_2; **b** water volume used from a turbine 16.7 MW; **c** water volume used from two turbines 13.3 and 3.7 MW

$$E[Q] = \int_0^1 Q(P)dP = IQ(1) - IQ(0) = 2.5(m3/s) \quad (20.24)$$

The answers to questions 1, 2, and 3 now are:

1. For a time period of one year, i.e., $T = 31.56 \times 10^6$ s, this yields an annual volume of $2.5 \times 31.56 = 78.9$ hm^3. According to Eq. (20.4), this corresponds to a theoretical energy production of

$$E_{\text{theor}} = \left(1000\ \text{kg/m}^3\right)\left(9.81\ \text{m/s}\right)\left(78.9 \times 10^6\text{m}^3\right)(400\ \text{m})(0.85) = 263.1 \times 10^{12}\text{J} = 73.1\ \text{GWh}. \quad (2.25)$$

2. From Eq. (20.1), we get that the 16.7 MW turbine has a nominal discharge of $Q_1 = 5$ m^3/s (twice the average inflow). Considering that the lowest discharge at which the turbine operates is 20% of the nominal, we get $Q_2 = 1$ m^3/s. The volume of water that is exploited for a given range of discharges Q_1 and Q_2 is composed by V_0 and V_1 (Fig. 20.13a). In particular, V_0 is the volume passing through the power station with the nominal discharge Q_1, when the inflow is greater than Q_1, and V_1 is the water volume within the operational range Q_1 and Q_2, which correspond to exceedance probabilities P_1 and P_2 (with $P_1 < P_2$). All this amount of water passes through the power station. The two volumes are calculated as:

$$V_0 = TP_1Q_1, V_1 = T\int_{P1}^{P2} Q(P)dP = T(\text{IP}(P_2) - \text{IP}(P_1)) \quad (20.26)$$

where $P_1 = P(Q_1) = (1 + 5/10)^{-5} = 0.132$ and $P_2 = P(Q_2) = (1 + 1/10)^{-5} = 0.620$ (Fig. 20.13b), so that after the calculations IP(P_1) = 1.15 and IP(P_2) = 2.33. Thus, $V_0 = 31.56 \times 0.132 \times 5 = 20.8$ hm^3 and $V_1 = 31.56$ 1.18 = 37.1 hm^3. The volume corresponding to flow values lower than 1 m^3/s is $V_2 = 31.56 \times (2.5 - 2.33) = 5.4$ hm^3. This amount cannot be used by the turbine. Therefore, the annual water volume to exploit is $V = V_0 + V_1 = 57.8$ hm^3 and the corresponding electric energy production is 192.8×10^{12} J = 53.6 GWh. This system operates 62% of the time (since the lower flow corresponds to probability $P_2 = 0.62$), and the water volume exploited is 73% of the total (i.e., 57.8 out of 78.9 hm^3, as estimated before).

3. We consider that two turbines (A and B) of power 13.7 and 2.3 MW are installed. We find from Eq. (20.1) that the 13.7 MW turbine has a nominal discharge of $QA_1 = 4$ m^3/s and we assume that the lowest discharge at which it operates is $QA_2 = 0.8$ m^3/s (20% of the nominal). The 2.3 MW turbine has a nominal discharge of $QB_1 = 0.8$ m^3/s and a lowest $QB_2 = 0.16$ m^3/s.

For the first turbine operating alone, $PA_1 = P(QA_1) = (1 + 4/10)^{-5} = 0.186$, $PA_2 = P(QA_2) = (1 + 0.8/10)^{-5} = 0.681$, so that after the calculations IP(PA_1) = 1.395 and IP(PA_2) = 2.382. Thus, $V_0 = 31.56 \times 0.186 \times 4 = 23.5$ hm^3 and $V_1 = 31.56 \times 0.988 = 31.2$ hm^3. The volume

Table 20.4 Comparison of examined schemes, with one and two turbines

	One turbine	Two turbines
Installed power capacity (MW)	16.7	16.0 (13.3 + 2.7)
Discharge range (m^3/s)	1–5	0.16–4.8
Operation time (%)	62	92
Water volume exploited (hm^3)	57.8	62.3
Water volume to total (%)	73	79
Energy production (GWh)	53.6	57.7

corresponding to the period in which the discharge is lower than 0.8 m/s is $V_2 = 31.56 \times (2.5 - 2.382) \times 0.8 = 3.0$ hm^3 and this is not used by the turbine. The annual water volume exploited is and $V = V_0 + V_1 = 54.6$ hm^3 and the corresponding electric energy is 50.6 GWh. The turbine operates 68% of the time and the water volume exploited is 69.2% of the total.

For the second turbine operating alone, $PB_1 = P(QB_1) = (1 + 0.8/10)^{-5} = 0.924$, $PB_2 = P(QB_2) = (1 + 0.16/10)^{-5} = 0.681$, so that after the calculations $IP(PB_2) - IP(PB_1) = 2.494 - 2.382 = 0.112$. Thus, $V_0 = 31.56$ $0.681 \times 0.8 = 17.2$ hm^3, $V_1 = 31.56 \times 0.112 \times 0.16 = 3.5$ hm^3. The volume corresponding to the period in which the discharge is lower than 0.16 m/s is $V_2 = 31.56 \times (2.5 - 2.294) \times 0.16 = 0.03$ hm^3 and this is not used by the turbine. The annual water volume exploited is and $V = V_0 + V_1 = 20.7$ hm^3 and the corresponding electric energy produced is 19.2 GWh. The turbine operates 92% of the time and the water volume exploited is 26.3% of the total.

The combination of the two turbines exploits a flow range from 0.16 (the lowest of the small turbine) to 4.8 m^3/s (the sum of the nominal discharges of the two turbines). Thus, $P_1 = P(Q_1) = (1 + 4.8/10)^{-5} = 0.141$, and $P_2 = P(Q_2) = (1 + 0.16/10)^{-5} = 0.924$ (Fig. 20.13c). The annual water volume exploited is $V = 62.3$ hm^3 and the corresponding electric energy is 57.7 GWh. This system operates 92% of the time and the water volume exploited is 79% of the total.

A summary of the two schemes is given in Table 20.4. An interesting outcome is that the use of mixed turbines, with a little lower total power capacity (−4%), ensures higher annual energy production (+8%), since the different turbines can exploit a wider range of flows. For this reason, the combined system operates 92% of time, while the single-turbine system remains out of operation during the low-flow period (about four months per year, on average).

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Nikos Mamassis was born in Athens, Greece in 1960. He is Associate Professor of Hydrology in the School of Civil Engineering of National Technical University of Athens (NTUA). His scientific interests are in the fields of Hydrology, Hydroelectric Energy, Hydrometeorology, Geographical Information Systems (GIS), Hydrological Modeling, Water Resources Engineering and Investigation of Ancient Hydraulic Works. He is author of 36 journal papers, 6 book chapters, 26 conference papers, and more than 200 technical reports. He has over 25-year experience in teaching undergraduate and postgraduate courses in NTUA and other Universities. He has supervised more than 100 diploma and master theses. Website: http://www.itia.ntua.gr/nikos/.

Andreas Efstratiadis is Assistant Professor of Renewable Energy and Hydropower Works in the National Technical University of Athens. He has over 20-year research, teaching and engineering experience in hydrology and water resources technology. He is author of 38 journal papers, more than 100 conference talks and publications and 4 book chapters ($\sim$280 scientific, academic & technological publications, receiving $\sim$2000 citations). He is Associate Editor of Hydrological Sciences Journal. He contributed to the development of innovative hydrological and water management software tools and model calibration algorithms.

Panayiotis Dimitriadis is a Civil Engineer graduated from the National Technical University of Athens in 2006. In 2008 he received his Master of Science from Imperial College of London under a scholarship from the Eugenidion Institute in Hydrology for environmental management, and in 2017, he received his PhD in stochastic analysis of large-scale hydrometeorological and small-scale turbulent processes. In 2018 he worked as a post-doctoral researcher at the National Observatory of Athens in stochastic analysis of flow dynamics in natural rivers, and in 2019 as an adjunct assistant professor at the University of West Attica in the course of Fluid Mechanics. Dr Dimitriadis has collaborated with consultancy companies and worked as a research assistant in scientific programs held at NTUA, in the subjects of water resources management, computational fluid dynamics, flood risk management, stochastic simulation of renewable energy resources, and laboratory hydraulic experiments in spillways design and sediment transport. He has more than 300 citations with h-index and i-index 9, and more than 30 publications in scientific journals and conference proceedings, and scientific reports.

Theano Iliopoulou is Civil Engineer, Ph.D at the National Technical University of Athens (NTUA) pursuing research in the field of stochastic hydrology. She has a diploma in civil engineering from NTUA and a MSc degree in hydrology and water resources management from Imperial College London. Her main research interests revolve around rainfall hydrology, hydroclimatic extremes, stochastic methods in environmental research, and renewable energy projects. She has published relevant papers in various scientific journals and has over 40 presentations in international conferences. She also acts as a Reviewer for several journals in hydrology and environmental sciences.

Romanos Ioannidis is a Ph.D student on the Landscape Integration of Renewable Energy at the National Technical University of Athens. He has a diploma in Civil Engineering and has won awards and scholarships throughout his studies. Currently he is teaching assistant in Renewable Energy and Hydroelectric Projects, Hydraulic Works and Dams and Geographical Information Systems. He has published his research in Scientific Journals, International Conferences and Invited Lectures.

Demetris Koutsoyiannis is professor of Hydrology and Analysis of Hydrosystems in the National Technical University of Athens. He has served as Dean of the School of Civil Engineering, Head of the Department of Water Resources and Environmental Engineering, and Head of the Laboratory of Hydrology and Water Resources Development. He was Editor of Hydrological Sciences Journal for 12 years (2006–18), and member of the editorial boards of Hydrology and Earth System Sciences, Journal of Hydrology and Water Resources Re-search. He has been awarded the International Hydrology Prize–Dooge medal (2014) by International Association of Hydrological Sciences (IAHS), UNESCO and World Meteorological Organization (WMO), and the Henry Darcy Medal (2009) by European Geosciences Union (EGU). His distinctions include the Lorenz Lecture of the American Geophysical Union (AGU) (San Francisco, USA, 2014) and the Union Plenary Lecture of the International Union of Geodesy and Geophysics (IUGG) (Melbourne, Australia, 2011).

21 Water Management and Stewardship in Mining Regions

Nadja C. Kunz and Chris J. Moran

Abstract

Mining operations interact with water in complex ways. Ore is essential for society while water is an essential input for the extraction and processing of orebodies. Mining can pose threats to surrounding water bodies. Increasingly, mining companies, investors and governments recognize water as a key risk to expansion of the sector, with projects increasingly constrained by a lack of water, too much water, or social opposition over impacts to water. Issues associated with water and mining are set to intensify. Average ore grades are declining such that, without technological change, future mining operations will require more water and energy to process and generate greater quantities of waste material. This chapter summarizes water and mining challenges as they relate to diverse stakeholders. The industry's journey from Mine Water Management to Mine Water Stewardship is described, and key advances in mine water accounting and reporting practices are emphasized. An organizing framework is proposed to distinguish research needs across spatial scales and at different stages of the mine life cycle. There is a need for heightened attention to mine water issues as they relate to linked sites in mining regions, and during exploration and mine closure phases. Interdisciplinary thinking is required that considers how humans interact with both natural and engineered mine water systems.

Keywords

Mining • Water risk • Water accounting • Water stewardship • Cumulative effects

Abbreviations

ARD	Acid Rock Drainage
AWS	Alliance for Water Stewardship
CEO	Chief Executive Officer
CSRP	Centre for Sustainable Resource Processing
FIFO	Fly-In-Fly-Out
GIS	Geographical Information System
GRI	Global Reporting Initiative
GVA	Gross Value Added
ICMM	International Council on Mining and Metals
IFC	International Finance Corporation
MCA	Minerals Council of Australia
MCA-WAF	Minerals Council of Australia Water Accounting Framework
NSW	New South Wales
SMI	Sustainable Minerals Institute
TDS	Total Dissolved Solids
TSF	Tailings Storage Facility
WAF	Water Accounting Framework

21.1 Introduction to Mine Water Issues

Water is emerging as a growing constraint to expansion of the mining sector globally. As an essential input for mining operations, water is the primary medium for mineral separation and processing, transporting ore and waste, tailings management, dust suppression, and washing equipment (Côte et al. 2010; Gunson et al. 2012). Large-scale, artisanal and small scale mining sectors all interact with water, however this chapter focuses on water issues as they relate to the large-scale mining sector.

N. C. Kunz (✉)
School of Public Policy and Global Affairs, University of British Columbia, Vancouver, Canada

Norman B Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, Canada
e-mail: nadja.kunz@ubc.ca

C. J. Moran
Curtin University, Perth, Australia
e-mail: Chris.Moran@curtin.edu.au

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It has been estimated that the large-scale minerals industry[1] (excluding coal, oil sands, and aggregates) withdraws between six to eight billion m^3 of water per annum, roughly equivalent to meeting the basic water needs of 0.8 to 1.1 billion people (Gunson 2013). Some argue that mining represents an economically desirable use of water in terms of the economic value generated from the sector's consumptive water use. For example, mining can be shown to contribute significantly more Gross Value Added (GVA) per unit of water used than other sectors such as agriculture (Moran 2006; Ossa-Moreno et al. 2018). However, the mining sector's interactions with water can pose detrimental impacts on local communities and the environment.

This section outlines key trends in water issues as they affect mining companies, and the social and environmental issues associated with mine water use and management practices.

21.1.1 Mine Water Management Challenges

Increasingly, mining projects are operating in regions where water is scarce. By recent estimates, roughly two thirds of the world's largest mines are located in countries experiencing severe water scarcity (Metcalf 2013). Consequently, mining projects may account for a large proportion of the water withdrawn at a local level. In Australia for example, mining accounts for approximately 4% of national water consumption,[2] dwarfed by that of agriculture at 58% (Australian Bureau of Statistics 2017). However, water use is heavily clustered in mining regions; for example, in Western Australia mining accounts for 26% of the state's water consumption. High reliance of water at a local level can put mines in competition with surrounding water users and compromise industry access to water (Fraser and Kunz 2018). In extreme cases, significant water withdrawals by mining can interfere with natural hydrological pathways and/or contribute to groundwater depression (ERMITE-Consortium et al. 2004).

Excessive quantities of water at mining operations can likewise compromise production and pose impacts on surrounding communities and the environment. Unanticipated flooding events encountered by the Australian coal mining sector in 2010 following heavy rainfall caused billion-dollar production losses and concerns about the impacts of saline water discharge on downstream ecosystems (Gao et al. 2017). Excess water in tailings storage facilities can also be a contributing factor, or in some cases a primary cause, of tailings dam failures (Davies 2002; Strachan and Goodwin 2015).

Water quality must also be actively managed within mining projects. During minerals processing, salinity changes can affect flotation chemistry and compromise minerals recovery (Liu et al. 2011). Inadequate mine waste management practices can lead to water quality impacts and legacy issues such as acid rock drainage (ERMITE-Consortium et al. 2004). A notable example is the Ok Tedi mine in Papua New Guinea which has been associated with numerous environmental incidents on surrounding waterways, largely due to historical decisions associated with waste rock and tailings disposal (Zorn 2018).

On account of the many negative legacies associated with the mining sector, it is little surprise that water often represents a leading trigger for conflict between mining companies and communities (IFC and ICMM 2017). A failure to address the issues of concern to communities can prove incredibly costly for mining companies (Franks et al. 2014). For example, the proposed Taseko mining project in British Columbia was rejected by the Federal Government due to concerns among First Nation leaders about the impacts of the proposed tailings disposal system on Fish Lake (Federal Review Panel 2013). The company subsequently revised its entire mine proposal in an effort to address negative effects but it was again rejected on environmental grounds, after the company had already spent over $130 million trying to develop the project (Topf 2017). While conflict can have detrimental consequences for both communities and companies, the potential for conflict can sometimes lead to positive outcomes through motivating companies to change water management practices. For example, mining companies may invest in water infrastructure for communities that might have previously lacked access, or install treatment systems to restore regional water quality (Fraser 2018; Fraser and Kunz 2018).

Mine water issues, for both companies and communities, are set to intensify. Demand for minerals is rising globally and yet average ore grades are declining (Prior et al. 2012). Future mining operations are thus expected to require more water and energy for processing and to generate greater quantities of waste material per tonne of product (Scott 2018). Climate change is predicted to further intensify mine water issues through increased frequency of floods and droughts and higher peak flows in some regions due to more rapid snowmelt (Northey et al. 2017; Pearce et al. 2011). The gradual but sustained growth in community-company conflict (Hodge 2014) suggests that many communities remain dissatisfied with the mining sector's ability to mitigate future

[1]Commodities considered: Bauxite, Chromite, Cobalt, Copper, Diamonds, Gold, Iron, Lead, Manganese, Molybdenum, Nickel, Palladium, Phosphate, Platinum, Potash, Rhodium, Silver, Tantalum, Tim, Titanium, Tungsten, Uranium, Zinc.

[2]The Water Account, Australia, distinguishes water use from water consumption. Water consumption is defined as total water use (sum of distributed water use, self–extracted water use and reuse water use) less in–stream water use and distributed water supplied to other users.

negative legacies. These issues, as well as the significant exposure of some mining company's asset portfolios to water-related risks due to floods and droughts (Bonnafous et al. 2017), is now also gaining the attention of mining investors. In the recent words of the Gold Fields CEO: *"Investors say to us: 'don't talk to us about returns'; they want to know how we're managing water"* (Lewis 2017).

21.1.2 Mining's More Unique Interactions With Water

Mining operations interact with water in ways that are distinct from other forms of 'industrial' water systems, such as manufacturing, refining and off-mine minerals processing operations. Many industrial users of water rely on third party suppliers for which water inputs are directly monitored, while the outputs of water from such facilities can be well estimated because there are minimal water losses throughout water reticulation systems. Identifying the main consumptive uses of water therefore tends to be limited by the availability of monitoring data rather than comprehension of the system. Mine sites differ markedly because there can be considerable uncertainty about water inputs and outputs. Operations typically span large geographical areas whereby overall inputs and outputs of water to/from site are closely coupled to the climate. In such cases, it becomes necessary to estimate water inputs through rainfall-runoff models, which can be difficult to validate due to high uncertainty over rainfall/run-off relationships and poor historical rainfall records (Kunz and Woodley 2013). Similarly, there is often uncertainty about the overall outputs of water from mine sites because water is typically stored in large storage dams (sometimes with a surface area spanning hundreds of hectares) that are open to the atmosphere thus losing water through evaporation. Additionally, in many freshwater storage dams, water is lost through seepage to groundwater and this can be challenging to estimate.

A useful terminology to distinguish mine site water systems from many other industrial water systems is to contrast "store-" from "flux-" dominated sites. Mine site water systems can generally be described as "store-dominated" meaning that there is a significantly greater proportion of water stored onsite relative to the total amount of water consumed for operations. In contrast, most manufacturing, refining and minerals processing operations tend to be "flux-dominated" whereby the proportion of water that is stored onsite is lower than the total amount of water consumed for operations. On account of the mining sector's close relationship with water, some have suggested that mining companies are not only in the mining/processing business, but also in the water management business. This is exemplified in recent calculations by Goldcorp, a major Canadian mining company, which revealed that the quantity of water handled at some of the company's sites is over 15 times the quantity of material processed (O'Brien 2018).

Compounding these challenges is the dynamic nature of mining operations. The overall configuration of water infrastructure on most industrial operations tends to be relatively stable over the life of an operation. Conversely, mine water infrastructure, encompassing the storage facilities that capture or discharge water and the pipelines that transport water between them, can change markedly over the course of the mining life cycle (Fig. 21.1). As ore is mined, the volume of site storage dams and the overall landform may change leading to variations in the dimensions of receiving catchments and the shape and location of water storage facilities. Water must also be actively managed during the mining process itself, particularly when ore is being mined from beneath the water table. These dynamics can pose challenges for representing the configuration of a water system at any given point in time, because it can be challenging to estimate flows such as rainfall, runoff, evaporation and seepage.

21.2 Describing Mine Water Systems

Water management is an important task during all stages of the mining life cycle (Fig. 21.1). In early stages of exploration and feasibility, there is minimal use of water; primary uses including drilling or domestic uses within the mining camp. However, exploration is an important stage for collecting baseline data about the state of surrounding water systems and for identifying possible water access points for subsequent construction and operations. Exploration is also a critical stage for understanding the concerns of surrounding communities in relation to water. Early pre-feasibility is also an important stage for making choices about project design options (e.g. how to source water for operations) which can have significant impacts on local communities. A failure to acknowledge and mitigate such impacts can have notable 'rebound' effects on mining projects and their feasibility (Kemp et al. 2016).

As a project progresses into operations, a water balance model is an important tool for managing and optimizing water use, e.g. understanding how key changes in a site's configuration could contribute to changes in risks (e.g. water shortages or overflow events associated with climatic variations or deviations in mine planning). The demand for consistent and regular water accounting and reporting is also essential to meet the expectations of diverse stakeholders including governments, communities and investors. At the mine closure stage, water is often one of the most important considerations. In some cases, particularly if poor decisions have been made in mine waste management during

Fig. 21.1 Typical stages in the life cycle of a mining operation, and the associated water management activities; modified from (Government of Canada 2017; Department of Industry, Science, Energy and Resources 2016)

operations, the impacts of mining on water must be actively managed into perpetuity (e.g. acid rock drainage).

Figure 21.2 depicts a mine water system using a representation that has been gradually but consistently adopted for application by the mining sector (Côte et al. 2010; Danoucaras et al. 2014; Department of Resources Energy and Tourism 2008; Fraser and Kunz 2018; Gunson et al. 2012; Kemp et al. 2010; Minerals Council of Australia 2014; Northey et al. 2019). Most recently, this representation has been incorporated into the water reporting guidelines of the International Council on Mining and Metals (ICMM 2017a), to which all ICMM member companies were required to comply by November 2018.

This section summarizes each component of the mine water system (Fig. 21.2; consistent with ICMM 2017a), describes progress towards more consistent mine water accounting and reporting practices, and summarizes recent data on water use metrics for the mining sector.

21.2.1 Accounting for Mine Water Use

Mining operations interact with the natural environment and surrounding communities through water *withdrawal, discharge, consumption* and *diversions* (below definitions based on ICMM 2017a). The overall change in water volume over a period of time is given by:

$$\Delta Storage = Withdrawals - Discharge - Consumption$$

Due to the store-dominated characteristics of mining operations, it is rare for a water balance to be neutral in any given year; positive or negative water balances are therefore common.

Withdrawals refer to water that enters the operational facility and is intended for use. This water can be classified into four categories:

- Surface water—precipitation, runoff, rivers, creeks, external surface water storages such as dams and lakes;
- Groundwater—aquifer water that is intercepted during the mining process, bore fields, water entrained in the ore that is mined;
- Sea water—water extracted from an estuary, or the sea/ocean; and
- Third-party water—contract/municipal water that is traded, or waste-water from another organization or community.

Discharge refers to water that exits an operational facility and can be classified into four categories:

- Surface water—water that is discharged to surface water bodies, or for the intention of supporting environmental flows;
- Groundwater—seepage during mining operations, and/or water that is deliberatively reinjected into aquifers;
- Sea water—discharge to an estuary, or the sea/ocean; and
- Third-party water—water that is on-supplied to a third party, e.g. other industrial users.

Consumption refers to water that is used by an operational facility but is not returned to the water environment or a third party. It can be classified into the following categories:

- Evaporation—water lost to the atmosphere;

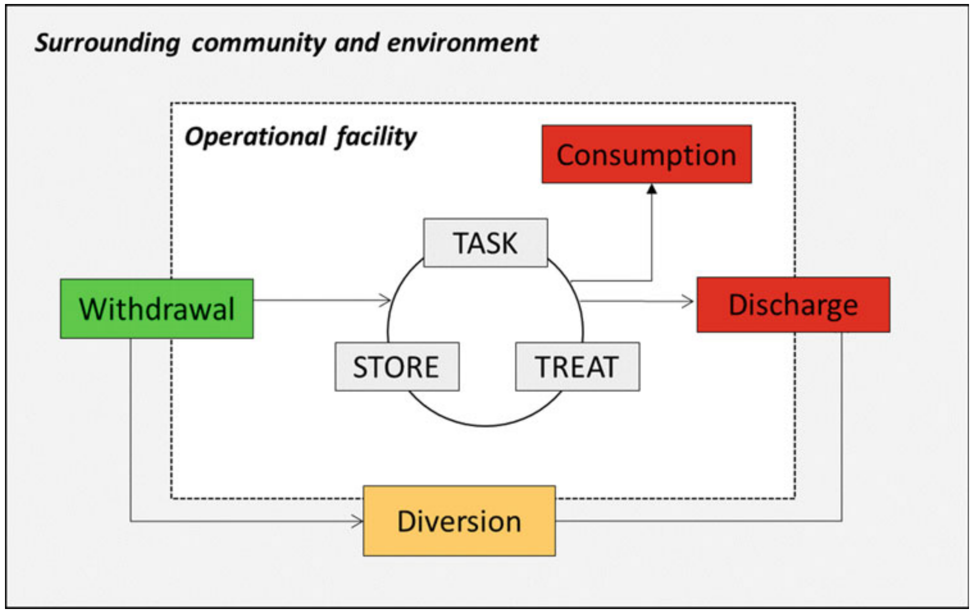

Fig. 21.2 Mine water system representation. Image adapted from: (Danoucaras et al. 2014; ICMM 2017a; Sustainable Minerals Institute and the Minerals Council of Australia 2014). The withdrawal category (green box) is consistent with the MCA-WAF "Input" category", while the Consumption and Discharge categories (red boxes) are consistent with the MCA-WAF "Output" category

- Entrainment—water incorporated into product and/or waste streams; and
- Other—operational losses that cannot be attributed to other categories.

Diversions represent water captured by an operational facility but not intended for use; for example, aquifer water that is intercepted during underground mining but is immediately reinjected to groundwater without use. Essentially, diversions refer to excess water that must be actively managed by the operation in order for mining to occur. Mines located in high rainfall environments or that are mining below the water table will have larger water diversions. Diversions are accounted for separately to the mine water balance for an operational facility, and are not explicitly reported as part of the ICMM water reporting guidelines (ICMM 2017a).

A number of practical considerations can influence the choice of water withdrawal for a given mining project, resulting in different risks to a company (Table 21.1). For example, the Chilean mining sector is having a growing dependence on desalination as a 'climate-resilient' water source for mining operations, despite the high energy costs associated with pumping and treatment (Campero 2018; Campero and Harris 2019). Conversely, the Argyle Diamond mine in Australia withdraws water by pipeline from the nearby Lake Argyle, a Ramsar wetland with high environmental value (ICMM 2012).

Alternative sources of water, and any water that is discharged from an operational facility, can also be assigned water quality attributes. Water quality may vary with respect to pH, turbidity, total dissolved solids (TDS), metal constituents, coliforms, etc. Acceptable discharge concentrations are typically regulated according to the local receiving environment and the nature of the operational facility. During water accounting, the MCA Water Accounting Framework (Sustainable Minerals Institute and the Minerals Council of Australia 2014) distinguishes between three broad categories of water quality, while the ICMM Water Reporting guidelines (ICMM 2017a) distinguish between two (Table 21.2). The minerals sector is often able to use water of a lower quality than other competing users (e.g. agriculture, urban), which can reduce pressure on available water supplies within a given mining region.

21.2.2 Task-Treat-Store Cycle

Water moves through a mine water system by interacting with tasks, treatment plants, and stores. These components are defined as follows (Côte et al. 2009; Danoucaras et al. 2014; Sustainable Minerals Institute and the Minerals Council of Australia 2014):

- Tasks—operational activities that use water (e.g. processing, dust suppression);
- Treatment plants—used to alter the quality of water to make it suitable for a particular purpose; and
- Stores—facilities that capture and/or hold water.

For the purposes of water accounting, tailings storage facilities (TSF) are typically considered to be tasks because

Table 21.1 Examples of practical considerations and risks in selecting a water withdrawal source for a mining project

Withdrawal category	Practical considerations	Risks that may arise for the company
Surface water	Most practical for sites located in high rainfall environments	Climatic variations can compromise water supply security. Difficult to be certain how much surface water is intercepted from rainfall/runoff
Groundwater	Requires availability of large, preferably shallow, aquifer sources Water quality may be unsuitable or require specific infrastructure to use	Reliance on groundwater may compromise access for other users, and potentially impact aquifer availability or connectivity. Calculation of sustainable withdrawal limits can be challenging. Aquifers can have very slow replenishment times Communities can have particular fear over groundwater impacts because the water cannot be seen
Seawater	Most practical for sites located close to coastal environments	High energy cost associated with desalination (and sometimes pumping). Plant intake and outlets can interfere with port activities
Third Party Water	Most practical for sites located nearby to urban areas, where wastewater is generated Water quality can be unsuitable or variable (or both)	Relies on a third party, changes in contract conditions and/or supply disruptions, may increase costs

Source Author

Table 21.2 Water quality descriptions attributable to water withdrawals and discharge flows for the purposes of water reporting

ICMM definition	**High quality water:** high socio-environmental value with multiple beneficial uses and/or receptors both internal and external to the catchment. Examples include: water supply (drinking, agriculture, food production and industry); amenity value; and/or ecosystem function requirements		**Low quality water:** lower socio-environmental value as the poorer quality may restrict potential suitably for use by a wide range of other users/receptors, excluding adapted ecosystem function
MCA definition	**Category 1:** may require minimal and inexpensive treatment (for example disinfection and pond settlement of solids) to raise the quality to appropriate drinking water standards	**Category 2:** Individual constituents encompassing a wide range of values. It would require moderate level of treatment such as disinfection, neutralisation, removal of solids and chemicals to meet appropriate drinking water standards	**Category 3:** Individual constituents encompassing high values of TDS, elevated levels of dissolved metals or extreme levels of pH. It would require significant treatment to remove dissolved solids and metals, neutralise and disinfect to meet appropriate drinking water standards

ICMM 2017a; Sustainable Minerals Institute and the Minerals Council of Australia 2014

their main function is to contain waste material, although some TSFs can store substantial volumes of water before operational reuse (Danoucaras et al. 2014).

The quality of water inevitably changes as it passes through an operational facility, depending on factors such as the nature of processing method, the quantity of "fresh" water received by rainfall and runoff, the chemicals used during minerals separation, or nitrates used during blasting within the mining stage. A common rule of thumb at many mining operations is to 'keep clean water clean' and thereby minimize water quality deterioration. The "status" of water within an operation can be distinguished into three broad categories:

- Raw water—"new" or "fresh" water that has been received to site, but not yet passed through a task;
- Worked water—water that has passed through a task; and
- Treated water—water that has been treated on-site before use within a task or before it is discharged to the environment.

Accounting for water status is a necessary step before calculating the water reuse or recycling efficiency for a given operation. Water reuse efficiency is given by (ICMM 2017a):

$$WaterReuseEfficiency = \frac{\sum(WorkedWaterFlowsToTasks)}{\sum(AllWaterFlowsToTasks)} \times 100\%$$

21.2.3 Recent Data on Water Use Metrics for the Mining Sector

Mining companies regularly report water performance metrics through annual sustainability reports, and a number of studies have compiled global datasets to investigate key trends (Gunson 2013; Mudd 2008; Northey et al. 2019). Various factors may explain differences between mines, including choice of processing methods, mine water management practices, commodity type, and ore grade. For these reasons, comparisons between water use per tonne of ore mined or commodity/concentrate produced should be interpreted in context. For example, a recent analysis by Northey et al. (2019), which compiled 359 mining company sustainability reports accounting for 23 commodity groups, found that water withdrawals ranged between 0.1 and 17 m^3 per tonne of ore processed for 90% of the mining operations studied.

Further interpretation of the data collated by Northey et al. (2019) provides a snapshot of the distribution of water sources relied upon by the mining sector globally (their dataset spanned a 30 year period from 1986 to 2016). An analysis of their summary statistics on mine site water withdrawals by category reveals that the mines studied unsurprisingly relied dominantly on groundwater and surface water (mean groundwater withdrawal was calculated at 1.5 m^3 per tonne of ore processed, and mean surface water withdrawal at 1.2 m^3 per tonne of ore processed). However, *median* surface water withdrawal (0.84 m^3 per tonne) was slightly higher than groundwater (0.52 m^3 per tonne) suggesting that surface water is the main water source for the majority of mines studied. The use of third party water was comparatively lower (0.12 m^3 per tonne of ore processed), while their dataset did not include any mines that reported the use of seawater.

Northey et al. (2019) showed that mining companies report less information about the discharge of water from operational facilities than withdrawals. This may reflect a less sustained demand for such information by interested stakeholders such as investors, who may perceive that withdrawal data is the most relevant for understanding water risk exposure. This represents an interesting finding since, for example, Anglo American reported that mines are typically at higher risk of production losses due to floods than droughts (Fleming 2016). It also signifies a surprising attitude, i.e. that greater environmental stress is perceived as a result of withdrawal than discharge, which is in reality contestable.

There is considerable variability in the water reuse efficiency between mining operations, ranging between 13–94% for 90% of the mining operations studied (Northey et al. 2019). This may reflect different priorities at an operational level about the importance of reducing water withdrawals. It may also reflect historical differences in the definitions used for water reporting. As explained by Northey et al. (2019), the industry has historically adopted a variety of alternative definitions (e.g. raw water use divided by worked water use) which are not directly comparable to the robust definitions endorsed by the MCA and ICMM standards (see Sect. 2.2).

21.3 Mine Water Management

Mine Water Management involves the adoption of a risk-based approach to identify and mitigate water issues that can individually or collectively compromise production at a mining operation (Department of Industry, Science, Energy and Resources, 2016). Côte et al. (2010) define an effective mine water management system (using coal as a case study) as one that: (1) meets operational constraints, such as avoiding water shortages and abiding by license requirements for water discharged from the mine, (2) maintains worked water quality at a salt concentration that is desirable for processing, and (3) adopts strategies that will reduce water imported to site and maximise the volume of water reused and recycled.

This section reviews progress towards improved mine water management practices in the mining sector, from the perspective of both technical and human management systems.

21.3.1 Technical Aspects of Mine Water Management

In 2007, the Centre for Sustainable Resource Processing (CSRP) in Australia published a report reviewing key trends in water management within the field of resource processing (Côte et al. 2007). As part of this work, a five-level hierarchical framework was developed to identify research needs based on the building blocks of mining and minerals processing operations. The hierarchy represents unit operations at the lowest level up to linked networks of sites at the highest. Through workshops with industry participants, research priorities were identified for each level of the conceptual hierarchical framework (Table 21.3).

Looking back on the research priorities identified by industry experts in 2007 (Côte et al. 2007, see summary in Table 21.3), there have been significant advances in addressing these issues from both an academic and applied perspective. Governments and industry associations, often supported by academic research, have produced many guidance documents for improving mine water management practices within the sector. For example, the Australian Government published a leading practice handbook in 2008 that outlined drivers for the sector to address water risks, provided tools for risk management, and offered guidance on developing mine site accounts and water balances (Department of Resources Energy and Tourism 2008). Likewise, in 2006–2007, South Africa's Department of Water Affairs and Forestry published a series of 15 best practice guidelines covering topics including water resources protection, waste management, and integrated water resources management (Munnik and Pulles 2009).

These and other efforts, including formal refereed literature and conferences, have contributed to improvements in many technical aspects of mine water management. For example, a lack of consistency in mine water use reporting historically presented a major barrier for benchmarking performance across sites and collating mine water use data at regional scales (Mudd 2008). However, the growth in voluntary disclosure standards by industry associations has improved the consistency in water reporting across national jurisdictions and internationally. The Water Accounting Framework (WAF) developed by the Minerals Council of Australia (MCA) and University of Queensland (2014), which is based upon the water systems model described earlier (Fig. 21.2), has made progress to address this gap. MCA member companies have now endorsed the Input–Output model and associated water quality descriptors. This has improved the consistency in water reporting and promoted water data disclosure. For example, mines operating in the Upper Hunter Valley in New South Wales (NSW) Australia are now reporting their combined water use data on an annual basis to facilitate informed discussions with local communities (NSW Mining 2013). The minimum disclosure standard for water reporting recently published by the ICMM (2017a) has laid a foundation for further improving mine water accounting and reporting internationally, and aligns with the requirements of other reporting standards including the Global Reporting Initiative (GRI).

The development of a robust mine water balance and account is an essential first step for exploring opportunities for a given operation to reduce water consumption. This is particularly important for a sector which exhibits significant variability in water metrics (e.g. water reuse efficiency, water consumption per tonne of ore processed) for similar mineral commodities (Northey et al. 2019). Towards this end, there has been increased recognition about the utility of "systems models" for exploring alternative mine water management scenarios (Côte et al. 2010; Gunson et al. 2012; Kunz and Moran 2016). Studies have found that the adoption of improved water management strategies could reduce water consumption by up to 60% at some mines (Côte et al. 2010), while others have reported that the adoption of new technologies such as advanced tailings thickening and ore pre-sorting could reduce water consumption by up to 74% (Gunson et al. 2012).

Any given site will have a suite of options available for improving water use efficiency. Kunz and Moran (2016) distinguished three main categories, roughly ordered from the least to most costly to implement:

- *Operational*—changes in management practices, e.g. varying the frequency of dust suppression trucks to avoid overwatering;
- *Technological*—installation of new products, e.g. process control systems to optimize distribution of water between existing storages; and
- *Infrastructure*—fundamental changes to the site configuration, e.g. installation of new water storage dams, pipes and pumps, or significant changes to process design.

While a mine's water management strategy will be heavily site and context dependent, there are diminishing returns with the investment costs required to achieve incremental improvements in water reuse efficiency. Up to a threshold of expenditure (the maximum a business case can justify) in any given investment period, a mine should invest in the activity that will reduce water consumption by the most amount per dollar spent. Then the next most efficient and so on until the budget that can be justified is expended. There are always competing demands for available capital investment and trade-offs against water savings are required. On top of this, some investments in water savings create tensions with other goals, e.g., energy savings because the installation of new technologies such as water treatment plants and advanced tailings thickening require energy to operate (Gunson et al. 2010; Nguyen et al. 2014). While there has been some progress towards characterizing such trade-offs, it remains an attractive area for future research. Other trade-offs which have to date been underexplored include:

- *Closure trade-offs*—Advanced filtration systems allow mines to minimize the volume of discharge to a tailings storage facility (TSF), however lower moisture content can contribute to higher risk of acid rock drainage (ARD) by increased exposure to oxygen.

- *Social trade*-offs—A drier TSF typically generates more dust and can negatively affect communities.
- *Ecological trade-offs*—Mines sometimes utilize saline water or chemical additives to manage dust, however the ecological effects of long-term use (e.g. salt plumes) are understudied.

21.3.2 The Importance of Human Systems

While advances in the technical aspects of managing water issues on mines will continue to remain an important area of research, there is also a need for commensurate attention on human and management systems. Many mine sites have divisional management structures organized around stages in the production process, e.g. mining, processing, environment, social responsibility (Fig. 21.3). Consequently, the individuals/teams with responsibilities for connected parts of a mine site water system are typically disconnected in formal management structures (Kunz et al. 2017). This poses challenges for improving system-wide efficiencies in mine water management practices, and mechanisms are needed for managing water issues across organizational boundaries. The issue is further complicated by the reliance of many mining sites on external contractors and the fly-in-fly-out (FIFO) workforce.

The coordination challenges faced in managing mine water systems are similar to those in other contexts, e.g. urban water management (Brown et al. 2006), and catchment-scale water governance (Horlemann and Dombrowsky 2012). However the application of tools such as social network analysis and decision analytics are to date relatively unexplored in the area of mine water management (Kunz et al. 2017), offering fruitful opportunities for future research.

21.4 Mine Water Stewardship

There are several definitions for distinguishing Mine Water Management from that of Mine Water Stewardship. Here, we suggest that they can be distinguished largely based on scale and scope. Mine Water Management strategies focus on managing operational water risks within the mine lease boundary and therefore involve efforts to optimize water use within the use-treat-store cycle (Fig. 21.2, or Levels 1–4 in Table 21.3). Mine Water Stewardship strategies consider the impacts of mining activities on water systems at broader (regional) scales, and therefore seek to improve how mines interact with the communities and the environment beyond the boundary of the operational facility (i.e. broadening to Level 5 and in Table 21.3 and extending beyond mining/mineral operations in the region).

This section summarizes the mining sector's transition towards Mine Water Stewardship as an operational

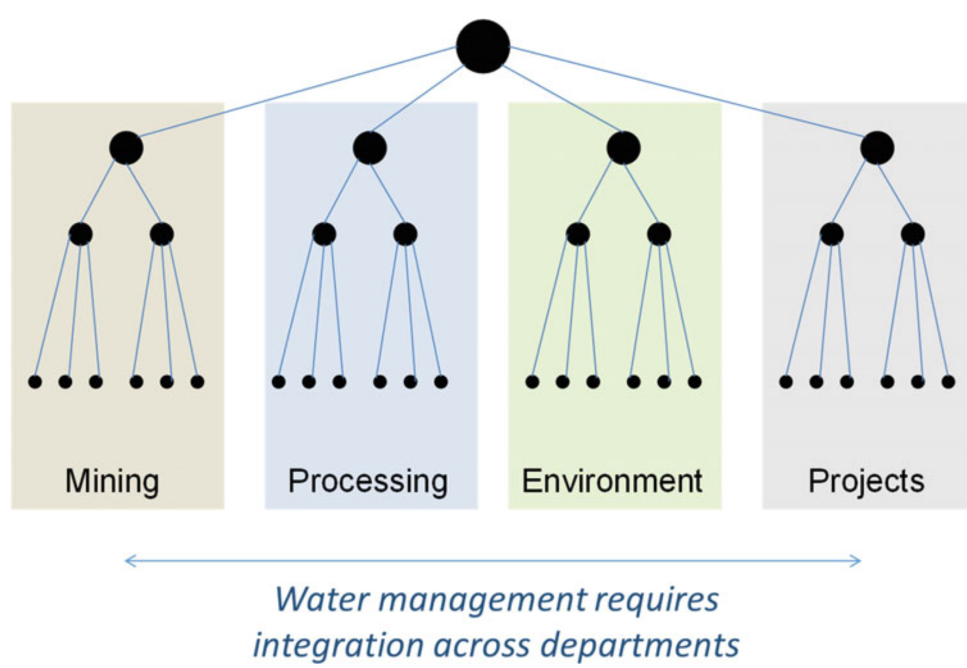

Fig. 21.3 Mining sites typically have divisional management structures, which can impede interaction between departments and create challenges for improving system-wide water management practices

Table 21.3 Selected summary of research priorities identified by Côte et al. (2007) during workshops with industry experts

Level of the hierarchical framework	Examples of research priorities identified at each level
Unit operation (Level 1)	• To gain the most benefit from the proposed conceptual model, a generic description of a unit process is needed that ensures the major sustainability and operational issues are dealt with effectively • Conduct a data survey to quantify water, energy and reagent fluxes entering and leaving unit operations. This information would enable completion of the framework at the technical level. Such a tool would assist all parties to better understand the implications of proposed water management initiatives
The processing plant (Level 2)	• Develop a tool or information database for quantifying the differences in water, reagents and energy uses between one set of linked unit operations and another, enabling the estimation of overall system performance in terms of expected output, (e.g. mineral recovery or commodity purity level), operating and maintenance impacts on profitability and contribution towards sustainability objectives
Site-level (Level 3)	• Guidelines are needed that can assist sites in developing a 'good practice' water balance • Compare the issues associated with managing water from a site versus regional level. Develop guidelines for the effective management of water resources. Such a project would involve comparing the costs and benefits associated with central versus remote water planning/action teams • Research is needed into how to improve the level of transparency within a site, i.e. for management to ensure widespread understanding about the issues that impact various components of the system
Operation as a unit (Level 4)	• It is often not recognized that the complexity of sustainable development may require new methods and skills in community engagement. There is a priority need to understand the differences in community engagement under a site-by-site legal compliance approach and an integrated sustainability approach • A more effective method to regulate water use needs to be developed
Linked sites (Level 5)	• Better modelling tools should be developed to demonstrate a wider range of potential synergies (and their benefits) to complement the current documentation of existing case studies • Investigation of options for cost and risk-sharing that will make synergies more attractive by overcoming too narrow a view of how profitable linkages can be implemented

philosophy, describes trends in associated research, and identifies opportunities for the mining sector to enhance adoption of Mine Water Stewardship practices.

21.4.1 The Evolution of Mine Water Stewardship

In January 2017, ICMM members committed to a Position Statement on Water Stewardship in which they adopted the definition of water stewardship as given by the Alliance for Water Stewardship (AWS): *Water stewardship is the use of water in ways that are socially equitable, environmentally sustainable, and economically beneficial.*

The ICMM statement (ICMM 2017b) substitutes the completion of the Alliance definition, i.e., *achieved through a stakeholder-inclusive process that includes both site- and catchment-based actions,* with a statement of three requirements on members. These are:

(1) Apply strong and transparent water governance;
(2) Manage water at operations effectively;
(3) Collaborate to achieve responsible and sustainable water use.

The ICMM statement includes additional commitments to those that the members have agreed to under the Sustainable Development Framework. In particular, it requires ICMM members to contribute as active partners in addressing water issues at the catchment scale. This is a significant change from the past, when it was generally accepted that the role of mining companies in issues of water allocation should be restricted to negotiating, generally with governments, to secure access to water.

As with a great deal of literature on Integrated Water Resources Management (IWRM, from which Water Stewardship might be argued to have sprung) the above statement and its commitments do not provide adequate operational meaning (Kunz 2016). Supporting decision frameworks and management systems are needed to help mining companies operationalize water stewardship concepts, and to identify the stakeholders who should be involved in a given endeavor (Kunz and Moran 2014). The recent Water Stewardship Protocol released by the Mining Association of Canada (2019) under its Towards Sustainable Mining framework represents one such effort to provide tangible steps that companies should follow.

Since some time before release of the ICMM Water Stewardship Statement, some mining companies were already collaborating with a range of stakeholders including communities, governments, industry and civil society, to address shared water risks. The IFC and ICMM (2017) recently published a report that traces global examples of collective action across Mongolia, Peru, South Africa, Canada and Australia. These case studies reveal examples of mining companies adopting water stewardship strategies through regional water quality and quantity monitoring, increasing water data disclosure, and providing shared water and sanitation infrastructure to local communities. The pressure on companies to contribute to water stewardship initiatives within mining regions is likely to grow ever greater due to factors such as increased complexity of water challenges, the need to manage cumulative impacts, and the rise in community-company conflicts (Fraser 2018).

Mining company aspirations towards water stewardship do however raise concerns about the legitimacy of private sector involvement in water governance, a task that should ideally the responsibility of nation states (Kunz 2016; Sojamo 2015). For example, Hepworth and Orr (2014) have argued that:

> … if the public sector is doing its job in overseeing the sustainable management of water and effectively managing shared risk, there is little or no justification for business engagement in water policy.

However, it could conversely be argued that efforts towards IWRM aspirations might have failed precisely because of a lack of involvement by key water users including the private sector. That is, more desirable catchment-scale outcomes are more likely to be effective if there is a defined and functional role for all actors who are operating in a given context. Rather than there being a problem with private involvement per se, we posit that there is a need to be mindful of undue influence in water governance processes, and to consider the appropriate level of private sector involvement on a case-by-case basis. A research challenge that emerges from this is to determine and test what could form a sound basis upon which such decisions could or should be made.

Kunz and Moran (2014) proposed that defining of the system boundary indicated conceptually in Fig. 21.2 could default to a physical boundary which would typically entail the domain over which the decision maker exercises control or can create sufficient influence; for example, regarding the control of infrastructure to move water to potential uses. An overarching principle, though, is that governments must maintain responsibility for defining what can be controlled via the setting of regulations. Conflicts of interests with private entities may also preclude their involvement (although governments may choose to consult in setting regulations). The criticality of capability in governments to manage this responsibility becomes apparent and justifies maintenance of existing efforts to provide assistance with growing governance capability globally.

21.4.2 Trends in Mine Water Stewardship Research

The past several decades have seen a significant increase in research on mine water management globally (Fig. 21.4). This rise has been particularly prominent from 2006 onwards when there was an 80% increase in research outputs relative to the yearly publication average during the prior 1987–2005 period. In contrast, research on water stewardship and governance in mining regions has only emerged over the past decade. Although publications on these topics have expanded since 2011 (see Fig. 21.4), they remain only a fraction of the overall publications in this field.

The lack of research on mine water stewardship suggests that while significant progress has been made in addressing the research priorities identified by Côte et al. (2007), there has been less advancement on addressing mine water issues at higher levels of the hierarchical framework. A recent analysis of water management practices at a case study mining operation (Kunz 2018) reached a similar conclusion. Through a survey of 145 employees, it was found that respondents were most involved in activities at lower levels of the hierarchical framework (e.g. maintaining water infrastructure, water monitoring, maximizing water recovery from tailings), and had considerably less engagement in activities at higher system levels (e.g. collaborating with other organizations to address regional water challenges, engaging with community and other stakeholders on water issues).

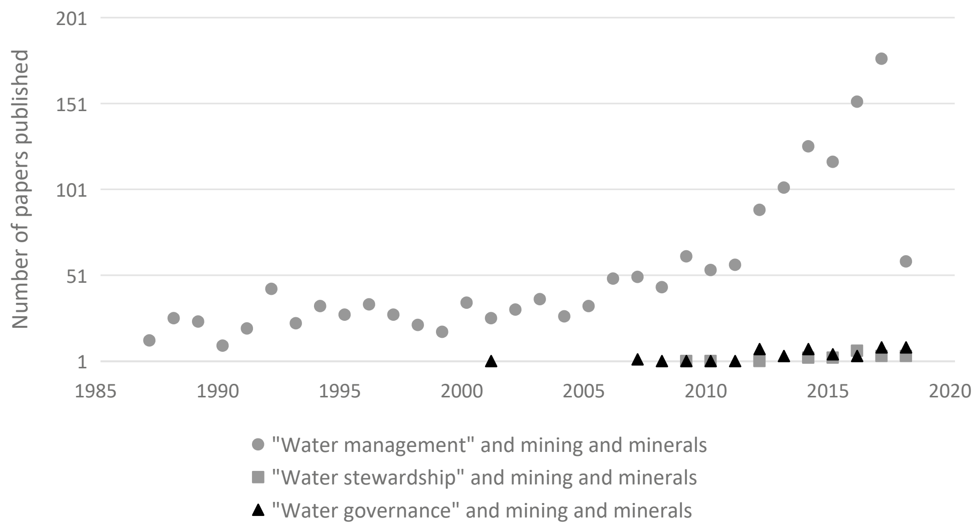

Fig. 21.4 Number of papers published between 1987 and 2018 using the shown search terms. Literature search completed using the Elsevier ScienceDirect database

21.4.3 Identifying Opportunities for Mine Water Stewardship

Whilst it is true that there is a paucity of research publications in the area of water stewardship in mining and minerals *per* se (Fig. 21.4), there exists a body of literature that deals with mining and water related issues at the landscape scale. A significant proportion of this literature can be encapsulated under the concept of cumulative effects/impacts.

The cumulative effects lens has been applied to assess indicators of the social, economic and environmental contributions of mining and pastoralism as the major land uses over large tracts of land (Moran et al. 2013). This has demonstrated that accounting (not accountability) for the benefits that have accrued as a result of long-term access to water is feasible. Also at regional scales, specific trade-offs between water for mining, biodiversity and communities have been quantified (Sonter et al. 2013). Consequently, a scenario-based case study approach for determining the relative significance of the decisions of various stakeholders in practical water stewardship implementation has been validated.

Franks et al. (2013) argue that it is not necessary to have multiple mines operating in a given area to create the need for management of cumulative effects. Indeed, Sonter et al. (2017) showed extensive off-lease impacts on deforestation in the Amazon with a mine-by-mine analysis. We argue, therefore, that there is a role for individual mines to engage in water stewardship even if their location is remote and they are isolated from other mining activities.

For example, in regions where the mining industry operates close to high population density, there may be opportunities for companies to capitalise on the existence of other third party water users. For example, in many regions, cities struggle to discharge used water and often do so at very significant costs. Examples of mines using recycled sewage water certainly exist but as the aforementioned analysis by Northey et al. (2019) illustrates, the current use of third party water as a water supply for the mining industry is minor compared to surface and groundwater withdrawals. Opportunities for mines to utilize third party water supplies as a primary water source will be more likely be sought and implemented in regions where a focus on and/or commitment to water stewardship is evident. Kunz and Moran (2014) proposed a framework that could be operationalized in any particular situation to guide a mining company decision maker towards defining water stewardship goals that could minimize the risks to mining operations the environment and surrounding communities. A key issue raised by Kunz and Moran (2014) is that water supply agreements must include formal rules to deal with situations that could arise as a result of climate variability, so that in times of both plenty versus scarcity the various water users are not cast into conflict but rather apply pre-agreed sets of rules based upon sound risk principles that have been previously contextualized for the region.

Where multiple mines and /or mining companies are operating, an even greater argument can be made for their involvement in, if not leadership of, water stewardship. In many countries and globally via the ICMM, mining companies often act in concert and in some cases in collaboration with other water users to develop water stewardship plans and initiatives. For example, in the Upper Hunter Valley in NSW Australia, several coal mining companies operating in this same region have been working on the concepts and operational implementation of various cumulative effects issues (including water) for over a decade. Significant progress has been made through investment in research, via industry-led initiatives and under state regulation, towards one of the world's best examples of regulated water stewardship for cumulative effect management—the Hunter River Salinity Trading Scheme (Vink et al. 2013).

In short, we argue that there are promising opportunities for future research on water stewardship to adopt a cumulative effects lens that considers human and environmental land uses at a regional scale. This could identify synergies where mining coexists with other water users and particularly where several mining companies might come together to work with other local water users and regulator(s) under the framework of water stewardship.

21.5 Discussion—Towards a Framework for Future Research

Progress in improved management of water resources in all domains has been associated with the use of robust frameworks. Integrated Water Resources Management (IWRM) is an example of a framework that has provided insight and actionable ideas, technologies and processes. Whilst there is justifiable criticism of IWRM (Biswas 2008), it has also been recognized for leading to delivery of better water resources outcomes in some contexts through better balancing water uses between competing production, environment and community uses (Karthe et al. 2015; Ross and Connell 2016). Within the broad domain of IWRM, it is also necessary to use case-specific frameworks to allow greater fidelity in the recognition and resolution of issues and challenges in specific water use domains.

To organize and, at least in part, prioritise research opportunities we employ a framework. The framework (Fig. 21.5) combines a modified and simplified version of the hierarchical systems model presented by Côte et al. (2007) overlain with the mine life cycle (exploration to closure).

The framework acknowledges production-level *tasks*, for example, tailings thickening or water filtration at the individual (unit operation) level and when they are linked together to form various aggregations of flow sheets. The whole of the operation is represented at the next level of the hierarchy and incorporates the land, water and engineered entities that are connected by water pathways—natural and engineered. The boundary that is defined by the mine site lease is hereafter termed “within the fence”. The top of the hierarchy has been altered from the original model of Côte et al. (2007) because the focus on the issues that link individual mine sites provides fewer opportunities to find and resolve water issues than taking a more holistic view of the interactions between mine sites and the regions and communities within which they sit.

Overall, we conclude that the majority of research and the best evidence of research uptake by the mining sector exists at the operational stage and at the level of linked tasks. Although, it should be noted that the linked task work is still mostly exploratory beyond the linking of environmental management with operations in a broad sense (Kunz et al. 2017). Linked task flow sheets for mining and mineral processing have promise to improve water management but modelling remains rudimentary and mostly an add-on (or completely separate to) mainstream metallurgical accounting or flowsheet design. So-called “breakthrough” approaches, such as flexible circuits and the potential for systems optimization to contribute towards water management improvements remain largely untapped except at the level of operational sites (Côte et al. 2010; Gunson et al. 2012; Kunz and Moran 2016).

It is noted that research to support good water stewardship at the time of exploration is not extensive. If companies approach exploration with the stance of water stewardship, significant threats can be minimised. Through the adoption of a stewardship approach from the outset, it is more likely that potential community opposition to a mine can be overcome or avoided should the exploration prove prospective. A significant challenge with this is that exploration and mining companies are frequently not the same entities. Exploration companies are often small enterprises and may claim that they do not have the financial and human resources available to adopt a stewardship approach. Thus,

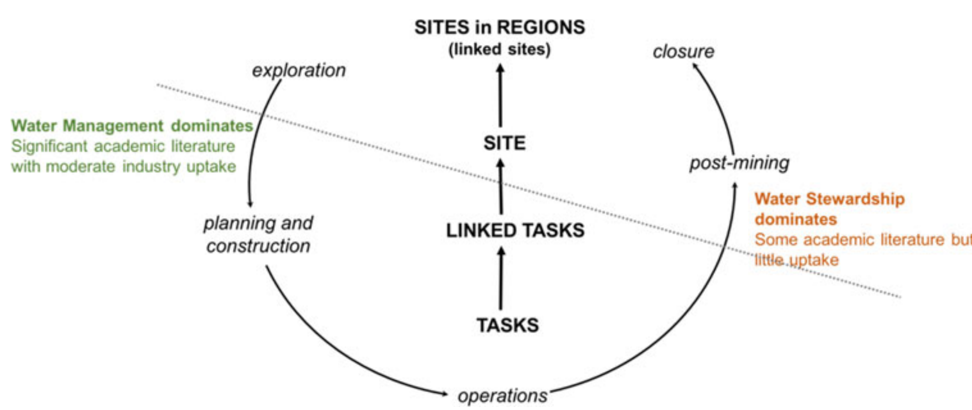

Fig. 21.5 Framework for water in mining that integrates management (production and geographic scales) with the mine life cycle

an opportunity to bring the community on board with a shared value approach to the possible development of a mine may be jeopardised. This is an example of an oft-found constraint to the stewardship paradigm, that is, that benefits and risks can transfer across institutional boundaries and we lack formal or even practical approaches to deal with the "winners and losers" that result from these boundary effects. One might argue that the price of a discovered ore body could be higher if stewardship is adopted at exploration on the basis that the mining company will incur fewer costs for mine development because of the expenditure of the exploration company on stewardship activities, i.e. stewardship could be seen as building asset value. A pioneering effort towards such an approach is evidenced by the Bayan Khundii gold project project in southwestern Mongolia, where the project proponent (Erdene Resource Development Corporation) is implementing water stewardship initiatives as a mechanism to build trust with local communities and earn a social license to operate (Fraser et al. 2019).

There is least evidence of robust research to support site and regional water stewardship during post mining activities and ultimately mine closure. In terms of reputation risk and ultimately challenges to the mining sector overall, closure is likely to continue to be a rising risk and water management within closure a dominating issue. The effects of climate change on the legacy risks associated with water is also a growing issue of concern. For example, in the northern regions of Canada, warming temperatures due to climate change may influence permafrost integrity and compromise the stability of tailings storage facilities (Instanes et al. 2016).

As noted earlier, challenges exist at the interface of government and private institutions over water stewardship. In particular, tensions can arise between governments seeking to exercise good practice authority, and private sector efforts to strengthen governance capability. Potential conflicts of interest can arise if private entities are permitted to be involved in decision making about water governance, e.g. permitting and allocation. These challenges are fertile territory for future research in terms of defining effective bounds for water stewardship efforts to support situation-appropriate regulatory environments.

A final consideration for systemic research comes from the potential range of changes to the operation of mines and minerals enterprises in the digital age. On the one hand, improved sensing, data transmission, storage, integration and modelling capabilities offer new opportunities to improve water knowledge and associated management. On the other hand, fundamental changes are likely to occur in the operating workforce at the mine project level as automation and machine-assisted operational decision-making becomes increasingly dominant. Whilst automated information and physical control systems for water infrastructure are likely to lead to improved efficiency, larger scope environmental considerations may be compromised. Under current circumstances, it is often the site environment team that develops the knowledge of the local environment and connections with local communities. Even if mines decide to maintain site staff for liaison they are most likely to be community specialists rather than environmental or water experts. It is probable that water stewardship will be more effective when those with ongoing connection to landscape and environments have direct involvement in planning and local decision-making. There is a case to be made that water and environment could be an exception to industry 4.0 trends to centralize mining operations in cities via remote operating centres where the majority of the workforce prefer to live and work. Given that the time from exploration to mine closure of an operation could be decades and even longer in a mining region, it is likely valuable to conduct research into the possible benefits of treating water stewardship as a special case of both local capacity building in terms of local knowledge of modern environmental management (data, modelling and infrastructure) and the associated business acumen that can be developed in the community as a result of the decades available. This may be particularly attractive in regions where the future livelihoods of local indigenous peoples is a matter of concern for mining operators.

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Nadja Kunz Canada Research Chair in Mine Water Management and Stewardship, is an Assistant Professor at The University of British Columbia where she holds a joint appointment across the School of Public Policy and Global Affairs and the Norman B Keevil Institute of Mining Engineering. She is also a Faculty Associate at the Institute for Resources, Environment and Sustainability.

Dr. Kunz obtained her Ph.D. from The University of Queensland in Australia, where she remains an Adjunct Fellow. Prior to joining UBC, Nadja spent 2 years as a Postdoctoral Fellow at the Eawag Aquatic Research Institute in Switzerland. Dr. Kunz has practical experience with mining companies and development institutions, including as a water consultant for The International Finance Corporation.

Chris Moran FTSE is the Deputy Vice-Chancellor, Research, at Curtin University developing and implementing strategies, frameworks and activities to achieve the University's strategic goals in research and IP commercialization and is the current Chair of the Universities Australia Committee of Deputy Vice-Chancellors, Research.

Professor Moran is a member of advisory boards for the International Centre for Radio Astronomy, Bankwest Curtin Economics Centre, the Centre for Crop Disease Management and the Fuel Energy Technology Institute.

In the International domain, Professor Moran was a Director of the AusAID-funded International Mining for Development Centre and established an International Centre of Excellence for the mining industry in Chile.

Prior to joining Curtin, Professor Moran was Director of the Sustainable Minerals Institute (SMI), at The University of Queensland (UQ).

22 Water-Related Hazard and Risk Management

Wolfgang Kron, Tawatchai Tingsanchali, Daniel P. Loucks, Fabrice G. Renaud, Janos J. Bogardi, and Alexander Fekete

Abstract

Water-related hazard events are extreme hydrological phenomena that cause loss of lives, injuries, damage to properties, socio-economic and environmental impacts. Damage can be reduced by using control and mitigation measures that can be classified as structural and non-structural measures. This chapter introduces several, even seldom considered hazards. Floods being swift and devasting events receive a special attention. Flood flow computation can be carried out by using hydrological and hydrodynamic models for flood prediction and flood forecasting, etc. Return periods of floods can be determined by probability analysis of extreme events such as maximum streamflow data from past records. The return periods are used as a bench mark in determining the extent of floods for planning and design purposes. Different levels of hazard are considered in estimating the risk level for planning and design of mitigation measures. Vulnerability of population and their assets depends on types of land use, their socio-economic values, exposure and environment. Damage due to extreme events depends on hazard magnitude and types of objects such as population, their assets and infrastructures threatened by these hazards. Risk maps can be drawn to show spatial variation of risk under different magnitudes of hazard and vulnerability. Risk control and adaptation as well as risk sharing are given ample emphasis in this chapter.

Keywords

Hazards • Risks • Vulnerability • Disaster management • Flood and drought assessment • Insurance

22.1 Hazard, Vulnerability, Exposure and Risk in the Context of Water Resources Management

22.1.1 Hazard

Extreme climatological (like heat and cold waves, drought or wildfire), meteorological (storms, blizzards, tornadoes, etc.) and hydrological (floods, mass movements) (Below et al. 2009), events are basically naturally triggered, sometimes even spectacular phenomena. These processes can negatively affect people, their assets and livelihood. Hence, within a socioecological context these extreme events can be identified as hazards.

Human activities themselves and especially the failure of technological processes can also become hazards. The two types of hazards can coincide or occur sequentially, when a natural hazard event triggers failure of technical equipment or infrastructure (so-called "natech" hazards). Natural hazard events may trigger technological events like the Fukushima

W. Kron
Retired, Geo Risks Research, Munich Re, Munich, Germany
e-mail: wokron@hotmail.de

T. Tingsanchali
Water Engineering and Management, Asian Institute of Technology, Klong Luang, Pathumthani, Thailand
e-mail: tawatchai2593@gmail.com

D. P. Loucks
Civil and Environmental Engineering, Cornell University, Ithaca, New York, USA
e-mail: loucks@cornell.edu

F. G. Renaud
School of Interdisciplinary Studies, University of Glasgow, Dumfries, Scotland, UK
e-mail: Fabrice.Renaud@glasgow.ac.uk

J. J. Bogardi (✉)
Center for Development Research, University of Bonn and Institute of Advanced Studies Kőszeg (iASK), Kőszeg, Hungary
e-mail: jbogardi@uni-bonn.de

A. Fekete
Institute of Rescue Engineering and Civil Protection, TH Köln - University of Applied Sciences, Cologne, Germany
e-mail: alexander.fekete@th-koeln.de

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nuclear power plant disaster in Japan in 2011. This was a classic example of the so-called "cascading" hazard, when the unfolding technological hazard was the direct consequence of an earthquake and the subsequent tsunami.

The consequences of hazards, once they affect people and their assets can turn into disasters. Disasters happen when/if hazard consequences (such as number of victims, extent of monetary losses) exceed a certain magnitude (number of casualties, percentage of the affected GDP above a pre-determined threshold). Disasters are typically characterized by the inability of the affected community to recover from the consequences of a hazard event without (substantial) external help. As the size of the affected communities and the source of assistance can vary considerably disasters can be distinguished by scale (such as international, national, regional or local ones). Thus, whether a hazard impact leads to a disaster depends on many factors beyond the magnitude, duration or other features of the hazard event.

22.1.2 Risk

The magnitude of a possible disaster is unknown in advance. However, for taking adequate precautionary measures, designing and implementing structural defences against potential hazards or/and other non-structural steps of disaster preparedness need an assessment of the potential losses to be reckoned with should the respective hazard occur and impact a (well defined) community and its associated assets. This assessment of potential consequences means to calculate the risks of a disaster. Risks are inherently multidimensional as loss of life, material losses, loss of cultural heritage etc. have different dimensions and refer to different groups of people and assets. However, these incommensurate potential losses associated with certain hazards aggregate to, what may be called risk.

Risk has a multitude of definitions (Thywissen 2006) and sometimes even contradicting colloquial connotations. The term disaster risk has not much in common with "risk" of losing money which might be juxtaposed with gaining money in a gambling or game context. Disaster risks are potential losses. Mitigating these expected losses costs "real money". The potential gains if risks would not materialize are then the "not suffered" losses, rather than cash at the hand as shown in Sect. 22.2.3.7 in case of Hamburg. The difference between real invested financial resources for risk reduction versus potential reduction of losses as reward of those investments in case of hazard events is a major reason while disaster preparedness is a difficult political sell. Progress in disaster risk reductions are usually feasible after major disasters. Using this unfortunate "window of opportunity" is more than morally justified, but certainly not a good example of science-based precautionary policies. However, not using these windows of opportunity would be on the other hand an example of gross professional neglect.

Irrespective of these drawbacks, it is essential to emphasize that risk is a pre-event estimation of (multiple dimensions) of potential losses. Whether these losses are materialized in case of a hazard event depends on several factors. The hazard is a co-determinant of the risk associated with a potential disaster, the expected (multidimensional) losses of people and their assets. A hazard may or may not result in a disaster, depending on whether and how people, their assets or resources are involved and how they cope with an extreme event.

22.1.3 Vulnerability, Exposure and Resilience

The "whether and how" aspect can be identified as the (potential) exposure of the values at risk (people, assets) to the hazard, whereas the potential to be hurt depends on an array of social, economic, health, educational, technical, structural, non-structural etc. factors which are usually independent from the type of the hazard. This feature can be described as susceptibility of the potentially affected persons and assets. Susceptibility may turn into hazard-specific vulnerability once people were exposed to it (like living in dry lands or other drought-prone areas or in flood plains). Thus vulnerability *(V)* is the function of susceptibility *(S)* and exposure *(E)*:

$$V = g(S, E) \tag{22.1}$$

On its own turn vulnerability is also multidimensional. It is usually characterized by its social, economic, environmental, physical and institutional dimensions (Birkmann 2006; Cardona et al. 2012). Vulnerability implies the question "vulnerable to what?", hence without being exposed to this particular "what"—a hazard—people may not seem to be vulnerable to that particular threat.

Vulnerabilities of all kinds—of society, of a herd or cropland or the environment—can be mitigated through certain capacities or capabilities *(C)*. These capacities can be both structural and non-structural. Structural capacities are, for instance, reservoirs, cisterns, irrigation canals, wells, etc. as far as droughts and dikes, polders, flood retention reservoirs, bypasses, etc. as far as floods are concerned. They modify both the magnitude of hazards, but also that of vulnerabilities. These structures can, however, contribute to what may be called a false sense of security. Hazard controlling structural measures eliminate the chance that the occurrence of smaller and medium events become disasters but may be insufficient if the natural extreme event surpasses the design value or intended usage of the structure. A community suddenly exposed to an unexpected extreme event can prove very vulnerable. Non-structural capacities, capabilities and skills people might have acquired and might deploy prior, during or after the occurrence of a hazard event. For example, in case of slow onset hazards such as droughts temporary migration and emergency food supply distribution can also be classified as mitigating capacities. Capacities such as knowledge of the hazard, savings, and insurance (as risk sharing mechanism) can directly offset vulnerabilities.

Resilience is increasingly used as an all-encompassing term describing all positive features and attributes mitigating vulnerability (Cutter et al. 2008; Manyena et al. 2011; Bogardi and Fekete 2019, 2018) or even beyond, like the report of the UN Secretary General's Global Sustainability Panel (2012). It is argued that this "extensive and extended" use of this term is false both linguistically (resilire in Latin means: jumping back, cf. Manyena et al. 2011) and theoretically. In context of disaster risk the meaning of the word is to describe the phenomenon to bounce back into the original state after having been exposed to the impact of a stressor (Hashimoto et al. 1982, Duckstein et al. 1987; Manyena et al. 2011; Munich Re 2017). Meanwhile, the adoption of the term resilience is increasingly questioned (Levine et al. 2012; Alexander 2013; Bogardi and Fekete 2018). The term "capacities" is opted for to cover the vulnerability mitigating options, of which resilience (bouncing back), or moving to a new more favourable state (bouncing forward) is one. Given the multitude of their dimensions and their nature as a potential inclination to be hurt and/or suffer losses, vulnerabilities can be approximated prior to their manifestation during a disaster only with the help of proxy variables. As a tool for planning or hazard risk forecasting, the selected vulnerability estimates often refer to administrative entities. This is often a compromise driven by data availability that typically lacks the precision offered by assessments of individual persons, households or objects. However, administrative units offer the advantage of being directly linked to units used by decision-makers at local, regional, national and international levels (Fekete et al. 2010; Naumann et al. 2013).

Hence the "residual" vulnerability which remains to contribute to risk would be:

$$\mathrm{V} = \mathrm{h}((\mathrm{S}, \mathrm{E}) - \mathrm{C}) \qquad (22.2)$$

where *(C)* represents capacities and capabilities to resist, to respond, to bounce back (being resilient) and to adapt. It includes also coping or even the ability to suffer or to absorb harm without sustained breakdown of the impacted socio-economic and socio-ecological subsystems.

22.1.4 Advance Assessment of Disasters

Vulnerability in the broadest sense is defined as the predisposition to be hurt by hazard(s) (UN/ISDR 2004, IPCC 2012). Risks are defined as the function (product) of hazard and vulnerability whereby vulnerability is often the least known component of an equation which may express risk *(R)* as a function of the hazard *(H)* and vulnerability *(V)*:

$$\mathrm{R} = \mathrm{f}(\mathrm{H}, \mathrm{V}) \qquad (22.3)$$

Risk is the estimate of the magnitude of a disaster before it happens, with a yet unknown, combined potential of hazard and vulnerability parameters. Hazard parameters describe the stimulus event itself (magnitude, duration, frequency etc.), while vulnerability describes the pre-disposition of the subjects and objects that are potentially impacted by the hazard, as well as their setting and context. Losses due to hazards as well as the impacts of climate change cannot be addressed by hazard analyses alone but must consider vulnerability estimates (Bogardi 2009; IPCC 2012). Thus forecasting the hazard may not tell the whole story about the inherent risk, which ultimately matters more than the natural, or man-made/technological phenomenon itself. Forecasting risk must imply the prediction (or at least an estimate prior to the occurrence of the hazard event) of vulnerability *(V)*. Vulnerability considerations and even more the quantitative assessment of vulnerability are recent research areas. At present many assessments use proxy indicators. Adger et al. (2004) describe two different procedures for indicator selection, the deductive approach and the inductive approach. Irrespective which way the indicators have been selected at present the results of vulnerability assessments can either become quite trivial or dependent on which indicators were finally retained (Fekete 2009, 2010, 2012; Damm 2010; Naumann et al. 2013).

A critical evaluation of the limitations of vulnerability indices and methods (de Sherbinin 2013) is an imperative given the fact that they link science and policy. By summarizing and simplifying reality they are useful to policy-makers, but the absolute certainties of information expected by decision makers are often incompatible with the uncertainties of the considered hazard event(s), vulnerability of society and the epistemological uncertainties of science itself.

A critical evaluation of the conceptual and theoretical debate about vulnerability, resilience, hazard and risk bears the same relevance for both science and policy (Fekete et al. 2014). Not only do disasters, as rare events, defy simplified modeling in their complexity—in contrast to regularly observable risks. Also, the terms used in disaster research defy precise definition due to their own complexity. Despite all this, the demand for techniques, tools and theoretically based knowledge on how to deal with complexities, future risks, trends and uncertainties, grows. This can be observed among sectors such as economy, environment, politics, society, and science.

22.2 Taxonomy of Floods and Flood Management Strategies

Floods of different origin are probably the most pronounced water-related hazards which can and should be confronted by various technical and other methods of water resources management. Hence, floods will be discussed here in some detail to exemplify the multifaceted aspects of these hazard phenomena, their hydrology and countermeasures before, during and after the events.

22.2.1 Different Types of Floods

22.2.1.1 River Flood/Lake Flood

River floods and the overflowing of lakes are caused by prolonged, often basin-wide rainfall or snowmelt far exceeding the ground's absorption capacity, or design levels of water resource management systems. As the soil becomes saturated, more and more precipitation flows directly into the rivers. The water is collected in the catchment drainage systems. In the main rivers and their tributaries, flood waves can be generated that propagate downstream. A river flood can even effect a whole catchment. The areas exposed to flood risk are those directly adjacent to watercourses and lakes. But also distant areas can be flooded, due to groundwater rise. A riverine flood typically starts from the river, and because the sequence of areas flooded is usually the same, it is possible to derive a relationship between flood intensity (for different return periods) and area affected (flood zones). However, no flood and no flood wave occur exactly at the same spot at the same magnitude of flood levels and discharge. Shapes of the flood waves can also widely vary.

As a rule, river and lake floods especially in lowland topography rise gradually and last for periods ranging from several hours to several weeks depending on the size of the basin and the characteristics of the triggering precipitation, thaw and melting process. The flooded area may be very large if the river valley is flat and wide and enough water is present. This type of flooding is more or less well defined as far as planners and emergency managers are concerned, especially if flooding has occurred in recent times.

The occurrence of floods in the same places, while widely different in magnitude, can be classified as fairly regular phenomenon. Flood control measures can be implemented based on past events. Forecasts can be made using, for example, mathematical models or observations. Based on these early warning can be issued, evacuation and/or other forms of preparation are possible (see Sect. 22.8). The pressure in many countries to provide dwelling and development areas has led to the intensive use of valley floors along major rivers and therefore it resulted in the exposure of hundreds of millions of people to flooding. Nevertheless, along great rivers people can learn how to live with floods, thus reducing their vulnerabilities and increasing their resistance and resilience.

22.2.1.2 Flash Flood and Off-Plain Flood

Most flash floods and off-plain floods are caused by high-intensity rainfall (often over a very small area and typically in conjunction with thunderstorms or tropical cyclones), during which the precipitation rate exceeds the infiltration rate and the drainage and storage capacities at the relevant site (Kron 2016). Unlike river flooding, it is not the total amount of rainfall but its intensity that counts. Where the terrain is flat or does not slope sufficiently, water accumulates on the surface, but, on a local scale, inundation can reach considerable depths—for instance where there are depressions in the landscape, which may not even be noticeable to the naked eye. On sloping terrain, water flows downwards, sometimes at high velocity and with extreme destructive force. The intensity and destructive power of the flood is increased by floating matter (debris, branches, trees, etc.), transported sediment, ground and channel erosion, and the undermining of foundations of buildings, roads and bridges.

Flash floods can happen anywhere, without exception. They are almost always surprise events. Streams in particular can be transformed in a matter of minutes from gently flowing brooks to raging torrents, eroding their embankments and beds. Flash floods are generally of limited duration: after a few hours, or at most a day or two, the water will have receded. Since such floods cannot be forecasted sufficiently far in advance, responses such as protective measures are normally not an option, and lives are often lost. While the area affected by a thunderstorm is usually limited, such events are by no means always local. A single atmospheric disturbance can generate a line of thunderstorms extending for hundreds of kilometers. Rainfall intensities during tropical cyclones can also be very high, and may trigger flash floods over large areas. The 1000–1600 mm rainfall Hurricane Harvey precipitated in Houston and the surrounding area on the US Gulf coast in August 2017 is a prime example (Munich Re 2018). Hence, flash floods can occur simultaneously over a substantial area, and subsequently can trigger also river floods.

22.2.1.3 Backwater Flood

Backwater can be produced by the insufficient drainage capacity of a man-made channel (or culvert, pipe, etc.) or a narrowing in a channel such as a bridge passage or a natural constriction. Other natural causes are landslides into a watercourse and ice jams (see Sect. 22.6). In these cases, the sudden blockage causes the upstream water level to rise rapidly. Here, potential inundation of the surrounding area is not the most serious problem: the greater danger is that a natural or man-made dam will overflow. The loose material it comprises quickly erodes upon overtopping, giving way to the backed-up water. As a result, a devastating wall of water surges downstream. Back-up floods may also have non-natural causes, such as the collapse of a bridge or a sunken vessel, although neither will generally cause significant flooding. During the 2008 Sichuan earthquake in China some 15,000 landslides occurred, of which 256 created landslide dams, blocking rivers (Xu et al. 2009). In some cases, secondary disasters due to breaking of such barriers could just barely be avoided.

22.2.1.4 Ice-Jam Flood

Most ice jams are caused when floating ice encounters a constriction in the river, e.g. under bridges, at the head of an island, in a bend or along shallow stretches. The ice sheets pile up, hindering the flow. The resulting back-up raises the water level, even though the discharge may not be particularly high. The ice barrier can suddenly break up, rapidly releasing backed-up water and large chunks of ice, and potentially inflicting serious damage on structures further downstream. To prevent dangerous flooding of this type, the build-up of ice jams is sometimes prevented by blasting.

Northward-flowing rivers in the Northern Hemisphere are especially prone to this kind of hazard. Along the southern upstream reaches and headwaters of such a river, snowmelt may have already started, while the northern reaches are still frozen, preventing drainage and causing the water to back up. Ice-jam floods happen time and again on the rivers in Siberia, on the upper Heilong, Songhua and Nen Rivers and their tributaries in the Chinese province of Heilongjiang (Munich Re 2013), and in the Red River of the North in the United States and Canada. In Hokkaido and northern Honshu (Japan), rivers are iced over for several months each winter. Severe ice runs and ice jams occur here frequently. As a consequence of global warming, the frequency of ice jams has been declining considerably in recent decades. Ice-jam floods were historically common even in Europe until the nineteenth century but due to increasing discharge of cooling and processing water into rivers they have virtually disappeared.

22.2.1.5 Glacial lake outburst flood (GLOF)

When glaciers block a valley or if melt water collects on or behind a glacier or an end moraine, lakes may be formed. They last for periods ranging from a few days to several years or even decades. The retaining ice or debris barrier tends to fail very suddenly and with drastic consequences, as a surging flood wave with potentially extreme discharge values may rush down the valley. Damage can occur up to hundreds of kilometers downstream. Discharges from GLOFs are among the highest observed, especially if the flood is produced by volcanic activity (melting of ice caps). The flows transport large amounts of sediment and debris, which makes them even more destructive (see subsection 22.2.1.7).

Lakes dammed by glaciers form in Asia mainly in the Himalaya Mountains while end-moraine dammed lakes occur in the Karakorum and Tien Shan mountains. The Himalayas have attracted much attention in the context of changing climate as the rapid melting of glaciers has resulted in the formation and expansion of glacial lakes. Outbursts from glacier-dammed lakes often occur in years of very high air temperature, and about two thirds of all failures happen between August and September when the storage capacities of glacier lakes reach their limit. Outbursts from moraine-dammed lakes are most often caused by ice avalanches plunging into the lake with their waves eroding the dam. Four out of five of these dam failures occur during July to August when ice avalanches are frequent (Ding and Liu 1992). Dozens of exceptionally large outburst disasters have been seen in the past half century, claiming more than 600 lives, destroying power stations, roads, bridges and farmland. In one case, one of the major barley-producing areas of the Tibetan Plateau was destroyed in August 2000. More than 10,000 homes, 98 bridges and dikes were destroyed, with an estimated total cost of about US$ 75 million (WWF 2005).

22.2.1.6 Dam-Break and Dike-Failure Floods

Most dams and dikes are constructed—at least in part—for flood protection purposes. Dikes run parallel to a river and fulfil their purpose during floods only, whereas dams extend across a river. For this reason, dikes are not constructed in the same way as dams, which are traditionally built according to much higher engineering standards. Only in recent years have these standards been applied increasingly on a worldwide scale and extended to dikes as well—especially along major rivers—following catastrophic failures of old structures.

There are about 60,000 large dams in the world, i.e. dams that are taller than 15 m, or store more than 3 million cubic meters of water while being at least 5 m tall. Australasia accounts for 64% of the global total, the Americas for 21.5%, Europe for 11%, and Africa for 3.5% (ICOLD 2018). China alone has about 24,000 large dams.

The vast majority of dams are small, earthfill, non-engineered structures. They are often either insufficiently equipped with a flood spillway or have none at all, and have little resistance to overtopping. If overtopping occurs, erosion sets in immediately and quickly leads to breaching and failure. The water behind the dam is suddenly released, and has the potential to become an extremely destructive flash flood further downstream. A dam that has not been adequately constructed may also be prone to failure, for instance of piping, loss of stability (due to soaking) and sliding.

In the USA, the National Inventory of Dams (NID) database holds 91,468 dams (USACE 2019). Half of these are taller than 8 m, some 4,700 taller than 15 m. Almost a third of the dams have "significant" hazard potential (11,354), which means that loss of human life is possible, and significant property or environmental destruction is likely if the dam fails. 15,629 dams have "high" hazard potential, i.e. loss of human life is likely. The need for preparedness became clear in February 2017 when the Oroville (California) dam, the tallest dam in the U.S. at 235 m in height, experienced spillway damage and overtopping of the dam after an extended period of heavy rain and snowmelt, requiring the evacuation of 188,000 people for several days (CDWR 2017).

22.2.1.7 Debris Flow, Mudflow, Lahar

Moving water always carries solid materials. The higher the flow velocity, the higher the sediment transport capacity. In debris flows, the water transports large amounts of solid matter, typically between 40 and 70% by weight. These solid components of the flow continuum are made up of loose soil, sand, gravel, and rock debris (sometimes resulting from recent landslides) set in motion by high flow rates. Debris flows are slurries consisting of rock debris (whose size can be as large as a small truck) and water, and resemble wet concrete flows. Their yield strength and viscosity is sufficient to float gravel-sized rock fragments. Mudflows and lahars are highly concentrated flows of up to sand-sized particles. These hyper-concentrated flows are sufficiently dense and viscous to partially dampen turbulence during flow. They appear to have the viscosity of motor oil.

Lahar, a word that originated in Java denotes a mudflow in the context of ongoing or preceding volcanic eruptions. It may also be caused by fast-melting snow and ice during an eruption. The solids in lahars usually consist of unconsolidated volcanic ash and tephra (= volcanic matter). Such flows often produce significant damage downstream. The eruptions of Galunggung/Indonesia (1982) and Mount Pinatubo/Philippines (1991) volcanoes produced severe lahars. The event that caused the most deaths was eruption of Nevado del Ruiz volcano in Colombia whose hot mudflows buried the city of Armero killing 25,000 in 1985 (Munich Re 1999).

Debris flows can occur where the terrain is sufficiently steep, and come in so-called pulses. They move rapidly downslope, often reaching velocities of 5–8 m/s. At Mount Sakurajima, a volcano in southern Japan, such flows with speeds of up to 20 m/s (about 70 km/h) were measured (Watanabe and Ikeya 1981). Debris flows are extremely destructive. The water–sediment mixture's hydraulic properties differ significantly from those of pure water flows. It moves with little friction, virtually on a cushion of water. Debris flows typically cease abruptly once the water content falls below a certain level, or a decrease in the gradient causes the pressure within the water cushion to subside. The solid materials are then deposited, forming an alluvial debris fan. Some phenomena connected with debris flows are still not fully understood from a scientific perspective.

22.2.1.8 Groundwater and Subsidence Flooding

Large amounts of rainfall can cause the groundwater table to rise above basement floor level and even above the surface of the ground. If the basement floor or walls are not waterproof, water will enter the building. Such a situation is particularly troublesome if it lasts for a considerable time, although property damage may be limited. For instance, if water has to be pumped out of a basement for several months to keep it dry, substantial costs can be incurred. A shallow groundwater table can find itself above the ground surface if it is lowered by subsidence. In such a case, flooding can only be avoided by permanent lowering of the groundwater table by means of pumping. Groundwater-type flooding can also occur in a river valley experiencing long lasting elevated water levels, which may cause seepage even under flood protection dikes.

22.2.1.9 Flooding Caused by Storm Surges

Storm surges are generated when wind drives water ashore. They occur at the coast and along the shores of large lakes; precipitation does not play a significant role. Coastal storm surges are caused by tropical cyclones and extratropical storms. They have extremely high loss potentials and have caused hundreds of thousands of fatalities, even in the recent past. In Bangladesh, death tolls of 300,000 and 140,000 were reported in 1970 and 1991 respectively, and 140,000 died in Myanmar during cyclone Nargis in 2008. Typhoon Haiyan claimed more than 6,000 lives in the Philippines in November 2013. The greatest financial loss from a weather event occurred during Hurricane Katrina along the US Gulf Coast in 2005 (US$ 125 billion in original values) (Kron 2013); the majority of the losses was due to storm surge.

Major improvements in the enhancement of forecasting and early warning facilities in recent years have led to great storm surge disasters with many fatalities becoming less common. Nevertheless, storm surges still represent an immense loss potential in what is a relatively limited strip of land on the coast as Hurricane Sandy confirmed in 2012, when parts of New York were flooded.

In many countries, physical protection against storm surges is not available. This is not only related to the enormous financial means necessary to construct them, but also to the physical conditions of certain coasts. Huge delta coasts fissured by numerous outlets and consisting of hundreds of kilometers of irregular coastline cannot easily be protected by dikes. However, mangrove forests and wetlands have the capacity to hinder a storm surge to enter the coastal flats (World Bank 2016). The accelerating rise in sea levels that is to be expected will aggravate the risk of storm surge and coastal erosion all around the globe—and this will be one of the most detrimental effects of global warming.

22.2.1.10 Flooding Caused by Tsunamis

Tsunamis are flood waves generated by the displacement of large volumes of water due to an earthquake, a volcanic eruption or a landslide. They can occur in any body of water: oceans, bays, lakes, rivers. Almost all tsunamis are generated by geophysical events. Two tremendous tsunami disasters happened recently, in 2004 after the Sumatra earthquake, when more than 220,000 people died on the east and north coasts of the Indian Ocean, and in 2011 in Japan following the Tohoku earthquake when more than 19,000 lost their lives or are missing (Munich Re 2019).

22.2.2 Flood Management Strategies

22.2.2.1 Main Characteristics of Flood Management

Flood risk and loss reduction call for an integrated course of action. The flood risk must be shared between government, the communities, the enterprises concerned and the financial sector, in particular the insurance industry. The crucial factor in coping with flood risk is awareness on all levels. Proper selection of the site where a house or factory is to be built has a major bearing on the risk. Given that many dwellings and production areas already exist in flood-prone areas, measures that prevent flooding, allow mitigation of losses and reduce the overall risk for life, property and living conditions must be taken.

River flood is a hazard that is more manageable than any other of the main natural hazards. Windstorms, storm surges, volcanic eruptions and earthquakes cannot be prevented, the only way to respond is “building strongly and adequately”—or avoid areas at risk. Landslides, avalanches, wildfires and others can be avoided to some extent by advance management measures, but rarely during an ongoing event. In contrast to this, the generation of a river flood can be influenced by a cascade of management actions. This is possible because a river flood is a secondary hazard triggered by rainfall or warm weather (thaw flood) and the origin of the water—the catchment—is known. Additionally, the onset of a river flood is not sudden.

22.2.2.2 Prevention of Flood Occurrence

A flood occurs when there is significantly more water in a river, in a lake, on the ground, or below the surface than normal. Floods are part of the natural water cycle; but mankind has ways of intervening in this cycle. They include influencing the climate (e.g. resulting in more frequent and more intense precipitation), changing the infiltration capacity of the soil (e.g. impervious surfaces, soil compacted by agriculture), keeping the rainwater where it falls (e.g. decentralized retention, forced infiltration), discharging water into rivers and lakes (e.g. drainage ditches, sewers), and directing it towards the sea (e.g. river regulation, removal of flood retention areas).

22.2.2.3 Prevention of Flooding

Flooding (inundation of areas with values) occurs when the soil, a lake, or a river is unable to take up any more water. The water then stands or flows into areas that are usually dry. Flooding can be influenced by technological measures such as retaining the water at specially designated places (retaining basins, polders, reservoirs), or directing the flood waters by means of dikes and/or transfer canals into a predetermined area. All these measures are based on what is called a design flood, i.e. a relatively high flood discharge level used as the basis for designing protection measures.

22.2.2.4 Prevention of Losses

Losses occur when people and their possessions are exposed to and affected by flood waters. In such cases, damp, dirt, mechanical forces, and erosion play a major role. The precautions that can be taken are warding off the water or extricating oneself and one’s valuables from its effects. Solutions also include revising land-use regulations (prohibiting residential areas in flood-prone districts), adopting permanent and temporary structural measures (building elevated structures, waterproofing cellars and buildings), modifying the management of values (avoiding installations or objects of great value or susceptible to water in lower parts of buildings), and taking appropriate action in the event of an impending flood (e.g. clearing out threatened parts of buildings) (DKKV 2004; USACE 2015).

The individuals, companies, and communities immediately concerned have huge potential for loss reduction. People need to be informed and educated on how to build and behave in an appropriate manner, monitor the exposure of their property, be ready to act in an emergency and prepare for potential catastrophic losses by taking financial precautions, such as buying insurance. The type of building construction can make a big difference. Every additional decimeter of height achieved by landfilling, elevating buildings on pilings and locating living quarters and rooms containing valuable property on higher floors reduces the risk, as of course does choosing a design that does not feature a basement. The use of appropriate construction materials (concrete or bricks instead of wood) greatly reduces a building's vulnerability to water contacts. Attention should also be given to the lateral forces of flowing water and floating material that may hit a building. Valuable, water-sensitive items should not be placed on lower floors or in the basement. Company management, in particular, must be made aware of the need to listen to and act on advice. Insurers can play their part by explaining the financial arguments.

22.2.2.5 Prevention of Risk

The risk is derived from the combination of flood occurrence probability and the resulting consequences (Sect. 22.1 and Sect. 22.8.1). At any given place, the risk is nil either if there is no possibility of a flood occurring there or if there are no values exposed (or both). It can be minimized by suitable measures designed to prevent floods, flooding, and losses. Nevertheless, there will always be a residual risk; and that is where insurance, for example, comes in. Insurance makes the uncertainty of future financial strains calculable. In return for a premium, the policyholder can either buy complete freedom from that uncertainty or (by paying a lower premium) limit the loss to a certain deductible level (Kron 2009).

For flash floods the above does not always apply. The water appears suddenly and cannot be controlled, because it comes directly from the atmosphere without propagating through the landscape and in river channels. The other above introduced types of floods may either resemble the river or flash flood case.

Flood risk reduction is often seen as a task of the public (government) rather than of individuals, who reinforce their homes themselves against storm and earthquake. Another major factor is that the alleged controllability of floods, which seems more tangible than wind or ground shaking leads generally to underestimating the risk and to unexpected shocks.

In the discussion of flood control measures, the various sizes of floods are usually all lumped together. No distinction is made between relatively common floods (e.g. with a return period of up to twenty years), major floods (e.g. 100-year events), and catastrophic floods, which only occur on average every few centuries. This approach is fundamentally wrong and results in conflicting stances and solutions. A distinction must be made between frequent and very rare floods and between small and large catchments, because the measures called for in each case are quite different. Table 22.1 lists the most important measures for each group of events roughly in the order of their significance and efficacy. Of course, all other measures have to be incorporated as well, but the fact is that they are not always equally effective.

We will not be able to eliminate the flood risk. We have to live with it—and manage it. Managing the flood risk means sharing it, refraining from exposing values to risk, erecting and reinforcing protection installations, responding appropriately as potential flood victims, and preparing for disaster financially, i.e. taking out insurance cover. Even if all of these things are done, flood losses cannot be completely prevented, but large disasters can be. Numerous examples have confirmed that protection pays off. Unfortunately, action often starts *after* a devastating event. Creating and maintaining high risk-awareness at all levels of society plays an important role. Without the will of the members of a society to spend money, to contribute time and resources and to behave appropriately in flood-prone areas, the obstacles that hinder and often even prevent useful action remain too high. Effective flood risk preparedness is a long-term societal task to be based on scientific insights, precaution and consensus.

22.2.3 Examples of Flood Prevention and Management Efforts

22.2.3.1 China: Response to Devastating Floods, The National Flood Control Plan

In China, precautionary measures to reduce the flood risk are highly visible. The country experienced a devastating disaster in 1998 when flooding on central and northeastern Chinese rivers led to nationwide 4150 fatalities and losses in the region of US$ 20 billion (in original values) (Du et al. 2019). These floods were triggered primarily by river flooding that plagued both the Yangtze and Songhua rivers and their major tributaries. In the years after 1998, floods continued to occur, but none wreaked as much havoc as the events of 1998 and there was a marked decrease in the number of fatalities due to hydrological events. This can be attributed, to a considerable extent, to the extensive flood control program put in place by the Chinese government after the events of 1998. Within the framework of the National Flood Control Plan, more than 620 billion yuan (US$ 87 billion in values of 2010) was invested over the next ten years in protection against floods. Centers were set up for data collection, flood forecasting and early warning, and a flood management strategy was drawn up. By the end

Table 22.1 Measures designed for flood control and flood prevention, in the order of their effectiveness and importance

Frequent floods (T < 10 years)	Rare floods (T = 10–200 years)	Very rare floods (T > 200 years)
"Soft" structural measures	Technical measures	Organizational measures
– restoration – improved infiltration, unsealing of impervious surfaces – decentralized retention – dike relocation, widening of cross-section – dikes – early warning	– flood retention areas, retention basins – dikes – polders – early warning – dike relocation, widening of cross-section	– flood management – early warning – flood defense – emergency outlets – financial precaution

of 2006, 85,800 dams, retention basins and polders had been built or retrofitted. Roughly 280,000 km of dikes were built, providing protection for 550 million people and 45 million hectares of farmland (Kron and Cheng 2017). These measures have played an important role in mitigating the impact of floods and in reducing the average annual number of fatalities caused by flooding to less than 600 in the years following 1998. In the preceding decade the average annual death toll had been more than 2000. The massive floods that occurred in 2016 and caused damages of US$ 28 billion were not river floods and therefore the control and prevention measures in place against river floods had only limited effects.

22.2.3.2 Thailand: The 2011 Flood of the Chao Phraya River

The broad flat plain of the Chao Phraya River, Thailand's heartland, generates 40% of the country's gross national product. The 2011 flood was the worst Thailand had experienced in 50 years and, with overall losses of US$ 43 billion, it was then globally the costliest inland flood of all time (Kron 2012). Over the past 30 years, Thailand has developed rapidly. With its burgeoning population (1980: 46.5 million, 2010: 68 million) and economic growth, there has been a proliferation of huge new settlements, particularly commercial and industrial parks, with assets valued in the tens of billions US$. The traffic and supply infrastructures have also significantly expanded, especially in Greater Bangkok. With the economy booming, the flood hazard became a side issue and was generally underestimated. Protection measures such as local dikes were erected in a non-engineered manner and likely to fail in a crisis. At the same time, the flood hazard was increasing, as widespread tracts of land that had previously served as a buffer for flood waters were swallowed up by development.

When the flood came in 2011, it clearly went out of control. Many of the measures taken were based on trial and error rather than on strategic and prepared plans. Additionally, the large industrial value concentrations, which had been developed in a careless and negligent way in areas prone to flooding, were overwhelmed by the waters. The large industrial parks were the principal loss drivers. Seven such parks, with 1000 production halls in which almost half a million people worked, were meter-deep in water. Massive damage was caused to property, production was halted, and supplies and deliveries were interrupted, sometimes for weeks on end, ultimately with global repercussions. In Thailand, risk management had been clearly neglected and a high price had to be paid.

22.2.3.3 USA: Recurring Floods of the Mississippi

In May/June of 2011, the Middle and Lower Mississippi in the United States experienced the highest flows since 1927. That earlier event had been the signal for continuing flood control efforts. In 1928, the Flood Control Act was passed and the Mississippi River and Tributaries (MR&T) project launched. The U.S. Army Corps of Engineers (USACE) was given the task of implementing and maintaining these measures. Dikes have been erected over a length of 3500 km and the water is now detained by a large number of detention basins. Until 2017 the MR&T project cost US$ 15.1 billion (in original values). The Mississippi River Commission has estimated that it has prevented losses in the amount of US$ 823 billion, or 54 times the sum invested (MRC 2017).

The system includes three emergency floodways on the Mississippi. To prevent high flood losses, USACE in 2011 breached a section of a levee near New Madrid and opened the two downstream spillways. While losses did occur in the deliberately flooded areas, those flood management measures kept the Mississippi discharge below a level that would have posed a major threat to the cities of Baton Rouge and New Orleans, as well as to numerous industrial plants along the river's lower reaches. The damage and losses averted in 2011 for the Mississippi flood amount to several tens of billions of dollars. The long-term risk management paid off (USACE 2012).

22.2.3.4 Japan: The Value of Coastal Defense Programs in Case of Extreme Tsunamis

Japan is more aware of and prepared for natural hazards than any other country. The country had not only built huge tsunami protection structures, but also taken non-structural measures in the form of information, education and training/exercise programs concerning natural hazards. When, on 11 March 2011, a tsunami approached and hit the central Honshu coast, most coastal residents reacted quickly and properly, as they had been trained to do. They fled to locations they thought were high enough, such as the top of five-story buildings. The fact that some were washed away even from these heights was due to the enormous power and height of the tsunami. Although the tsunami walls were overrun by the wave in many places, they at least reduced the power of the water to some extent and gave people a few more minutes to flee.

Comments to the effect that the tsunami proved that “all the efforts undertaken in the past decades were in vain” were misplaced—and even irresponsible. If there had been no program of coastal protection and civil preparedness, the death toll of less than 20,000 would have been a great deal higher. The event was just too extreme for a disaster to be avoided. Even knowing that earlier tsunamis had reached similar heights, one could hardly have made coastal defenses much stronger and much higher. However, the urban development along such a high-hazard coast must be seen critically, despite Japan's shortage of suitable land. And the decision to build a nuclear plant like Fukushima Daiichi at a location like this is highly negligent and unforgivable. Japan's risk management in the past was largely comprehensive, but it vastly underestimated the occurrence probability of an event with extreme consequences, the nuclear accident.

22.2.3.5 Philippines: Storm Surge Devastation in 2013

Typhoon Haiyan's storm surge hit the island of Leyte and Tacloban City in an unexpected and surprising way. The danger of such an event does not appear to have been considered by authorities and/or scientists, so that risk reduction efforts had not been considered either. Commentators, rather than blaming anyone, talked about an unavoidable “accident``/"natural disaster``/"worst possible scenario``. Although some argued that the uprooting of mangrove forests to make way for shrimp farms in the absence of other sources of income meant that the surge was not weakened as much as it would otherwise have been (World Bank 2016), there was more or less a consensus that Tacloban could not have been protected against the disaster. Risk management could only have focused on preventing a high concentration of settlements close to the coastline—but who really could have enforced such a ban?

22.2.3.6 USA: Hurricane-Triggered Extreme Storm Surges

Hurricane Katrina's storm surge, which submerged New Orleans in 2005, and Sandy's in the New York area in 2012 were events close to a worst case. However, both storm surge scenarios had been described before and cannot therefore be called surprising. Despite good knowledge of the risk, no efforts were made to mitigate or prevent it. It was downplayed or ignored, or at least action was delayed. Both storms together cost more than US$ 170 billion. A small fraction of this sum invested in protective measures would have probably saved tens of billions of dollars in losses. Risk management must not stop at risk identification and assessment. Merely paying lip service to the findings is not enough—action needs to be taken without too much delay.

22.2.3.7 Germany: Coastal Defenses Pay Off, the Case of Hamburg

In December 2013, a winter storm (Xaver) produced a storm-surge water level in Hamburg that was the second highest (6.08 m above mean sea level) in 100 years and 38 cm higher than during the disaster in 1962. Then, roughly one sixth of the city was under water; 318 people lost their lives and the loss totaled €1.6 billion (US$ 1.8 billion) values of 2019. Hamburg invested huge amounts in flood protection in the years and decades that followed (€2.6 billion = US$ 2.9 billion, 2019 values). Although storm surges in the city today reach higher levels than they did 50 years ago, the city has remained practically unscathed through flooding. A cost–benefit analysis using different scenarios indicated gains of between €5.4 billion (US$ 6.1 billion) and around €15 billion (US$ 17 billion) (Kron and Müller 2019). The gain is defined as the difference between losses prevented and money invested. The lower figure is based on the assumption that the losses incurred in the affected city area during each storm surge of at least 5.85 m would be equal to the 1962 figure (minimum assumption). The higher figure takes into account the increase in concentration of asset values in the potentially flooded area, a more realistic view. Roughly €4.2 billion (US$ 4.8 billion) would have been attributable to storm Xaver alone. The efforts to reduce the flood risk by predominantly permanent and costly structural defense measures have been highly successful: the pay-off is of the order of 1000%.

22.3 Assessment and Management of Floods

22.3.1 Floods and Their Characteristics

Flood is a natural disaster that causes loss of lives, injuries and serious damages to properties and socio-economic and environmental conditions. Death, injuries and damages to private and public utilities and infrastructures can seriously affect well-being conditions of the people.

The causes of flood can be divided into two main sources: natural causes and human causes. Natural causes of flooding are due to heavy rainfall, rapid snowmelt, high tides, land depression, etc. The natural causes result in overbank flow of channel. Human causes are due to deforestation, urbanization, illegal cutting flood embankment and land subsidence, etc. Rapid growth of urban areas in developing countries raises important problems with regard to flood disaster prevention. Paddy fields, ponds and swamps in flood plains which formerly served as natural reservoirs for floodwater are converted into impervious paved areas thus reducing flood retention capacity and increasing speed of flood wave and height of flood peaks.

Floods normally occur in low-lying areas or flood plains. For rivers, flood plain extends from the river banks into land area on both sides of the river banks. Land outside the flood plain is flood free. Flooding can be due to heavy rainfall, overbank flow or storm surges. The conditions of flooding can be flash floods, slow rising floods and stagnant ponding floods depending on storm conditions and topographical conditions. Floods can be caused by local heavy rainfall, river overbank flow, high tides, coastal storm surges and failure of dams or flood walls, etc. Floods due to local heavy rainfall cannot be drained quickly due to insufficient or poor drainages. Blocking or obstruction of flood drainage ways is commonly found in urban areas. Floods due to overflow of river banks occur when river level rises above river banks. Excessive high river levels are normally caused by high runoff from upstream and backwater effect from downstream due to restricted channel flow capacity or high tides at river estuarial mouths. Urbanization in floodplains reduces floodplain storage and blocks floodways in the flood plains thus increasing flood damage. Flood dikes may breach due to high flood levels and cause severe flood damage. Cities in coastal areas are normally located in low lying areas where drainage is insufficient without pumping. High tides or storm surges can hamper flood drainage from rivers to the sea and can cause prolonged flooding with polluted flood water and health problems in cities. Effects of climate change may lead to more heavy rainfall, and more severe and frequent flooding which are difficult to predict and to mitigate when they occur.

Major types of flooding and their characteristics can be categorized as following:

(a) Flash floods

Flash floods normally occur in steep areas such as in hilly or in headwater regions due to heavy rainfall. Flash floods are sometimes accompanied by landslides, mud flows or debris flows. They occur locally and suddenly in a short duration up to a few hours without warning. They can cause death to people and severe damages to properties (Fig. 22.1).

(b) Gradually rising floods

Gradually rising floods normally occur in the middle and lower reaches of rivers where slope of rivers and flood plains are moderate or flat. This type of flooding is normally caused by overbank flow of floodwater from rivers as a result of excessive discharge from upstream. Its effect may be enhanced by heavy local rainfalls and high sea levels at downstream especially in estuarine areas. Flood water rises rather slowly and spreads over large flood plain areas possibly over a long duration of time ranging from days to months (Figures. 22.2 and 22.3). Gradually rising floods can be predicted in advance and can be protected from or mitigated. Proper flood forecasting, flood management, control and mitigation will significantly reduce flood damages.

(c) Stagnant ponding floods

Stagnant ponding flood stays for a long time almost without flow velocity and requires pumping for drainage. It occurs due to low lying or depression areas and poor drainage capacity. Problems associated with stagnant ponding floods include long term lost in land use activity and human settlement, water pollution and water-borne diseases (Fig. 22.4).

22.3.2 Estimation of Flood Flows

22.3.2.1 Flood Flow Modeling

Flood flow computation can be done by using rainfall-runoff hydrological models and hydrodynamic models. Before applying the rainfall runoff hydrological model, e.g. the NAM Model and the hydrodynamic flood routing model, e.g. the MIKE 11 model (DHI 2003), the models have to be calibrated with the observed runoff or streamflow hydrographs by adjusting the model parameters by trial and error method until acceptable agreement between computed streamflow and the observed data is obtained. A typical result of model calibration of the NAM model at Wichianburi streamflow gaging station of the Pasak river basin, Thailand in 1993 (Gautam 1997; Tingsanchali and Gautam 2000) is shown in Fig. 22.5. By keeping the calibrated

Fig. 22.1 Flash flood suddenly happens in steep areas

Fig. 22.2 Slow rising flood nearly overflowing river bank, Yom River, Thailand

model parameters unchanged, the model is verified by applying it to compute runoff or streamflow at the same station for other sets of given hydrological input boundary conditions, e.g. in 1995. If the computed runoff hydrographs or streamflow hydrographs in the verification agree closely with the observed data, the model is considered acceptable (Fig. 22.6). If the verification is not acceptable, the model calibration and verification have to be repeated incorporating more data of other flood periods. After calibration and verification, the hydrological model and the hydrodynamic flood routing model can be applied for flood flow prediction and flood forecasting, etc.

Of particular interest is flood forecasting and warning. Flood forecasting and warning is an important non-structural flood control measure. The forecast of streamflow at specified stations within the study area can be computed by using the rainfall runoff model and the hydrodynamic flood flow routing model accordingly. Flood forecasting and warning starts with real-time field data collection of rainfall, climatological data and streamflow data at various stations within

Fig. 22.3 Slow rising flood overflowing the dikes along Yom river banks

Fig. 22.4 Stagnant ponding flood in a living compound stands for 3 months

a river basin. The collected data is transmitted by wireless or landline to computing center for rainfall forecast. It is important to mention here that rainfall forecast can be done by various methods such as the use of advanced weather prediction numerical model or the use of a simple method such as using moving average rainfall or extrapolation of rainfall data. Given forecast rainfalls, real time forecast of basin runoff can be done by the rainfall runoff model. Rainfall and runoff forecast are used as input boundary conditions to the hydrodynamic flood flow routing model.

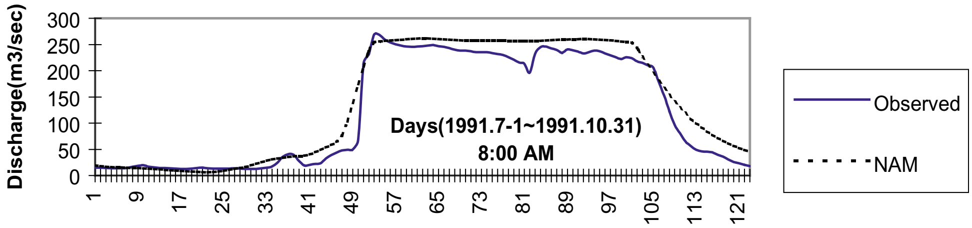


Fig. 22.5 Calibration of NAM model for 1991 Flood at Wichianburi station, Pasak River Basin, Thailand (Gautam 1997; Tingsanchali and Gautam 2000)

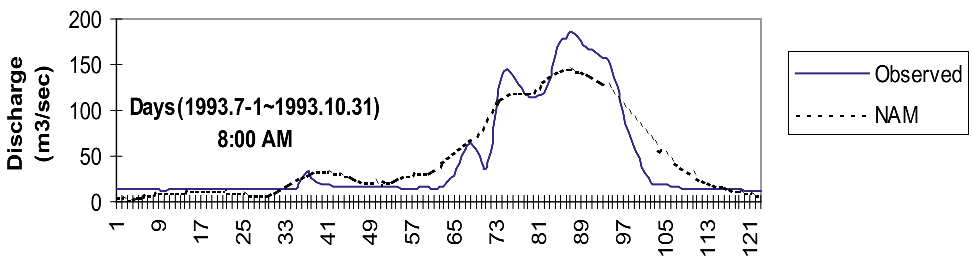


Fig. 22.6 Verification of NAM model for 1993 Flood at Wichainburi station, Pasak River Basin, Thailand (Gautam 1997; Tingsanchali and Gautam 2000)

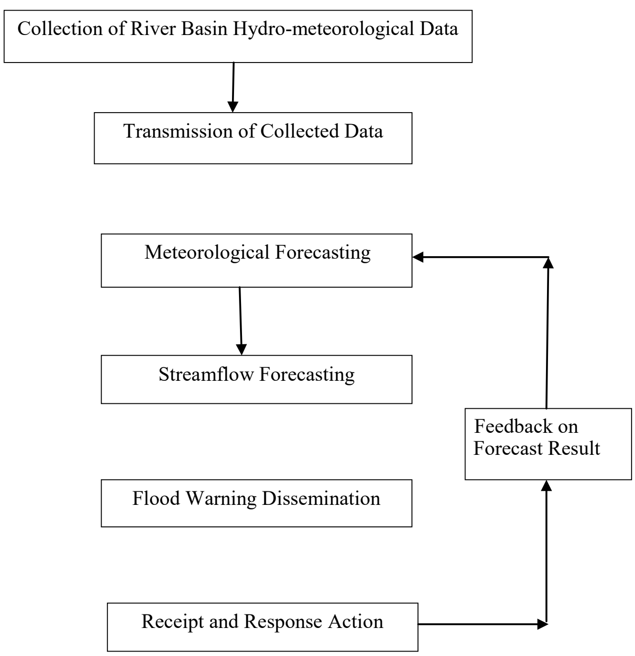


Fig. 22.7 Flood forecasting and warning procedure

The model computed flood forecast is used for flood warning and dissemination to concerned agencies and people in the river basin (Fig. 22.7).

22.3.2.2 Flood Forecasting

Recent development of streamflow forecasting is the application of the error time series in the immediate previous forecast period (hindcast period) to improve the accuracy of next-days forecast of runoff and streamflow such as river discharge and river water level. The forecast error correction technique constructs the error time series of the immediate past days of the hindcast period. A simple error time series such as Auto Regressive (AR) model is commonly used. The error time series constructed in the hindcast period using the AR model is applied to correct the error of the current forecast period to obtain the final forecast streamflow (Figures 22.8 and 22.9). The forecast period can vary from one day to several days ahead of the day of starting forecast) to the end day of the forecast period. Similar error correction techniques as described above have been used in other flood forecast models such as the MIKE 11 flood forecast model (DHI 2003), etc.

22.3.3 Flood Return Periods and Flood Magnitudes

Hydrologic systems are sometimes impacted by extreme events, such as severe storms, high floods, and severe droughts. A typical distribution of frequency of occurrence of annual maximum daily water level at a river gaging station versus its magnitude is shown in Fig. 22.10.

22.3.3.1 Return Period and Probability of Extreme Events

The magnitude of an extreme event is related to its return period. The return period or recurrence interval of an

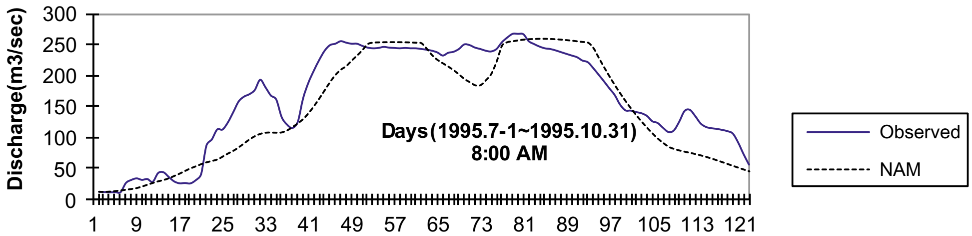


Fig. 22.8 Streamflow forecast using NAM model without forecast error correction at Wichianburi Station, Pasak River Basin, 1995 (Gautam 1997; Tingsanchali and Gautam 2000)

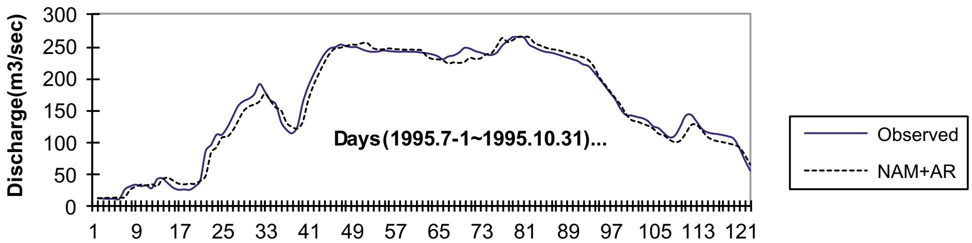
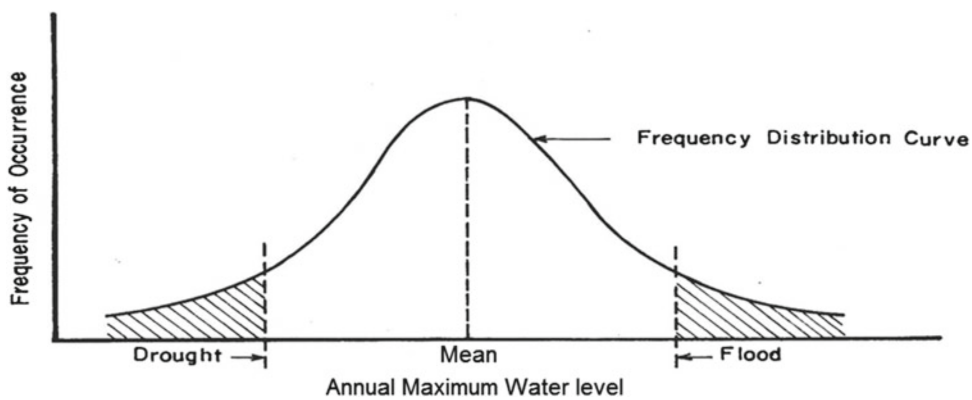


Fig. 22.9 Streamflow forecast using NAM model with forecast error correction by AR Model at Wichianburi Station, Pasak River Basin, 1995 (Gautam 1997; Tingsanchali and Gautam 2000)

Fig. 22.10 Distribution of frequency of occurrence of annual maximum water level



extreme event is equal to $1/P_{exc}$ where P_{exc} is the exceedance probability of that extreme event. In floods, the extreme event can be annual maximum rainfall, annual maximum water level or annual maximum discharge. For example, the return period of an annual maximum flood of 100-year return period has its probability (or chance) of exceedance of 1/100 or 1% in any year. Many people misunderstand that the flood of 100-year return period will occur in every 100-year cycle. The return period of extreme flood events is normally expressed as 10, 50, 100 or 1,000 years or so. To design a flood control structure, for example, based on a maximum water level of 10-year return period, the size of structure would be smaller than the design based upon the 100-year return period. The magnitude of an extreme event with a specified return period can be determined by using probability distribution functions. There are many probability distribution functions for extreme events, those which are often used in water resources engineering for extreme events are: Extreme Value Type I (Gumbel), Log-Pearson Type III, Normal and Log-normal (Chow et al. 1988). By using the probability distribution function as mentioned above, with limited amount of data on extreme values that may not cover the extreme event of the design return period, an extrapolation of the probability distribution function of an extreme event can be made to determine the magnitude of the extreme event beyond the available data for design purposes.

22.3.3.2 Plotting of Flood Magnitude and Return Period

By collecting data of annual maximum flood events, for example, annual maximum flood water level or discharge at a gaging station for a number of years say 30 years, the return period of the annual maximum flood discharge can be plotted versus its magnitude. The plotting can be done by using Weibull, Gringorten plotting positions or other methods, etc. (Chow et al. 1988).

The Weibull plotting position on horizontal axis of non-exceedance probability $P_{non\ exc}$ of a magnitude of annual maximum flood discharge or maximum water level, X is given by

$$P_{non\,exc}\,(X) = \frac{m}{n+1} \qquad (22.4)$$

where: n = total number of annual maximum flood water level X.

m = rank of annual maximum flood water level X arranging according to magnitude of order.

m = 1 for the smallest value of annual maximum water level X.

It is noted that the probability of exceedance P_{exc} = 1-$P_{non\ exc}$ and the return period T = 1/P_{exc}.

A typical distribution of return period versus maximum flood magnitude is shown in Fig. 22.11.

The flood return period can be used for many engineering purposes, e.g., for design of dams, spillway, levee, bridges, culverts, and other flood control structures. In the design of a dam, a magnitude of design flood is used for the design. If the return period of the design flood is selected too large, the dam height will be too large and hence also the cost of construction. If the return period for the dam design is selected too small, the dam height will be too small and the risk of dam failure or downstream damages will be high. The optimal return period or the size of the dam depends on the experience of the designer, the economic condition and social safety reasons. To judge what should the proper size of the structure, a benefit–cost study must be conducted (feasibility study). The social and economic factors and other factors have to be considered in the benefit–cost study.

22.3.3.3 Design Flood Magnitude

The design flood is a flood magnitude selected with an identified return period considered in planning and design of flood control structures. A suitable selection of the design flood would provide a realistic level of flood protection and a reasonable trade-off between the short term and long term implementation cost and flood damage costs. For design purposes, a table of return period for use as a guide for the designer to decide on the design return period is given in Table 22.2 below (ESCAP 1991).

Construction of excessively large flood control measures requires high investment and it is worthwhile only if land use is socio-economically significant. A large flood return period in the design of flood control structures is only considered if they are important. A compromise between the risk of flood damage and the design capacity of the flood control structures has to be optimized. In general, a design flood magnitude of 100 year return period (1% chance of occurrence) is considered mostly for important structures or water resources projects by many authorities.

22.3.4 Flood Hazard

Flood hazard is a measure on the strength of a flood expressed in terms of flood characteristics such as flood discharge, depth, velocity and duration, etc. The degree of flood hazard is generally classified as low, medium, high and very high. In flood hazard assessment of a particular area, one or more flood hazard parameters can be considered in the assessment depending on the flood magnitudes, geographical and land use characteristics of the study area (UNDRO 1991). In large floodplains with flat topography and multiple land uses, the flood depth and flood duration are normally considered for flood hazard assessment. The flood flow velocity and the rate of rising of flood water level are generally small over large and flat floodplains and hence are not significant in flood hazard assessment.

22.3.4.1 Flood Depth and Flood Duration

Hydrologic and hydrodynamic models can be used to calculate flood discharge, flood depth and flood duration for estimation of flood hazard. For example, the MIKE 11 model and MIKE Flood model developed by the DHI Water and Environment (DHI 2003) can be used as the hydrologic and hydrodynamic models to calculate flood depth and duration (Tingsanchali and Karim 2005, 2010; Keokhumcheng 2012; Keokhumcheng and Tingsanchali 2012). The MIKE Flood model integrated 1D channel flow model and 2D flood plain flow model. The model consists of channel junctions or nodes and channel links that connect the nodes. Cross sections of channels and flood plain bathymetry are input into the model. The flood plain areas on the banks of the channels were subdivided into smaller areas, each represented by a network of nodes interconnected by flow channels. Direct heavy rainfall in the study area can be input to the model. Along the boundaries of the study area, there may be embankments constructed to protect flood inflow from outside into the study area. Overflow of flood water from the channels into flood plains can be calculated by using weir equation as discussed in (DHI 2003; Keokhumcheng 2012; Keokhumcheng and Tingsanchali 2012).

In the same way as described in Sect. 22.3.2 in calibration of hydrologic and hydrodynamic models, the model boundary conditions for model calibration are measured rainfalls and measured flood water levels at nodal points in the networks of channels and flood plains in the study area. The model outputs are the computed flood water levels,

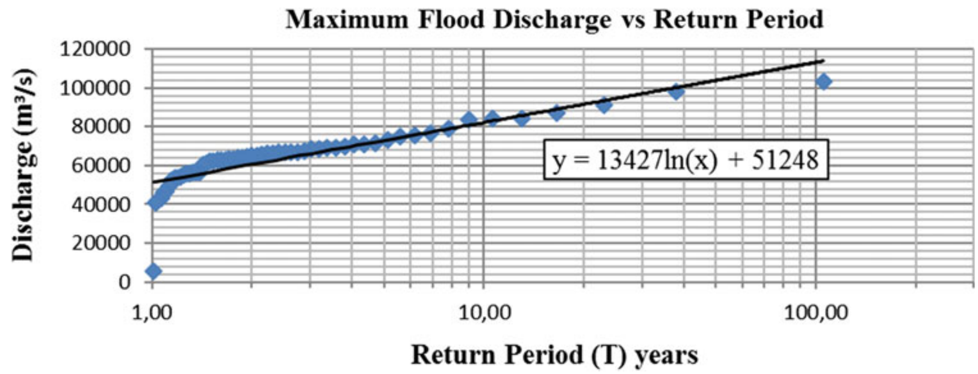


Fig. 22.11 Annual maximum flood discharge versus return period at a river gaging station

Table 22.2 Typical return periods for design flood in various countries (ESCAP 1991)

Country	Commercial	Industrial	Residential	Rural	Agricultural	General
Australia	50–100	50–100	50–100		5–50	
Bulgaria	100–500			30–100	5–10	
China	200			100		
Czechoslovakia	100	50			7–10	
Hungary						60
India	50				25	
Indonesia						5–20
Japan	10–200	10–200	10–200	10–200	10–200	
Malaysia	5–100	5–100	5–100	5–100	5–30	
Philippines	100			50–70		
Poland	1,000	500		100	20–100	
Singapore	5	5	5			
Turkey	100–500	100–500				
Thailand	25–100	25–100	25–100	25–100	50–200	
UK	10–100	10–100	10–100		1–10	
USA	25–100				5–25	
USSR	1,000				10	
Venezuela						5–10
Viet Nam						20–50

flood discharges in channels and flood plains. They are compared with the observed data at gaging stations for model calibration.

The Manning's n roughness coefficient and weir coefficients are adjusted by trial and error to obtain acceptable agreement between the observed and computed water levels or discharge hydrographs at gaging stations. After model calibration, the calibrated model should be verified using data of other floods. This step is called model verification. The model accuracy on calibration and verification is determined by using statistical parameters such as coefficient of efficiency (e), relative error (RE) and correlation coefficient (r), etc. For perfect agreement, the value of e should be 1 and RE should be 0. The r values between the computed and observed data should be 1 is for the perfect agreement.

After the model calibration and verification is completed, the Manning n values and the weir coefficients are kept unchanged. The model is applied to predict flooding conditions in the channels and flood plain for given boundary conditions of desired return periods, for example, of 25-, 50-, and 100- year return periods respectively.

22.3.4.2 Flood Depth Characteristics

The flood plain area is divided into small grids, for example of size 200 m by 200 m in which flood depth category of each grid can be determined and classified accordingly.

From the computed maximum flood depths for a design return period of rainfall, the flood depth classification of each grid was done on the basis of the given marginal depths. The marginal depths are obtained from analyzing the results of questionnaire survey in the study area.

An example can be cited here is based on the results from the questionnaire survey of surrounding area of the Suvarnabhumi International Airport in Thailand in 2010 (Tingsanchali and Keokhumcheng 2006). It was found that the average plinth level of most buildings or dwellings was about 0.45 m above the ground level. When the flood depth was less than 0.45 m there was no damage. When the flooding depth was from 0.45 to 0.90 m, there was a possibility of significant damages to agricultural production. When flooding depth was from 0.90 to 1.20 m, the damage was relatively high and extensive. Therefore, three marginal depths were defined as 0.45, 0.90 and 1.20 m respectively. These marginal depths were used in classifying the flooding area into four different categories, i.e., low flood for flood depth range 0 to 0.45 m, medium flood for 0.45 to 0.90 m, high flood for 0.90 to 1.20 m and very high flood for flood depth more than 1.20 m. It was found that in most part of their study area, the flooding depth was within the depth 0.00 to 0.90 m. Only a small part of the study area had the depth of more than 1.20 m. The flooded area for each depth category was expressed as a percentage of the total study area. A typical flood depth map is shown in Fig. 22.12.

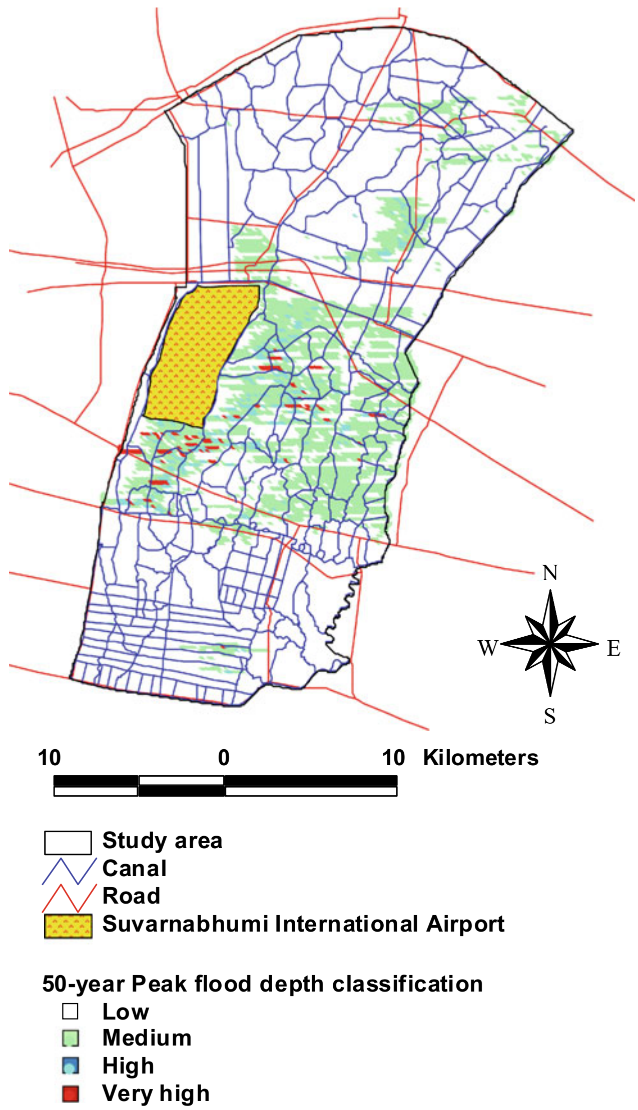


Fig. 22.12 Classification of maximum flood depth for 50-year return period, in surrounding area of Suvarnabhumi International Airport (Keokhumcheng 2012)

22.3.4.3 Flood Duration Characteristics

From questionnaire surveys, the impending depth can be found. The impending flood depth is an average flood depth that causes difficulties to the livelihood of people in the study area. To classify the types of flood duration, the area is digitized into small square grids, for example of 200 m by 200 m. Three inundation maps are chosen based on the computed depths from the hydrodynamic model and the digital elevation model. These inundation maps are used to classify the flood duration category of a specific area: one map when flood level at a reference gaging station just rose above the impending depth, one map when peak flood at the reference station is just reached and one map when flood level at the reference station just dropped below the impending depth. The flood areas appeared inundated in all three inundation maps are considered to have a "very long flooding duration". The areas appeared inundated in any two inundation maps are considered to have "long flooding duration". The areas appeared inundated in only one inundation map are considered to have "medium flooding duration". The areas that do not appear inundated in all three inundation maps are considered to have "short flooding duration". The above-mentioned criteria which was suggested by (Islam and Sado 2000) for a large mud flat flood plain in Bangladesh is used in this study.

The areas of "short flooding duration" have the insignificant flood damage to crops, agricultural activities, asset, dwellings or infrastructures. The areas of "very long flooding duration" have the complete flood damages to crops, agricultural activities, assets or interruption of transportation. The areas of "medium flooding duration" and "long flooding duration" are in between short duration and very long duration. The areas of flooding under each flood duration category area determined by counting the number of grid units occupied by that specific area. For a selected return period of boundary conditions, such as a 50-year return period, the area under each category of flood duration can be expressed as a percentage with respect to the total study area. A typical flood duration map is shown in Fig. 22.13.

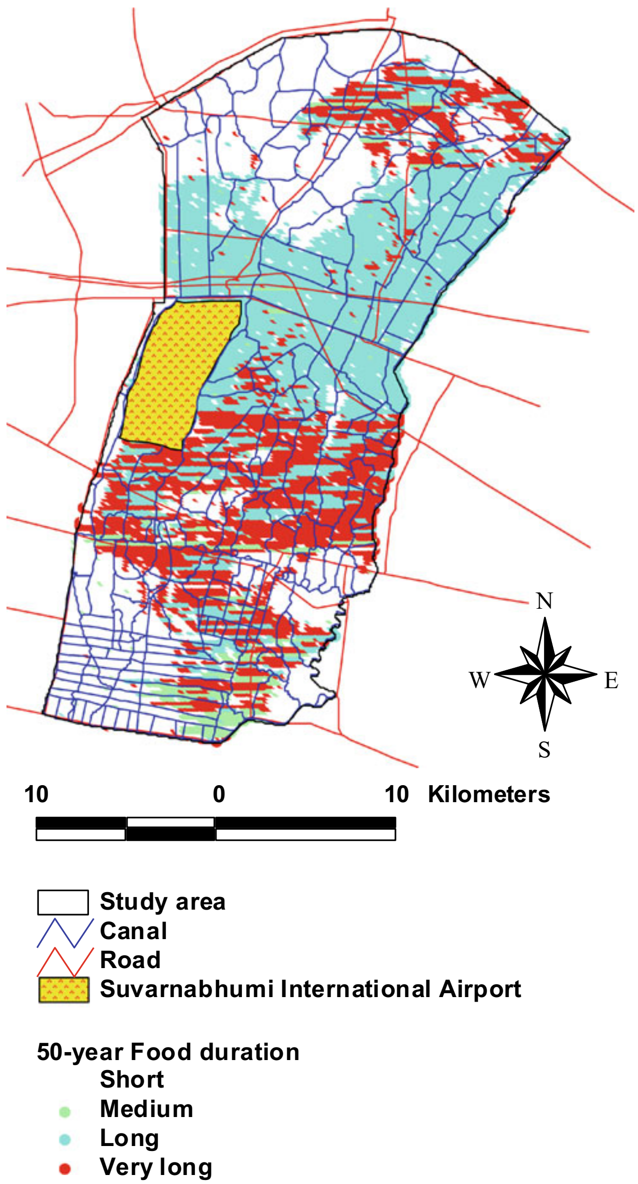


Fig. 22.13 Classification of flood duration for 50-year return period, in surrounding area of Suvarnabhumi International Airport (Keokhumcheng 2012)

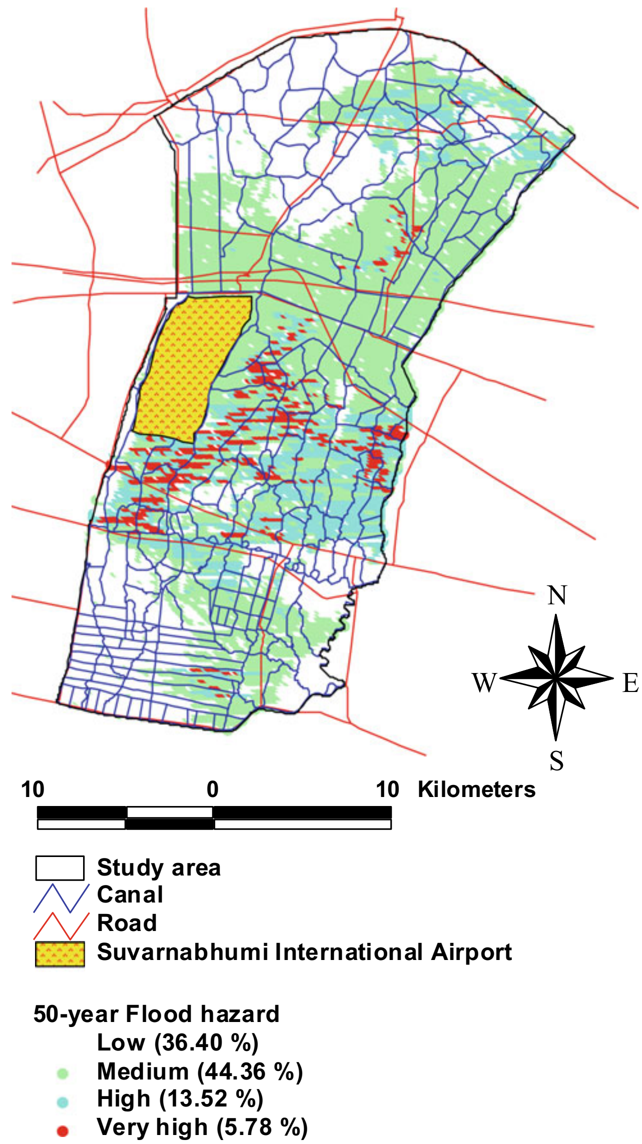


Fig. 22.14 Flood hazard map for 50-year return period, in surrounding area of Suvarnabhumi International Airport (Keokhumcheng 2012)

22.3.4.4 Flood Hazard Indicators

As mentioned earlier, flood hazard depends on flood depth and flood duration. The severity of flood hazard is usually represented by flood hazard indicator (FHI). There are two flood hazard indicators namely: flood hazard indicator for depth (FHI)y and flood hazard indicator for duration (FHI)t (Tingsanchali and Karim 2005, 2010; Keokhumcheng 2012; Keokhumcheng and Tingsanchali 2012). Karim and Chowdhury (1995) made a sensitivity analysis for the three proposed alternative scales of hazard indicator, i.e. (1) the hazard indicator increases linearly with flood depth, (2) the increasing rate of the hazard indicator varies linearly with the flood depth, and (3) the hazard indicator increases geometrically with the flood depth. They found that the scale for hazard indicator which increases linearly with flood depth was the best alternative (alternative 1) for flat and low lying areas. Following (Karim and Chowdhury 1995), a number of options of a set of small integer numbers with uniform increment of 1, i.e., (0, 1, 2, 3) or (1, 2, 3, 4), etc. was used to represent the hazard indicators for low, medium, high and very high categories respectively for flood depth in low lying areas (Tingsanchali and Karim 2010; Keokhumcheng 2012; Keokhumcheng et al. 2012). This is shown as an example in Table 22.3 the integer numbers 1, 2, 3 and 4 were assigned for low, medium, high and very high flood depths. According to Table 22.3, the ranges of flood depth for low,

Table 22.3 Typical flood hazard indicator for flood depth

Flood depth, y (m)	Hazard category	Flood hazard indicator for depth (FHI)y		
		Option 1a	Option 2a	Option 3a
$0.00 < y \leq 0.45$	Low	0	1	2
$0.45 < y \leq 0.90$	Medium	1	2	3
$0.90 < y \leq 1.20$	High	2	3	4
$y > 1.20$	Very high	3	4	5

medium, high and very high are (0–0.45 m) for low, (0.45–0.90 m) for medium, (0.90–1.20 m) for high and (depth >1.20 m) for very high respectively. Three options of the flood hazard indicator for depth (FHI)y are shown in the Table 22.3. The best option of integer sets is selected by comparing the computed hazard condition with the prevailing actual hazard condition. This will be described in more detail in the next section on flood hazard factor.

In their study area where land use is mainly for agricultural purpose, the damages due to flood duration follow the same trend as that of flood depth (Tingsanchali and Keokhumcheng 2006). Four categories of flood duration were considered and the linear scale of flood-duration hazard indicator (FHI)t is adopted similar to the linear scale of (FHI)y. The same sets of integer numbers, e.g. (0, 1, 2, 3) and (1, 2, 3, 4) are assigned for short, medium, long, and very long flood durations respectively. The (FHI)t values for different categories of flood duration hazard indicator are shown in Table 22.4. The best option of integer sets is selected by comparing the computed hazard condition with the prevailing actual hazard condition. This will be described in more detail in the next section on flood hazard factor.

22.3.4.5 Flood Hazard Factor

The flood hazard factor (FHF) represents the combined flood hazard indicators of flood depth (FHI)y and flood duration (FHI)t. The FHF for each grid area can be computed by the following equation:

$$\text{FHF} = \mu(\text{FHI})\text{y} + (1-\mu)\,(\text{FHI})\text{t} \qquad (22.5)$$

where μ is the weighting factor ranging from 0 to 1.

The proper values of μ can be determined by comparing the computed FHF (1) with actual hazard conditions. Three or more values of μ for example, 0.25, 0.50 and 0.75 can be considered. The computed flood hazard factors FHF for various values of μ are compared with the actual flood situations such as depth and duration to see the consistency of flood hazard potential. The value of μ that yields acceptable agreement between the flood hazard factor and the actual flood hazard condition is taken as the proper value of μ.

The proper value of μ should result in flood hazard zones consistent to the actual situation.

22.3.4.6 Classification of Flood Hazard Zones

In Fig. 22.14, Keokhumcheng (2012) normalized the computed flood hazard factor FHF from 0 to 100. The normalized FHF values were subdivided into four equal intervals for example: Low Flood Hazard for $1 \leq \text{FHF} \leq 25$, Medium Flood Hazard for $25 < \text{FHF} \leq 50$, High Flood Hazard for $50 < \text{FHF} \leq 75$, and Very High Flood Hazard for $75 < \text{FHF} \leq 100$. The use of equal range provides relatively uniform representation of the flood hazard zones and their spatial distribution. The areas of different flood hazard categories can be expressed in terms of percentages of the whole study area.

Even though flood hazard magnitude is related directly to flood depth and flood duration but the following impacts due to flood hazard can be used indirectly as a measure for hazard classification. In the low hazard zone, the expected property damage is relatively low and the number of deaths or injuries is insignificant. Wading is safe but vehicle movement is affected. In the medium hazard zone, the expected property damage and the number of deaths or injuries are considerable compared to the number of people living in the zone. Both wading and vehicle movement are not safe. Certain development work in this zone is allowed to provide flood proofing and flood warning. In the high hazard zone, property damage is mostly extensive. Possibility of death, injury and social disruption are relatively high. In the very high hazard zone, severe damages are expected at all levels, with extensive damage to buildings and houses. The number of deaths or injuries is relatively very high.

22.3.5 Flood Damage Vulnerability

Changing economic, demographic and physical conditions in flood prone areas have greatly increased flood disaster vulnerability. Rapid economic growth over the past decades has caused a shift from a primarily agrarian society to an urban society, concentrating growing population density in

Table 22.4 Typical flood hazard indicator for flood duration

Flood duration	Hazard category	Flood hazard indicator for duration (FHI)t		
		Option 1b	Option 2b	Option 3b
Short	Low	0	1	2
Medium	Medium	1	2	3
Long	High	2	3	4
Very long	Very high	3	4	5

smaller spaces. The frequency and severity of flood disasters has increased significantly. Many inhabitant areas in rural or urban areas are located in flood plains because the land is fertile and flat which is suitable for agriculture and urban development. Rivers provide water supply for domestic, industrial and irrigation uses; they also provide convenient means for navigation, transportation and communication. Highly populated urban areas carry high economic values and when faced with flooding, it results in disaster that can set back to urban development for years.

Flood damage vulnerability is a measure of the intrinsic susceptibility of elements at risk that exposed to potentially floods. Flood damage vulnerability depends on population, physical, social, economic, and environmental factors of a community or assets at flood risk. When flood waters physically encroach on people and infrastructures, then the vulnerability of people and infrastructure is decisive for the degree of harm and damages.

A flood of a certain return period will have different levels of vulnerability according to the population, land use characteristics and exposure to potential damage. The vulnerability analysis, therefore, consists of identifying the land use areas under the potential influence of a flood of particular return period. The International Strategy for Disaster Reduction (UN/ISDR 2004) defines vulnerability as the conditions determined by population, physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impacts of hazards.

Birkmann et al. (2007) developed the Bogardi-Birkmann-Cardona framework (BBC-framework) which aims at exploring various characteristics of the vulnerability in the social, economic and environmental dimension. The BBC framework emphasizes the fact that vulnerability is derived from exposed and susceptible elements on one hand, and the coping capacities of the affected entities (for example social groups) on the other hand. Additionally, the BBC-framework shows that it is important to address the potential intervention tools that could help to reduce vulnerability in the social, economic and environmental sphere (Birkmann 2006) such as early warning, training and capacity building.

The elements exposed to risk can be buildings/ infrastructures, population, economic activities, public services and utilities which can be impacted by flood hazard. The quantification of vulnerability depends on the degree of loss of a given element at risk at a given severity level (UNDP 1994). This in turn is determined by conditions of susceptibility of the community (physical, social, economic or environmental) to flood hazard (UN 2006).

According to (IPPC 2012), flood damage vulnerability is a susceptibility of elements exposed to flood hazards. It depends on land use characteristics and population. There are many kinds of elements exposed to risk such as population, assets or properties at risk, economic activities and public infrastructures, etc. The data required for vulnerability assessment are the number of population in a unit area such as a sub-district, land use type and the values of asset at risk per unit area. Questionnaire surveys and field surveys have to be done to collect the data on asset values and number of population including types of land use and economic activities.

22.3.5.1 Flood Damage Vulnerability Indicators

Elements at risk exposed to flood hazard are mainly population and value of assets in the study area. The number of people in the study area and land use classification is required. The questionnaire survey is necessary to collect the data on people's experiences and asset values in different categories of land use. The data required for flood damage vulnerability assessment are the number of people in each sub-district, the data on land use characteristics and the value of asset per unit area.

The flood damage vulnerability is classified based on the degree of susceptibility of elements at risk exposed to potentially flood. The flood damage vulnerability is expressed in linear scale of using an indicator from 0 (no flood damage vulnerability) to 1 (very high flood damage vulnerability).

For population at risk, the flood damage vulnerability indicator of population at risk (FVI)p of each sub-district is considered to vary proportionally with population density and number of people. The value of (FVI)p can be estimated by dividing the people density of each sub-district by the

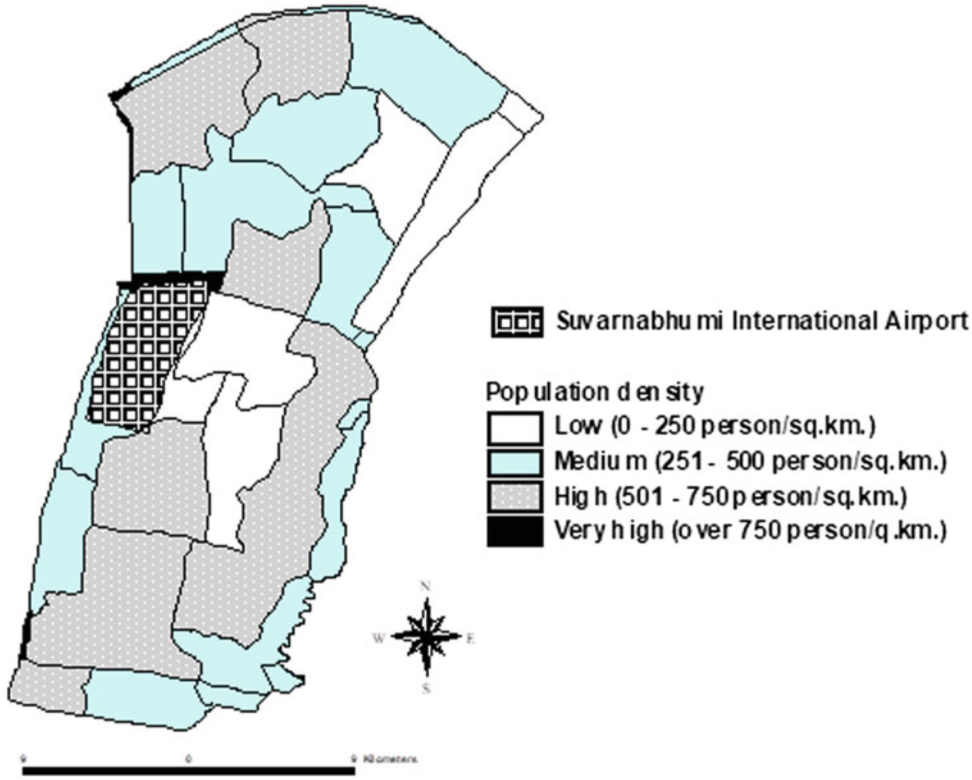


Fig. 22.15 Distribution of population density in each sub-district, in surrounding area of Suvarnabhumi International Airport (Keokhumcheng 2012)

maximum population density of all sub-districts in the study area.

For assets at risk, the flood damage vulnerability indicator of asset at risk (FVI)a of each land use type was estimated by dividing the average asset value per unit area of each land use type by the maximum asset value per unit area among all of land use types in the study area. From the questionnaire surveys, the values of asset of each land use type in the sub-district area are evaluated. Figures 22.15 and 22.16 show the maps of typical vulnerability factors of population and of assets at risk in a study area surrounding the Second Bangkok International Airport (Suvarnabhumi Airport) respectively.

By using the similar procedure in estimating flood hazard indicators, the flood damage vulnerability indicators for population (FVI)p and assets at risk (FVI)a are computed and combined to obtain the flood damage vulnerability factor FVF. This is described in the next section.

22.3.5.2 Flood Damage Vulnerability Factor

The flood damage vulnerability factor FVF represents the degree of susceptibility of elements at risk to flood damage in the study area. The flood damage vulnerability factor FVF is equal to the combined vulnerability of population at risk (FVI)p and assets at risk (FVI)a. Similar to flood hazard factor, the magnitude of FVF was determined by the following equation:

$$\mathrm{FVF} = \lambda\,(\mathrm{FVI})\mathrm{p} + (1-\lambda)\,(\mathrm{FVI})\mathrm{a} \tag{22.6}$$

where (FVI)p and (FVI)a are the flood vulnerability indicators of people and of assets at risk respectively; λ is the weighting factor and λ ranges from 0 to 1. From the questionnaire surveys, the interview of the people in the study area and estimation of damage costs, the weighting factor λ can be decided. For example, in case the vulnerability of population and of assets at risk is judged to be equal, the weighting factor λ of 0.50 may be used. The FVF rank represents the degree of susceptibilities of elements at risk to damages caused by floods.

In the low flood damage vulnerability zone, the expected susceptibility to flood damage of elements at risk is relatively low and the value of flood losses is rarely significant. In the medium flood damage vulnerability zone, the susceptibility to flood damage of elements at risk is medium or tolerable by the residents. In the high flood damage vulnerability zone, properties damage are mostly extensive. Possibility of death, injury and social disruption is relatively high. In the very high flood damage vulnerability zone, the susceptibility to flood damage of elements at risk is highly extensive and intolerable by the residents.

FVF is normalized within the range from 0 (no damage) to 100 (maximum damage). The normalized FVF were subdivided into four equal intervals to classify the vulnerability levels for

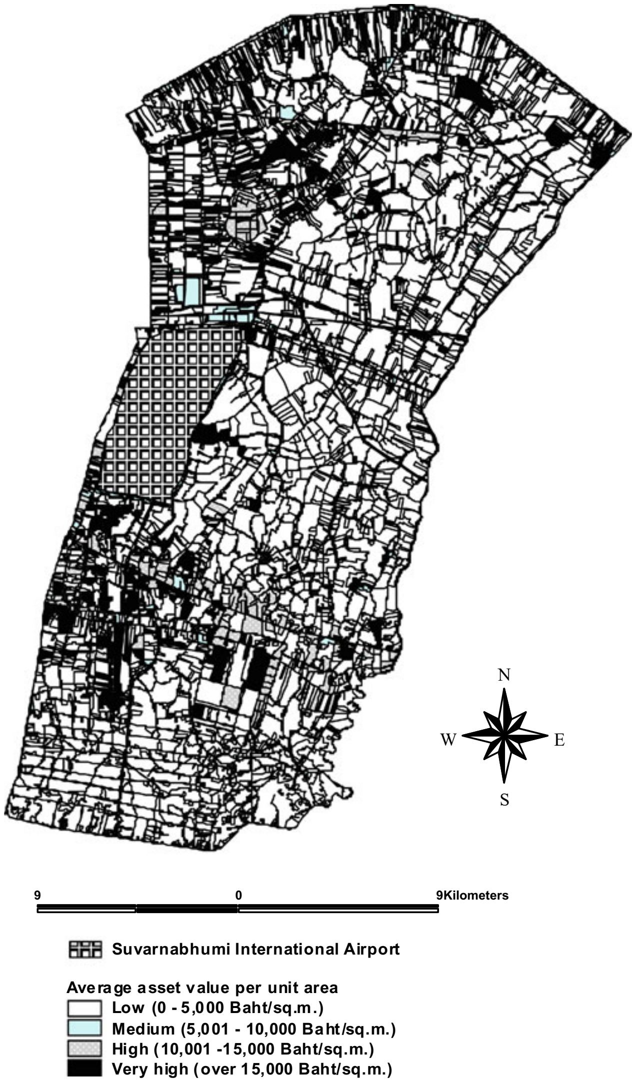


Fig. 22.16 Distribution of asset value, in surrounding area of Suvarnabhumi International Airport (Keokhumcheng 2012)

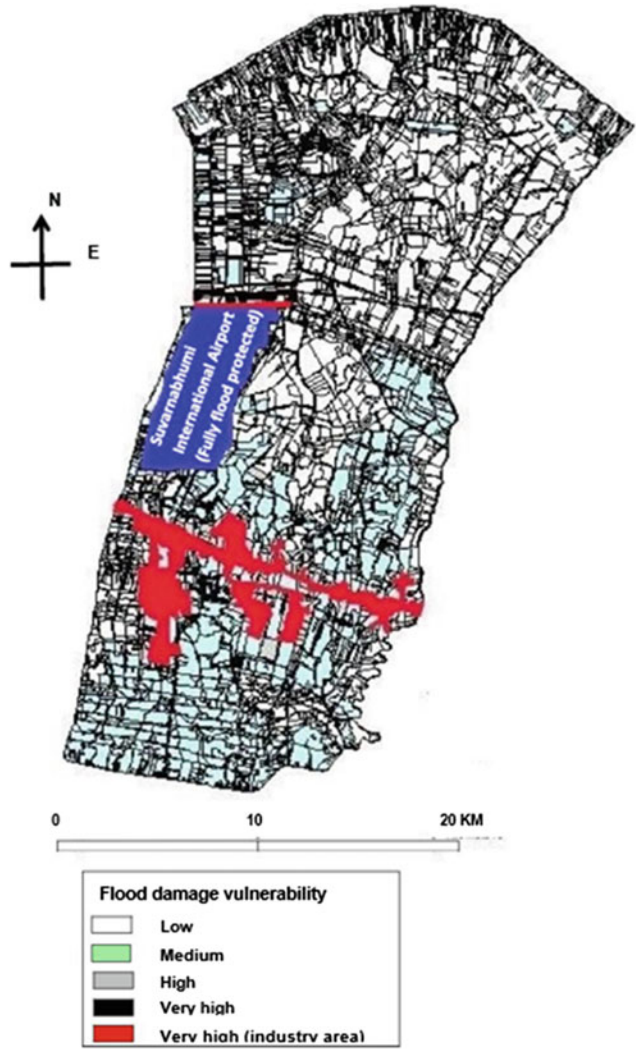


Fig. 22.17 Distribution of flood damage vulnerability in surrounding area of Suvarnabhumi International Airport (Keokhumcheng 2012)

example: low, medium, high and very high. The use of equal interval of FVF is to provide relatively uniform range of comparison of flood damage vulnerability zones. In the classification, FVF can be equally divided into four intervals, for example: $0 \leq \text{FVF} \leq 25$, for Low Flood Damage Vulnerability, $25 < \text{FVF} \leq 50$ for Medium, $50 < \text{FVF} \leq 75$ for High, $75 < \text{FVF} \leq 100$ for Very High. It is noted that the economic losses caused by floods can be found even in the areas which are devastated by very low flood hazard. Figure 22.17 shows a typical map of vulnerability areas where the industrial areas in the very high vulnerability category are shown in red.

22.3.6 Flood Risk Assessment

Risk is the probability of harmful consequences or expected loss resulting from interactions between hazards and vulnerable conditions. The probability of flood risk is related to flood hazard and vulnerability. In the scientific community, it is widely agreed that risk is the product of hazard and vulnerability. The vulnerability may include exposure of elements at risk, such as population and assets. The elements at risk have both spatial and temporal domains and dependent on the level of human intervention in the floodplains. Several researches have defined methodologies for the flood risk assessment. Gilard (1996), Chowdhury and Karim (1997), BUET (1997) presented an approach that divides the flood risk into the factors of vulnerability and hazard whereas the vulnerability is described as the sensitivity of land use to the flood damage, which depends on land use type and social perception of the risk. The second factor, hazard, depends on the flood flow regime of the river and is independent of the land use in the floodplains. Consequently, the same flow will flood the same area with the same physical parameters; whatever should be the real land use. Where there are no people or assets that can be affected by a flood, there is no risk. The risk can only occur when people and/or their assets are harmed. For instance, a very big flood in an uninhabited region without humans and/or assets cannot result in risk. In the other hand, a big flood in a well-prepared region to cope with floods will not be catastrophic. In a poorly prepared region, however, even a small flood may cause a devastating catastrophe.

22.3.6.1 Computation of Flood Risk

Knowing flood hazard and flood damage vulnerability, flood risk is computed as

$$\text{Flood Risk} = \text{Flood Hazard x Flood Damage Vulnerability} \quad (22.7)$$

Given the flood hazard factor FHF and the flood damage vulnerability factor FVF, the flood risk factor FRF can be calculated by multiplying FHF by FVF. The FRF is then normalized by taking its maximum value equal 100. Considering that FRF varies from 100 to 0, the other smaller values of FRF are normalized proportionally within the range of FRF of 100 and 0. According to (Tingsanchali 2005, 2010; Keokhumcheng 2012; Keokhumcheng et al. 2012), their study areas were divided into small grid areas, e.g. of 200 m by 200 m in which the flood risk for each grid is determined.

22.3.6.2 Classification of Flood Risk

The study area can be divided into various risk zones according to FRF values. For example, the areas with FRF values from 0 to 25 is categorized as low risk zone, from 26 to 50 as medium or moderate risk zone (MFR), from 51 to 75 as high risk (HFR) zone and from 76 to 100 as very high risk (VFR) zone. The use of equal interval of FRF is to provide a uniform step of classification for the flood risk zones. The flood risk assessment can be developed for 100-, 50- and 25-year return periods for comparison. Figure 22.18 shows a typical flood risk map for a flood plain with flat topography with multiple types of land use.

Generally, the HFR and VFR zone areas continuously increase with the increase of return period of rainfall or flood inflow. The HFR or VFR zones may contain some areas of medium flood hazard which has high vulnerability. Flood risk assessment is important in planning for mitigating severity of flood disaster (NFRAG 2008; FEMA 2007; Penning-Rowsell 2005). Plate (2000) described that flood risk assessment requires a clear understanding of the causes of a potential disaster, which includes both natural hazard of a flood, and the vulnerability of people and their assets at risk. The outcome of flood risk assessment will identify the variation of risk level of flood over the study area with time

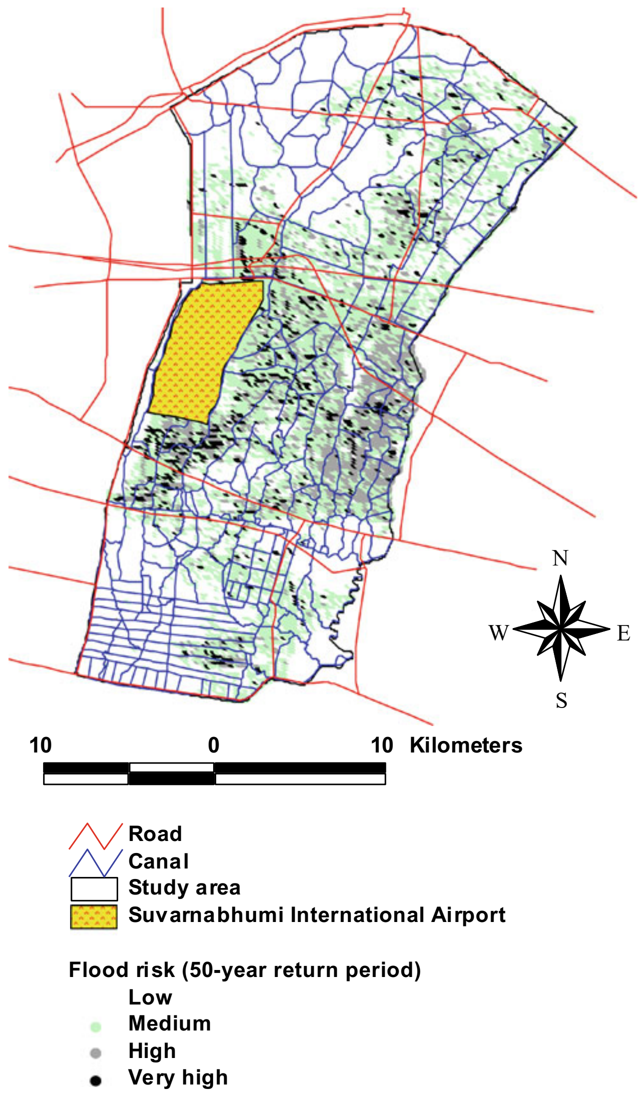


Fig. 22.18 Flood risk map for 50-year return period, in surrounding area of Suvarnabhumi International Airport (Keokhumcheng 2012)

and specified return periods. The flood hazard maps and flood risk maps provide useful information for flood mitigation planning and management to concerned authorities on flood mitigation projects, while the residents in the floodplain will be informed for self-preparedness to minimize the impact of flood on their livelihood.

22.3.7 Flood Disaster Management and Mitigation

22.3.7.1 Flood Disaster Management

Flood and flood plain management is an essential component of flood loss reduction and mitigation taking into consideration socio-economic and environmental impacts. Flood plain management is a critical part of the overall river basin management. Integrated flood plain management should have involvement of various stakeholders including concerned authorities such as planners, civil and water resources engineers, civil disaster prevention and mitigation authorities, health and social services and local residents, etc.

Impacts due to floods are in terms of economic losses both direct and indirect. This depends on existing flood control measures, density and number of population, capacity of flood drainage systems, high economic values of properties and infrastructures, and land use types, etc. Both direct and indirect flood losses can be reduced through better flood disaster management.

Successful flood disaster management and mitigation must be based on a clear policy considering both engineering aspects and socio-economic and environment aspects. Flood prevention and mitigation are most effective if the flood control measures are comprehensive and effectively operated. The implementation of flood disaster prevention and mitigation must receive legislation support for all necessary activities for long-term implementation and short-term response and recovery purposes. The flood disaster prevention and mitigation must be continually monitored and evaluated so as to respond or adjusted timely to changing pattern of hazards, vulnerability and available resources.

22.3.7.2 Flood Control Measures

As quoted by (NSWG 1986) and (ESCAP 1991), flood prevention and mitigation should include both structural and non-structural measures. Structural measures relate to physical construction work such as dams and retarding basins, diversion structures, flood control gates, coastal estuarine sea barriers, flood bypass channels, channel improvement, river dikes and flood embankment, flood drainage and pumping systems, etc. Non-structural measures are not related to construction works and they include watershed control and conservation, land use planning and management, land reclamation and appropriation, laws and regulations, flood forecast and warning systems, flood risk assessment, people awareness, capacity building, flood proofing of buildings and flood fighting, flood way clearance, flood insurance and people evacuation, etc. Various aspects of non-structural measures are environment friendly and commonly accepted as part of sustainable development. The structural measures are designed to protect from floods to a certain design flood magnitude. However, once the design flood magnitude is exceeded, catastrophic flood damage may occur. Non-structural measures can increase effectiveness of structural flood control measures and they can be implemented without much cost. Therefore, comprehensive flood management usually requires a combination of both flood control measures (Plate 2000; NSWG 1986; ISDR 2004).

22.3.7.3 Flood Loss Prevention and Management

In vulnerable areas, flood mitigation cannot be achieved with structural means only; further flood risk reduction via non-structural measures is indispensable as shown in Fig. 22.19. A combination of structural and non-structural measures should be used for most effective outcome of the implementation.

The aim of flood loss prevention and management is to minimize the socio-economic loss of the community caused by flooding. On the economic aspects there are many factors that cannot be expressed in monetary terms such as difficulty in running business due to floods, traffic jams, etc. While in social aspects, environment quality, these may include sickness and mental stress and social well-being of people, etc. These non-monetary components should be considered as indirect benefits in the overall benefit of the flood loss prevention program.

The implementation of flood loss prevention and management program should rely upon one leading coordinating organization which has sufficient technical and management expertise in setting up flood loss prevention standard and to give technical advice for development and implementation of structural and non-structural measures. The leading organization should take the prime responsibility for development and implementation of flood mitigation plan. The implementation of flood control projects is usually staged to meet the need in time. Responsibility for implementing the plan should rest with a leading flood authority which should have all resources necessary to complete the flood management system.

Flood disaster prevention and preparedness would reduce loss of life and lessen property damages. It consists of both long-term measures and short-term measures. The long-term measures concern with policies and implementation programs to cope with disaster occurrence. The short-term measures are the necessary actions to be taken during the approach and the impact of a possible flood disaster. The reduction of physical vulnerability can be done by developing workable evacuation plans in close cooperation with the affected people. Provision of evacuation shelters, supply of fresh water, food, medicines, etc. should be considered. Building codes play an important role in decreasing physical vulnerability of houses and infrastructures. Based on delineation of risk zones, building codes provide regulations with reference to the type of construction material, the structural features of the construction, the occupancy and utilization of houses.

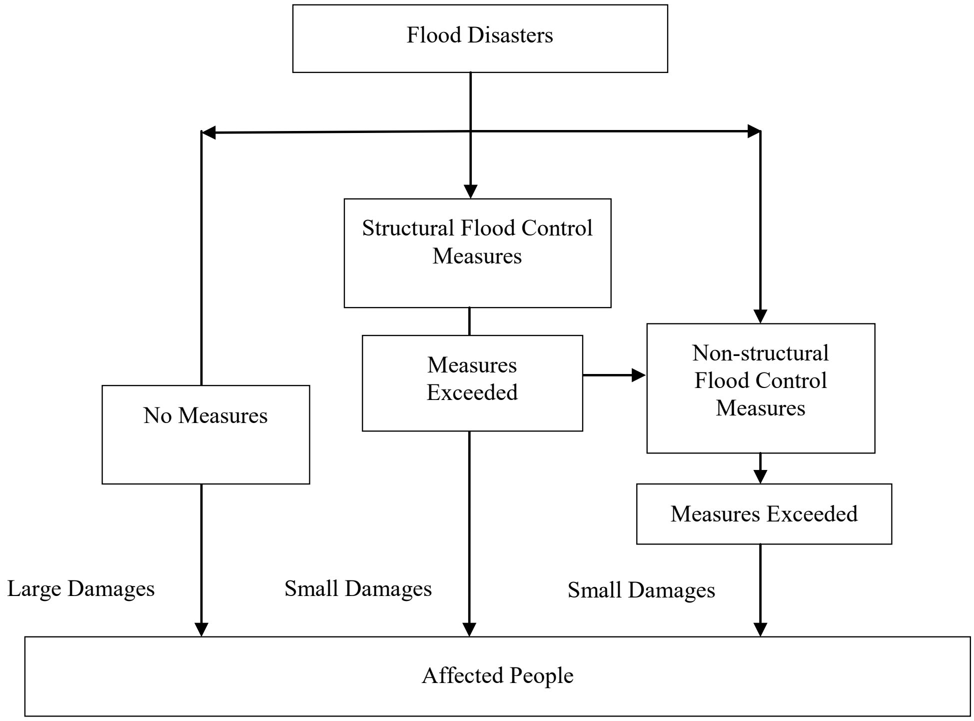


Fig. 22.19 Structural and non-structural flood control measures in comprehensive flood loss prevention and management

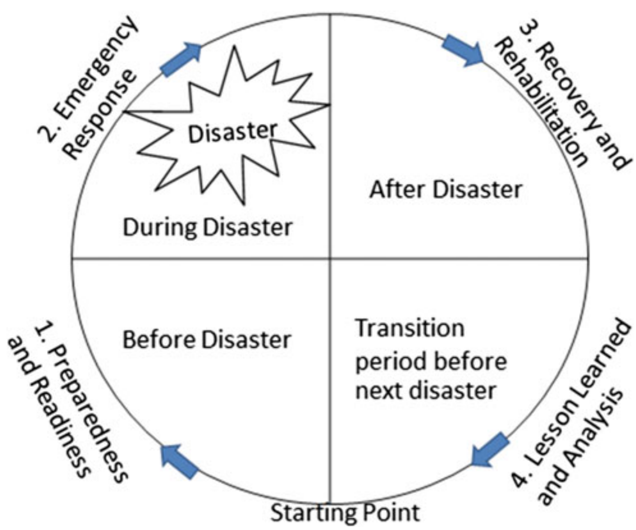


Fig. 22.20 Flood disaster management circle (Tingsanchali 2011, 2012)

As described by (Tingsanchali 2011, 2012), flood disaster management circle consists of four main chronological activities as shown in Fig. 22.20 as following:

Activity 1: Preparedness and readiness.

Preparedness is to develop plans and further implementation to cope with incoming floods to reduce losses of lives and damage of infrastructures.

Readiness enables organizations, communities and individuals to respond rapidly and effectively to disaster situations. Readiness measures include formulation of viable or immediate disaster plan, maintenance of resources and training of personnel.

Activity 2: Emergency response.

This is taken immediately prior to and following attack of a disaster. Response effectiveness is a matter of providing speedy and professional emergency assistance to flood victims. This includes among others rescue, transport, shelter, medical care, material support and assistance to victims.

Activity 3: Flood recovery and rehabilitation.

This is to bring communities and the nation returning back to their proper level of functioning after a disaster. Recovery process can be very protracted, taking 5–10 years or even more. This includes three main activities namely: restoration, rehabilitation and reconstruction.

Activity 4: Lesson learned and analysis.

This is done after the flood disaster is over to review, to study and analyze the previous mistakes or deficiency faced during the previous disaster period. The aim is to avoid the mistakes and to further improve the planning and operation of the flood disaster mitigation in the future.

22.3.7.4 Flood Disaster Mitigation

Flood disaster mitigation includes the following:

Updating Laws and Legislation: This is to support role and activities of responsible organizations in flood management.

Institutional arrangement: This is to have them with clear roles and responsibility without redundancy among various organizations. A leading agency that is fully responsible to overall flood management should be established.

Community Based Approaches to Disaster Mitigation: Effective planning and implementation can be obtained by public participation of community. Brainstorming and coordination with related organizations, public sector and people are required for planning.

Establishment of Information System: Flood forecast and warning systems should be established through multi-media to disseminate warning information to the communities at risk. Success of such a system is closely related to people's knowledge of flood risk and their familiarity with emergency response to incoming floods.

Capability Building: This consists of training and education that can increase knowledge and skill to people. Training and education for government and non-government officers and people in flood risk area should be carried out.

Public awareness: People who live in flood risk areas should be aware and understand flood disaster and warning information and to react in preventing loss of their life and properties.

Establishment of Database System: Database systems should be in geographic information system (GIS) format and must provide the important information that will be used in planning of flood management. The main data in the database consist of geography of areas, characteristics of basins, hydrological data, meteorological data, geology and river cross-section data, forest and land use data, flood risk area data, social and economic data, highways, locations of villages and other related data.

Flood Safety Standard: This should be established to control or mitigate flood damage by considering hydrology and hydraulic criteria for implementation of the flood control measures.

Flood Risk Maps: Flood risk mapping is an efficient tool to assess the risk and support risk management plans and allocation of funds and other resources. The results of risk assessment can identify the development priority of the flood control measures.

Land Use Control and Land Conservation: This can be done based on hazard map and geography of the area. Land use planning and regulation can minimize the effect of flood disaster. Conservation of upland watershed and afforestation are good examples.

Insurance Schemes: Existence of appropriate schemes of insurance, emergency support reserve funds, compensation of losses not covered by insurance, are important components of flood preparedness. These mechanisms are needed in order to help flood victims to recover after losses.

22.3.8 Conclusions

Floods are extreme hydrological phenomena. They cause loss of lives, injuries, loss of properties, serious damage and hardship to socio-economic and environmental conditions. Floods and their impacts can occur within a short time while occurrence of drought can be foreseen longer in advance. The impacts of floods can be pronounced within a short time. The causes of flood can be classified into two main causes: natural causes and human causes. Types of floods are flash flood, slow rising floods and stagnant ponding floods depending on storm and precipitation conditions, topographical conditions, flood drainage capacity, land uses and other factors. Floods can occur in steep areas or in low lying areas, while their characteristics and propagation differ.

Effective flood control and mitigation can be achieved by using both structural and non-structural flood control measures. Both measures should complement each other to obtain the full benefit of flood control and mitigation. Flood modeling is useful in prediction of effects of flood control measures. Flood modeling is useful in predicting the effects of flood control measures or for flood forecasting and warning. Real-time flood monitoring, flood forecasting computation, dissemination of forecast results and warning to concerned agencies and public facilitate operation of flood control structures, planning of emergency measures and property protection, flood fighting, minimization of disruption and increase public awareness.

The probability of exceedance of an extreme flood event above a design limit such as a maximum flood level is equal to the inverse of return period. The probability of exceedance can be determined by various probability distribution functions of extreme events. The return period of maximum floods increases with the flood magnitudes. It is used in the design of flood control structures and planning for mitigation measures. By analyzing historical data of maximum floods and fitting it with probability distribution function, the magnitude of maximum flood of a design return period can be determined. Statistical projection of the probability distribution functions of maximum floods beyond past flood records can be done for a very high return period for safety reason. Well known probability distribution functions for extreme events such as Gumbel, normal, log normal and Pearson Type III, etc. are available in the literature and have been applied in many cases.

Flood hazard depends on flood magnitudes such as flood depth, velocity and duration. The flood hazard is classified based on the level of severity of flood characteristics. The degree of flood hazard is normally classified as low, medium, high and very high. One or more parameters can be considered in the hazard assessment depending on the characteristics of the study area and floods. Flood hazards can be estimated by using measured flood data of the past or by simulation using mathematical models or physical hydraulic models. The models have to be calibrated and verified before applying it to predict the flood hazard under various existing and future conditions. Flood hazard of different return periods can be predicted by using mathematical or physical models.

Vulnerability of objects such as population and assets exposed to flood risks depends on socio-economic values and land use types. Where there are no people or no properties, there is no vulnerability. Flood damage is a function of vulnerability and flood magnitudes. People living conditions, their social activities and values of their properties and infrastructures are the basic parameters that relate to flood damages. Damage estimation needs field data collection and questionnaire surveys to determine vulnerability index. By using the same procedure in estimating flood hazard factor, the flood damage vulnerability indicators for population (FVI)p and assets at risk (FVI)a are then combined to obtain the flood damage vulnerability factor or FVF.

Flood risk is the probability of harmful consequences or expected loss resulting from interactions between flood hazards and flood damage vulnerable conditions. Where there are no people or assets that can be affected by a natural disaster, there is no risk. The risk can only occur when people and/or their assets are harmed. Risk is the product of hazard index and vulnerability index. Flood risk factor FRF is equal to the product of flood hazard factor FHF and the flood damage vulnerability factor FVF. Calculated flood risk varies over the area of study from one location to another location. Flood risk maps can be drawn to illustrate its variation under different magnitudes of hazard return periods and different types of land use and population. Flood risk map provides information for decision makers to decide which kinds of suitable mitigation measures should be planned or implemented.

The implementation of flood loss prevention and management program should rely on one leading organization which has adequate technical and institutional expertise in setting up flood loss prevention standard and to give technical advice for effective development of structural and non-structural measures. The leading organization should be established to take prime responsibility for development and implementation of flood mitigation plan. Flood disaster prevention and preparedness would reduce much loss of life and leads to less property damages. Flood mitigation measure consists of both long-term measures and short-term measures. The long term measures concern with policies and implementation programs to prevent disaster occurrence in the long run. The short term measures are designed to cover the actions necessary to be taken while a possible flood disaster is approaching, during and right after the flood incident.

22.4 Infrastructure Capacity Planning For Future Hydrologic Extremes

22.4.1 Introduction

Infrastructure capacity planning for reducing the risks of damage from floods, droughts, and water pollution is not a new subject. Approaches for defining risks have typically been based on historical events. The challenge today however is that the statistical characteristics of these historical events may no longer be representative of what we might observe in the future. The probabilities of extreme hydrologic events and their impacts are changing, and the frequencies and magnitudes of those changes are uncertain. Estimates of the probability of exceeding any particular drought event or any particular flood flow or stage based on historical data are likely to underestimate these probabilities for the same events in the future. The same seems to apply for water pollution events that result from changes we observe in our population, in our use of our land and water resources—including urbanization, and in our climate. Trends in recent hydrological data suggest that the magnitude and frequency of hydrologic extremes are increasing (Changnon et al. 2000; USGCRP 2017; NOAA 2018; Hall et al. 2014). Hence, if our goal is to protect against say a 100-year event in the future, how can we do this when the event associated with a 100-year return period in the future is unknown? In other words, a 100-year event may become a 75-year event within the life span of a given infrastructure option. In short, how can we identify the risk we are protecting ourselves from when the event associated with that risk is changing? Of all the options we have available for reducing the likelihood of adverse hydrologic, economic, and environmental events, how much of each option should we implement and pay for now, and on into the future, that will keep the probability of such events at acceptable levels when the probabilities of such events, together with what is considered acceptable are changing? This chapter offers an approach to addressing this question.

The approach outlined in this section for planning infrastructure capacity investments for reducing extreme hydrologic events and accompanying damages is a conceptual one. For any site-specific project the functional relationships would have to be based on site-specific data. The specific infrastructure being considered would be known, as would its effectiveness in reducing various measures of damage, whether economic, environmental or social. For a specific location and type of infrastructure, detailed simulation studies may have to be made to identify the relations and data needed for carrying out the approaches described here only conceptually.

This chapter focuses on, and limits itself to, the risks of hydrologic extremes, whether they be floods, droughts, or water pollution. Damages resulting from extreme hydrologic events can be expressed in economic, environmental or social terms, as applicable at specific locations. Infrastructure costs are typically expressed in monetary units. Clearly all of these possible future impacts are uncertain, and this uncertainty needs to be considered when engaged in planning the siting, design and operation of infrastructure for reducing damages at specific locations and times.

22.4.2 Infrastructure Options and Impacts

A number of options exist for preventing or mitigating the adverse impacts associated with droughts, floods or water pollution. Some common ones together with their impacts on damage and/or risk reduction are identified in the three subsections below.

22.4.2.1 Droughts

There are several mitigation measures that can be used to reduce the impacts caused by droughts. These include any measure that reduces the demand for water, including for example:

- soil and water conservation and irrigation practices that result in less water use.
- xeriscape landscaping that reduces or eliminates the need for supplemental water from irrigation in dry environments.
- low-flow toilets, shower heads, and washing machines.

They also include measures that increases the supply of water, such as:

- desalination of seawater, water recycling, and rainwater harvesting.
- conjunctive use of surface and groundwater supplies.

Prolonged droughts can lead to substantial health, social, economic and political impacts. Any measures taken in advance of drought events that address these potential impacts are also ways we have to reduce if not prevent their adverse impacts. Such measures can include:

- Storage and distribution of food, drinking water, and medical supplies.
- Unemployment and crop failure insurance.
- Provision of alternative sources of energy to make up any reductions due to lack of water, say for hydropower or cooling.

None of these options can change the duration and severity of droughts. What they can do is to reduce the damage resulting from them. Of interest here is the tradeoff between the costs of drought damage reduction measures and the extent of such damage reductions.

To outline how such tradeoffs can be estimated, assume data exist that allow the definition of damage functions, however measured, as a function of the expected return period of a drought of a specified intensity and duration, or equivalently the probability of the impact from such a drought being exceeded. Such a damage function may appear as shown in Fig. 22.21.

In Fig. 22.21, both the drought return periods (as expression of risks) as well as the resulting damages are uncertain (Read and Vogel 2015, 2016a; Vogel and Castellarin 2016). Hence the single function shown in Fig. 22.21 could be just one of a set of such functions resulting from a set of future damage prediction scenarios. It could represent the expected damage, or the damage that has a specified probability of being exceeded based on all these future damage scenarios. Specific measures taken to reduce the damage stemming from a drought alters the damage function, as shown in Fig. 22.22.

Measures taken to mitigate drought impacts can be implemented in stages as the severity of drought increases. Drought management triggers can be assigned to specific return periods. If the return periods associated with various drought events are able to be estimated, say from historical drought events or from multiple scenarios of future drought events, probability of exceedance functions, at least for a specific time period (Read and Vogel 2016b), can be defined. Such a function is shown in Fig. 22.23.

From these three functions one can derive the probability of exceeding any specified damage level and the expected annual drought damage. Figure 22.24 is a graphical representation of how this can be done.

In Fig. 22.24, the upper right quadrant is the damage function defined in Fig. 22.21. The upper left function simply transfers the drought event values from the vertical axis of the upper right quadrant to the horizontal axis of the lower left quadrant. In addition, the return periods of these drought events are defined on that horizontal axis. The

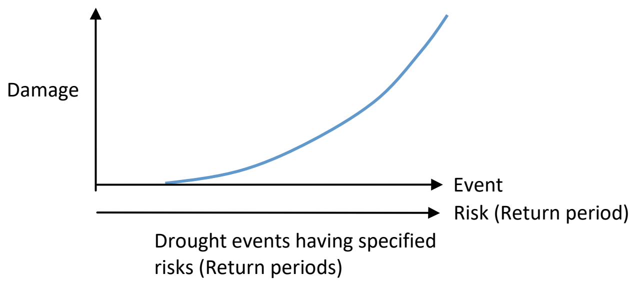


Fig. 22.21 Function showing increasing damage, however measured, as a function of increasing drought severity as measured by its expected return period

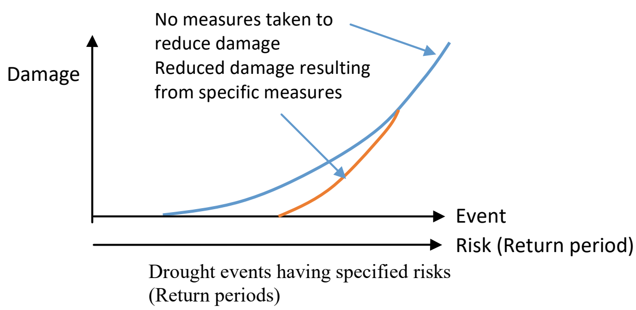


Fig. 22.22 Impact of specific infrastructure or other measures implemented to reduce damage associated with drought events

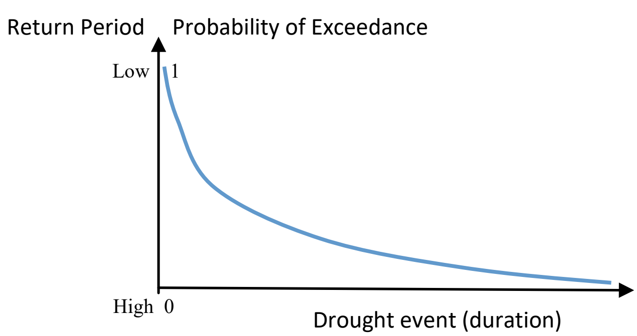


Fig. 22.23 Function showing probability of exceeding any specified drought event. Given any specific drought return period, R, the probability of being equaled or exceeded is 1/R

function in the lower left quadrant, as defined in Fig. 22.23, converts these return periods to probability of exceedance values on the vertical axis of the lower quadrants. The two functions shown on the upper right and lower left quadrants are based on data. These two functions permit the construction of the function shown in the lower right quadrant. The area under the probability of exceedance function in the lower right quadrant is the expected annual damage resulting from droughts. This probability of exceedance function is typically shown as in Fig. 22.25.

Depending on how the damage function (Fig. 22.21) is defined, this expected value derived from computing the area under the curve in Fig. 22.25 may itself be associated with a probability of exceeding a certain damage value other than 50%, as implied if the damage function is an expected value.

Next consider the implementation of measures that reduce the damages associated with droughts. Such measures alter the drought damage function as illustrated in Fig. 22.25. They do not alter the probability of exceedances or return periods of drought events. Using the same procedure as shown in Fig. 22.24, the resulting probability of exceedance function decreases due to drought damage reduction measures, as illustrated in Fig. 22.26.

The derivation and use of expected annual damage reduction values as described above is just one approach for informing those responsible for deciding which measures to take to hedge against future droughts and their damages. Another approach is to decide what level of drought risk to protect from, and identify the set of measures that will accomplish that. That selection process could be based on cost, or other criteria as deemed appropriate. The illustrative cost function shown in Fig. 22.27 identifies the least cost needed to protect from a range of drought events. Identifying such a cost function is itself an optimization problem that considers a range of damage reduction measures and their costs.

As with the damage functions defined in Fig. 22.21, functions defining future annual costs are clearly uncertain. Hence any annual cost function as shown in Fig. 22.27 can either represent an expected value or the cost having a specified probability of being exceeded based on many cost estimate scenarios.

Considering a range of events of various return periods to protect from and the least-cost ways of doing each, cost-return period protection tradeoffs can be identified, as illustrated in Fig. 22.28. Obviously different drought reduction measures will result in different expected annual damage reductions, and cost different amounts of money. Considering different sets of drought reduction measures and their annual damage reductions and costs, tradeoffs between those damage reductions and costs can be defined as illustrated in Fig. 22.28. If damages are expressed in monetary terms, say dollars, the particular set of measures that maximizes the expected damage reduction less cost can be identified.

All of the above discussion has assumed known risks or return periods, perhaps based on historical data (Vogel and Castellarin 2016). Of course we know these return periods are changing due to many factors, including climate change (Rogers 1997). Furthermore, these changes are uncertain and this uncertainty is unknown (Hall et al. 2014; Read and

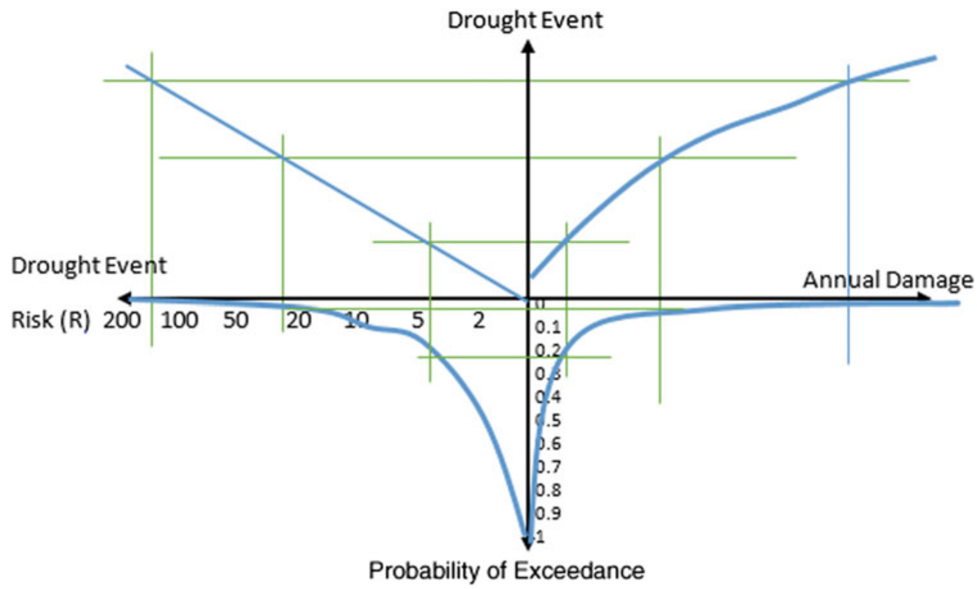


Fig. 22.24 Defining the probability of exceeding various damage values shown in the lower right quadrant

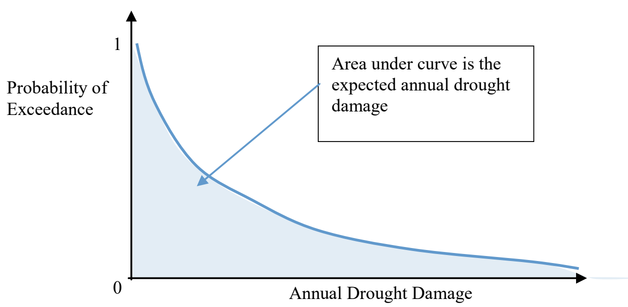


Fig. 22.25 Function defining decreasing probability of exceedances associated with increasing drought damages derived from Fig. 22.24

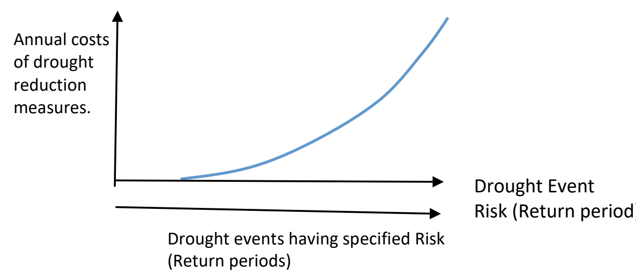


Fig. 22.27 Function showing minimum costs of protecting from droughts having specified return periods. Actual cost functions may include fixed costs together with economies of scale that are not shown in this example

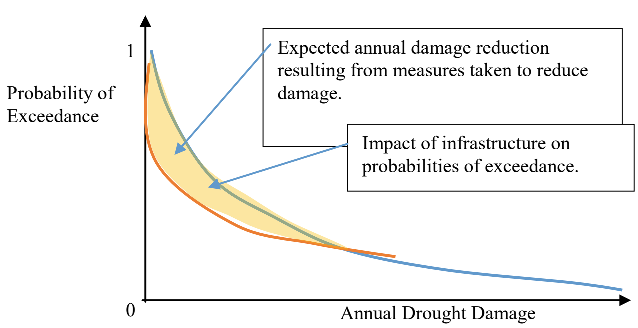


Fig. 22.26 Annual expected drought damage reduction associated with measures taken as illustrated in Fig. 22.22, and as computed using procedure shown in Fig. 22.24

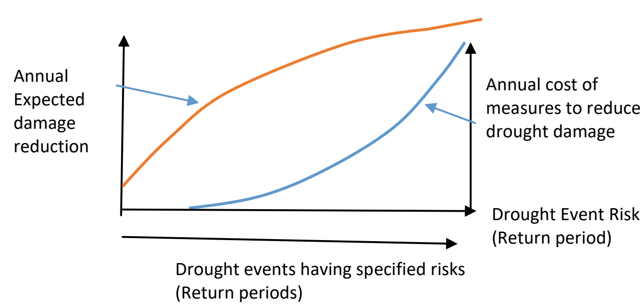


Fig. 22.28 Functions showing tradeoffs between minimum costs of protecting from drought events having specified return periods and annual drought damage reduction benefits. Actual cost functions may include fixed costs together with economies of scale that are not shown in this example

Vogel 2015, 2016a, b; Sales et al. 2018). So the question of what and the extent of measures to take to accomplish future drought damage reduction targets or to protect from droughts having specified return periods is still unaddressed. These issues will be examined after a discussion of flood and water pollution risks that follow.

22.4.3 Floods

Unlike droughts, floods can occur relatively quickly giving less opportunities for adaptive measures as the severity of a flood increases. Strategies to reduce threats to life and property from flooding include those that reduce:

- the likelihood and extent of flood damage and disruption
- the adverse impacts of floods on the individual and the community
- the flood stages and/or durations themselves.

The likelihood and extent of flood damage and disruption can be reduced through appropriate floodplain zoning and other regulations pertaining to land use development and drainage, disaster preparedness, assistance, and recovery planning and programs, flood-proofing, and the development and use of flood forecasting and warning capabilities. The adverse impact of flooding on individuals and the community can be reduced through information and education programs, flood insurance, tax adjustments, emergency and rescue services, and flood damage recovery efforts.

Flood stages and durations can be reduced through the operation of reservoirs, installation of dikes, levees, and floodwalls, channel dredging and modification, high-flow diversions, floodplain modifications and detention storage. Along coastal shorelines, structural measures include barrier protection; interior flood gates; road/rail elevation, levees, floodwalls, bulkheads, seawalls, revetments, beach restoration, breakwaters, storm system drainage improvements.

Coastal zone flood management options include building retrofit (elevation and flood proofing), managed coastal retreat, emergency evacuation plans, early warning systems, public education, flood insurance, wetland restoration, and implementing living shorelines, green stormwater management, reefs, and submerged aquatic vegetation.

Each, or a combination of these flood damage reduction measures can change the relationships defining damages and the probability of exceedances or return periods associated with flood events, as shown in the upper right and lower left quadrants of Fig. 22.29.

In Fig. 22.29, the use of levees represents any of many options that do not alter the magnitude or duration of a flood itself, but only the damage that may result from a flood event. Clearly the implementation of levees, or any other means of increasing channel flood flow capacity, may alter the return periods of flood flows at downstream sites but not at the site of interest where flood damage reduction measures are being considered. But unlike levees, the flood storage capacities and operating policies of upstream reservoirs can change the downstream flood flows or stages. This is illustrated in the lower left quadrant of Fig. 22.29. Their effect on the probability of exceedance of various damages is shown by the orange line in the lower right quadrant.

As with droughts, the procedures shown in Fig. 22.29 can be used to identify tradeoffs among the annual costs of different flood damage reduction measures and the corresponding annual expected damage reduction. Or they can be used to identify the tradeoff among annual costs of measures taken to meet various flood risk reduction targets, expressed as return periods. Such tradeoffs are illustrated in Fig. 22.30.

22.4.4 Pollution

Common causes of water pollution result from liquid wastes discharged by industries, agricultural and urban runoff, discharge of domestic wastewater, garbage, and solid waste, oil and liquid fuel spills, air pollutant deposition, and heated water discharged from power plants. Impacts from water pollution can be economic, environmental, ecological, social, and can impact human health. Measures available to reduce water pollution events include decreasing the use of polluting chemicals, both at homes, on the fields, and in industries, wastewater treatment, measures that reduce non-point runoff, recycling wastewater, more effective monitoring and measures to prevent accidental spills from pipelines, boats, industries and other sources. It is not always obvious how much and when some of these measures will reduce the adverse impacts of pollution. So called soft solutions such as use of ecosystems and nature are therefore often effectively employed (UN-WWDR 2018).

For any water body, there is typically a background pollutant load, perhaps punctuated by pulses of pollutants that may stem from storm runoff or accidental spills from pipelines, boats, or industry. It is not likely the return periods of such extreme pollution events can be estimated. Nevertheless, pollution events will occur. When such events occur, the social and human and ecological health impacts or 'damages' can be difficult to assess. It thus seems reasonable to simply identify the costs of combinations of measures needed to reduce the discharge of pollutants in water bodies, focused on the most likely and impactful sources. Otherwise depending on whether the measures affect the damages stemming from pollution events and/or their probability of exceedances or return periods, the methods described above for droughts or floods can apply.

22.4.5 Impact of Changing Return Periods

The conceptual approaches outlined in the sections above for identifying the tradeoffs between expected damage reductions and cost all focus on the expected return period, such as 1 in 100 years on average, or equivalently, the probability of exceeding any specified event, such as 0.01. We all know that estimates of future values of these return periods or probability of exceedances cannot be based on historical data because of changes caused by the increasing number of us

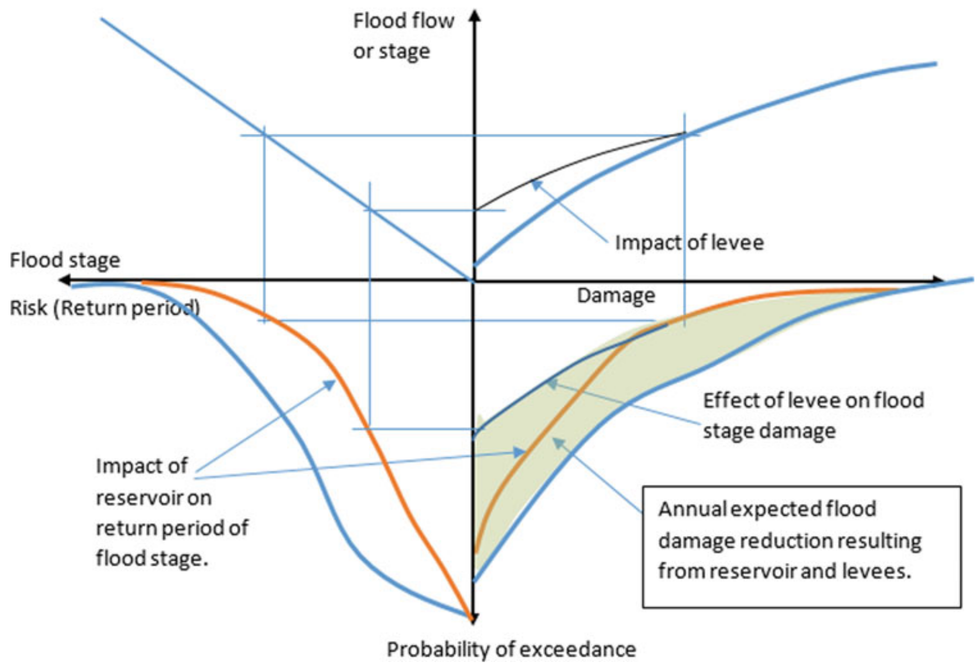


Fig. 22.29 Deriving the annual expected damage reduction resulting from reservoir and levee flood damage reduction measures

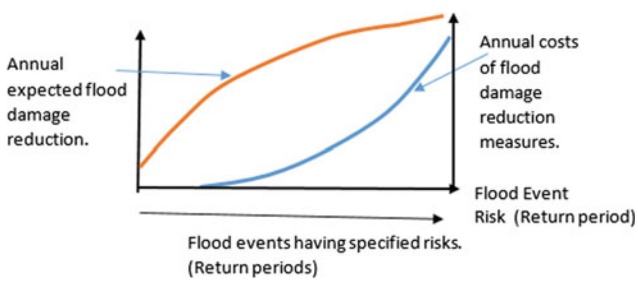


Fig. 22.30 Functions showing tradeoffs between minimum costs of protecting from floods having specified return periods and annual flood damage reduction benefits. Actual cost functions may include fixed costs together with economies of scale that are not shown in this example

and the way we manage land and water, as well as on changes in our climate, as appropriate in specific cases. Furthermore, these changes are uncertain. We cannot predict them with certainty. Even our hydrologically related probability distributions are changing, i.e., are non-stationary, and that change is also hard to predict (Blöschl et al. 2015; Hu et al. 2018).

Current observations of these changes suggest that return periods of extreme hydrologic events are decreasing. What was considered to be an event expected once every 100 years, say, on average, seems to occur now more frequently than it did historically (USGCRP 2017; NOAA 2018; Blöschl et al. 2015; Hall et al. 2014). Assuming this is true, the impact of these changes can be seen using approaches similar to what is shown in Figs. 22.24 and 22.29.

Referring to Fig. 22.31 below, the translation of the event values on the vertical axis of the upper right quadrant to the horizontal axis of the lower left quadrant is accomplished by the blue line in the upper left quadrant as before. This assumes the scales of both axes are the same with respect to the events themselves. However, the change in the expected return periods associated with those events can be defined by a non-linear function that lies under the straight linear blue line. In the illustration of Fig. 22.31, it is the green line in the upper left quadrant. This then changes the probability of exceedance functions in the lower two quadrants.

As seen in Fig. 22.31, decreases in the return periods of hydrologic events will result in increased expected annual damages. This will impact the tradeoffs between annual expected damage reductions and annual costs of measures taken to achieve such reductions. It will also impact the tradeoffs between target return periods and the annual costs of measures taken to avoid events less than or equal to those target values such as illustrated in Figs. 22.28 and 22.30. All this seems intuitive given the assumptions. However, what may not be obvious is the answer to the question of what measures, hard or soft, should be taken today to provide the desired level of protection the public expects when the hydrologic extreme events themselves and their associated damages are increasing in uncertain ways. Failure to take into account the changing and uncertain future can result in infrastructure investments or policies that will fail to function or serve society for as long as planned and hence be unnecessarily costly (Davenport 2018; World Energy Council 2015).

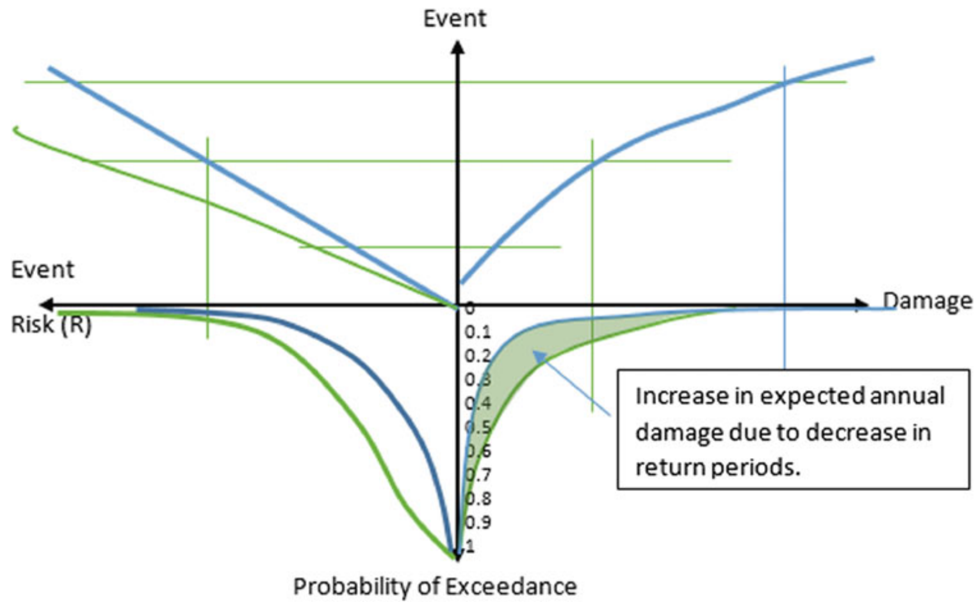


Fig. 22.31 Estimating the impact of decreasing return periods associated with various hydrologic events

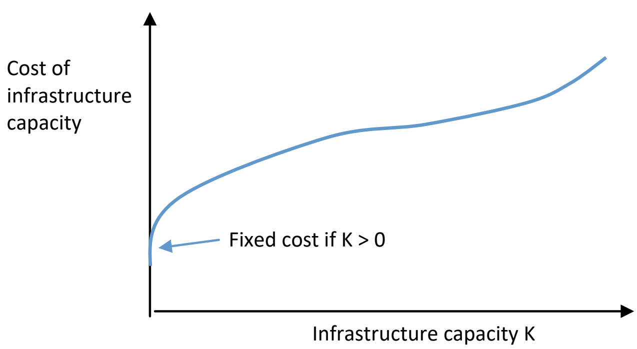


Fig. 22.32 Infrastructure capacity cost function having a fixed cost component and showing economies of scale (decreasing average cost) over a range of capacities. Actual cost functions can have multiple fixed costs in some cases

22.4.6 Infrastructure Capacity Planning Over Time

Capacity planning addresses how much infrastructure capacity to build and when in order to meet the desired risk or expected damage reduction goals over time. Whether the goal is to maximize the difference between the expected annual damage reduction and annual infrastructure cost or to achieve protection up to a specified return period at minimum cost, the question of what types of infrastructure and their design capacities should be built is not a trivial one. Even assuming no change in risks or potential damages over time, the fact that infrastructure costs typically include fixed as well as variable costs and exhibit economies of scale, as shown in Fig. 22.32, makes it cost-effective to build more capacity than is needed at the time construction takes place. Add to this the need to meet an increasing future demand, the issue is how much to build and when. Here our demand is the capacity required to protect from an increasing hydrological event associated with a specified return period, or the capacity required to meet increasing expected damage reduction targets.

Based on observed trends and analyses as outlined above, assume one can estimate the demand for infrastructure capacity that is needed to meet specified risk or expected damage reduction goals over the next several decades. Also assume we can estimate the costs of new infrastructure capacity over this period, and the interest rate that allows us to compute present values of costs. All of these values are uncertain, and the impact of this uncertainty needs to be addressed, but first assume such data can be estimated.

Let K_t be the existing capacity of infrastructure at the beginning of time period t. Except for K_1 for the current period, t = 1, these values need to be defined for future periods such that they meet or exceed the assumed known capacity demand targets, KD_t. These KD_t values are based on projections of infrastructure capacities needed in future periods t. (The following section addresses the uncertainty associated with these projected values.) Clearly there are many values of K_t that will meet this constraint ($K_t \geq KD_t$) for each period t, as shown in Fig. 22.33. Which values are best depend on the criteria chosen for determining what is optimal. If a least-cost capacity expansion schedule is of interest, then cost estimates are needed for capacity additions, KA_t in each period t. Assume such costs can be estimated and then discounted to the present time. Let the function $C(KA_t,K_t)$ be the present value of the cost of adding KA_t capacity to an existing capacity K_t in period t. Using these data an optimization model can be developed and solved to identify a least-cost capacity expansion schedule

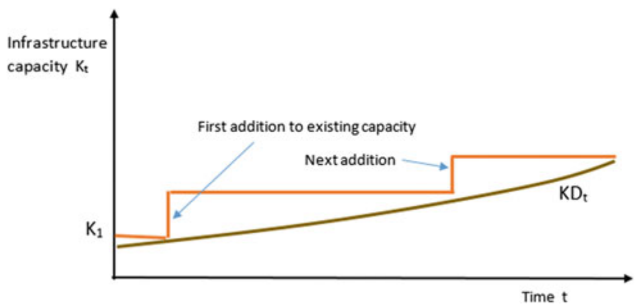


Fig. 22.33 Illustrative capacity expansion schedule that satisfies the demand, KD_t, for infrastructure capacity over time

identifying how much capacity to add and when, i.e., the values of KA_t (see Box 22.1). One such schedule is illustrated in Fig. 22.33.

Box 22.1. Capacity optimization model

Minimize present value of total costs over a time horizon = Σ_t C(KA_t,K_t).

Subject to: $K_t + KA_t = K_{t+1}$ and $K_t \geq KD_t$ for all time periods t.

22.4.7 Uncertainty Impacts

Any infrastructure capacity expansion schedule, such as illustrated in Fig. 22.33, defines the additions to capacity needed to meet some criteria. It defines how much capacity to add and when to add it over some time horizon. It is reasonable to question the optimality of such a schedule given the uncertainty in the future demand (which are based on future risks), future costs, future discount rates, and an assumed time horizon when in fact time will continue beyond any selected time horizon. The future is not only unknown but non-stationary, i.e., we don't even know probabilistically what the future may be. Under such conditions, any capacity expansion schedule needs to be adaptive (Kwakkel et al. 2016; Pahl-Wostl et al. 2016; Söderholm et al. 2018). What is of interest in the analysis represented by Fig. 22.33, is the current decision to make in the current time period, not in later time periods. The capacity to add, if any, during the current time period surely needs to be based on our best guess of future demands and costs and discount rates and capacity additions. But the actual future capacity additions should be based on the then-current conditions and estimates of future demands and costs, not on those we can make today.

Before committing to any capacity expansion decision in the current time period one should determine how sensitive such a decision, (i.e., KA_1) is to changes in assumed future demands, costs, discount rates and time horizon. Clearly such changes will likely change future capacity additions identified in any optimization model, as illustrated in Fig. 22.33, but of interest is any change in the capacity to be added in this current period (KA_1). If the current decision, KA_1, does not change, one can be more assured that the recommended addition, if any, will satisfy the criteria used to find the optimal expansion schedule. If not, then one must base their decision on the conditions considered most likely in the future. If the current decision is impacted by changes in the assumed time horizon, then it should be extended until there is no impact on the current period's decision.

22.4.8 Conclusions

Readers of this section may no doubt conclude that whatever results come from analyses outlined above are all based on guesses, guesses about the future hydrologic events, future economic and environmental damages and costs, and future social goals and objectives, and so why bother. They would be correct in their conclusion that all of this is based on guesses about a changing future, and those changes are uncertain to the extent we don't even know their probabilities. However, analyses such as those outlined in this chapter, and in many other documents (e.g., Hall et al. 2012; Haasnoot et al. 2009; Hu et al. 2018; Kwakkel et al. 2016; Ray and Brown 2015; Salas et al. 2018; Vogel and Castellarin 2016; Wyrwoll et al. 2018) permit one to estimate which of the many assumptions are influencing the decisions being identified as satisfying specified economic, environmental or social objectives. Given such knowledge, one can focus on those guesses that most influence the decisions being made, and not on the others. And again, the decision of interest is always what to do now in the current period given a predicted future, not what to do in the future.

Once a capacity expansion plan or hazard damage mitigation policy has been defined it is prudent to simulate it, incorporating scenarios covering all the uncertainties inherent in making future predictions. One can establish various threshold levels for various performance measures, and determine, though simulations, the reliabilities of meeting each threshold, along with measures of resilience and vulnerability associated with each threshold (Hashimoto et al. 1982). Such statistics are being used quite commonly to give decision makers a more complete understanding of how well a specific plan or policy may perform with respect to multiple objectives of interest (Borgomeo et al. 2016).

22.5 Droughts and their Management

22.5.1 The Nature of Drought

In the past decade disasters triggered by water-related natural hazards have dominated the headlines much more frequently than earthquakes and tropical cyclones. However, while floods provide spectacular images and volleys of loss estimates for short periods of time, droughts tend to trundle along in the background of the world's media coverage, and only pop up briefly in the news every now and then before fading into oblivion again. Nevertheless, drought is globally one of the most significant hazard events in terms of spatial extent, duration and long-term socioeconomic and environmental impact (UNDP 2013) and "the unremitting stress of drought, famine and deepening poverty threatens to create social strains, in turn creating the potential for involuntary migration, the breakdown of communities, political instability and armed conflict" (Ban 2010). It seems that despite modern technologies, from satellite observation and communication to cooperation partnerships and computerized optimization of water use, drought events are still occurring frequently all over the world and in almost every region.

The Global Risks Report 2016 (WEF 2016) stated that water crises would constitute the biggest risk to the world in the coming decade. This topic had already been recognized as the front-runner with respect to impacts in 2015, and it ranked 3rd in 2016 and 2017, 5th in 2018 and 4th in 2019. In the decade outlook, "water crises" was followed by "failure of climate change mitigation and adaptation", "extreme weather events", "food crises", and "social instability". These five items look like they have been copied from a "wanted poster" describing droughts. They are closely interconnected.

Drought cannot be defined in absolute terms. It is an exceptional deviation from the regional rainfall norm, and signifies a prolonged and abnormal moisture deficiency. Annual rainfall of just 500 mm in one region instead of the normal 1,000 mm can lead to a serious drought there, while 500 mm in another would mean twice the normal rainfall. Yet deviation from the mean is not the only relevant factor, with variability in water yield and deviation from normal seasonal distribution being equally important. Therefore, drought must always be seen in the context of normally prevailing local and regional conditions.

Droughts are not only caused by the current weather situation. They are often the result of previous conditions, and have a very strong tendency to persist. The probability of a drought occurring depends on many factors—among other things, on the supply of water stored in aquifers, the soil, and in reservoirs and lakes at the beginning of a dry period. Deficits accumulate in dry years, which consequently cannot be compensated in subsequent years with just average precipitation levels; above-average rainfall is needed to achieve recovery. This means that an extreme shortage could easily arise in the event of a moderate—albeit non-critical—shortage of water in the previous year. Droughts are usually exacerbated by higher rates of evaporation due to excessive temperatures, intense sunshine, low humidity and sometimes high winds.

Droughts are events which unfold slowly and usually affect a relatively large area. Problems arise gradually, and people tend only to become aware of a drought once it has fully developed. Hence, no steps are taken to adapt to the situation unless a critical stage has either already been reached or is imminent. To a large extent, however, whether a dry period becomes a drought depends on how water resources are managed in the area concerned. Typically, suitable measures are taken in those areas in which droughts are relatively common. Areas that are rarely affected by drought, but in which water is permanently in short supply, pose a greater problem. In such areas, a crisis may arise within a short span of time as there is no buffer. Given the large-scale impact, losses in many, if not all, sectors of society can be very severe.

There are also cases when drought affects only a limited area. Several years ago the Spanish city of Barcelona had to be supplied with water by tankers as the local water sources had fallen dry (Keeley 2008), and Atlanta in the USA was brought to its knees by drought conditions in a relatively small watershed from which the city drew its water supply (Goodman 2007).These cases show similarities to the recent multi-annual drought in South Africa's Western Cape Province, threatening the water supply of Cape Town (see Box 3.2 in Sect. 3.2.5) In these and many other cases the water management systems were not flexible enough to overcome unexpected periods of shortage. But sometimes also simply mismanagement leads to drought.

The problem of drought as opposed to permanent aridity is that both nature and humans, in particular with respect to agriculture, have not adapted to temporary dryness, and consequently have difficulties coping with it. Drought therefore must not be viewed as a merely physical phenomenon or natural event. Its impacts on society result from the interplay between natural conditions and the demands people place on the water supply.

More than any other climate feature, climate change will alter the occurrence of extremely dry and hot weather conditions, in many (most) parts of the world (IPCC 2013). Climate change is responsible for a shift to warmer days, including a change in the proportion of extremely high to extremely low temperatures. This makes the topic even more worthwhile to concentrate on when we prepare for a livable and sustainable future for billions of people.

22.5.2 Drought Definitions

Due to the relative nature of drought, there are several definitions, each of them relating to a specific point of view (NDMC 2019).

22.5.2.1 Meteorological drought

Meteorological drought is the temporary imbalance between actual precipitation (or soil moisture) and the average over a given time span. It tends to be localized and short-termed, but its influences may be severe on plants (crops). For example, a country such as Bangladesh, which is known for its severe floods, actually fears the absence or delay of (some) rainfall even more.

22.5.2.2 Hydrological drought

Hydrological drought affects the entire water resources system in a region, consisting of surface water, snowpack and artificial storages (reservoirs), as well as soil moisture and groundwater. It represents the cumulative effect of prolonged deficits in precipitation. Meteorological droughts usually precede hydrological droughts, but are not a prerequisite. They are often "co-sponsored" by humans overexploiting the water resources, which may take a long time to recover, as aquifers, in particular, are often replenished very slowly. There are also sub-types of hydrological droughts, such as soil moisture drought and groundwater drought.

22.5.2.3 Agricultural drought

Agricultural drought relates to a specific kind of crop, depending on various factors including the type of crop and its ability to store water, the stage of the growth cycle, soil type, temperature, etc. It describes the water stress on a crop determined by water supply and evapotranspiration, which may arise from both unexpected lack of rainfall or bad planning of the water demand during the growth cycle, e.g. by planting the crop too early or too late. Agricultural drought may lead to poor yield, but also to total crop loss.

22.5.2.4 Socio-economic drought

Socio-economic drought links human activity with the above drought definitions, which are described by purely physical/biological characteristics. In very general terms, it may be described as a failure of the water supply to meet the water demand of a—local, communal, regional or national—society. Both sides may contribute to this type of drought: the supply side through lack of rainfall, and the demand side through overuse of existing resources. This is the type we are talking about in the context of drought disasters.

22.5.2.5 Further Drought Classifications and Measurement

Further characterizations of droughts refer to duration, geographical extent and severity. While seasonal droughts usually only cause material losses and temporary, but potentially severe, inconvenience, multi-year droughts ("megadroughts") have led to mass migrations of people throughout history and an irreversible loss of species. The larger drought-affected regions become, the more difficult it is to assist them with external supplies, in particular in areas with poor transport infrastructure. Recurrent droughts in a region may lead to desertification, i.e. the degradation of land that transforms originally productive land into wasteland (UNDP 2013).

Drought severity is commonly described by way of indices, which are mostly based on meteorological parameters. The indices consider relative rather than absolute conditions and enable comparisons of spatially different regions and their "normal" climate.

The Palmer Drought Severity Index (PDSI) (Palmer 1965), (see also Chapter 2, Sect. 2.2.4) is one of the most commonly used indices. Precipitation and temperature data for the current and preceding months, as well as the locally available water content of the soil, are included in the calculations. The PDSI can be used to define long-term droughts (months) and evaluate their impact on agriculture. It is a standardized parameter which is calibrated to the local climate. Its advantage is that different parts of a country can be compared with each other. Integrating the PDSI over a year and over the entire area of a country, and then presenting it as a time series of annual values, allows us to identify drought periods extending to several years.

22.5.3 Droughts Do Not Come Alone

The principal consequence of drought—lack of water—is not the only impact. And it is not only lack of precipitation that causes it. As a rule, droughts are linked to heat waves. Hence excessive temperatures, intense sunshine, low humidity and sometimes high winds often exacerbate evaporation rates and thus "consume" water. The simultaneous occurrence of heat and lack of water also intensifies the physiological stress for humans, animals and plants. One immediate consequence is the drastically increased wildfire hazard. The loss of fertile soil—if not expressed in the form of a dust storm—is a less spectacular, yet still severe feature. In certain regions, subsidence occurs when soils shrink, potentially causing great damage (see Sect. 22.6.4).

Lack of drinking water for people and animals is the most critical potential consequence of a drought. In developed countries, this problem can practically always be avoided with the help of technical means (e.g. water trucks). In sparsely populated, remote areas, there may be no solution, thus making drought a deadly threat to people—and animals (pets and livestock).

Households and businesses are the first to feel the impact of restrictions placed on the use of water, e.g. for non-essential cleaning and watering purposes, such as washing the car or watering lawns and gardens. These restrictions gradually become more and more drastic until they finally affect hygiene.

Some branches of industry require enormous amounts of water for the production process, especially for cleaning and cooling. Food products cannot be produced without water.

As regards infrastructure, it is mainly heat that can cause physical damage. The asphalt pavement on roads and highways becomes soft and buckles. Metal items, including railway tracks and pipes, expand and buckle, with the consequence that trains may derail and water lines burst. Electric power transformers can fail or sustain damage, causing interruptions to power supplies. Levees may dry out and crack, with the damage inflicted potentially remaining unknown until the next flood (CIRIA 2013).

High temperatures are also responsible for many other impacts. They can impair human health and sometimes cause death. Dehydration, strokes, cardiovascular and breathing problems, lack of sleep, fatigue, nervousness and general stress are among the most common symptoms (Steuer and Kron 2012).

In agriculture, water is vital for plant growth and survival, as well as for a good harvest. This sector is probably the most affected of all.

Insofar as river transportation can be operated at all, only smaller cargoes can be carried when water levels are low. The vessels are also obliged to travel at lower speeds, and there is often not enough width for two vessels to pass one another owing to narrowing of the navigable channels.

Hydroelectric power production is impaired, as rivers carry less water, and water levels in reservoirs are low. Thermal power plants require large amounts of cooling water, and its unavailability consequently leads to a reduction in power generation, while high temperatures in summer increase demand for power.

In addition to the shortages created by falling water levels in aquifers, rivers and lakes, the process of providing a safe drinking water supply also becomes more complex at higher water temperatures. Biological purification of sewage can be impaired if dilution is inadequate. Discharge rules may be violated. This results in greater pollution levels in rivers and lakes.

Heat and drought are a source of stress for wildlife and plants. In extreme cases, plants wither, animals die, and ecosystems are affected. The water quality in rivers and lakes suffers in general. If the discharge drops while the load of pollutants remains the same, their concentration in the water increases, potentially harming aquatic flora and fauna. Water temperature rises. Pollutants and toxic material increasingly settle, as flows decrease. In future floods, these constituents are reactivated from the sediments, and may cause poisonous surges. Access to rivers and lakes can be impeded by low water levels, making some recreational activities impossible. Pathogen counts in the water may also rise at high temperatures.

Dry soil is very easily eroded by wind, and the resulting dried-out vegetation no longer acts as a buffer against erosion. When it subsequently rains, the water causes erosion damage as it runs off. Prolonged droughts may lead to irreversible loss of fertile soil and eventually to desertification.

Apart from the direct adverse effect of dust on human and animal health, dust storms may contain pesticides, pollen, fungi and other substances that irritate human lungs and eyes. Dust particles can cause a variety of health problems, including asthma, especially in children, the elderly and those already suffering from respiratory or cardiovascular disease. While most particles from windblown soils are large and deposited quickly, very fine dust remains in the air for long periods.

The danger of wildfires rises with each hot and dry day. Thus droughts might trigger cascading disasters.

Soils with high clay content shrink when they dry. This can lead to subsidence damage (Kron et al. 2016).

The degradation of groundwater near coasts allows salt water to intrude and to lastingly spoil the aquifer. Coastal wetlands may be affected, damaged, or even disappear, which can have dramatic consequences on natural coastal protection.

Finally, water rights disputes arise. These may occur between farmers, businesses, communities and entire nations, potentially leading to violent conflicts.

While many of the above are temporary consequences and no longer relevant when the period of heat and drought ends, they may be irreversible in some cases.

22.5.4 Drought is Not Only a Natural Hazard

Drought as opposed to permanent aridity is a phenomenon that neither nature nor humans have adapted to. Consequently, they have difficulty coping with it. Drought therefore must not be viewed as a merely physical phenomenon or natural event. Its impacts on society result from the interplay between natural conditions and the demands people place on the water supply, and the vulnerability of the region concerned.

In most cases, drought crises and drought disasters are the consequence of improper management of existing resources—and often even mismanagement. Reasons for these may be poorly developed societal and governmental structures and responsibilities, but also overuse and overexploitation of existing water resources. In this regard, drought is not a hazard that affects societies at different stages of development with different degrees of severity; it can seriously affect any society. The only difference is that in the one case (poor countries), people may die or get sick, in the other (rich countries), they may have to pay for emergency supplies and the likes.

Many states, regions and cities must take the blame for water-related problems themselves, rather than shifting it to nature. It is a lack of awareness, and sometimes even ignorance, that precedes a crisis. If the people in charge are sufficiently aware and practice good governance, the risk of drought can be reduced considerably. The term risk should be stressed here, in contrast to consequence. Reducing risk means acting in advance, before a crisis starts, while efforts (actions, but often only plans) to mitigate consequences are typically undertaken when the crisis is already manifest—which is therefore less efficient and has to be carried out under time pressure.

22.5.5 Drought Management

Everywhere, except in naturally dry countries such as those in the Sahel in Africa where every drop of water is appreciated, the most important feature in the context of water usage is permanent awareness—from the top level of government to every single citizen—that the availability of sufficient water is not a law of nature. Water is a natural resource that—like most other resources—is limited. If societies include this perception in their everyday actions, the biggest step towards the sustainable use of water resources has already been taken. This behavior includes avoiding the careless, wasteful use and pollution of water (even if it is available in plentiful quantity), water-consuming production lines (crops, industries), excessive settling in areas with water scarcity (for example Las Vegas), overexploiting groundwater and surface water bodies, etc. To stop or slow down such developments, let alone reverse them, is always more difficult than not being too lavish in the first place.

Contingency plans, monitoring the weather situation, and early-warning systems with strictly enforced rules and restrictions are also needed. The capacity to better forecast upcoming dry conditions, for instance, enables farmers to prepare for possible droughts in advance. Natural climate variabilities such as El Niño or La Niña are associated with distinct regions where reduced precipitation is more likely, and thus allow the regions concerned to prepare for and react to possible consequences at an early stage. New technologies such as remote-sensing are developing rapidly and can assist in agricultural management regarding plot identification, yield estimations, assessment of the vegetation status and loss estimations, to name but a few.

In many developing countries, farmers retain the risk of crop losses. Their risk management often only consists of diversifying their income sources by planting a variety of crops and by additionally breeding livestock. Implementing further risk management systems and tools is key for drafting sustainable development strategies, but also for adapting to the changing climate.

Insurance is the last but not least important component of drought management. As a remedy, it covers the loss, but as a prophylactic measure it also provides planning security. A farmer will not be ruined by a disastrous drought, but will be given a financial cushion with which to restart his/her life. Sovereign risk insurance schemes can be a first step towards implementing a market system (Kron et al. 2016).

In agricultural insurance, a system approach in the form of public–private partnerships is needed. This structure can provide the adequate legal, institutional and organizational framework in which insurance products and other risk management tools can work efficiently, and in favor of all parties involved. A national agricultural insurance system must involve the different production sectors, and address the interests of all stakeholders (producers, government, lending institutions and the insurance industry). Its main objective is to make insurance cover available to the majority of production sectors and farmers.

Droughts are silent killers, with the potential to cause enormous losses to society as a whole. Outside the agricultural sector, losses may initially remain insignificant. However, they can suddenly spiral if developments triggered by a drought, especially in combination with extreme heat, cause events such as power blackouts. Climate change will certainly intensify extreme drought situations in many parts of the world.

Overall awareness is a key factor in being prepared to cope with drought and avoid catastrophic consequences. While extremes of dry weather are not avoidable, disasters are. They are the net result of the effects of extreme weather events and the response to them. Effective prevention measures are both achievable and indispensable, but they will never provide complete protection. If societies, from governments to individuals, are prepared for frequent and normal extremes, and the residual risk from rare events is transferred to the finance industry, we can achieve enough resilience to guarantee sustainable living.

22.6 Water and Mass Movements

22.6.1 The Role of Water in Mass Movements

Mass movements shall be understood here as events during which large volumes consisting primarily of solid matter are displaced from their original location. Mass movements can occur suddenly or in a process lasting over a long time. Landslides and debris flows constitute the most common, but probably not the most damaging type of mass movement. They usually affect a limited space and are often only a change in the landscape without causing damage. If they hit human property or infrastructure they can be extremely destructive though. Snow avalanches are similar in this respect. Subsidence and heave, in contrast, are usually widespread and develop gradually. While most mass movements are water-related they can also happen due to other causes: landslides can be triggered by earthquakes, volcanic eruptions and other natural geological processes; or they happen as a consequence of human activities such as undercutting slopes, pumping groundwater, mining, etc.; lastly, dams and human-made deposits (landfills) may fail. These "other causes" are not considered here.

22.6.2 Landslide and Debris Flow

Landslide is the most common form of mass movement. Most of their occurrences are related to and even triggered by water. Landslides are generally understood to encompass all processes involving the sudden downward movement of soil and rock materials. Slope failures occur if the equilibrium of gravitational and adhesive forces is disturbed, for instance when weight is added to or removed from sections of the slope. This may, among others, be due to rainwater, the erection of a heavy structure, excavation works or the erosion or drying of the soil (Highland and Bobrowsky 2008). Land mismanagement—particularly in mountain, canyon and coastal regions—often leads to increased landslide activity.

At sites where a wildfire has destroyed the vegetation and the heat has changed the soil chemistry, the mass movement hazard increases. Similarly, earthquakes often set the stage for increased landslide activity by loosening the ground. Debris flows especially are more likely to be triggered by high-intensity rainfall events in the years immediately following a fire or an earthquake. A good example is Sichuan/China where numberless potential debris flow sites have been existing since the large earthquake in 2008, with some disasters happened in 2010 already (Xu 2010).

Landslides occur when rain or snowmelt water lubricates the boundary between two soil layers (especially where a pervious layer is superimposed on a layer with lower permeability), so that the friction between the layers is reduced, and a slip plane activated. While water is mainly the trigger of a landslide (in which the proportion of solids is far higher than that of water), it becomes—at least partly—a driving force in debris flows (in which water and solids have a comparable share of typically $50 \pm 20\%$) (See subsection on Debris Flow, Mudflow, Lahar in Sect. 22.2.1).

Landslides may happen at any location where there is a slope, but underlying geological conditions play a crucial role. The main influencing factors on landslide susceptibility are topography (angle, shape, orientation, height of the slope), geology (stratification, sequence of soil layers), bedrock structure (texture of rock and soil, weathering condition, fracturing), vegetation coverage (percentage of cover, root depths), earthquake activity, human factors (e.g. undercutting), soil water conditions and rainfall (accumulation, intensity).

Landslides can crop up suddenly, with little or no warning, or may be preceded by perceptible signs such as minor tremors, noises, the opening-up of cracks in the ground, or small rocks and chunks of soil that roll downhill. Their speeds vary from less than one centimeter per day to several meters per second. Some cover only a short distance but have the capacity to completely destroy a building or even whole settlements/villages. Others move several kilometers before coming to rest (Tilling et al. 1990). Landslides happen locally. However, although typically small in extent they can have major consequences. A single slide seldom causes significant direct material damage but the average overall annual loss from the many individual events adds up to millions of dollars every year.

Practically every strong rainfall event is likely to generate landslides. While the majority of these slides occur in uninhabited, mostly mountainous, areas in which damage is generally limited to roads, railways, power lines and fields, or blocked traffic and rivers, even the small percentage (the absolute number is still high) that occurs in or near developed areas and human settlements amounts to considerable losses.

Based on Highland and Bobrowsky (2008), mass movements can be classified into four major categories according to their form of movement, velocity and the role water plays.

1. Soil or rock fall (free fall, no influence of water on transport process)
2. Debris flow (water-solids mixture; high influence of water; velocities in the order of 5–15 m/s)

3. Landslide or earth slide (water often serves as a lubricant; velocities in the order of 0.1–10 m/s)
4. Ground creeping (usually little influence of water; velocities in the order of less than 1 m/day)

On the one hand, the development of unstable areas means more and more buildings are exposed to mass movement damage, on the other, the hazard itself may be increased if development has an adverse effect on geological stability. Human modification of the land is a major factor in slope instability. This may involve, among others, firstly, changes to the drainage regime arising from deforestation and the re-routing of irrigation systems or streams; or, secondly, the overloading of slopes or, thirdly, the blocking of drainage channels by artificial fills or embankments and, fourthly, the extreme steepening or undercutting of the slope by excavation and blasting works.

Climate changes will also lead to greater landslide activity. Extreme storms and precipitation are likely to increase with respect to both intensity and frequency in many regions, and permafrost found in northern regions and at high altitudes in the mountains will thaw or even disappear completely, leaving the slopes highly susceptible to slide (Patton et al. 2019).

A landslide, being a secondary hazard by itself, may cause tertiary events, for instance by blocking a watercourse or induce a tsunami. The greatest known tsunami run-up in modern times (525 m) was caused by a rock fall and immediately following landslide into Lituya Bay, Alaska in 1958 (Dickson 2018). In the past, severe tsunamis happened in several Swiss lakes due to the same phenomenon and even the Yangtze River in China was (and perhaps still is) prone to tsunamis in the Three Gorges region. After the 2008 Sichuan earthquake in China dozens of dangerous river blockages had to be handled, some of them with very large dimensions (see subsection on Backwater Flood in Sect. 22.2.1). The space behind these natural dams fills up rather quickly and once they are overtopped they may fail immediately releasing all the stored water in a disastrous dam-break wave (see also subsection on Glacial Lake Outburst Floods in Sect. 22.2.1).

22.6.3 Avalanche and Ice Movements

Snow avalanches and glacial ice avalanches resemble landslides in their effect. Snow avalanches occur in two main forms: powder avalanche and flowing avalanche (SLF 2019). The first may reach velocities exceeding 300 km/h and exert their destructiveness mainly by the involved high air pressure, whereas the latter consists typically of wet snow flowing with less speed (<100 km/h) but burying people and buildings under heavy snow pack. Glacier avalanches combine both features: the ice slab breaking loose from a glacier is extremely dense and moves very fast. This type of event can be even more destructive than snow avalanches and landslides, if a large mass of water imbedded in the glacier is released at the same time. A glacial avalanche or a surging glacier can set the stage for a GLOF (see the corresponding subsection in Sect. 22.2.1), if they block the course of a river. Parts of glaciers plunging into a lake or the sea may cause tsunamis.

22.6.4 Subsidence and Heave

Land subsidence is the gradual settling or sudden sinking of the earth's surface owing to the subsurface movement of earth materials. The common causes are water withdrawal from aquifers, drainage of organic soils, underground mining, natural compaction, changes in the volume of soil constituents, underground erosion, sinkholes, and thawing permafrost (Kron et al. 2016). Regional hydrological changes that accompany climate change can also lead to movements of the ground.

A specific type of ground-surface movement relates to expansive soils. Some clay minerals, and in particular montmorillonite, shrink when they dry and swell when they become moist. A sample of pure montmorillonite—also known as bentonite or smectite—can alter in volume by a factor of 15. Natural soils do not contain a high percentage of expansive minerals, but can still expand more than 1.2-fold (i.e. by 20%). Given that a 3% volume increase is already potentially damaging for buildings, two-digit-percentage changes can be very destructive. Swelling clay can produce enormous heave forces, which a house built on top may be unable to withstand (Kron 2012).

The phenomenon varies greatly within a short distance. As water migrates beneath a house built on expansive soil, the edges of the foundation may be pushed up, potentially causing cracking in the drywall and in the foundation itself. Subsequently, as the moisture increasingly migrates towards the center of the slab, center-lift may occur, causing additional damage. Buildings get cracks and jammed windows and doors.

In the case of drying the process runs in the reverse way, with similar consequences. Clay shrinkage may impair the support of the foundations. Even if the extent of swelling and shrinkage is too weak to have immediate consequences, swell-shrink sequences exert alternating stresses on buildings, which may eventually be weakened and damaged. In the course of the process, ground fissures may develop, exacerbating the situation by causing rainwater to penetrate more deeply. The greatest damage tends to occur in situations where there are frequent, substantial changes in moisture conditions. Losses not only depend on precipitation, but also on temperature, which increases evaporation from the surface and transpiration of vegetation. Plants located near to homes can also cause damage to foundations. As trees age, their roots may grow under the foundations, extracting moisture from the soil and causing it to dry out and shrink. This can result in additional settlement of the structure many years after the original construction. When the roots die and decay, they predefine ways for water to reach the dried-out soil, which expands again.

Swelling soils are among the most prevalent causes of damage to buildings and infrastructure. While the visible effects are mostly not very spectacular, the hazard is highly relevant, being a mass phenomenon in some regions of the world that causes billions of dollars of damage each year. In the United Kingdom and France these soils are quite common. Here problems occur primarily during dry periods in the form of subsidence. In the UK, every year insured subsidence-related losses accumulate to a three-digit-million-dollar amount (ABI 2018). After dry summers, such as 1990–1991, they can even exceed US$ 1bn. The insured figures are representative as most buildings (>75%) in the UK are covered against this type of hazard.

In the southwest of the United States, it is the wet weather or climate episodes that cause the soil to expand and generate annual losses in the range of several billion dollars. Cracked driveways, sidewalks and basement floors, heaving of roads and highway structures, structural damage to buildings, and disruption of pipelines and sewer lines are among the most frequently observed consequences. The American Society of Civil Engineers (ASCE) estimates that one in four U.S. structures features damage caused by expansive soils (DMME 2019). However, it is still seldom recognized, as the visible damage develops slowly and, even if noticed, is often attributed to other causes (such as poor construction quality or aging).

Widespread subsidence where land sinks on a large scale is not usually critical for buildings and does not cause structural damage. However, the flood hazard could be increased, since water may collect at the site concerned during heavy rainfall. The world's largest subsidence area of this kind is California's Central Valley, where the ground has settled by as much as 9 m in some places (USGS 2019). Here, compaction of organic soils due to groundwater extraction is the main cause. It weakens levees (which may even fail for this reason) and thus increases the potential for flooding.

The flood hazard is in particular increased substantially in many coastal regions, especially deltas. In some cases, land sinks below the average sea level, allowing intrusion of storm surges further inland and generally higher tidewater levels. Water from rivers and rain can converge in the lowered areas during adverse weather. Rainwater that can no longer flow freely into the sea driven by gravity must be continuously pumped out.

22.6.5 Prevention and Mitigation

Subsidence only becomes dangerous when buildings are poorly designed and executed. For newly erected buildings problems can be avoided easily if appropriate measures are applied (ABI 2019; ASCE 2019). Retrofitting of existing buildings to a higher level of subsidence resistance is very costly. Plants should not be placed close to a building in critical areas, because they increase the drying out of the soil.

Soil maps can give first indications, but it is recommended that further advice be sought from the state geological service or from a geologist. Soil survey reports will provide fairly detailed information on the site concerned. If the decision to build on a critical site is taken, there are ways of mitigating the risk of future damage.

Where the critical soil layer (e.g. clay) is relatively thin and close to the surface, it can be removed and replaced by non-expansive filling material. Protection barriers around the foundation of a building can prevent infiltration by surface water, and subsequent swelling. Swelling induced by pre-wetting the soil prior to construction can limit future heave, but this method functions only if the higher moisture level is maintained. Applying hydrated lime to swelling soils is a common remedy and an effective treatment for preventing or reducing expansion. Calcium from the lime replaces the sodium in the clay, reducing its ability to swell. However, it is far cheaper to avoid collapsible and expansive soils than to remediate them.

Foundations should be strong and, preferably, post-tensioned. This solution makes them less vulnerable to the momentum forces exerted by uneven settlement. The main measure is to ascertain that moisture conditions beneath and in the immediate vicinity of the structures are stable. This involves, for example, making sure that water drains away from the building, and that drainage is not impeded.

One can sum up that ground movements due to soils that interact with water in the form of swelling and shrinking are one of the most underrated natural hazards.

22.7 Deltas and Coasts

Coastal regions in general and deltas in particular are areas that are favored for human settlement, particularly in tropical and temperate climatic zones. For deltas, their flat topography, abundant water supply, and the constant deposition of sediments (when unencumbered by human activity) provide opportunities for the development of highly productive agricultural and aquaculture systems, for the development of human settlements, and for the exploitation of natural fluvial and coastal ecosystems (see e.g. Kuenzer and Renaud 2012). Many coastal regions and deltas are therefore highly densely populated (Ericson et al. 2006). For example, the portion of the Mekong delta in Viet Nam has one of the highest population densities in the country (Garschagen et al. 2012), the highest being in the Red River delta.[1]

However, coasts and deltas are also exposed to many natural hazards such are eustatic sea-level rise, coastal and riverine floods, hurricanes and storm surges, tsunamis, droughts, coastal erosion, and salinity intrusion (Kuenzer and Renaud 2012; Ellis and Sherman 2014). Impacts of these hazards on coastal communities can lead to dramatic consequences as has been seen historically with rapid onset hazards such as tsunamis (e.g. 2004 Indian Ocean tsunami with 220,000 fatalities and US$ 10 billion in damages[2]; the Great East Japan Earthquake and Tsunami of 2011 with 15,880 fatalities and US$ 210 billion in damages[3]); cyclones and storm surges (e.g. hurricane Katrina in 2005 with 1,720 fatalities and US$ 125 billion in damages[4]; cyclones in Bangladesh, e.g. Sidr with 3,295 fatalities and over US$ 3.7 billion in damages[5]; typhoon Haiyan in the Philippines with > 6,000 fatalities and US$ 9.7 billion in damages[6]); but also of creeping processes such as droughts, for example, the El Nino-related droughts and salinity intrusion affecting the Mekong delta in Viet Nam in 2016 (CGIAR 2016; UNDP 2016).

The high impacts of natural hazards observed in coastal areas and deltas are due to high levels of exposures linked to the high population densities in these regions, high levels of vulnerability, and the potential increased frequency and magnitude of natural hazards linked partially to the effects of climate change. Vulnerabilities are linked to the sometimes high levels of poverties observed in these regions (for example, the Mekong delta in Viet Nam registers some of the lowest levels of socio-economic indicators in the country —Garschagen et al. 2012), but also lack of disaster preparedness including early warning systems. Regarding the latter, much progress has been made in the last decades with notable examples in Bangladesh (e.g. Haque et al. 2012).

Climate change will increase the risk these regions will face in the future (IPCC 2014a), but other factors can have more immediate and serious impact on coastal areas and deltas (Nicholls et al 2008). Indeed, the impacts these hazards can have on communities have historically been and currently are aggravated by human activities such as subsoil natural resources extraction which can lead to rapid land subsidence, basin- and local-level land use changes as well as infrastructure development (e.g. dams, dikes, canal networks), and rapid and often unplanned urbanization (Kuenzer and Renaud 2012). This is of particular concern for coastal deltas which are now "sinking", due primarily to direct human interventions such as sediment trapping behind dams, underground over-abstraction of resources leading to rapid subsidence, diversion of water for agriculture and other activities (Syvitski 2008). For example, Higgins et al. (2014) showed that for the Ganges–Brahmaputra delta in Bangladesh subsidence rates ranging from 0 to >18 mm/y are recorded depending on location and local stratigraphy which should be contrasted with average annual global rates of eustatic SLR of 1.7 mm/y over the period 1901–2010 (IPCC 2014b). Globally, Syvitski et al. (2009) showed that within the timeframe of the early 2000s, 85% of the 33 deltas they investigated suffered severe flooding and that 18 of these 33 deltas were in "peril" or "great peril" linked to high relative sea-level rise triggered by a reduction in natural aggradation rates and accelerated compaction both of which outweighed global sea level rise. It is also interesting to note that attempts to protect portions of a delta against one hazard (e.g. polderization to prevent flooding) can lead to increased vulnerability and risk of the same or adjacent social-ecological systems with respect to other hazards by either altering the functioning of the system in situ or transferring the problem to another location in the delta. It is also important to recognize that effects of disturbances are not felt homogeneously across deltas. For example, model simulations by Dang et al. (2018) show that the single and combined effects of (i) infrastructure development on the

[1] https://www.gso.gov.vn/en/population/

[2] 2015 Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE – As at July 2015. https://www.munichre.com/site/corporate/get/documents_E-997191797/mr/assetpool.shared/Documents/5_Touch/_NatCatService/Catastrophe_portraits/2004-tsunami-touch-en-update.pdf (since 2020 not available for public use)

[3] 2012 Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE – As at February 2012. https://www.munichre.com/site/corporate/get/documents_E-1363543178/mr/assetpool.shared/Documents/5_Touch/Natural-Hazards/NatCatService/Catastrophe-Portraits/event_report_eq_japan_2011_touch_en.pdf (since 2020 not available for public use)

[4] 2015 Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE – As at July 2015. https://www.munichre.com/site/corporate/get/documents_E-1089336415/mr/assetpool.shared/Documents/5_Touch/_NatCatService/Catastrophe_portraits/hurricane-katrina-touch-en-update.pdf (since 2020 not available for public use)

[5] 2008 Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE. https://www.munichre.com/site/corporate/get/documents_E195685267/mr/assetpool.shared/Documents/0_Corporate_Website/2_Reinsurance/Business/Non-Life/Georisks/NatCatService/Annual/2007/mrnatcatservice_natural_disasters_fatalities_en.pdf (since 2020 not available for public use)

[6] Munich Re Topic Geo 2013. https://www.munichre.com/site/touch-naturalhazards/get/documents_E1043212252/mr/assetpool.shared/Documents/5_Touch/_Publications/302-08121_en.pdf (since 2020 not available for public use)

Mekong and tributaries, (ii) land subsidence, and (iii) sea-level rise on the hydrology are different in the Cambodian lowlands as opposed to the Vietnamese portion of the Mekong delta. For example, the development of hydropower dams has more significant effects in dry years (by increasing water levels) as opposed to wet years, but this effect diminishes rapidly downstream and is barely noticeable in coastal regions of the Mekong delta. The reverse is however true when considering sea-level rise where the coastal and middle regions of the delta are most affected due to the tidal regime. Finally, local water infrastructure development, land subsidence and sea-level rise in the Vietnamese Mekong delta will have greater effects than in the Cambodian lowlands (Dang et al. 2018).

All the factors mentioned above affect coastal and delta freshwater resources severely. Climate change, through its multiple direct and indirect impacts will aggravate the pressure on these resources, in particular through increased salinity intrusion. Although not specific to coastal areas, it is generally accepted that one of the main impacts of climate change is on water resources (UN-Water 2010), affecting water security globally, including in coastal areas (UN-Water 2013). The IPCC SREX report (IPCC 2012) recognized that sea level rise induced salinity intrusion will exacerbate freshwater supplies in coastal areas, and the IPCC AR5 report (IPCC 2014a) recognizes that many groundwater resources are salinized principally through over-abstraction, with climate change aggravating the problem.

To address the issue, the primary goal should be to reduce human pressure on surface and groundwater resources and recognizing that these pressures are more relevant than future climate change triggered pressures. This is however easier said than done with increased demand on water resources and related ecosystem services globally. In coastal areas and deltas, there has been a preponderance of attempting to control water flows which has provided opportunities for development but has often generated many problems in parallel. Attempts to control further water-related hazards or supply problem typically focus on engineered solutions (e.g. construction of dikes, reservoirs, sluice gates), thus bringing further disturbance to water flows and aquatic ecosystems. Much less attention is paid to attempting to reduce pressure on resources and even less on finding more ecosystem-based solutions to the preservation of coastal water resources. Regarding the latter however, there is an increasing trend in finding alternative approaches to water management and hazard risk reduction with concepts such as Nature-based Solutions (Cohen-Shacham et al. 2016) and Ecosystem-based Disaster Risk Reduction (Estrella and Saalismaa 2013) emerging, and with increased scientific publications, practical implementation and favorable international policy environment attracting the interests of decision-makers globally (Renaud et al. 2016). These concepts encapsulate a wide range of approaches including the restoration of degraded mangrove habitats, coastal marshes, and coral reefs to protect coastlines, preservation of seagrasses, and floodplain management including components of the Room for the River programme in the Netherlands,[7] or adapting threatened farming systems as opposed to resorting to the systematic development of engineered structures to protect existing farming systems (Renaud et al. 2015; Tu et al. 2019).

22.8 Overview of Flood Hazard and Risk Control Methods

22.8.1 From Hazard to Risk

It is important to understand the circumstances under which flood disasters happen. Nature alone does not produce disasters, but only extreme events. A disaster happens if people and/or their possessions are affected so severely that a society's life is disrupted (UNISDR 2009). A well-prepared society is not likely to experience a disaster as easily as one that lacks many aspects of preparedness, from education and knowledge to building codes, and from functioning governance to availability of financial means. Disasters are hence not only products of chance but also the outcome of interaction between political, financial, social, technical and natural circumstances.

Similarly, the term “risk” should be defined and understood in an unambiguous and consistent way. In the scientific community, it is widely agreed that risk is the product of a hazard and its consequences (IPCC 2013). Where there are no people or values that can be affected by a natural phenomenon, there is no risk. An extreme flood in an uninhabited region with no human property cannot result in disaster, so there is no risk associated with it. Similarly, a major flood in a well-prepared region will not become catastrophic. In a poorly prepared region, however, even a moderate event may cause a devastating disaster. The flood hazard is clearly highest in the first case mentioned, while the flood risk is highest in the last case.

Hence, three components determine the risk (Kron 2005):

(a) The likelihood that a natural event may occur
(b) The presence of people/property/other values
(c) Their vulnerability (this term describes here what is called susceptibility in Sect. 22.1)

In a simplified but widely used way, risk can be defined as:

[7] https://www.dutchwatersector.com/news/room-for-the-river-programme

$$Risk = Hazard\,x\,Values\,at\,risk\,x\,Vulnerability \qquad (22.8)$$

Hazard is the threatening natural event and its probability of occurrence; the values at risk are the buildings/objects/humans/habitats/natural features that are present at the location involved; and vulnerability denotes the lack of potential resistance to damaging/destructive forces. Vulnerability can refer to human health and wellbeing (human vulnerability), structural integrity (physical vulnerability) or personal wealth (financial vulnerability). Insurance's contribution to risk control addresses the last of these factors. Values at risk and vulnerability are sometimes combined to form "consequences". Thus, risk can also be written as:

$$Risk = Hazard\,x\,Consequences \qquad (22.9)$$

The overall risk is determined by computing the integral over all possible threatening events (intensities and frequencies) and their respective consequences (associated losses) (Kron 2005). Hence, risk is identical to the (expected) average annual loss if the hazard is specified in terms of exceedance probability (return period) in any given year.

The flood risk changes continuously as each of its components changes. The hazard varies with measures taken in the catchment area that influence drainage conditions, and climate change may lead to drier or wetter conditions and/or to more extremes at both ends of the flood frequency distribution. On the coast, the sea-level rises and the intensity and frequency of storms increases or decreases as the climate changes (IPCC 2012).

Rising values at risk and in particular their concentration in some areas certainly account for the highest share in the change of risk. Megacities with burgeoning populations and industrial development are making many regions ever riskier, in particular those on coasts and in flood plains. Also, the number and value of people's possessions are continuously rising.

Finally, vulnerability is increasing despite damage prevention efforts. In general, modern equipment and building materials are highly vulnerable. Almost any item contains electric or electronic components prone to damage when exposed to flood water or even humid (and/or salty) air. Drying them out and then using them again as in the past is no longer an option. The high concentration of people and dense infrastructure networks increase vulnerability too. Many objects depend on each other, and practically everything depends on electric power. Failure at one point in the system may have a domino effect and cause the whole system to fail. However, vulnerability can be—and often is—reduced by flood control measures.

Insurers and reinsurers have always needed to assess the probability of flood losses as a basis for their business operations. This requires risk modeling. But there has also been a shift from hazard modeling to risk modeling in both science and engineering in the past decade or so, as societies have recognized too that providing protection for high values (e.g. a city) and low values (e.g. a crop field) for the same flood frequency does not make much sense economically. The goal should be to minimize the flood risk for a society, not to make it equal for everything and everyone.

22.8.2 Flood Risk Reduction

There are no defined boundaries that separate hazard, values at risk and vulnerability. "Hazard" is really a natural phenomenon that may become consequential if it assumes an extreme intensity. This component cannot be influenced by humanity except—in the long run—by mitigation of climate change.

In the context of a flood, this may be seen differently. As stated above, flood is a secondary hazard, the magnitude of which depends on several influencing parameters. We cannot influence rainfall intensity, but we can—to some extent at least—control the formation of a hazardous flood. Deforestation, the draining of wetlands, urban development and surface sealing, mono-cropping in agriculture, and river training often intensify the hazard; afforestation, river restoration and the establishment of retention areas may mitigate it. Hence, flood control systems consisting of dikes, retention basins, reservoirs, diversion channels, etc. can also be quoted as ways of influencing the hazard, which is essentially the flood wave (or run-off).

Only if the hazard phenomenon exceeds a potentially damaging magnitude do the other two risk components become important. The most efficient way of controlling values at risk is to avoid settlement in hazardous locations. If a house is built not right by the river bank or the beach, but further away or inland on higher ground, a flood or storm surge cannot inundate it or tear it from its foundations. Raising buildings above a critical water level and avoiding placing any vulnerable items inside the building below that level can have a similar effect. Theoretically, preventing people from moving to areas where they expect better living conditions is a good idea, but it does not work easily in practice. Trying to convince people that they should leave their homes and move elsewhere is an even more futile exercise.

All other measures can be seen from the perspective of reducing vulnerability. Vulnerability reduction measures need to be permanent to be effective. Early warning enables people and goods to be evacuated and defense measures to be taken, but does not guarantee that there will be sufficient time to do so. Hence, dikes, solid flood walls and high-lying entrances to basements and ground floors are better than mobile elements and plugs for doors and windows. However, the latter can be still very wise and cost-effective investments, as are waterproof cladding and making the lower parts of a building's interior water-resistant.

It is easy to understand the need for protection against a river flood, as the source of flooding—the river—is known. However, protection measures need to be well planned and designed. Furthermore, they are expensive. Providing protection against flood damage resulting from intense local precipitation is usually a much simpler affair—but often not considered necessary by owners. And yet a few inexpensive measures can prevent losses, at least from moderate flash flooding. In this context, short-term loss reduction measures can be more or less ruled out, because it is almost impossible to forecast a flash flood with sufficient accuracy and early enough to enable defensive measures to be taken.

The flood risk can be more effectively reduced by appropriate measures than the risk from any other natural hazard (Kundzewicz et al. 2018). Furthermore, flood prevention and flood control are highly cost-effective; every dollar/euro spent on flood control eventually yields a much greater benefit in losses prevented (Kron and Müller 2019). Many countries have improved their situation, but it was always a disaster that triggered the efforts: in the Netherlands and in Germany after the storm surges in 1953 and 1962 respectively, in the United States after the Great Mississippi flood in 1927, in China after the flood year of 1998, and so on (see Sect. 22.2.3). The risk is reduced for the moment—no question. However, whether it remains at a lower level depends on the developments on "the dry side of the dike".

An adverse effect of highly developed flood control and preparedness is the "feeling of security'. People tend to ignore or eventually forget about the residual flood risk if nothing happens for a while, and increase the risk by accumulating assets. Alternatively, they may be lulled into a false sense of security, totally relying on flood protection and preventive measures. It is quite likely that systems that "always work" may not do so in the event of disaster.

A rather typical feature of flood impact is the disappearance of risk awareness after long periods without large events, or—false—trust in existing protection. It usually takes an extraordinary flood to wake up a country, as was the case in 2011 in Thailand. Then politics, the industrial sector and the general public again realize that a flood risk exists and plans for flood control, flood protection and financial flood risk reduction are set up.

Although technical flood protection is certainly the most important factor in preventing large disasters, we need to be aware that even the strongest, best-designed systems have a limited effect. The consequences of the 2004 Indian Ocean tsunami and the 2011 tsunami triggered by the Tohoku earthquake at the Eastern coast of Japan and hurricanes Katrina in 2005 and Sandy in 2012 devastating the US coasts showed that 100% safety is not possible. It is therefore crucial not to rely on a purely structural approach to the problem, but to include the so called "soft" factors and approaches.

22.8.3 Risk Reduction Partnership

Risk and loss minimization call for an integrated course of action. The flood risk must be shared between government, the communities, the enterprises concerned and the financial sector, in particular the insurance industry (Kron 2009). Only if they cooperate with each other in a finely tuned relationship and in a spirit of risk partnership can flood loss prevention be truly effective.

All of the risk-reduction efforts cannot work if there is not an adequate level of risk awareness in all societal strata, from the homeowners to the government. Awareness must be raised and maintained. Unfortunately, this is best achieved the hard way: by repeated occurrence of losses. No education campaign and no incentive are as effective as a flood event that confirms the hazard. Through the event the probability-linked term "risk" becomes "loss", i.e. the probability becomes certainty. Proper selection of the site where a house or plant is to be built has a major bearing on the risk. Flood plains are inherently risky, as the flood risk is never zero, no matter what measures are taken.

22.8.4 Public Authorities

The task of government is primarily to reduce the underlying risk for society as a whole. This involves ensuring access to observation and early-warning systems, building dikes, deploying flood retention areas, determining the framework for the use of exposed areas through legislation and preparing emergency plans, including programs to facilitate recovery (temporary housing, financial assistance, tax relief, etc.). In some countries, insurance programs are state-run. Much of the responsibility for flood protection lies with the public authorities.

22.8.5 Flood Forecasts and Warnings

Some types of flood form and develop slowly enough to allow time for forecasting and warnings. This is particularly true of river floods and storm surges. With other types of flood, there may or may not be sufficient time. Warnings may sometimes merely consist of general, qualitative statements such as "severe weather with flash floods likely", last-minute alerts, which leave people little time to react, or precautionary evacuation rulings, when a dam is expected to fail (Alfieri et al. 2012).

Staying informed during or ahead of a flood crisis is not only the duty of citizens and company managements, but is also necessary for the insurance sector. Insurance companies can offer clients technical advice and prepare for potential losses. The value of being insured must be made clear to people and enterprises *before* a flood happens.

22.8.6 Structural Flood Control

22.8.6.1 Reservoirs and Polders

In contrast to earthquake and windstorm, where homeowners themselves are responsible for ensuring that their houses are properly protected, in the case of flooding the onus is largely on the authorities. The most visible government action concerns structural flood control measures, aimed at lowering the hazard by reducing the frequency and probability of inundation. Much can be done with regard to rivers, but it is very difficult to influence the risk posed by local torrential rain and flash flooding because, unlike river floods, the source of flooding cannot be located.

Dikes cannot prevent flooding completely. They are designed for a flood with a relatively low annual occurrence probability, for instance 1% or 0.2%, but not zero. If an event exceeds this protection level, further flood management measures will be necessary. Large reservoirs and retention areas are the most efficient measures to control large floods—even though they are sometimes condemned by critics because they can severely intervene and impair ecological and economic systems in the region where they are built. Ideally, the flood peak is cut, i.e. the maximum discharge, which usually creates the highest flood level, is reduced. A dam backs up a river and thus can considerably reduce floods if its storage is managed appropriately. Storage control is not always easy, as reservoirs usually serve several purposes. Those responsible for retaining water for supply or hydropower production have other aims than flood managers. The first want to maximize the pool level, while for flood control purposes the available storage capacity should be maximized.

Polders are retention areas besides the river. They are—ideally—filled if the expected flood peak and volume exceed a harmful discharge at downstream reaches. In this way, they are managed like a dam-formed reservoir; hence flood forecast is essential. Some polders do not have a controllable inlet device but just a fixed weir crest, and start to be inundated if a certain water level is exceeded in the river. This type of polder is less efficient as it does not primarily focus on reducing the peak discharge, but generally reduces the volume of the flood wave downstream.

Flood storage is devoted to checking the volume of a flood wave above a critical threshold of flow, i.e. when (catastrophic) flooding and damage downstream are likely. In extreme flood cases, the available storage is less than the required volume; hence an optimal management strategy has to be found in the form of a trade-off—often during the event. Unfortunately, the outcome is sometimes not successful from the viewpoint of riverside property owners downstream.

22.8.6.2 Flood Walls and Mobile Dikes

If river passes through a city, there is often not enough space to raise a dike. A permanent flood wall is the only solution of choice. Such walls can be made of concrete, steel or aluminum and are highly effective if constructed properly, but they almost always collide with a free use of river embankments and disturb a nice scenery, no matter how much effort is put into architectural beauty. Hence, mobile or dynamic solutions are preferred where possible.

There is a myriad of temporary systems ranging from inflatable rubber tanks, that are filled with water or sand to form a barrier, or systems consisting basically of anchors/foundations, lateral guides and stop logs, which can be mounted in a short time, to systems that are permanently in place, but sunk under the surface during no-flood times. For all systems it must be made certain that they are not shifted by the lateral water load; therefore, a permanent foundation or anchoring is often essential.

The problem with temporary compared to permanent solutions is the generally lower stability and reliability of the first. A stab with a screwdriver may already make a water-filled rubber element useless, and many things can happen to delay the timely completion of a wall of mobile elements. However, there is the possibility for some systems to provide an automatic erection (dynamic systems). They are usually moved below the ground surface and brought up when needed.

For individual structures such as residential buildings, mobile elements are highly recommendable devices. With them, basement windows and door openings can be closed very quickly and successfully.

22.8.6.3 Super-Dikes

If water overtops a dike, it is quickly eroded and breaks, allowing water to flow in for many hours. A super-dike is much wider (up to several hundred metres). It has the same seaside slope as a conventional dike, but a much lower gradient on the landside, with a cascade form (TDLC 2017). These characteristics prevent overflowing water from eroding the dike and render under seepage impossible. The structure's stability (including resistance to earthquakes) is much higher. While a conventional dike and the immediate neighborhood must not hold any structures or be planted with trees, the top of a super-dike may be used for residential buildings, commercial zones and urban recreational areas. Furthermore, no bulkhead is seen, but there is a pleasant interface between land and sea allowing easier access to the shore. Even the interior of a super-dike can be used, e.g. for parking and service structures. Super-dikes are very costly and therefore only viable where the flood risk is reduced to such an extent that the investment pays off in the long run. Several such structures are found in Japan, in particular in Tokyo.

22.8.6.4 Bypasses and Emergency Outlets

Sometimes the capacity of the existing river cross-section (including forelands) is not sufficient to convey an extreme discharge through a city. Then a bypass is the most effective solution—if the geographic boundary conditions allow it to construct one. There are many examples in the world, large-scale solutions such as in Tianjin, Vienna, or Sacramento, but also thousands of small-scale examples for towns all around the world.

Various rivers of the Haihe basin in Hebei/China converge near Tianjin to form a 70 km long trunk of the Haihe before it discharges into Bohai Sea. Tianjin was spared with huge efforts from being severely flooded in 1963, when thousands of people perished in the catchment. After the flood, 85 large and some 1500 small reservoirs and 4300 km of dikes were constructed in the basin area, plus ten additional outlets to the sea to divert the water around Tianjin. Since their completion in 1979, Tianjin has been virtually "safe" from floods (Paltemaa 2016).

The Sacramento River passes right through California's capital Sacramento, one of the cities with the highest flood risk in the USA. Designed in the 1920s, Yolo Bypass, a 65 km long flood channel west of the city of Sacramento relieves the flow in the river by 85%. It is fed via two weirs—one with a fixed crest, another operated manually. The 24,000 hectares (240 km^2) area hosts a valuable wildlife area and is used for farming outside the flood season (YoloWRA 2007).

Bangkok was (in 2011) not so much saved by "organized" diversion (it just happened that the river breached its banks north of Bangkok and thus the water was diverted), but by dike protection of the inner city. In the centennial flood of the Chao Phraya river in Thailand in 2011, the capital, Bangkok, was largely spared by the flood waters—except in some peripheric districts. Most of the water was guided around the city proper, which was protected by dikes. After the flood, a large-scale diversion of the Chao Phraya involving the creation of a new 110 km channel west of Bangkok has been under discussion. In Sect. 22.2.3 more detail can be found on the flood in Central Thailand in 2011.

Vienna, Austria's capital, features two Danubes: the "Old Danube" (the original river) and the "New Danube". The latter is a channel that runs 21 km parallel to the original river in only 100–250 m distance. During a flood, flow through the New Danube is activated by opening a gate, during normal times the channel is separated from the river, the water is still and clear, and serves as a popular recreational area. The structure was built from 1972 to 1987. It can take over almost 40% of 14,000 m^3/s total discharge capacity of the Danube in Vienna, which is roughly equivalent to the highest-ever experienced flood (in 1501) and corresponding to a return period in the order of 10,000 years (Schnabl et al. 2014).

After the catastrophic Mississippi flood event in 1927, the Mississippi River and Tributary Project (MR&T) was established (Camillo 2013). Besides large dams with more than 90bn m^3 retention capacity and 3500 km of dikes, three emergency outlets were installed: (1) The Birds Point-New Madrid floodway which begins opposite the confluence with the Ohio and can discharge up to 15,500 m^3/s of water from the Mississippi. It flows outside the river between dikes, partly flooding farmland in the process and returns into the Mississippi more than 100 km downstream. (2) The Morganza Spillway, via which up to 34,500 m^3/s can be discharged into the Atchafalaya River and from there into the Gulf of Mexico west of the Mississippi delta. (3) The Bonnet Carré Spillway from where 7000 m^3/s can flow directly to Lake Pontchartrain. These relief measures are only taken when catastrophic flooding would otherwise occur. When they are applied, farmland and buildings will be flooded, but more valuable regions are prevented from being inundated. In 2011, for the first time ever, all three emergency spillways were opened and thereby the level of damage and loss in cities such as Baton Rouge and New Orleans drastically reduced (USACE 2012).

22.8.7 Non-Structural Measures

Extreme floods cannot be prevented or significantly reduced without technical measures. However, non-structural measures are equally important. This starts with retaining as much water in the catchment area as possible when a flood situation becomes imminent. Restoration of land (in particular wetland and former wetland) should be done wherever possible (e.g. Rohde et al. 2006). The objective is keeping as much of the area in a condition that is closest to a natural type and giving the creeks and rivers as much "room" as possible so that the concentration time, the time in which a flood builds up, becomes as long as possible. Along coasts, wetlands and mangrove forests are quite effective in reducing storm surges. They slow down the rise of the water level further inland and use up much of the energy of surface waves reaching the coast (World Bank 2016).

On the exposure side it is desirable to keep values-at-risk out of areas that are prone to flooding, at least of those areas that have a probability of being inundated of more than 1% per year, i.e. the 100-year flood zones (see Sect. 22.3). In cases, where this is not possible, or where developed areas already exist in this zone, information, awareness raising and education how to behave can be highly efficient. The goal should be “to live with floods”. This means, be prepared—mentally, physically, and financially—that a damaging flood may hit you. All these soft measures together may contribute as much to flood damage reduction as technical measures, but most of their effect is on top of the latter.

22.8.8 Flood Hazard Maps

A hazard map indicates the probability that a flood event of a given magnitude will inundate a specific location. In most cases, it specifies neither the depth of inundation nor the flow velocity. It gives no indication as to the potential loss, i.e. the risk.

Flood maps alone are useless. They must be actively used by (potential) owners and/or enforced by authorities. Insurers have strong leverage in requiring adaptation measures (or urging avoidance of a certain location) by including information on hazard zoning in their risk assessment (Kron 2009). Such stipulations are still asserted far too rarely.

However, hazard maps can be misinterpreted. Let us assume that we have a hazard map that specifies the 100- and 500-year flood zones (Fig. 22.34). The 100-year boundary defines the area inundated in the case of a flood that occurs, on average, at least once in 100 years. It does not mean that a less-than-100-year flood will not at least partly inundate the area. The same applies to the 500-year zone. The map does not indicate the extent of a 110-year or 200-year flood and they may reach any point between the 100-year and 500-year boundaries. Interpolation can be very misleading. In theory (leaving aside safety margins and other measures also normally deployed to prevent flooding), a 110-year flood can potentially cover almost the entire 500-year flood zone. Consequently, to be on the safe side, the 500-year zone is to be used when estimating the area that would be flooded during a 200-year event, if no specific knowledge is available.

22.8.9 Those Immediately Affected

The individuals, companies, and communities immediately concerned have huge potential for loss reduction. The crux is whether they maintain their risk awareness. Even people who do not overlook the danger of flood at the outset tend to forget about it, especially if nothing happens for quite some time. They rely on flood control systems, while acquiring additional items—in many cases susceptible to water damage—that further increase the value of their property. Anyone proposing to erect residential or commercial properties must be informed and educated to ensure they are constructed in the appropriate manner. The owners need to check the level of exposed values, be ready to take action in an emergency and put in place financial precautions to deal with catastrophic losses. People need to be informed and educated on how to build and behave in an appropriate manner, monitor the exposure of their property, be ready to act in an emergency and prepare for potential catastrophic losses by taking financial precautions, such as buying insurance.

The type of construction can make a big difference. Every additional decimeter of height achieved by landfilling, elevating buildings on pilings and locating living quarters and rooms containing high-value property on higher floors reduces the risk, as of course does choosing a design that does not feature a basement. The use of appropriate construction materials (concrete or bricks instead of wood) greatly reduces a building’s vulnerability to water. Attention should also be given to the lateral forces of flowing water and floating material that may hit a building. Valuable, water-sensitive items should not be placed on lower floors or in the basement. Company managements, in particular, must be made aware of the need to listen to and act on advice. Insurers can play their part by outlining the financial arguments (see Sect. 22.9).

22.8.10 Citizen Safety

The number of deaths from flood disasters in general has decreased over the past decades. Still, death tolls of several hundred occur in some events every year—and any fatality is one too many. Floods claim lives for different reasons, but in most cases it is the surprise effect of a sudden, unexpected flash flood. People who are caught unprepared have no chance, and their death is unavoidable. Many others are, however, avoidable. These include children (and adults) who drown in standing water simply because they have never learnt to swim, those who are swept away while trying to save possessions or a pet and those who dismiss warnings and alerts. Many, if not most, flood fatalities are not due to shortcomings in the forecasting or protection systems, but occur because people underestimate the forces of flowing water, and drive or wade into it.

A mere 30 cm of water is enough to float the average car, and there is almost no way of recognizing places in the roadbed that have been eroded by turbid floodwater. Flowing water—even if it is not very swift—is highly dangerous. Experiments (Maijala 2001) have shown that, independent

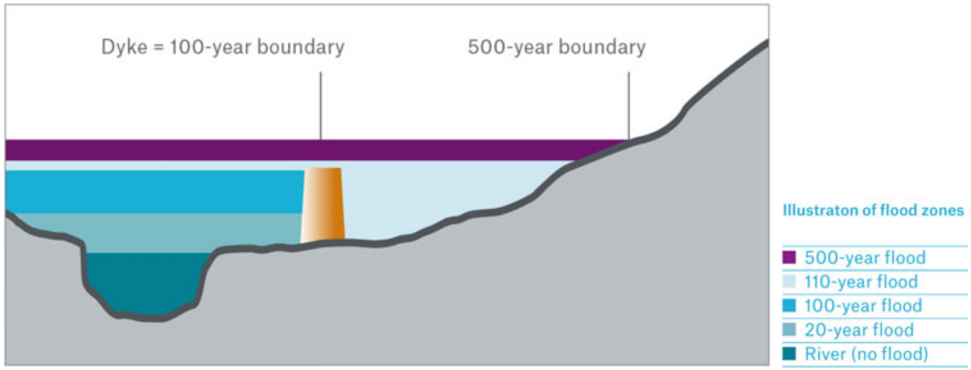


Fig. 22.34 Schematic presentation of flood zones (Source: adopted from Kron 2012)

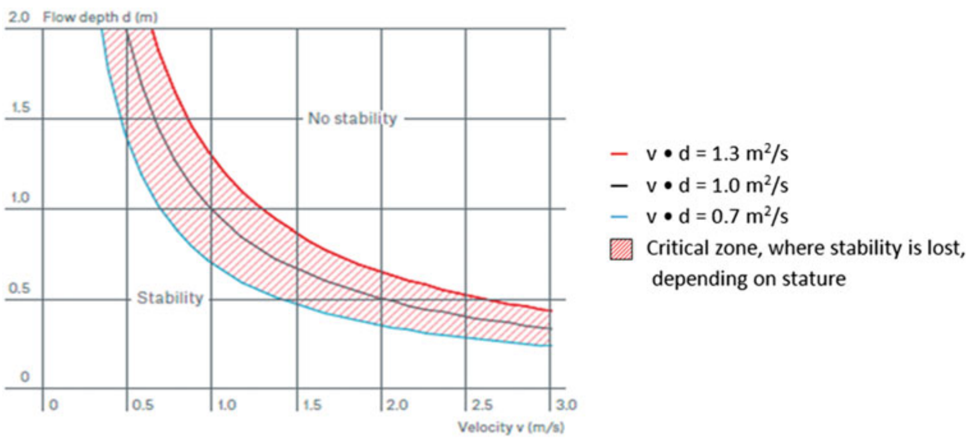


Fig. 22.35 Human stability in flowing water. If the product of flow velocity (v) and water depth (d) exceeds a threshold, humans can no longer withstand the forces of flowing water. Small, light persons can be swept away at v • d = 0.7 m^2/s, and even tall, heavy persons at v • d = 1.3 m^2/s. Source: adopted from Kron (2012)

of physical condition, a person standing in flowing water cannot withstand its power if the product of velocity and depth exceeds 1.3 m^2 per second (Fig. 22.35). Stability problems start at 0.7 m^2/s. As a rule of thumb, the product of 1 m^2/s may be used to assess a critical situation. Once unbalanced, a person caught by the current may be carried to deeper water and drown.

The flood hazard is especially prevalent in low-lying areas near water, or downstream from a dam. Even very small streams, gullies, creeks, culverts, dry stream beds, and low lying ground that appear harmless in dry weather can flood. An advice: “Avoid water, no matter how benign it may look. Don’t gamble with your life!!”.

22.9 Flood Disasters and Insurance

22.9.1 Flood Disasters

Water-related extreme events are responsible for most disaster losses in the world (Kron 2015; Munich Re 2018a, b). Billion-dollar flood losses have been incurred almost annually in recent decades with increasing consequences as countries have experienced enormous economic and population growth. Of all weather-related catastrophes, flood disasters are the most frequent and those with the highest accumulated annual loss, at least with respect to overall losses (for insured losses storms are the leading cause).

While floods can happen at any location, their frequency of occurrence varies geographically. Exposure to flooding is increasing everywhere; prevention and risk reduction in the form of proper land use and adequate construction is frequently neglected or ignored, or just not possible due to high development pressure and poverty. The development and improvement of flood control and protection measures can counteract this trend, but are hardly evident—if they can be found at all, it is only in certain locations and along certain rivers. Flood protection measures do pay off, but are relatively expensive (Kron and Müller 2019).

Table 22.5 Water-related disasters in the period 2000–2018 in which material losses of US$ 5 billion and more (original values) occurred. Source: Data from Munich Re NatCatSERVICE database; retrieved 2019

Year	Country/region	Event/basin(s)/area (Flood, if not specified otherwise)	Overall losses due to water/lack of water (US$ billion)	Insured losses due to water/lack of water (US$ billion)	insured (%)
2017	USA	Hurricane Harvey (Gulf Coast)	95	30	32
2005	USA	Hurricane Katrina (Gulf Coast)	83 [2/3]	41.5 [2/3]	50
2011	Japan	Tsunami	55 [1/4]	9 [1/4]	16
2012	USA, Canada, Caribbean	Hurricane Sandy (Northeast)	46 [2/3]	19.7 [2/3]	43
2011	Thailand	Chao Phraya	43	16	37
2016	China	Center, North, East	24.5	0.6	2
2012	USA	Drought (Midwest)	20	12	60
2002	Central, Southern Europe	Elbe, Danube, Italy	16.5	3.4	21
2008	Caribbean, USA	Hurricane Ike	13 [1/3]	6 [1/3]	46
2013	Central Europe	Danube, Elbe	12.6	3.1	25
2002	USA	Drought (Great Plains)	10	2	20
2004	Indian Ocean	Tsunami	10	1	10
2008	USA	Midwest, Missouri River	10	0.5	5
2016	USA	South	10	3,4	34
2010	Pakistan	Indus	9.5	0.1	1
2018	Japan	Honshu	9.5	2.4	25
2000	Italy, Switzerland	Southern Alps	8.5	0.48	6
2004	Caribbean, USA	Hurricane Ivan	8 [1/3]	5 [1/3]	60
2010	China	East, Southeast, South	8	0.15	2
2012	China	East, Northeast, Southeast	8	0.18	2
2003	China	Center, South, East, Northwest	7.9	–	–
2004	China	Southwest, Center, Northwest	7.8	–	–
2005	Caribbean, Mexico, USA	Hurricane Wilma	7 [1/3]	4 [1/3]	57
2007	China	South, Southwest, East, Center	6.8	–	–
2001	USA	Tropical storm Allison (South)	6	3.6	60

(continued)

Table 22.5 (continued)

Year	Country/region	Event/basin(s)/area (Flood, if not specified otherwise)	Overall losses due to water/lack of water (US$ billion)	Insured losses due to water/lack of water (US$ billion)	insured (%)
2004	USA	Hurricane Frances	6 (1/2)	2.6 (1/2)	43
2017	China	South, Center	6	0,25	4
2013	Canada	West (Calgary)	5.7	1.5	26
2013	Philippines	Typhoon Haiyan (Leyte)	5.2 (1/2)	0.35 (1/2)	3
2004	Bangladesh, India, Nepal	Monsoon rains	5	–	–
2005	India	Monsoon flash flood (Mumbai)	5	0.77	15
2011	USA	Hurricane Irene (Northeast)	5 (1/2)	3 (1/2)	60
2013–2015	Brazil	Drought (Sao Paulo)	5	–	–

(1/4) / (1/3) / (1/2) / (2/3) The loss figure shows the—roughly estimated—losses attributed to flood (one quarter/one third/half/two thirds of the overall/insured losses); the remainder is attributed to windstorm or to ground shaking during earthquake. Example: the overall loss of Typhoon Haiyan was US$ 10.4 billion, ½ of it (US$ 5.2 billion) was due to water

Table 22.6 Flood disasters in the period 2000–2018 in which more than 1,500 people died. Source: Data from Munich Re NatCatSERVICE database; retrieved 2019

Year	Region	Event	Deaths*
2004	Indian Ocean (12 countries)	Tsunami	220,000
2008	Myanmar	Cyclone Nargis	140,000
2011	Japan	Tsunami	15,880
2013	Philippines	Typhoon Haiyan	6,334
2013	India	Flash floods	5,500
2018	Indonesia	Tsunami	4,340
2007	Bangladesh	Cyclone Sidr	3,295
2004	Bangladesh, India, Nepal	Floods	2,200
2007	India, Bangladesh, Nepal	Floods	2,096
2004	Haiti, Dominican Republic	Floods	2,074
2004	Caribbean, USA	Hurricane Jeanne, floods	1,844
2017	India, Bangladesh, Nepal	Floods, Landslides	1,787
2010	China	Floods, Landslide	1,765
2010	Pakistan	Floods	1,760
2005	USA	Hurricane Katrina	1,720

*Death figures include all causes (such as earthquake, windstorm, landslides, etc.) not only flood; those missing are not included

Tables 22.5 and 22.6 show the costliest flood disasters (>US$ 5 billion overall loss) and those with the highest death tolls (>1,500) since the beginning of the century, taken from Munich Re's NatCatSERVICE (NCS), the most comprehensive database on losses from extreme natural events (Wirtz et al. 2012; Munich Re 2018b). Disasters with high financial losses occur mostly in well developed countries, whereas high numbers of fatalities result from events in poor regions where, though disasters do not often produce very high losses in monetary terms, they may still be severe and momentous for the country affected.

Table 22.5 also reveals that the insured portion for the costliest events is much higher in developed than in poor

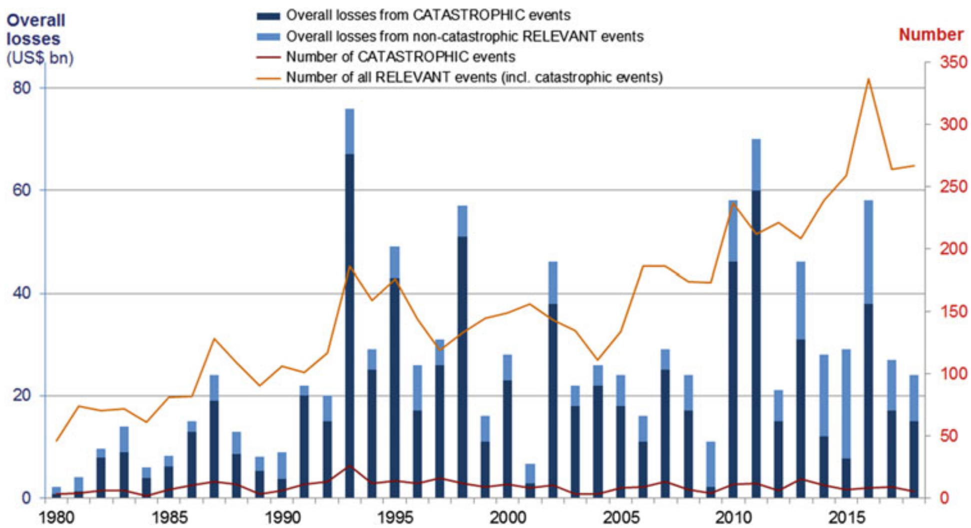


Fig. 22.36 Inflation-adjusted (to 2018 values) overall and insured annual inland flood losses (bars) and number of flood events (jagged lines) per year from 1980 to 2018, derived from "relevant" and "catastrophic" flood events. Relevant event: $\geq$ 1 fatality or normalized overall losses $\geq$ US$ 100,000, 300,000, 1 million, or 3 million; Catastrophic event: $\geq$ 1,000 fatalities or normalized overall losses $\geq$ US$ 100 million, 300 million, 1 billion, or 3 billion; depending on the assigned World Bank income group of the affected country (https://natcatservice.munichre.com/assets/pdf/180220_NCS_Glossary_en.pdf). Only floods that are not associated with named tropical cyclones are included in the analysis (Kron et al. 2012). Source: Data from Munich Re NatCatSERVICE database; retrieved 2019

countries. The insurance industry can assume a considerable share of the costs (and therefore also the risk), thus relieving the burden on a nation's budget and economy. Disasters usually affect poor countries much more severely than rich countries (Munich Re 2014).

Disasters can assume very different forms: in terms of the area affected (regional intensity or large-scale impact), high number of fatalities, huge monetary losses and severe impact on the local economy. Many disasters happen on coasts. Due to the concentration of people and assets, they are certainly the high-risk areas of the world—and home to a third of the world's population (Kron 2013).

There is no doubt that disasters, especially floods, have been increasing in frequency and intensity. Figure 22.36 shows the annual numbers of all relevant events (upper jagged line) and of catastrophic events thereof (lower jagged line). Relevant events are those with at least one fatality or normalized overall losses $\geq$ US$ 100,000, 300,000, 1 million, or 3 million, depending on the assigned World Bank income group of the affected country. An event is defined as catastrophic, if 1000 and more people die or normalized overall losses of $\geq$ US$ 1 million, 3 million, 1 billion, or 3 billion occur. Normalization accounts for the fact that exposure (values-at-risk) in flood-affected areas increase over time. Hence, a normalized loss figure of an event in the past represents the as-if loss for the case that this past event happens today. In the NatCatSERVICE database, normalization is executed using changes in local Gross Domestic Product (GDP), the only proxy quantity for normalization that is globally available (for details, see Eichner et al. 2016).

The number of relevant events increases over the period shown from less than 100 per year in the early years to more than 200 in recent years. In contrast to this, the line for the catastrophic events shows no trend, but rather quite some variation between 3 and 16 events per year with one exception: 1993 with 26 events.

The corresponding annual overall losses (= height of bars, adjusted for inflation) does not reveal a trend. The only observation that can be made is the high volatility of global annual flood losses and their general higher level after about 1990, which may partly be due to improved reporting (nowadays events are registered more thoroughly), but certainly due to increased values-at–risk.

It is noteworthy that the accumulated overall losses in any one year mainly result from great, catastrophic events (indicated by the dark, lower parts of the bars in Fig. 22.36. The percentage of catastrophic losses related to all relevant losses, on average over the whole period, is as high as 87%. This finding means that a high accuracy in estimating large losses is crucial for trends. Unfortunately, it is the large events for which the uncertainties in loss estimates are usually high.

The insured portions of the annual losses, shown in Fig. 22.37 are rather small. Their percentage shares in any one year is indicated by the diamond symbols. For the whole period of 39 years this percentage averages just 12% for all relevant events, a very low figure. However, the insured share displays a significant upward trend of roughly 1% per

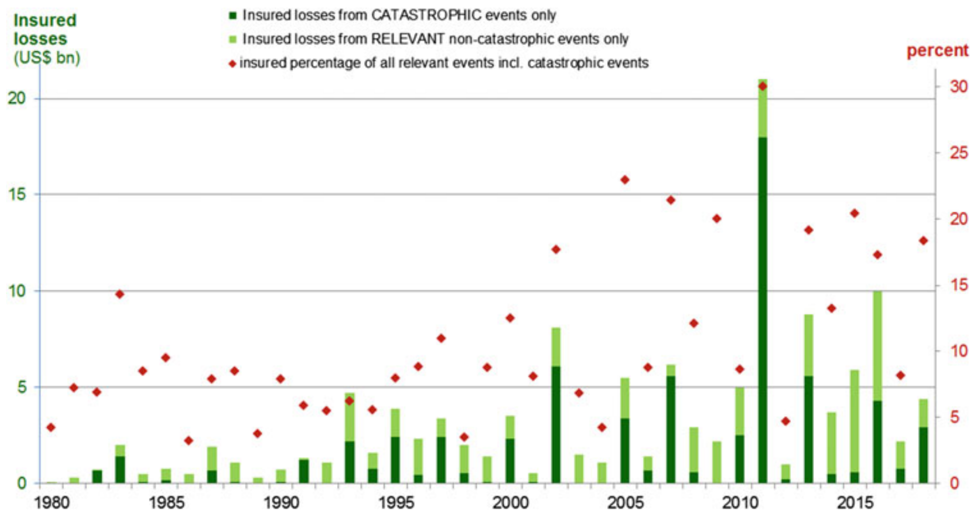


Fig. 22.37 Insured monetary losses (bars) from relevant and catastrophic flood events (Inflation-adjusted to 2018 values) and insured percentages (diamonds) of all relevant overall losses including catastrophic losses; Source: Data from Munich Re NatCatSERVICE database; retrieved 2019

about 3 years (0.31% p.a.) for all relevant losses (0.26% p.a. for catastrophic losses only), hence insured losses went up from 5–8% in the early eighties to around 15% nowadays.

Recent large events have shown that financial losses resulting from physical damage are no longer the only significant ones. Indirect losses such as business interruption (bi), contingent business interruption (cbi) and the loss of market share of a company due to being out of business for a while are growing. These losses are not limited to the area directly affected by disasters, but may occur anywhere in the world, even far away from the location of a flood. For instance, the floods in Thailand in 2011 caused a globally felt shortage of hard disk drives, as a quarter of hard disk drives produced worldwide are manufactured there (Munich Re 2012a).

22.9.2 Insurers and Reinsurers

The true task of insurance companies is to compensate financial losses that would have a substantial impact on insureds or even cause their financial ruin (Kron 2009). Insurers bear the financial risk from events that have such a low probability that they cannot be considered foreseeable. Insurance redistributes the burden borne by individuals among the entire community of insured people, which is ideally composed in such a way that they all have some chance of being affected—even if the degrees of probability differ. Furthermore, the insurance industry performs educational and public relations services, for example by publishing brochures in which they draw attention to hazards and explain ways of dealing with them (e.g. Munich Re 2008, 2012b, 2013, 2015).

It is essential for the insurance sector's role to be promoted prior to any crisis. and its role must be actively fulfilled. Suspending the acceptance of new contracts in the face of an impending flood is just one precaution a company needs to consider.

Insurance companies, like private individuals, try to avoid volatility in their payments. Natural perils insurance is highly volatile. Large single losses (from one event) can be reduced if part of the risk is transferred to the reinsurance sector, where business is often transacted worldwide. Catastrophic losses that occur in one country are distributed all over the world, thus relieving the burden on the local insurance market and possibly even preventing its collapse. Insurance, and especially reinsurance, companies have to be ready to pay large amounts of money after major events.

The case of Hurricane Gilbert that struck Jamaica in 1988 shows, how effective the idea of transferring local losses via the reinsurance sector to a worldwide system works. The island suffered losses amounting to about US $1 billion, of which 70% was insured. This US$ 700 million would have destroyed the Jamaican insurance industry completely. It survived because nearly 99% or US$ 690 million was reinsured and was therefore paid by the world's reinsurance industry. For the local companies a mere US$ 10 million obligation remained. In developed countries, reinsurance rates usually range between 50 and 90%,

Large accumulation losses were traditionally associated with windstorms and earthquakes. In this respect, floods and most other natural perils were not the principal focus of the insurance industry—until 2011 when the flood of the Chao Phraya River in Thailand produced the highest insured inland flood losses ever—in global context (see Sect. 22.2.3.2). In this flood about US$ 10 billion of the total insured loss of US$ 16 billion were industrial losses from Japanese companies, insured in Japan and reinsured there with a rate of about 80%. The estimated amount of internationally reinsured losses was eventually US$ 13 billion, or 81% of the US$ 16 billion total insurance burden.

In North America and Europe reinsured percentages of losses are—because of the strength of the local insurance markets—significantly lower than 50%.

22.9.3 Insurance Issues

The percentage of insured losses is lower for floods than for windstorms. Most homeowners' insurance policies do not cover flood water damage. Although their highest insured losses usually trail behind the highest insured windstorm losses —generated by typhoons—certain events (again, Thailand 2011 serves as a prime example) have proved that things are changing. Nevertheless, wind is still of more concern for insurers because this hazard is better insured, particularly in the countries with generally higher insurance penetration (Munich Re 2018a). In countries where the majority of homeowners and small businesses do not have cover for flood water damage, flood losses result mostly from insured industries.

22.9.4 Adverse Selection

Typically, only those frequently affected by flooding are interested in insuring against it, which is what makes flood insurance problematic. The underlying reason is also connected with one of the principles of insurance, namely that protection can only be provided for unpredictable events, as that is the only way of balancing out the risk over time. However, in many cases, this does not apply to river floods. Often, it is merely a matter of time before the next flood happens. On the other hand, people who do not live close to a body of water believe themselves to be safe and reject offers from insurance companies. As a result, the insured community remains relatively small and consists of people exposed to a high level of risk. This effect is known as adverse selection. Adverse selection can be avoided by offering multiple risk insurance packages. The portfolio is then composed of all kinds of clients: those that live close to a river (flood risk), those in a geologically active region (earthquake risk), those on a mountain slope (landslide and avalanche risk), etc.

22.9.5 Insurance Penetration

Flood insurance penetration is generally low in most countries of the world (Fig. 22.37). In many cases, relative poverty is the main reason. In other words, most people or businesses have other more pressing—or even basic—daily needs to contend with so that they are usually reluctant to insure against an event with just an "abstract" probability. Sometimes, extreme events give an incentive to both the government and individuals/companies to seek better financial protection against future occurrences. However, if a reaction does not come immediately, awareness fades away very quickly and gives way to carelessness and negligence. Insurance penetration is also hindered by—clearly necessary—government support after disastrous events. People who rely on the government frequently do not take precautionary measures. The insurance industry must increase efforts to convince potential clients of the advantages of insurance, which would put them in a much better position than others in the long run.

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Wolfgang Kron studied civil and hydraulic engineering at Karlsruhe University and water resources and hydrology at the University of California, Davis. From 1983 to 1994, he was research associate at Karlsruhe University specializing in deterministic and stochastic modeling of hydrological and hydraulic processes, and statistics. He gained his Dr.-Ing. degree with the application of reliability theory to sediment transport processes. He then served as the Secretary to the Scientific Advisory Board of the German Committee for Disaster Reduction in the framework of the UN-IDNDR at the German Geo Research Centre in Potsdam.

In 1996, he joined Munich Re. In the reinsurer's Geo Risks Research Department, he was, as the head of research for hydrological hazards, in charge of all water-related natural hazards worldwide, ranging from floods and storm surges to mountain hazards and droughts. He retired in 2019.

He has played an active part in national and international committees such as the United Nations High-Level Experts and Leaders Panel on Water and Disasters (HELP), and is author of more than 190 scientific articles.

Tawatchai Tingsanchali is Emeritus Professor of the Asian Institute of Technology (AIT), Thailand. He received his doctoral degree in Water Resources Engineering from AIT in 1975. He received many awards such as Alexander von Humboldt Research Fellowship in 1983-84; Outstanding Hydrologist of Indian Institute of Hydrologists in 1995, Outstanding Researcher of National Research Council of Thailand in 2001 and Honorary Distinguished Engineer of ASEAN Federation of Engineering Organization in 2004. He has 40-year experience in teaching, research and water resources engineering consultancy projects. He published 74 papers in international journals, 200 papers in conference proceedings and 41 research project reports.

Daniel P. Loucks is an emeritus professor on the faculty of the School of Civil and Environ-mental Engineering, Cornell University. He continues to conduct research in the development and application of economics, ecology and systems analysis methods to the solution of envi-ronmental and regional water resources problems. He teaches a graduate course in water resource systems planning and management at the Technical University of Vienna, Austria, and a course in public systems modeling to graduate students in the Cornell Institute of Public Affairs. In the past he has held positions in over 10 other universities and research institutes in Australia, Europe and North America, and in various US and UN agencies, NATO, and the World Bank. He has consulted on water development projects in Africa, Asia, in the Americas, and in Europe. He is a fellow of AGU, a distinguished member of ASCE, and a member of the US National Academy of Engineering.

Fabrice Renaud is Professor of Environmental Risk and Community Resilience at the School of Interdisciplinary Studies, University of Glasgow, Scotland, UK. His main fields of re-search are ecosystem-based approaches for disaster risk reduction and climate change adaptation, and the analysis of vulnerability, risk and resilience of social-ecological systems exposed to environmental hazards. His focus is mainly on coastal and deltaic regions.

Janos J. Bogardi is senior fellow of the Center for Development Research of the University Bonn. where he is also professor for water resources management. He is senior scientific advisor of the Institute of Advanced Studies Kőszeg (iASK) in Hungary and fellow of the Stel-lenbosch Institute of Advanced Study (STIAS), South Africa. Since 2014 Distinguished Adjunct Professor of the Asian Institute of Technology (AIT, Bangkok). He was executive officer of the GWSP (2009-2012). He served till his retirement from the UN as director of the United Nations University (UNU) Institute for Environment and Human Security 2003-2009 and as Vice Rector a. i. in Europe 2007-2009. He was Chief of Section in the Division of Water Science in UNESCO, Paris (1995-2003) and chair professor of hydrology, hydraulics and quantitative water resources management at the Wageningen Agricultural University in the Netherlands 1989-1995. He was associate professor at AIT between 1985-1988. Between 1969 and 1985 he had research and consulting appointments in Europe and in Africa. He graduated in civil engineering at the University of Technology Budapest in 1969. He holds a doctorate in water resources engineering (Dr.-Ing.) from Karlsruhe University 1979 and three Dr. honoris causa distinctions from universities in Poland, Hungary and Russia.

Alexander Fekete is Professor of Risk and Crisis Management at TH Köln—University of Applied Sciences, Cologne, Germany. His research focuses on studying the systemic interrela-tions of natural, technical and man-made hazards with social vulnerabilities and critical infra-structures. He previously worked from 2009-2012 as a Project Officer at the German Federal Office of Civil Protection and Disaster Assistance in the field of Critical Infrastructure Pro-tection. From 2005-2009 he was Research Scholar at the United Nations University—Institute for Environment and Human Security (UNU-EHS) and obtained his PhD degree working on social vulnerability to river-floods under the supervision of Prof. Dr. Janos J Bogardi.

Groundwater and Conjunctive Use Management

23

Sankaralingam Mohan and Neenu Kuipally

Abstract

The chapter comprehensively discusses the management of groundwater including artificial recharge and the importance of conjunctive use of surface water and groundwater in satisfying demand for water. It reviews different levels of groundwater management, transboundary groundwater management, artificial recharge and its advantages and disadvantages among others. Planning and management of conjunctive use, its advantages and models available for that are also presented.

Keywords

Conjunctive use • Watershed management • Stream-aquifer interaction • Groundwater management • Artificial recharge • Sustainable groundwater • Optimal planning • Groundwater quality

Abbreviations

APFAMGS	Andhra Pradesh Farmer Managed Groundwater Systems Project
ASR	Aquifer Storage and Recovery
AWWA	American Water Works Association
BCM	Billion Cubic Metres
COTAS	Technical Groundwater Users Council
CSIO	Central Scientific Instruments Organisation
DH	Dirham
EPA	Environmental Protection Agency
EU	European Union
EUR	Euro
FAO	Food and Agriculture Organization
GA	Genetic Algorithm
IHA	International Hydropower Association
ISARM	Internationally Shared Aquifer Resource Management
IWMI	International Water Management Institute
KWMB	Karst Water Management Body
PHM	Participatory Hydrological Monitoring
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
$	Dollar
km^2	Square kilometres
km^3	Cubic kilometres
kWh/year	Kilowatt hours per year
m^3	Cubic metres

S. Mohan (✉) · N. Kuipally
Environmental and Water Resources Engineering, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, 600 036, India
e-mail: smohan@iitm.ac.in

N. Kuipally
e-mail: kneenu@gmail.com

23.1 Introduction

Groundwater is the water that occupies all the voids in a soil matrix. Groundwater can be described as the hidden treasure of the world. A groundwater basin is a group of aquifers that are connected by means of some semi permeable units. Therefore, it acts as a physiographic unit with number of interconnected aquifers, where the water is flowing to a common outlet. The groundwater is in continuous motion from the recharge zones to its natural outlet. Figure 23.1 shows the movement of groundwater in the saturated and unsaturated zone from where it is getting infiltrated from the soil to the final discharge at the sea.

23.1.1 Global Groundwater Assessment

Groundwater, one of the most reliable sources of potable water, constitutes about 94% of the total freshwater sources. The volume occupied by groundwater is almost 100 times of

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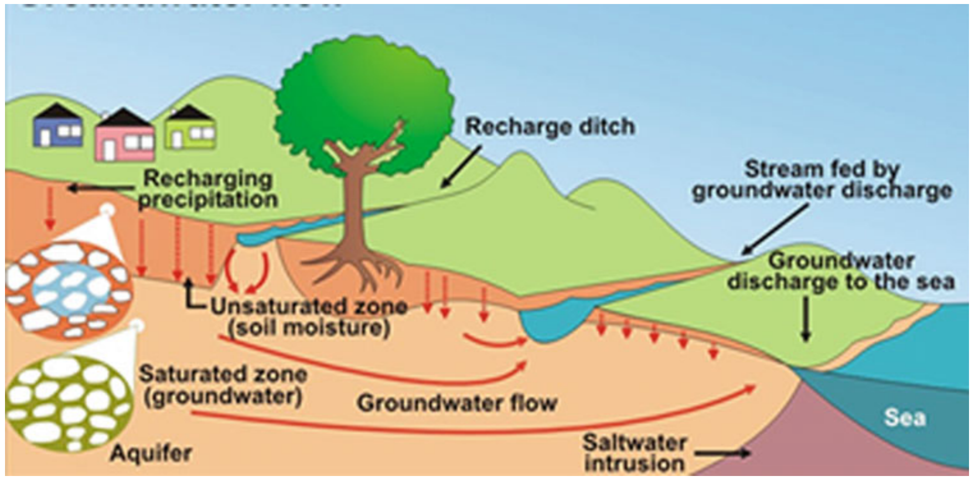

Fig. 23.1 Groundwater flow (*Source* Bachmat 1994)

that of surface water accounting to 10,530,000 km^3 (Chevalking et al. 2008). In recent times due to increase in population and elevation in economic growth the extraction of groundwater has increased. As the dependency is increasing, so is the vulnerability of groundwater to pollution. Many agricultural countries in the arid and semi-arid regions depend on groundwater supplies for their water demands. Technological advances have also made the exploration of groundwater easier. Moreover, groundwater is not easily affected by sudden climatic variations unlike surface water.

There is a tremendous shift in water usage from surface water to groundwater for irrigation purposes. Unlike surface water which require canals for transporting water, groundwater can be easily supplied by installing pumps, which reduces the transportation cost from the source. As a result, countries like Yemen, India and China, where they depend excessively on groundwater for agricultural purposes are under a threat due to over exploitation of the resources.

23.1.2 Groundwater Statistics in India

India is one of the largest users of groundwater in the world. Due to heavy demands on groundwater, India is on the threshold of a very serious groundwater crisis. The groundwater crisis occurs mainly due to excessive pumping of water resulting in aquifer depletion. And another reason is due to contamination of groundwater mainly from different sources which makes it unfit for various usages. The sources of contamination may be geogenic ones such as Arsenic and Fluoride along with anthropogenic sources of contamination primarily due to poor disposal of waste and wastewater.

Groundwater crisis can be mitigated by a twofold approach which requires large scale community participation and other from the side of government by implementing regulations and legislations. Aquifer management programme implemented by the government of India is a good initiative to protect the aquifers from depletion. Community based initiatives has been successfully implemented in states like Andhra Pradesh, Maharashtra, Gujarat and Rajasthan. Collaboration, combination of ideas and community partnerships hold the key to the success of groundwater management in India.

The growing water demands are constrained by degrading water quality. High nitrate concentration can also be one of the reason for groundwater contamination, which comes from the agricultural supplies to groundwater. The use of pesticides on the land also contribute to groundwater contamination. Spills from tanks or pipelines carrying products and chlorinated hydrocarbons, other gaseous or liquid pollutants can infiltrate to the water table and then move to the rest of the aquifer in the form of a plume from the point of contamination.

23.1.3 Why Management of Groundwater?

The main source of water in India is rain and snow. The annual average water resources in India is estimated to be 1,999 BCM (Billion Cubic Metres). Out of the total water resources 57% can be utilized, which accounts to 1137 BCM. Among the total utilizable water, 61% includes the surface water which accounts to 690 BCM and 39% includes the groundwater, accounting to 447 BCM (Central Water Commission 2020). The groundwater sources are mainly formed by the water that percolates into the ground during rainfall or snowmelt. The degree of percolation varies from region to region depending on the soil exposed to the surface, the porosity, cracks and faults in the soil or rock media, land slope and other topological features. The amount of water that is available for percolation depends on the amount of rainfall received by the region and climatic factors like temperature and humidity. Therefore, the volume of water available as groundwater varies with region. Therefore, the dependency on groundwater varies from place to place depending on the availability of other water resources.

Regions with low rainfall and arid climates mostly depend on groundwater supplies as their surface water supplies are unreliable with variations in climate. The low rainfall countries normally depend on groundwater for their major water needs i.e. agricultural and domestic purposes. In regions predominated by hard rocks, the probability of recharge is low as it requires interconnected fractures or faults to store and transmit water.

In India, alarming groundwater levels were reported in 13 states due to intense pumping of groundwater in drought prone areas. Moreover, the amount of water getting recharged to the underground reserves is getting reduced due to increased urbanisation which further reduces the open land available for natural recharge. Therefore, it is necessary to adapt artificial recharge techniques to ensure replenishment of groundwater.

Globally, groundwater withdrawals total 750–800 km^3/year (Shah et al. 2000). Groundwater is being pumped at far greater rates than it can be naturally replenished, so that many of the largest aquifers on most continents are being mined, their precious contents never to be returned (Femiglietti 2014). These include the North China Plain (Feng et al. 2013), Australia's Canning Basin, the Northwest Sahara Aquifer System, the Guarani Aquifer in South America, the High Plains (Scanlon et al. 2012) and Central Valley (Femiglietti et al. 2011) aquifers of the United States, and the aquifers beneath north-western India (Rodell et al. 2009) and the Middle East (Voss et al. 2013).

When groundwater withdrawals exceed the amount of water replenished by natural recharge (by rainfall recharge), then the aquifer gets depleted over time. In order to protect the aquifers from getting depleted, the aquifers have to be recharged by artificial means. Therefore, artificial recharge is the most effective method of groundwater management. Thus, by artificial recharge we can ensure augmentation of groundwater resources, conservation of excess flood waters into the underground aquifers, prevention of progressive depletion of water levels due to continuous use over a long time.

23.2 Groundwater Management Strategies

23.2.1 Levels of Groundwater Management

A three level system can be considered for the groundwater management process. They are as follows:

- The strategic level, which sets long-range objectives, determines decision criteria and constraints, and prescribes policy guidelines.
- The tactical level, which translates the directives of the strategic level into long- and short-term plans and projects.
- The executive or field level, which controls the specification and implementation of the projects.

The first stage in the management of groundwater is the development of a dynamic model, which can predict the behaviour of the groundwater system at different point of time. These models assess the behaviour of the system under different stress conditions and the quantity and quality of the groundwater at discrete locations. For developing a dynamic model, the major requirement is the knowledge of the hydrogeological details beneath the surface of the region under consideration. The information obtained from the borelogs are used to create the lithological profile for the entire region to be modelled.

The primary step in modeling includes conceptualisation of the aquifer. Conceptualisation includes identification of the primary hydrological processes, pathways, boundary conditions, inputs and outputs to the system and constraints. The conceptual model is the foundation of the groundwater flow model. Any inaccuracy in the conceptualization can lead to serious errors in mass balances and recharge estimation, which undermines the whole purpose for which the model is developed. The essential components required for a recharge estimation flow model are as follows:

- Evapotranspiration in the area.
- Lateral inflows and outflows.
- Quantity of overland flow.
- Datum in the profile beyond which drainage becomes groundwater recharge.
- Frequency of recharge events.
- Hydraulic pathways that water may take through the soil profile.

Once the hydrogeological information is obtained, next step in model development is the determination of water levels in the observation wells. The water levels in the observation wells during the starting period of the simulation becomes the initial condition for the model. The major inflows into groundwater include recharge from rainfall, return flows from irrigation, leakage from rivers or streams and injection into the wells. The major outflow components in groundwater are return flow to the sea and pumping. The pumping taking place in the study domain has to be incorporated into the model by accurately indicating the pumping location and the quantity of pumping. Another important factor in groundwater modeling is the boundary condition. There are different methods to estimate the boundary water levels depending on the availability of data. The property of the soil media has to be assigned before running the model.

Once all the inputs and initial and boundary conditions are given, the model can be run which gives the outputs of water level for various times considered for modeling. Therefore, the main items of a conceptual model can be summarized as follows:

- Boundaries, subdivision, and interconnection of aquifers and aquitards in the region of interest.
- Substances of interest (e.g., groundwater, solutes, and/or suspended matter which are pertinent to water quality requirements) in the case of flow and transport modeling.
- State variables which are relevant to the substances (e.g., groundwater density, piezometric head, temperature, concentration of solutes).
- Sources and outlets of the substances within the domain of interest.
- Processes of transport and transformation that are relevant to the substances (e.g., groundwater flow, evaporation, mass transport of solutes, chemical reactions within the liquid phase, mass transfer between the solid matrix and the liquid phase) within the domain of interest.
- The environment of the considered domain and the processes of exchange of mass of the substances across the boundaries with the environment.
- Assumptions about relevant physical, chemical, biological and other properties of the substances.

The conceptual model is then converted to a mathematical model. Basic equations that represent the system are used in converting to a mathematical model. For groundwater flow, the basic mass balance equation along with the groundwater flow equation as proposed by Darcy is used for developing the mathematical equation. Converted mathematical model comprises of:

- Mathematical formulation of the configuration of the boundaries of the system.
- Formulation of the balance equations of mass of the substances of interest.
- Formulation of the transport equation for each substance in terms of relevant state variables.
- Formulation of source and sink functions of each substance of interest in terms of observable quantities and/or state variables.
- Formulation of initial values of the relevant state variables.
- Formulation of the boundary conditions which express the transport of each substance across the boundaries of the system in terms of relevant state variables.

The developed model needs to be calibrated to ensure that the model is an accurate description of the field. The parameters are adjusted to ensure match between historical data and the model predicted data. The calibrated model needs to be validated with another set of data.

In some cases, the simulation model can be linked to an optimization model, if there are multiple solutions to a problem and the best one needs to be chosen. The use of management model for groundwater modeling is required due to a variety of reasons mainly:

- Lack of a mandatory, clearly defined, and duly implemented methodology and procedures of utilizing quantitative models, and information derived for decision-making process.
- Low credibility of the models, especially those pertaining to groundwater quality.

Apart from physical means of control that can be applied directly to the groundwater subsystem to its physical environment, there is a variety of nonphysical means of control that can enhance the effectiveness of groundwater management. These may include any combination of the following categories:

- Managerial (e.g., enhancement of public participation in the processes and procedures of decision-making, follow-up, and control of implementation).
- Economic (e.g., prices, charges, taxes, loans, subsidies).
- Legal (e.g., modification of laws and regulations).
- Administrative (e.g., allotments).
- Political (e.g., treaties).
- Educational (e.g., dissemination of information, provisions of guidance, training).
- Scientific (advancement of knowledge about processes, technologies, and techniques).

23.2.2 Management of Groundwater Resources

Groundwater resources can be effectively managed if technology, science and people's participation are brought together. The role of women is very high in managing the water resources. Various management techniques adopted world-wide to conserve groundwater resources are listed below.

23.2.2.1 Restrictions on Groundwater Use and Well Development

Restrictions were implemented on groundwater use in order to protect it from getting depleted. Rules that are easy to monitor are often the easiest to implement. Some of the rules that are commonly adopted include:

- Minimum distance rule.
- Zoning.
- Ban on certain crops.
- Ban on certain wells.

Some of the case studies based on groundwater protection rules are mentioned below with examples.

23.2.2.2 Banning High Water Consumption Crops

Saudi Arabia faced depletion of its coastal aquifers, so in order to protect the coastal aquifers they have enforced a ban on crops which consume huge quantity of water. Banana cultivation was one of the major cultivation that consumed huge quantity of water. Apart from banana, there was ban on rice also.

Many villages in Ananthpur, one of the driest districts in Andhra Pradesh State of India voluntarily imposed ban on paddy cultivation in the dry season. This ban was implemented to reduce the lowering of groundwater levels which led to severe water shortages during the dry season.

23.2.2.3 Regulating Pumping

Installation of monitoring equipment in every well to measure extraction and changes in water levels is one of the most common method used world-wide to regulate pumping. There were cases in Italy's Perugia where mineral water bottling company was forced to take groundwater conservation measures including strict limits on the water withdrawal during the dry months.

23.2.2.4 Controlled Sand Mining to Safeguard Recharge

Sand mining in the river beds is a common activity, where the riverbed sand and gravel are mined and used for construction purposes. The sand and gravel material in the river bed helps in recharging the groundwater and also acts as a buffer during floods. Once the river bed material is mined out, it limits the capacity of river to recharge groundwater. Many villages have taken measures to prevent the sand mining activities. One of the most successful initiative is done in Ananthpur district in the state of Andhra Pradesh, India. Ananthpur, has succeeded in preventing the entry of trucks from sand mining by excavating a trench. These trenches prevent the entry of trucks near the river bed. Moreover, they have also kept guards to prevent illegal entry near the river beds.

23.2.2.5 Restrictions Imposed on Local Groundwater Management Practices

The restrictions imposed on water management practices vary from region to region and from community to community. In Indian context, water management is normally done by government officials, religious leaders or community leaders. They emphasize mainly on ban on drilling boreholes and promoting local recharge measures thereby regulating the use of wells and encouraging water saving measures.

Local groundwater management in Pakistan is managed through informal committees where they have specific rules regarding well spacing, ban on dug wells and the incorporation of zoning concept. In Egypt, the water users' association is conserving groundwater by maintaining a network and banning installation of any new wells. Similarly, in Yemen, the drinking water association has implemented the concept of zoning and a ban on agricultural wells. These case studies show how groundwater is managed by different associations in different countries.

23.2.2.6 Reducing Agricultural Water Demand

Agricultural water demands can be reduced by reducing the evaporation losses and by improving the efficiency of water use. Some of the methods that can be employed for efficient water use are given below:

- Covering the field soil with crops all the time of a year reduces the evaporation.
- Evaporation can be reduced by ploughing, wherein the soil is thoroughly moved. As a result, the soil can retain more water and reduce the evaporation.
- Evaporation and soil erosion can be prevented by providing shelter belts along the fields as they reduced the wind speed near the fields and reduce the rate of evaporation.
- More water can be allowed to percolate through the ground by growing trees, shrubs etc., near the fields. These bushes reduce the force of rain and let the water percolate to the ground. The amount of water percolating the ground will be comparatively higher than the total evapotranspiration from the surface.
- Artificial surfaces such as netting can be constructed on top of the crops, which can trap fog and dew. They contain considerable amount of water, which can be utilized by the crops.

- Salt resistant crops can be grown in areas where there is a salinity problem, thereby the demand on freshwater can be reduced without effecting the productivity.
- Enabling the use of efficient watering systems such as drip irrigation, which reduces the overall water consumption by the crops.

23.2.2.7 Land Levelling

Land levelling was done to reduce the groundwater use and improve the irrigation efficiency in Mexico. The levelling was done with laser technology thereby the farmers obtained levelled land with good precision. A levelled land ensures reduction in the loss of fertilizers applied and a better distribution of water over the area. Thus the productivity is ensured with less inputs.

23.2.2.8 Drip Irrigation

Drip irrigation is a method employed in water scarce countries. Israel, being a water scarce nation, has used this scheme to irrigate their fields. This method is also known as micro irrigation, where water is applied drop by drop near the root of the plant by a surface or sub surface system. Since water is applied directly to the roots, it reduces the amount of evaporation. Moreover, the loss by wind is also insignificant.

23.2.2.9 Changing Cropping Pattern

Changing the crops and their water requirements lowers the water demands and the necessity to abstract groundwater. Changing the pattern of crops from the traditional practices has saved the amount of water that needs to be extracted. For example, in Mexico, farmers have changed the cropping patterns from the traditional production of wheat (four irrigation turns) to barley (three irrigation turns), chick peas (two irrigation turns) and canola (one irrigation turn). Farmers producing fodder crops have changed from alfalfa production to fodder maize.

23.2.2.10 Use of Mulch Material

Mulch is a kind of organic or inorganic material used for reducing the erosion caused by wind or water. The mulch material keeps the soil cool and reduces the rate of evaporation.

Organic mulch: leaf mulches, crop residue, coir pith, woody material, straw mulches, grass mulching and manure.

Inorganic mulch: Layers of rock, gravel, pebbles or sand are spread over fields or piled around individual plants leaving the space between open for cultivation.

23.2.2.11 Worm Composting

The capacity of soil to retain water can be increased by worm composting. In this technique the compost is prepared using a container that is kept away from light that allows the entry of moisture. The container is provided with aeration holes in the lid and drainage holes in the bottom. Worms are then used for processing the domestic organic waste. The compost when mixed with the top soil improves soil moisture retention capacity, water holding capacity, reduces salinization and soil erosion, increases soil productivity and induces resistance to pest and disease attacks.

23.2.2.12 Reuse Water for Irrigation

Reusing the water for irrigation is adopted in many countries. The common example is the case of USA. In Oregon, USA, wastewater quality is managed to take advantage of the available nutrients. Nutrient deficiency for a particular crop in the pumped out groundwater is analysed and is provided in addition to meet its requirements. For example, if the concentration of nitrogen is below 25 mg per litre then extra nitrogen is added to meet the crop's requirements.

23.2.2.13 Saving Water in Each Household

The domestic water requirement forms a major component in the total water consumption. A careful and a managed strategy can conserve a huge amount of water within a household. Some of the water management policies that can be adopted by individuals within a household both indoor and outdoor are summarised below.

- While using washing machines, adjust the machine water level to the size of the load of laundry.
- Reduce the use of showers for bathing, instead use buckets.
- Collect excess running water while you are waiting for hot water in basins or buckets and use it to water plants.
- When using dishwashers, make sure it is used in full loads.
- When washing vegetables, make sure all the vegetables are put in a basin full of water rather than washing it under running water. The water that is used for washing vegetables can later be used for watering plants.
- Ensure that the leaking faucets, shower heads and toilet tanks are fixed immediately.
- Install low-flow showerheads and faucet aerators.
- Replace an older model toilet that uses a large flush volume with a lower six litre flush volume model.
- Apply only the water that is needed for the gardens. Reduce the frequency of watering to once in five days and

water thoroughly to 2.5–5 cm at a time which promotes deep root growth.
- Collect the water from rooftops during rains and use it for washing cars and watering gardens.
- Reduce watering on windy days.
- Use wise water plants, which do not consume much water for landscaping.
- Cover swimming pools, when not in use to reduce evaporation.
- Wash cars with water filled in buckets rather than using a hose as it reduces wastage.

23.2.2.14 Economic Incentives

For better management of groundwater, economic incentives were put forward. Some of the incentives taken in different parts of the world are given below.

23.2.2.15 Economic Incentive to Improve Nitrogen Management

The Lower Salt Creek Groundwater Reservoir Advisory Group in USA was established in 2002. This group assisted in developing incentive programmes to implement the best management practices that improve nitrogen management and reduce leaching which leads to better protection of groundwater. The incentives that are still in practice are:

- 75% cost-share for a fertilizer flow meter.
- 75% cost-share for a water well flow meter and moisture probe.
- 75% cost-share for soil sampling.
- 75% cost-share for establishing irrigation water best management practices.

23.2.2.16 Tax Incentives for Constructing Impoundments

Construction of impoundments is done to collect the available surface water and use it, thereby reducing the dependence on groundwater. For incorporating these techniques, income tax credit was made available in Arkansas, USA by filing an application in their tax incentive website. This was initiated by the Arkansas Natural Resources Commission to encourage the water users to invest (Chevalking et al. 2008).

23.2.2.17 Subsidy for Diverting Run Off from Impermeable Surfaces

In cities where most of the land area is impermeable, the runoff volume can be collected to a separate infiltration basin, where natural recharge can be made feasible. In Nijmegen, Netherlands the local government together with the Rivierenland Water Board provides a subsidy of 4.55 Euro for each m^2 of impermeable surface for diverting the runoff volume into infiltration basins and the associated cost in construction of the basins.

23.2.2.18 Substitution for Groundwater by Partnership

Groundwater was the major source of water for irrigation in the Guerdane area in Morocco. But as the groundwater was getting depleted the irrigation in this area was under threat. To compensate for the declining trend of groundwater resources, surface irrigation schemes where developed using the public private partnership. Although the government would remain the asset owner, contracts were put out to a private party in order to provide the operation of the irrigation canals.

The willingness to pay for surface irrigation among farmers was high. The private operators were expected to bring in 43%, whereas the government supported the project for 28% and a concessionaire loan for another 28%. The government investment allows the water fee to be on a par with current groundwater pumping costs. The supply risk of the project was covered under an arrangement whereby the government undertakes to compensate the service provider for any water deficit of more than 22.75%.

The private operators were not supposed to start until subscriptions reached 80% of the project water allocation. The PPP was then tendered and special efforts were made to encourage Moroccan contractors. The service providers were responsible for the project design. The contract with the service provider indicated a limited number of technical criteria for guaranteeing good service quality and minimal environmental impact.

Evaluation of the bids was on the basis of proposed users' contribution and irrigation water price per m^3. The consortium that won the contract (a Moroccan company with French irrigation companies in the group) (Chevalking et al. 2008) was able to provide its services at a connection fee of DH (Dirhams) 8,000/ha and a price of 1.48 DH/m^3. The PPP option in all respects was better value for money than the state operated or water user-operated packages.

23.2.2.19 Water Pricing

There were no water charges for groundwater withdrawals in many countries. In other countries where water was priced, they were very much below the value. Normally the cost of groundwater was limited to the cost of pumping, cost of well construction and the cost of treatment if required any. As a result of this groundwater started to get depleted and they became more prone to pollution.

Although much work needs to be done in this area, the EU's Water Framework Directive prescribes the principle of cost recovery of water services. Applicable to both surface water and groundwater, the directive requires Member States to take account of the principle of recovery of the costs of water services, including environmental and resource costs. 'Recovery of the costs' is determined through an economic analysis of water services based on long-term forecasts of supply and demand for water in the river basin. The 'polluter pays principle' is also taken into account. Notably the EU Framework Directive steers clear of 'full cost pricing' as most people are more amenable to the sound of full cost accounting and full cost recovery.

Another scenario of water pricing was reported in the municipality of Port Elgin, Ontario during 1991 where they installed 2,400 residential water meters at a cost of Canadian $550,000 instead of building a $5.5 million expansion of the local water treatment plant. As a result, the consumption of water in summer was reduced to 50% and an overall reduction of 25%, and the municipality saved $12,000 in sewage treatment operating costs.

23.2.2.20 Sustainable Land Use

Sustainable land use policies were developed in France in order to keep the aquifers clean. 'Vittel' was one of the largest mineral water supplying company in France. The area in which this aquifer belongs was a heavily farmed one, where the insecticides and pesticides were leaching into the groundwater and contaminating the aquifer. So the company decided to purchase the farmlands and undergo reforestation, building infiltration zones, stimulating the farmers to switch to organic farming. The company purchased 1,500 ha land above the market price and offered profitable price for farmers for their participation.

23.2.2.21 Rationalizing Flat Tariff Charges on Electricity Consumption

India is one of the countries with the highest groundwater use. Approximately 40% of the agricultural water demands are met by groundwater (Chevalking et al. 2008). As per the surveys, subsidies on electricity encourage overuse, as farmers tend to run their pumps 40–250% longer than those farmers who purchase diesel for their pumps. The installation of meters for the water pumps faces a lot of difficulties such as meter-reading, billing, collecting charges and ensuring buy-in from farmers. Thus the substitute for this method is to supply a regulated annual high quality of farm water matching the supply with peak periods of moisture stress. Such a regulated measure would reduce the wastage of groundwater by 12–18 km^3 of water per year in Western and Southern parts of India. These methods can also reduce the power expenditures without compromising farmer's satisfaction.

23.2.2.22 Selling Water to Cities

Farmers in semi-urban areas extract water from wells and sell it to the cities where water demands are high. An example for this can be found in the state of Tamil Nadu, India, where the farmers from the rural area supply water to the rapidly growing Chennai city. The net benefits obtained from selling water is more than the income from crops. State laws prioritize domestic use above agricultural use, therefore during droughts, there is more pressure on existing water resources being abstracted and traded to the urban areas. Although the practice of selling water enables some farmers to expand their income generating activities, there are also some farmers who are now forced to buy water to irrigate their crops.

23.2.2.23 Energy Pricing Coupled to Water Rights

Coupling electricity tariff and groundwater rights is one of the initiative to manage groundwater. The Mexican government through the Federal Electricity Commission has implemented this right wherein the electricity use that falls within the water rights gets heavily subsidized; all energy above the concession volume has no subsidies. In order to acquire the prescribed electricity rate user's need proof of a valid concession title and an Annual Energy Limit in kWh/year that is established for each well.

23.2.2.24 Separating Agricultural and Non-agricultural Electricity Feeders

Gujarat is one of the states in India which is over -exploited in terms of groundwater withdrawals. The Jyotigram scheme was implemented for separating the agricultural and non-agricultural feeders. The subsidy provided for groundwater irrigation has led to over extraction of groundwater leading to aquifer depletion.

The Jyotigram Scheme ensured that villages to get a 24 h three-phase power supply for domestic uses, schools, hospitals, village industries, subject to metered tariff. Tube well operators get 8 h/day of power at full voltage according to a pre-announced schedule.

23.2.2.25 Safeguarding Natural Recharge Capacity

The natural recharge capacity of streams and wetlands helps in retaining the surface flows and recharge it to the aquifers. But the use of river sand for construction purposes and their rising demands have depleted the natural storage capacity. The wetlands store the excess water and recharge the shallow aquifers and acts as a flood buffer. So it is essential to manage the natural storage capacity of the rivers and wetlands. A drastic change in the natural drainage can alter the storage capacity and lower the groundwater levels in shallow aquifers. This happens mainly because the recharge to the aquifer during wet season by the streams get reduced as they lose the buffer storage. The lack of contribution to groundwater in wet seasons makes the groundwater table to go down in dry seasons.

23.2.2.26 Reactivating the Flood Plains

The main idea of this concept is to increase the capacity of the rivers. By doing so, the capacity of rivers to hold the peak discharges during the flood is increased and also the storing time in the basin is enhanced. As a result, the stored flood water is recharged into the shallow groundwater aquifers. This idea was incorporated into the water management policy in Netherlands, following the flood of 1995. As a result, some of the smaller dikes were dismantled and the flood plains were restored.

23.2.2.27 Wet Watershed Management

Wet watershed management includes various landscaping techniques such as bunds to break the speed of runoff water and allow it to spread over a large area, which later percolates into the ground. This method will be effective in hilly terrains receiving very high amount of rainfall. In the Terai region of North Bengal in India, during the wet period the coarse subsoil quickly absorbs the water and low-lying areas are only temporarily inundated and large quantities of water are drained away through gullies and as sheet flows. However, by improving drainage patterns, the runoff was slowed down which avoids the loss of the thin fertile topsoil and improves the reliability of cultivating rain-fed paddy. In an evaluation scheme it was observed that these works confirmed extremely high return of investments as cropping intensities increased from 90 to 201%.

23.2.2.28 Porous Pavements

Impervious or built up areas reduce the ability of rainwater to infiltrate into the ground. In order to overcome such a situation, porous pavements were used, which allows the infiltration of rainwater into the ground. The first largest porous parking system was introduced in North Carolina, USA in 2002. For the construction of porous pavements, porous asphalt was used instead of conventional asphalt. Underneath the asphalt there is a stone recharge bed consisting of a clean-washed, uniformly graded stone mix. The runoff water which infiltrates into the stone aggregate contains pollutants thus the water infiltrating into the subsoil first goes through a filter fabric, which lines the subsurface bed.

23.2.3 Informal Systems of Groundwater Management

23.2.3.1 Norms to Ban Development of Dug Wells and Tube Wells

Qanats are horizontal wells stretched over a long distance. These qanats were used for irrigation purposes. In Panjgur, Pakistan, norms were given to ban development of dug wells and tube wells. The qanats pick up the sub-surface flow from the Rakhsan River and transport the water at a gentle slope before surfacing near the agricultural area. These norms were introduced when the qanats owners observed a rapid decline of groundwater table in the nearby area after the installation of electric dug wells. The ban concerned the development of individual dug wells.

23.2.3.2 Rules Related to Groundwater

Rules related to groundwater existed which specifies the minimum distance to be maintained between a well and a natural spring. One of the oldest rule that was followed in Islamic countries was known as ‘Harim Rule’, which indicates distances between wells and springs. As per this law, the minimum distance between two water points is prescribed as 350–500 m depending on the local geology. This rule is still in action in Middle East and West Asia.

23.2.3.3 Well Recharge Movement

This movement was started in Saurashtra, Gujarat, India (Chevalking et al. 2008). After three years of consequent drought from 1985 to 1987, people started adopting various techniques of rainwater harvesting to conserve the rainwater that falls on the roof tops, fields etc. The rain water captured by different techniques were then used to recharge the wells in individual houses. The rainfall received in the fields were conserved by constructing bunds. As a result of these measures, considerable increase in the groundwater levels were observed in this village. This triggered other villages to adopt similar strategies to conserve rainwater. Thus it became a movement on a large scale.

23.2.3.4 Promoting Local Regulation Through Participatory Groundwater Monitoring

Regulated groundwater use was the main pillar in this scheme adopted in Andhra Pradesh, India. The Andhra Pradesh Farmer Managed Groundwater Systems Project (APFAMGS) has successfully promoted behavioural change leading to voluntary self-regulation in groundwater use. The groundwater users were provided with necessary data, skills and knowledge to manage groundwater, thereby reducing the stress on available groundwater resources. The main pillars of the project are:

- Establishing institutions such as groundwater management committees at the village level.
- Gender mainstreaming through recognising and taking into account the attitudes, roles and responsibilities of men and women.
- Enhancing farmers' knowledge in areas such as water resource availability and management, data collection and analysis.
- Participatory Hydrological Modeling, transforming individual groundwater users into water resource "literates" (rainfall recharge relationship, pumping capacity of bore wells, crop water requirements).
- Crop water budgeting, collectively making crop plans (abstaining from paddy, crop diversification).
- Optimization of flood flows through artificial groundwater recharge, trapping basin flood flows in tanks or ponds.
- Data base and geographical information systems, enhanced collection and information access on individual and shared resources.

23.2.3.5 Identifying Measures in a Participatory Process

Participatory approach by including farmers is a common method for groundwater management. In the Amman Zarqin Basin in Jordan, the farmers developed common measures on groundwater management which includes stakeholder discussions, field interviews, and presentations of water overview, farmers' questions, group meetings and workshops. Through these sessions the awareness of farmers has increased and they were able to arrive at the conclusion that:

- Reducing irrigation water consumption without income losses.
- Gaining more information on conservation methods.

These conclusions helped in the ban on unlicensed drilling and the exploration of local water harvesting.

23.2.3.6 Multi-stakeholder Process Leading to a Water Allocation Plan

The Karst Water Management Body (KWMB) in Namibia has involved all the relevant stakeholders in addressing the water scarcity issues. This body consists of regional and local government, non-governmental institutions, farmers and the mining sector. The objectives of this body is to avoid over-abstraction of the aquifers and thereby ensuring maximum security in water supply. The KWMB helps in allocation of the available water resources to various water users groups. The priorities for water allocation are as follows:

- Water for local domestic and livestock consumption.
- Local industrial supply.
- Abstraction of groundwater for primary and secondary consumption.
- Local irrigation.

23.2.3.7 Groundwater Users' Association

The Water Act of 1985 in Spain created a similar framework for groundwater users' associations. Since that time, 1,400 groundwater users' associations have been established. Some of these associations focus on water distribution, while others concentrate on collective management of aquifers. Numerous associations have been able to establish accepted rules regarding resource access and use. Moreover, by collaborating with the water authorities and local universities, the long-term sustainability of the resource has become an issue of shared responsibility.

In groundwater users' association, the land users in a particular area agree to use a limited number of wells. They develop a network of pipelines to supply the water from the existing wells to the entire area under consideration. Construction of any new wells in this area is banned by this association to ensure that the groundwater levels do not go beyond a particular level. An example for this case is the Omar Enb al Khattab Water User Association developed in 1993 in the Eastern part of the Nile Delta in Egypt.

23.2.3.8 Participatory Hydrological Monitoring

Participatory Hydrological Monitoring (PHM) refers to a set of activities carried out to keep track of the changes in a hydrological cycle by the users themselves with little input from outsiders. Thereby the lack of understanding about groundwater resources is overcome.

The objectives of PHM are:

- Triggering a discussion at community level about rainfall, withdrawals, water level and their relationship.

- Evolving water use plans by the community based on utilizable groundwater resources.
- To develop people-managed groundwater systems.

The major task in PHM is to identify the stakeholders involved in groundwater management. They include the farming community (men and women), drinking water users, other groundwater users, government departments, local government, watershed or water supply programs and possibly others.

The major steps involved in the PHM are:

1. Preparation
   - Reconnaissance/meeting with opinion leaders.
   - Awareness raising.
   - Delineation of watershed/aquifer system.
   - Water Resource Inventory.
2. Setting up the monitoring
   - Joint site identification: Rain gauge stations and observation wells.
   - Social feasibility study.
   - Procurement of equipment/material.
   - Establishing rain gauge stations and observation wells.
   - Supply of equipment to community.
3. Getting the monitoring going
   - Training farmers in data management.
   - Erection of display boards/data display.
4. Crop water budgeting
   - Groundwater availability estimation at the end of Kharif. (Based on monsoons, Indian cropping seasons are classified as Kharif and Rabi. Kharif crops, also called as 'monsoon crops', are sown at the beginning of monsoon and the cropping season is from July to October during the south-west monsoon. Rabi crops, also called as 'winter crops', are grown in the beginning of winter and its cropping season is from October to March.)
   - Collection of farmer crop plans.
   - Groundwater balance preparation for Non-monsoon.

23.2.3.9 Source Protection Through Rural Drinking Water Committees

Rural water supply schemes play a major role in managing groundwater. The rural areas in Al Mawasit, Yemen were supplied with drinking water from 30 m deep dug wells. After the completion of this scheme water was available for all the 24 h. Revenues were maintained on special accounts and water rates for the local poor and health centres were reduced. In Al Dhunaib, the water committee issued a rule that no well could be drilled within one kilometre from the drinking water source. In an incident where a farmer tried to dig a well for irrigation, he was under huge pressure to back fill them. These kind of activities ensures that the rules set by the water committees are strictly followed.

23.2.3.10 Groundwater Users Monitoring Committees

The quantity of water withdrawn from the groundwater aquifers are monitored by groups maintained by farmers. In the aquifer of Jaral de Berrios, Guanajuato, in Mexico, farmers' monitoring groups have been formed. The farmers group consists of 10–15 farmers and they report the volume of groundwater extracted with the help of flow meters installed for the wells. The reporting is done twice a year. The data generated is collected by the Technical Groundwater Users Council (COTAS). The data from the different monitoring committees is processed by the COTAS for the whole aquifer.

23.2.3.11 Groundwater Management Districts

Groundwater Management District Associations are in place at several parts of the United States. Their roles vary. The primary issue in Kansas, Colorado and Texas for instance is groundwater quantity, while in Nebraska it is groundwater quality and quantity. In Mississippi and Florida, Districts are responsible for the joint management of surface water and groundwater. Some of the Districts have developed unique projects in education and management to preserve groundwater resources for future generations.

23.2.3.12 Locally Issued Groundwater Management Rules and Regulations

The main purposes of the Pumpkin Creek Basin Groundwater Management Sub-Area, established in 2001, Nevada USA are:

- Protect groundwater quality.
- Protect groundwater quantity.
- Provide for the integrated management of hydrologically connected groundwater and surface water.

The well operators maintain reports containing the total amount of water used, purpose for which the water is used, flow meter readings, area of each crop irrigated if the water is used for agricultural purposes. These operators should be well versed in the best management practices for water conservation, with valid certificates. The other limitations for groundwater use are irrigators may not irrigate land that is not certified, livestock operators may not exceed certified production capacity, and other uses may not exceed the amounts allocated to them.

23.2.3.13 Regulation by Local Government

There was a strict ban on the construction of new boreholes in Nellore district of Andhra Pradesh, India. This ban was made effective in 1995 after a severe decline in the groundwater levels over a period of 15 years after a severe drought. This rule was made effective by including the village government and the elderly influential people from the village. Punishments were given to people who violate the rules.

23.2.3.14 Court System Regulating Groundwater Rights

The rights regarding groundwater use in Colorado was determined by both administrative and court system. The well users have to obtain a permit from the State Engineer's Office (SEO). The permit will be obtained only after the proper inspection by the State Engineer. Proper recharge measures should be adopted in the land for acquiring the permission. Moreover, the applications may be rejected if the flow is indicated as critical. The court system must ensure a legal right to utilize groundwater in Colorado's system.

23.2.3.15 Discharge Permits to Prevent Degradation of Groundwater

In US, permits were established for discharging waste or wastewater into the groundwater. The permit applications were reviewed by the Department of Natural Resources and are given based on the hydrogeological conditions. The entire process of issuing the permit may take 90–360 days depending on the complexity of the problem.

23.2.3.16 Punjab Groundwater Policy

Punjab is one of the states in India with huge groundwater reserves. Since it is over exploited, the quality and quantity of the groundwater reserves is getting deteriorated. The following policies are included in the Punjab Groundwater Policy for managing the groundwater resources. They are listed as follows:

- Decide groundwater ownership rights.
- Prioritize inter-sectoral groundwater uses.
- Initiate process for a comprehensive water act.
- Fix operational range of groundwater reservoir.
- Rationalize surface water allowances.
- Strictly enforce EPA regulations to protect groundwater quality.
- Strengthen water related institutions.
- Prepare a drought contingency plan in view of climate change.
- Start water management in pilot projects.

By implementing these strategies, such as ownership rights, water acts etc., the groundwater scenario can be reversed and brought back to the previous state. Small scale water management plans as described in the above sections can help in raising the groundwater levels.

23.2.3.17 Controlling Abstractions to Stop Land Subsidence

Water abstractions laws were passed by the government of Japan during the mid-1950s onwards to stabilize the groundwater levels in Osaka district and control the land subsidence. After implementing the control, it is expected that the groundwater levels is projected to rise by 0.2–1 m and ground subsidence can be completely avoided in the future.

23.2.3.18 Groundwater Preservation Plan in Kawasaki, Japan

Rapid industrialization and urbanisation in the city of Kawasaki has disturbed the ecological cycle. Excess groundwater pumping has led to land subsidence, drying up of surface water sources. In order to manage the water scenario, the city was divided into sectors based on geohydrology, water quality, land subsidence and the number of abstraction wells. Decisions for each zones were taken based on the problem faced by each zone. Divisions with suitable aquifers and water quality were designated as groundwater protection areas, with emphasis on the preservation of natural vegetation and the promotion of rainwater harvesting systems. In the overused divisions, prevention of further contamination was the main priority. In these areas groundwater pumping was regulated and the prevention of negative effects of built-up areas was given attention.

23.2.3.19 City Government Initiative, Shanghai, China

Shanghai is also another city which faced lowering of groundwater level due to fast growing economy. 200 million m^3 water was abstracted in 1963 as newly developing industries required cooling in the summer. This resulted in rapid ground subsidence which measured a total of 1.75 m from 1921 to 1965, locally reaching up to 2.63 m (Chevalking et al. 2008). Due to the alarming situations, the government came up with a fourfold decision. They are listed as follows:

- Restriction in groundwater pumping in the down town areas (As per the reports the amount of water pumped in 2007 reduced to 40% of the levels in 1965).
- Requesting water users to inject the same quantity of water into aquifers in winter as they pump in summer.
- Setting up a research centre mainly a monitoring network of land subsidence and groundwater levels

23.2.3.20 Bringing Home Groundwater Legislation

The Water, Land and Trees Act was widely discussed in a training program on local groundwater management in Andhra Pradesh, India. The training was conducted in almost 970 villages where declining groundwater levels were observed. These training programmes helped in rising awareness among the farmers regarding the water use. The groundwater users welcomed the act when it was enforced in 2004.

23.2.4 Transboundary Groundwater Management

Number of organisations are involved in the monitoring and assessment of transboundary aquifers, such as ISARM (Internationally Shared Aquifer Resource Management) led by UNESCO. Some of the case studies of transboundary groundwater management are listed below:

23.2.4.1 Joint Studies and Dissemination

Project has been going on during 2003 and 2007 between the four countries Argentina, Brazil, Paraguay and Uruguay for the sustainable management of the Guarani Aquifer System. The main aim of the project was to enhance technical knowledge, establishing well monitoring networks and developing management strategies. The public was also involved in the aquifer management through internet sites which provide information such as talks, films, and games for children, seminars and workshops to include people's participation.

23.2.4.2 Monitoring Guidelines for Transboundary Water

Guidelines on Monitoring and Assessment of Transboundary Groundwater was developed by the UN-Water Task Force in 2000. Some of the key points included in the guidelines are as follows:

- Functions, pressures and targets of transboundary aquifers should be identified and priorities should be set.
- Monitoring strategies should serve as a guide in establishing realistic monitoring priorities, not only in terms of what should be monitored and where, but also in terms of timing and funding.
- Ranking and sectioning areas where potential pollution sources are located, or where groundwater use is high, will make the programme more effective.
- Data produced by groundwater monitoring programmes should be validated, stored and made accessible.
- The goal of data management is to convert data into information that meets the specified information needs and the associated objectives of the monitoring programme.

23.2.4.3 European Directive for Cleaner Groundwater

Groundwater is the largest source of clean and public drinking water in many parts of Europe. So these measures are intended to improve the groundwater quality and protecting it from getting polluted through hazardous substances such as cyanide, arsenic, biocides and pharmaceutical substances that seeps to the aquifers. Therefore, the member states have to take measures to prevent the entry of hazardous substances into the groundwater. To ensure this act, new legislation was approved by the European Parliament in December 2006. The member states were given a time of two years to translate the directive into national law.

23.2.4.4 The Nubian Aquifer Joint Authority

The Nubian Sandstone aquifer was shared by four countries namely Libya, Egypt, Sudan and Chad, which formed a joint Authority to manage the resources. The powers and responsibilities given to these countries to manage the aquifer are as listed below:

- Preparing and executing studies, in particular, related to the environmental aspects of groundwater development, desertification control and energy.
- Collecting and analysing information.
- Developing and executing a common policy, programmes and plans for the development and utilization of the groundwater resources.
- Establishing cooperation and disseminating information on the Nubian Sandstone Aquifer System.

Each Member State appoints three ministerial level parties to a Board, and the Board manages the Joint Authority.

23.2.4.5 Practices for Sanitation in Islands

Groundwater pollution in islands can be caused due to lack of sanitation. Some of the measures recommended to avoid pollution is listed below (Dillon 1997):

- Providing public information on the link between sanitation and drinking water quality.
- Planning regulations to restrict population density in unsewered areas.
- Developing public health regulations on design and maintenance of sanitation systems.
- Specifying well-head zones.
- Establishing monitoring procedures for pathogens and nitrogen in drinking water supplies and developing contingency plans in case water does not meet the required quality.
- Disinfection of water supply wells and/or finding alternative supplies.
- Establishing centralized water supply and sanitation systems.

23.2.4.6 Aquifer Storage and Recovery (ASR) Wells

In ASR, water is stored in deep aquifers and then used when in demand. This method is more suitable where the surface water is not up to the quality due to many reasons such as salinity issues, contamination etc. In certain parts of the Netherlands, surface water cannot be used for irrigation as they are saline and groundwater cannot be used as it is brackish. The ASR wells are injected with rainwater collected from roof tops to a depth of 15–50 m. These stored water is then used to irrigate the fields. The rainwater is stored in the aquifer regions where it is not brackish and then used in need.

23.3 Artificial Recharge

Artificial recharge is a technique for augmenting the natural recharge by means of structures or techniques to increase percolation of water above the natural rate into the aquifers. Thereby ensuring a certain quantity of water available for groundwater abstraction. This technique ensures enhancement of groundwater resources. The factors that needs to be considered for proving artificial recharge or planned recharge are as follows (O'Hare et al. 1986):

- Quantity of source water available.
- Quality of source water available.
- Resultant water quality (after reactions with native water and aquifer materials).
- Clogging potential.
- Underground storage space available.
- Depth to underground storage space.
- Transmission characteristics of the aquifer.
- Applicable methods (injection or infiltration).
- Legal/institutional constraints.
- Costs.
- Cultural/social considerations.

Artificial recharge techniques will be useful for controlling the floodwater, saltwater intrusion, movement of contaminants, etc. A variety of methods has been implemented for recharging the aquifers depending on the land topography, soil type, lithological characteristics, depth of the aquifer from ground etc. The methods of artificial recharge can be broadly classified into:

- Direct surface recharge.
- Direct subsurface recharge.
- Indirect recharge.
- Combination of surface -subsurface methods.

Direct surface methods work on the idea of natural percolation of water from the top soil to the water table, where water is conveyed directly into the aquifer. It is one of the simplest and widely used techniques. The factors that depend on the effectiveness of water recharged depends on the area of water spreading, duration the water in contact with the soil, the permeability of the soil medium between ground and water table. These techniques are cost effective but require large area for spreading. In areas where land is a constraint, this method cannot be applied effectively. The quality of water that is recharged is also a concern. If poor quality water is recharged, then it may clog the pore spaces in the soil matrix thereby reducing the efficiency of the water recharged.

Direct sub surface methods include techniques where water is recharged directly into the deep aquifers. In this method the availability of land is not a constraint. Moreover, the quality of water does not have much impact as clogging of soil pores is not significant in this case. Direct sub surface methods include construction of recharge wells and shafts. So construction cost is a major concern in this method.

Indirect methods of artificial recharge make use of the connection between surface water and a shallow aquifer. This is done by constructing infiltration galleries. The effectiveness of this method depends on the proximity of surface water bodies, hydraulic conductivity of the aquifer, area and permeability of stream bed. Groundwater barriers or dams have been built within river beds in many places, including India, to obstruct and detain groundwater flows so as to sustain the storage capacity of the aquifer and meet water demands during periods of greatest need. Construction of complete small-scale aquifers also seems feasible (Helweg and Smith 1978).

23.3.1 Identification of Areas for Recharge

The initial step in developing an artificial recharge management plan is to identify the area of recharge. The selection of the area should be based on the following criteria:

- The water levels in the selected area has a declining trend and is over-exploited for a period of time.
- Substantial part of the aquifer has already been desaturated i.e., regeneration of water in wells and hand pumps is slow after some water has been drawn.
- Water available from wells in this regions during the dry periods is very low to meet the demands.
- Area where there is no other alternate source of water and the available groundwater quality is poor.

23.3.2 Identification of Sources for Groundwater Recharge

The source of water used for recharging the groundwater should be of adequate quantity and quality. Some of the main sources for recharge are:

- Precipitation over the demarcated area.
- Large roof areas from where rainwater can be collected and diverted for recharge.
- Canals from large reservoirs from which water can be made available for recharge.
- Natural streams from which surplus water can be diverted for recharge, without violating the rights of other users.
- Properly treated municipal and industrial wastewater. This water should be used only after ascertaining its quality.

Rainwater available may not be meeting the quality in all the regions, therefore in such cases alternate sources for recharge has to be considered and transmitted to the recharge site. Assessment of the available sources of water would require consideration of the following factors:

- Available quantity of water.
- Time for which the water would be available.
- Quality of water and the pre-treatment required.
- Conveyance system required to bring the water to the recharge site.

23.3.3 Hydrogeological Studies

A better understanding about the hydrological aspects of the study area will help in designing the appropriate recharge system for the area. The aspects to be considered for a recharge scheme are:

1. Detailed information and maps showing
   - Hydrogeological units demarcated on the basis of their water bearing capabilities at both shallow and deeper levels.
   - Groundwater contours to determine the form of the water table and hydraulic connection of groundwater with rivers, canals etc.
   - Depth to water.
   - Amplitude of water level fluctuations.
   - Piezometric head in deeper aquifers and their variation with time.
   - Groundwater potential of different hydrogeological units and the level of groundwater development.
   - Chemical quality of water in different aquifers.

This information is usually available in groundwater reports prepared by the Central Groundwater Board (2000) and/or the State Groundwater Board and reports prepared by USGS.

2. Information from local open wells

The information from wells that need to be considered before implementing recharge schemes are:

- The unsaturated thickness of rock formations occurring beyond 3 m below ground level should be considered to assess the requirement of water to build up the sub-surface storage.
- The upper 3 m of the unsaturated zone should not be considered for recharging since it may cause adverse environmental impacts like water logging, soil salinity etc.
- The post-monsoon depth to water level represents a situation of minimum thickness of vadose zone available for recharge.

23.3.4 Methods of Groundwater Recharge

From the time people realized the value of harnessing the groundwater, different methods were adopted based on the type of topography. The suitable locations for artificial recharge are often determined using GIS techniques

(Ramalingam and Santhakumar 2000; Zehtabian et al. 2001; Ghayoumian et al. 2005; Mehrvarz and Oskouei 2007).

Water resources management was implemented in many regions with artificial recharge techniques (Donovan et al. 2002; Han 2003; Phien-wej et al. 1998; Tu et al. 2011). Artificial recharge is broadly classified into direct recharge and indirect recharge. Some of the methods that are implemented are Spreading Basins, Recharge Pits and Shafts, Ditches, Recharge Wells, Harvesting in Cistern from Hill Sides, Subsurface Dams, Farm Ponds, and Historical Large Well across Streamlet and Check Dams.

23.3.4.1 Spreading Basins

Spreading basins are effective for highly permeable soils in flat topography. This method involves surface flooding of water in basins that are excavated in the existing terrain. Water is spread in a thin layer. The effectiveness of this method depends on the infiltration rate, the percolation rate, and the capacity for horizontal water movement. These three factors decide the amount of spread water that goes into the aquifer. At the surface of the spreading basin, however, clogging occurs by deposition of particles carried by water in suspension or in solution, by algae growth, colloidal swelling and soil dispersion, microbial activity, etc. This method is effective when the water available for recharge is clear enough to prevent clogging. Figure 23.2 shows a photograph of spreading basin in Los Angeles.

Fig. 23.2 Spreading basin (*Source* Los Angeles Department of Water and Power www.dpw.lacounty.gov)

23.3.4.2 Recharge Pits and Shafts

The utility of surface spreading methods is reduced as low permeable material lie in between the surface and the aquifer. In such situation artificial recharge systems such as pits and shafts could be effective in order to access and replenish the dewatered aquifer. In case the water used is unfiltered, then sediments may be left behind the sides and bottom of the pit reducing the amount of recharge water into the aquifers. The residual water must be cleared off periodically to ensure proper working of the recharge pits and shafts.

Like the recharge pits, recharge shafts are also used to recharge water to unconfined aquifer whose water table is deep below the land surface and a poorly impermeable strata exist at the surface level. Shafts are normally circular, rectangular or square in cross section backfilled with a porous material. The excavations of the shafts are done till the bottom of the excavation is just above the water table. Recharge rates in both shafts and pits may decrease with time due to accumulation of fine-grained materials and the plugging effect brought by microbial activity. The schematic diagram of recharge pit and recharge shaft is given in Figs. 23.3 and 23.4, respectively.

23.3.4.3 Ditches

A ditch is a long narrow trench as shown in Fig. 23.5, with its bottom width less than its depth. Ditches are designed based on the topographic and geologic condition at the site. A layout for a ditch also includes a series of trenches running down the topographic slope. The ditches could terminate in a collection ditch designed to carry away the water that does not infiltrate in order to avoid ponding and to reduce the accumulation of fine materials.

23.3.4.4 Recharge Wells

Recharge wells are used to directly recharge the aquifers which are at certain depth from the ground level. Recharge wells could be dug through the material overlaying the aquifer and if the earth materials are unconsolidated, a screen can be placed in the well in the zone of injection.

Recharge wells are suitable only in areas where thick impervious layer exists between the surface of the soil and the aquifer to be replenished. They are also advantageous in areas where land is scarce, where other methods such as spreading techniques are infeasible. The recharge rate attained by this method is quite high compared to other methods, as water is directly injected into the aquifers. The disadvantage to this method is that it may cause clogging of the well screens, which requires maintenance. Figure 23.6

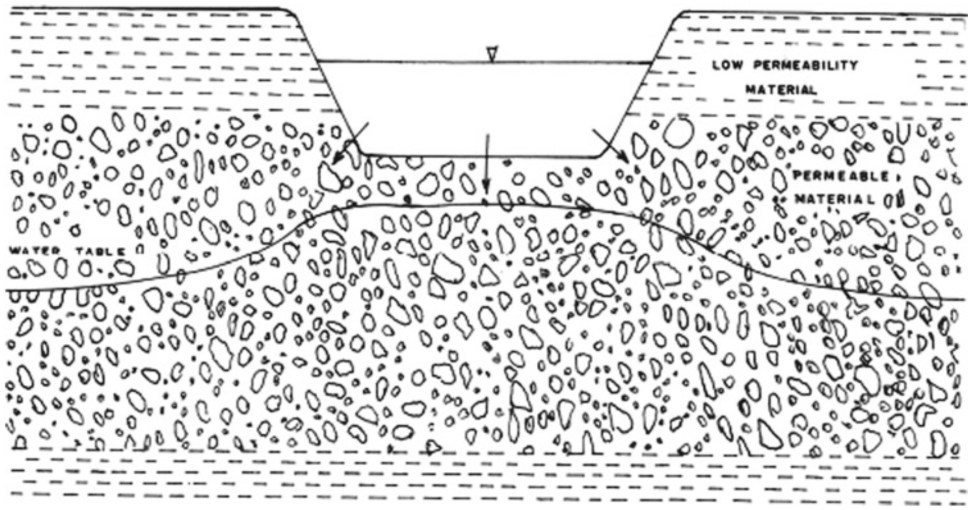

Fig. 23.3 Recharge pit (*Source* Central Groundwater Board 2007)

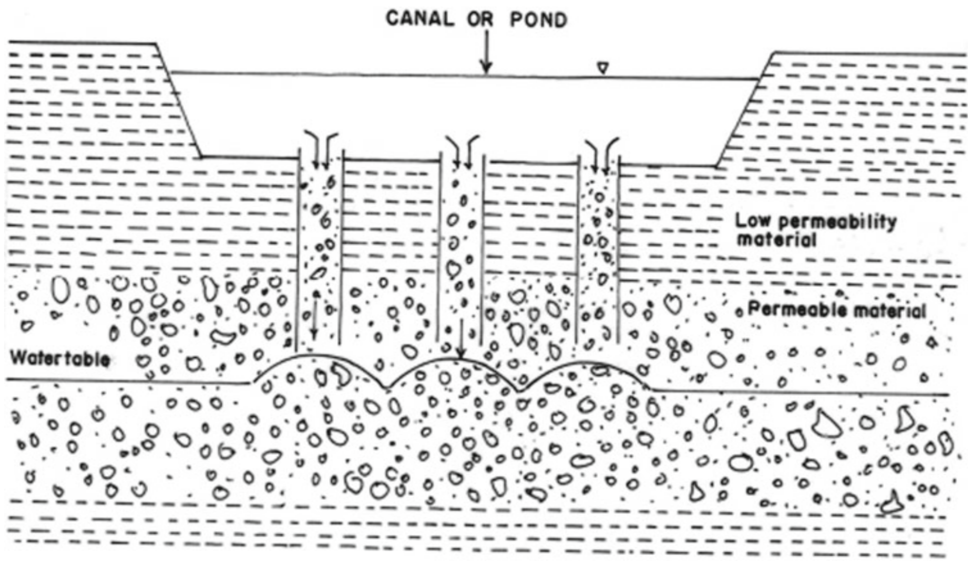

Fig. 23.4 Recharge shaft (*Source* Central Groundwater Board 2007)

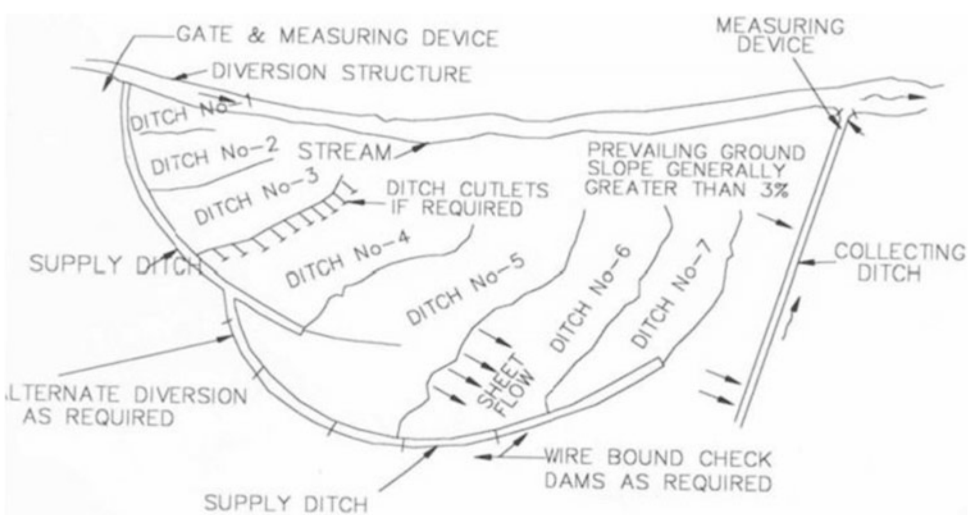

Fig. 23.5 Ditches (*Source* Central Groundwater Board 2007)

shows how recharging of groundwater is done through a recharge well.

23.3.4.5 Subsurface Dams

Groundwater moves from higher-pressure head to lower one. This will help the semi-arid zones especially in upper reaches where the groundwater velocity is high.

Subsurface dams are structures used to obstruct the groundwater flow of an aquifer and store the water below ground level as shown in Fig. 23.7. These dams are suitable for semi-arid regions where seasonally available water can be stored and used during dry periods for irrigation as well as domestic purposes. They can be built with locally available material but require large investment.

23.3.4.6 Farm Ponds

These are traditional structures in rain water harvesting, dug out in earth usually square or rectangular in shape as given in Fig. 23.8. Farm ponds are small storage structures collecting and storing runoff water and utilizing in the future for drinking as well as irrigation purposes. It is provided with inlets and outlets to regulate the water in the pond. The size and depth depend on the amount of land available, the type of soil, the farmer's water requirements, the cost of excavation, and the possible uses of the excavated earth. As per the method of construction and their suitability for different topographic conditions farm ponds are classified into three categories:

Excavated farm ponds—suited for flat topography.

Embankment ponds—suited for hilly and ragged terrains.

Excavated cum embankment type ponds—regions with flat and hilly terrains.

Selection of location of farm ponds depends on several factors such as rainfall, land topography, soil type, texture, permeability, water holding capacity, land-use pattern, etc.

23.3.4.7 Historical Large Well Across Streamlet

This concept is made into practice when a historical well, which has been used years back and is currently out of operation, is located near a stream. In such cases a portion of the water from the stream is diverted to the wells by means of drains. The diverted water is stored in the well and they act as recharge wells by recharging the deep aquifers.

23.3.4.8 Check Dams

Check dams are small barriers built across the direction of water flow on shallow rivers and streams for the purpose of rain water harvesting. The small dams retain excess water flow during monsoon rains in a small catchment area behind the structure as given in Fig. 23.9.

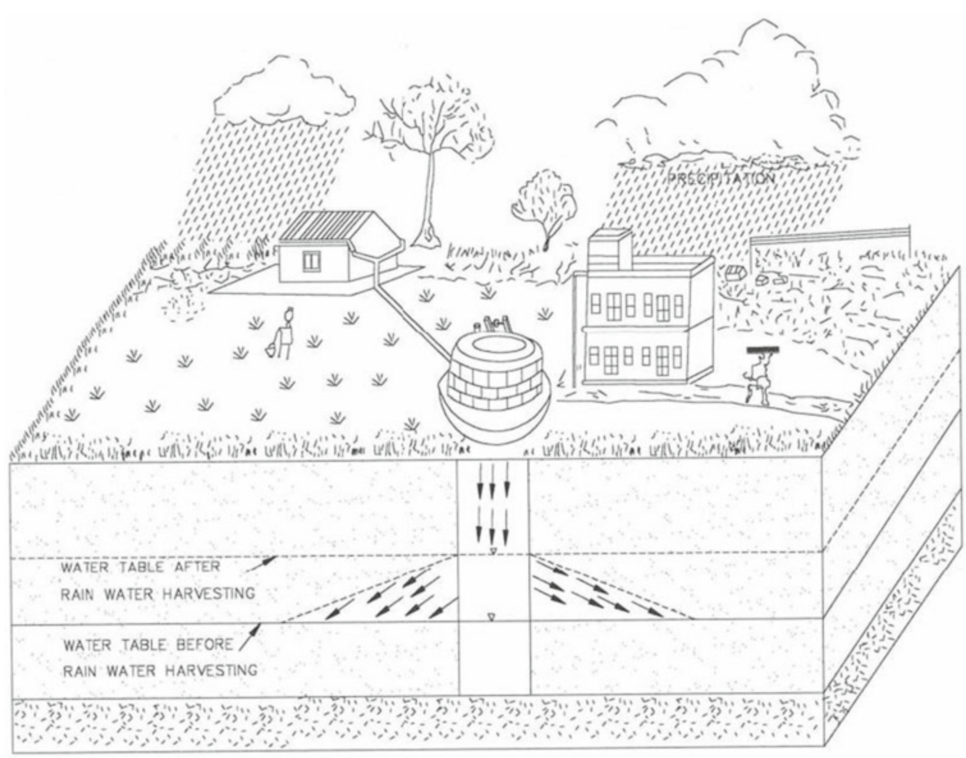

Fig. 23.6 Recharge well *(Source* www.megphed.gov.in)

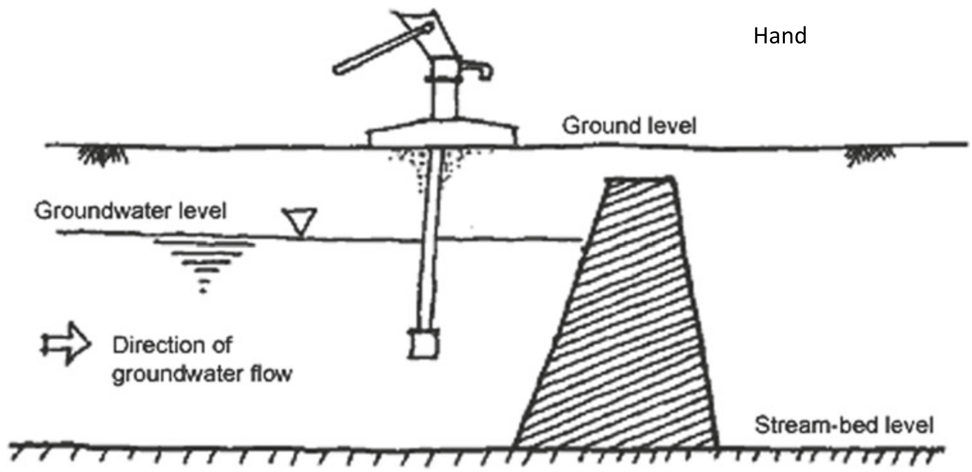

Fig. 23.7 Subsurface dams (*Source* www.rainwaterharvesting.org)

Fig. 23.8 Farm pond (*Source* Ramachandrappa and Thimmegowda 2016)

The major environmental benefit is the replenishment of nearby groundwater reserves and wells. The impounded water recharges the shallow aquifer beneath.

23.3.5 Advantages and Disadvantages of Artificial Recharge

Artificial recharge has both advantages as well as disadvantages. They are pointed out as follows (Bhattacharya 2010):

23.3.5.1 Advantages

- The use of aquifers for storage and distribution of water and removal of contaminants by natural cleansing processes that occur as polluted rain and surface water infiltrate the soil and percolate down through the various geological formations.
- The technology is appropriate and generally well understood by both the technologists and the general population.
- Very few special tools are needed to dig wells.

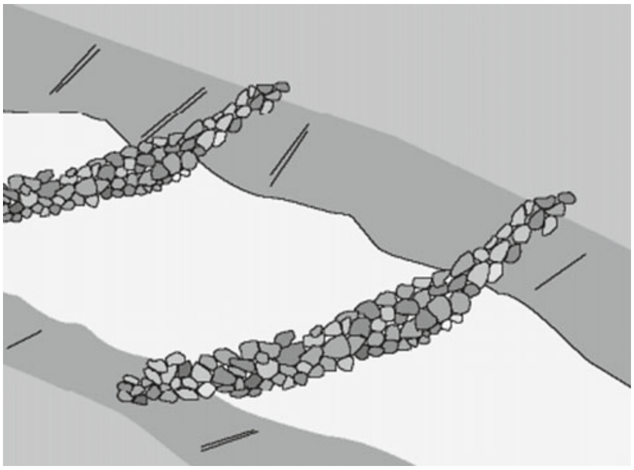

Fig. 23.9 Check dam (*Source* California Stormwater BMP Handbook 2012)

- Groundwater recharge stores water during the wet season for use in the dry season, when demand is the highest.
- The quality of the aquifer water can be improved by recharging with high-quality injected water.
- Recharge can significantly increase the sustainable yield of an aquifer.
- Recharge methods are environmentally attractive, particularly in arid regions.
- Most aquifer recharge systems are easy to operate.
- In many river basins, control of surface water run-off to provide aquifer recharge reduces sedimentation problems.
- Recharge with less-saline surface water or a treated effluent improves the quality of saline aquifers, facilitating the use of the water for agriculture.
- Storage without excessive evaporation losses.

23.3.5.2 Disadvantages

a. In the absence of financial incentives, laws, or other regulations to encourage landowners to maintain drainage wells adequately, the wells may fall into disrepair and ultimately become sources of groundwater contamination.
b. There is a potential for contamination of the groundwater from injected surface water run-off, especially from agricultural fields and road surfaces. In most cases, the surface water run-off is not pre-treated before injection.
c. Recharge can degrade the aquifer unless quality control of the injected water is adequate.
d. Unless significant volumes of water are injected in an aquifer, groundwater recharge may not be economically feasible.
e. During the construction of water-traps, disturbance of soil and vegetation cover may cause environmental damage to the project area.

23.3.6 Artificial Recharge: Case Studies in India

In India, utilization of groundwater is increasing at a high rate due to technological advancements which made the construction of bore wells and pumping from underground easier. Due to uncertainties in the monsoons, nowadays groundwater has become a reliable source in many parts of India. This dependency is increasing over the years. Replenishment of groundwater by artificial recharge of aquifers in the arid and semi-arid regions of the country is essential, as the intensity of normal rainfall is grossly inadequate to produce any moisture surplus under normal infiltration conditions. Artificial recharge should be applied to developing countries facing water scarcity in order to ensure water security for the future.

23.3.6.1 Ghaggar River Basin—Haryana

Induced artificial recharge through injection wells was undertaken by the Central Groundwater Board at two sites located in Ambala and Kurukshetra along the Ghaggar River in Haryana after detailed hydrological studies. Injection wells were made up to a depth of 15 m with cement sealing. Canal water was injected under pressure into the wells at a rate of 43.3 l/s. It was observed that the injection pressure of 1.6 atmosphere raised to 1.96 atmosphere within 30 min of injection and remained constant for about 4 h. Clogging of foot valves with grass caused violent vibrations and sudden increase in pressure to 2.5 atmosphere. After construction and development of another injection well with improved design, second injection recharge experiment was conducted with a recharge rate of 40 l/s for 389 h and with 22 l/s for another 24 h. The experimental results concluded that the hydrogeological conditions of the area are favourable for artificial recharge through injection method and the quality of canal water used for injection meets the requirements.

23.3.6.2 Moti Rayan and Bhujpur Area, Mandvi Kutch District—Gujarat

Eighteen check dams, 3 percolation ponds, 2 recharge wells and 1 sub-surface dam with four recharge wells were constructed to improve the groundwater reserves in the Mandvi Kutch District. The amount of water recharged was observed for low rainfall years, where they observed that the recharge structures received around two fillings and the total quantity infiltrated was accounted to 344.664 m^3. Therefore, it can be concluded that even during low rainfall years, the recharge structures are able to transmit considerable quantity of water to the groundwater reserves.

23.3.6.3 Nagpur—Maharashtra

Nagpur, being a metropolitan region, the recharge method cannot be stick to a single technique. In the densely populated areas, roof top rainwater harvesting and runoff rainwater conservation are employed. Whereas in the outskirts of Nagpur, where enough land is available, recharge is done through percolation tanks and check dams. In Nagpur city roof top rain water experiment was done in Ujjwal Nagar area where the roof top rain water collected from the concrete roof of 100 m^2 was diverted into the existing water supply dug well of the household. About 80,000 L was recharged during the monsoon.

The runoff water flowing through the roads and open grounds flow out of the city unutilized. Adopting steps to conserve this water can be a great move towards saving water and using it at the time of water scarcity. One such scheme prepared by the Central Groundwater Board for Ujjwal Nagar of Nagpur, in which 15,000 m^2 of catchment is intercepted where run off generated would be diverted in the recharge wells constructed in public gardens. The wells are provided with filters to make the runoff water silt-free.

23.3.6.4 Central Scientific Instruments Organisation (CSIO)—Chandigarh

Roof top rainwater harvesting is the common groundwater recharge technique adopted in urban areas at nominal cost to reduce the runoff. In Chandigarh, roof top rainwater harvesting was done on top of the CSIO building roofs of an area of 3,550 m^2. During 1998, 2,427 m^3 of rainwater was harvested and recharged into the groundwater through injection wells. For an effective impact on groundwater recharge, there should be a captive roof area of 100 m^2. Moreover, rainwater should be harvested by all individual houses and flats for effective recharge of the groundwater aquifer systems.

23.3.6.5 New Delhi

The Central Groundwater Board has initiated pilot projects in Jawahar Lal Nehru University (J.N.U.), for artificial recharge experiments. The storm water is stored in built up structures and then recharged to depleted aquifers. Four check dams were constructed on rivulets and sixteen piezometers were established to monitor the impact of artificial recharge on groundwater. The storage capacity of 49,000 m^3 was created in these dams and 125,000 m^3 water had already been recharged to the aquifer. Rise of water level maximum up to 4 m has been observed, apart from sustainable yield of tube wells and more vegetation cover around the check dams.

Excessive groundwater development in the Northern parts of Delhi have resulted in the decline of groundwater by 6–13 m. Artificial recharge in this area is done through two dried dug wells, one injection well, one vertical recharge shaft, two recharge trenches with injection wells. On an annual basis. 28,170 m^3 of rain water was collected and recharged to the groundwater aquifers.

In the Kushak Nala which with a catchment of 3.5 km^2, the excess runoff is captured to the ground through two Gabion bunds and two Nala bunds. Where Nala bunds are embankments constructed across rivers for checking velocity of runoff, increasing water percolation and improving soil moisture regime. After the implementation of these structures, it was observed that there was a net rise of 0.21 m in groundwater level in an area of 3.5 km^2.

Lodhi Garden in Delhi covering an area of 36 ha, is frequently flooded during the rains. About 25,000 m^3 of runoff volume is captured through three lateral shafts and three recharge pits. As a result an annual rise in water level of 0.35 m was observed in an area of 40 ha.

Roof top rainwater harvesting in Shram Shakti Bhavan, having an area of 11,965 km^2 is able to recharge an amount of 2,900 m^3 water every year that is going as waste at present. Artificial recharge to groundwater is also proposed through recharge trenches with two injection wells at selected locations. It is expected that 1.62 m rise in groundwater will occur in 12,000 m^2 area.

23.3.6.6 Haryana

The groundwater levels in Kirmich and Samaspur villages of Kurukshetra district are very deep, more than 11 m from the ground surface due to the presence of intermediate clay layers. Due to over-extraction, the groundwater levels are decreasing at a rate of 30 cm/year. The water that is stored in depressions can be recharged to deep aquifers through recharge shafts piercing the clay layers. After the construction of recharge shafts the expected rise in water level is around 1.12 m in an area of 500 ha.

Steep decline in water levels was observed in NSG Campus, Manesar, District Gurgaon, Haryana due to heavy withdrawal of groundwater in the campus. The decline in water level is at a rate of 40 cm /year, leading to failure of the tube wells. In these regions, gabion structures are proposed to retain surface runoff which will seep naturally. Besides this, treated sewage water will also be recharged to groundwater through vertical recharge shafts with inverted filter.

23.3.6.7 Punjab

The Golden Temple Sarovar (pond) is filled with canal water and water is pumped out regularly in the sewage drain. The groundwater level decline in the town is at a rate of 0.5 m/year due to heavy pumping. Sarovar water which is being discharged into sewage drain will be used to recharge groundwater. It is estimated that water available for recharge is 0.448 million m^3/year and an increase in water level of 0.45 m/year is expected over an area of 500 ha.

Amritsar City in Punjab depends on groundwater for their water supply requirements which has led to the drop in groundwater levels. A decline of 0.50 m/year was observed near the regions of Kheti Bhavan. The surplus runoff is being utilized for recharging the depleted groundwater reservoir.

The groundwater development in the village of Issru was estimated as 218%, i.e., the extractions are more than twice the rate at which they are replenished by natural recharge and the water levels were declining at a rate of 0.3 m/year. The rain water from the village area is collected in ponds and they are recharged to groundwater through vertical shafts and injection wells. About 10,000 m^3 of water is recharged to the groundwater aquifers.

In Nurmahal block in the district of Jalandhar in Punjab, water level has declined between 5 to 6 m in last 17 years. The spare water of Phillaur and Sarih distributary canals during monsoon period will be diverted to two storage tanks and same will be recharged to the ground through 6 vertical shafts. Annual water available for recharge is around 1.62 million m^3. Expected rise in water level in 1,000 ha will be around 0.81 m/year every year.

The villages Channian and Kalasinghian located in Jalandhar district and Kapurthala block in Kapurthala district experienced decline of water levels at a rate of 0.2 m/year. Therefore, the spare canal water and surface runoff generated during monsoon, were collected in the village ponds and used for recharge. Annual water available for recharge is estimated to be around 0.28 million m^3.

The water levels in the Samana block Patiala District in Punjab are continuously declining at a rate of 0.35 m/year from 1973 to 1998 and the stage of groundwater development is 88%. It is proposed to utilize spare water of main Bhakra Canal during the period of mid-October to mid-December and mid-February to mid-April when there is no demand of water for irrigation for artificial recharge to groundwater. Four lateral shafts with injection wells and five vertical shafts with injection wells are being constructed for recharge. It is expected that rise in water level in 500 ha will be 2.91 m/year.

23.3.6.8 Madhya Pradesh

In the Mandsaur Block, Mandsaur District, Madhya Pradesh, percolation ponds were used for recharging the aquifers, where the groundwater has declined in the range of 1.25–4.60 m for the last 20 years.

In Musakhedi, Indore, rainwater harvesting was done in the campus of Narmada Water Supply Project colony where six buildings with an area of 2,710 m^2 was used for harvesting. The water from the roof top is diverted to a dug well of 20 m depth. The quantity of water available for recharge is 2142 m^3 annually.

In the Tumar watershed in Mandsur district, 85% of the total irrigation is through groundwater. In 1998, the groundwater development was noted to be 1.18 times greater than the replenishment rate. Therefore, to augment groundwater recharge, two check dams at Roopwali and Khera villages, 19 Gabion structures where constructed. Total water available for recharge is 10,910,000 m^3.

23.3.6.9 Maharashtra

In Jalgaon District, Maharashtra, the water levels are steadily declining at the rate of 1 m/year. The depth to water levels ranges between 30 and 40 m below ground level. For conserving the runoff volume two percolation tanks and five recharge shafts are being constructed. It is estimated that 14,510,000 m^3 of water is available as surplus runoff. Sub-surface storage potential available is 153,000,000 m^3. Average thickness of aquifer that has become desaturated is about 12.00 m. Volume of sub-surface aquifer in which recharge can take place is 3,827,000,000 m^3.

23.3.6.10 Uttar Pradesh

The Chogwan area lies between Krishni and Hindon rivers covering parts of Binauli block, Baghpat district, Uttar Pradesh. Groundwater is the main source of irrigation in this region. The over-dependence of groundwater has caused decline of water levels in the range of 3–5 m over the past decade. The area has number of village ponds which have enough water even during summer season. During rainy season, the water overflows these tanks. At Garhi Kangran, this excess water is being used for artificial recharge through lateral shafts with three injection wells. It is estimated that 4,000 m^3 water is being recharged annually.

23.3.6.11 West Bengal

The status of development of the groundwater in the district of North 24 Parganas is quite high. The district has considerable area of water bodies like tanks, rivers etc. Most of these water bodies have been silted up. Due to which the reservoir capacity has decreased and recharge through the water bodies have been minimised. It is proposed to enhance the recharge rate by de-silting these water bodies which would result in an increase in groundwater levels.

The Purulia district in West Bengal depends on both surface water and groundwater for their irrigation demands. To conserve the monsoon water, artificial recharge structures such as sub-surface dykes, bunds, tank excavation, re-excavation of existing minor irrigation tanks and contour bunding are being constructed. The implementation of these schemes will store the excess monsoon run off on the surface which other than supplying water for irrigation will also recharge the shallow unconfined aquifer to create additional subsurface storage for further utilisation.

23.3.6.12 Rajasthan

In the Jhunjhunu city in Rajasthan, the average decline in water level is 0.54 m/year due to excessive withdrawal of water for irrigation and industrial purposes. For utilising some part of the available runoff for augmentation of groundwater resources, one subsurface barrier of 0.8 m height, 2.75 m depth and 89 m length and three gravity head inverted wells of 1.2 m diameter and 10 m depth were constructed.

Due to over development of groundwater for domestic water supply in Jaipur the groundwater levels are continuously declining. Experimental studies were done on the top of the CGWB Office building at Jhalana Dungri at Jaipur to utilize the roof top rainwater for recharge. The roof top / paved area of the building is 1,250 m^2. The depth to groundwater level is 29.0 m below ground level. For recharging the available runoff an injection tube well of 250 mm diameter and 50 m depth was constructed.

23.3.6.13 Kerala

In the Chirayinkil Block, Trivandrum District, due to drying up of the rivers the area faces acute water shortages during peak summer seasons. The average rainfall is 1,963 mm of which about 70% is received during south-western monsoon. In these regions, 75% of rainfall goes waste as run off due to very high gradient. Subsurface dyke is being constructed to arrest the subsurface groundwater outflow. The dyke will result in building up of groundwater levels that can be harnessed during lean season.

23.3.7 Cost Analysis

Cost plays a major role in deciding on the type of structure to be constructed for artificial recharge. In one of the study by Rushton and Phadtare (1989), they described the initial and running cost after conducting experiments on different recharge structure on two types of soil namely alluvial and limestone. The studies were conducted in Mehsana areas of Gujarat and the summary of their analysis is shown in Table 23.1.

From Table 23.1, it can be observed that the injection wells in hard rock areas are less expensive since they tend to be shallower and have a lesser risks of clogging. Percolation tanks appeared to be least expensive in terms of initial construction costs; this would be the case in areas where the tanks already exist. For economic reasons, the main uses of artificially recharged water are likely to be providing water for domestic needs, industry and environmental conservation. Because of its relatively high cost, recharged water is not generally suited for irrigation for any crop, but it can be used to provide supplemental irrigation water for rain-fed crops or to provide additional water to crops at a crucial growth stage during periods of water shortage. As a general rule in this regard, groundwater must be efficiently used and effectively applied such that the net benefits from its use are maximized over time.

23.3.8 Where Groundwater Recharge Can be Done?

The main requirement for doing artificial recharge is the availability of an aquifer in the area under consideration. Aquifers best suited for artificial recharge are those which can absorb and retain large quantities of water. The method of recharge to be applied depends on the type of aquifer. Unconfined aquifers can be recharged by surface spreading methods, whereas confined aquifers require deep injection methods. When considering the topography of the land surface, a flat and gentle slope is required for surface methods. Topography is not a concern for deep injection methods. The type of soil is a key factor that determines the rate of percolation to the unconfined aquifers.

23.3.9 Quality of Recharge Water

The physical, chemical and biological characteristics of the recharge water is an important factor that affects the method or technique to be applied for artificial recharge. Presence of suspended solids make the water unfit for surface spreading techniques. These particles may clog the soil pores which require periodic maintenance and cleaning. The recharge water should not chemically react with the soil medium. If chemical reactions take place, then it will reduce the aquifer porosity thereby reducing the recharge capacity. Similarly, biological components such as algae and bacteria can cause

Table 23.1 Cost of various artificial recharge schemes in India ($/m^3)

Artificial recharge structure	Initial cost	Running cost
Injection well (alluvial area)	100	100
Spreading channel (alluvial area)	9	10
Percolation Tank (alluvial area)	2	7
Injection well (limestone area)	6	21
Spreading channel (limestone area)	7	6

clogging of infiltration surfaces and wells, thereby reducing the quantum of water to be recharged.

23.4 Conjunctive Use of Surface Water and Groundwater

23.4.1 Introduction

Conjunctive use of groundwater and surface water is the process of using water from two different sources for consumptive purposes. In case of irrigation conjunctive use is defined as a situation where both groundwater and surface water are developed to supply a given irrigation canal-command although not necessarily using both sources continuously over time nor providing each individual water user from both sources (Foster et al. 2010). Alternatively, FAO (1995) described conjunctive use of surface water and groundwater consists of harmoniously combining the use of both sources of water in order to minimise the undesirable physical, environmental and economic effects of each solution and to balance the water demand and supply. Conjunctive use of surface and groundwater can be defined in an overall manner as the management of both surface and groundwater resources in a coordinated operation to the end that the total yield of such a system over a period of years exceeds the sum of the yields of the separate components of the system resulting from an uncoordinated operation.

Conjunctive use or conjunctive water management has been defined in different ways based on the way its purpose and implementation. Some of the major definitions as given in California Department of Water Resources (2016) are as follows:

Definition 1 "Conjunctive water use primarily changes the timing in the flow of existing water sources by shifting when and where it is stored and does not result in new sources of water. Conjunctive use is often incidental as water users intuitively shift between surface water and groundwater sources to cope with changes and shortages. While conjunctive use may prove successful for an individual or group of water users to manage an immediate situation, it is also possible for conjunctive use to unintentionally harm the groundwater basin and other groundwater users who are not involved in conjunctive use but are reliant on the same groundwater basin. "An alternative to conjunctive water use is conjunctive water management. The difference between the two is more than semantics. Conjunctive water management engages the principles of conjunctive water use, where surface water and groundwater are used in combination to improve water availability and reliability. But, it also includes important components of groundwater management such as monitoring, evaluation of monitoring data to develop local management objectives, and use of monitoring data to establish and enforce local management policies. Scientific studies are needed to support conjunctive water management. They provide important data to understand the geology of aquifer systems, how and where surface water replenishes the groundwater, and flow directions and gradients of groundwater."

(*Source* Dudley and Fulton 2006).

Definition 2 "Conjunctive use and conjunctive management describe the interchangeability of ground and surface water. Conjunctive use, with its roots in traditional water application, denotes an opportunistic or incidental interchangeability, as when an unplanned shortfall of natural ground or surface water availability causes a user to switch back and forth between sources. Typically, surface water users switch to groundwater available naturally beneath their land when surface supplies fall short of their needs. On the other hand, conjunctive management seeks to actively manage the balance of ground and surface water availability over a period of naturally occurring wetter and drier water cycles. The objective of conjunctive management is to intercede in natural groundwater recharge processes to even out the year-to year variations in regional water availability with potential peripheral benefits of flood management, environmental water, and water quality improvement. While conjunctive use is an inherently local concept, conjunctive management with an appropriate infrastructure has the potential to span multiple regions."

(*Source* St. Amant 2013).

Definition 3 "Conjunctive use of groundwater and surface water in an irrigation setting is the process of using water from the two different sources for consumptive purposes. Conjunctive use can refer to the practice at the farm level of sourcing water from both a well and an irrigation delivery canal, or can refer to a strategic approach at the irrigation command level where surface water and groundwater inputs are centrally managed as an input to irrigation systems. Accordingly, conjunctive use can be characterized as being planned (where it is practiced as a direct result of management intention—generally with a top down approach) compared with spontaneous use (where it occurs at a grass roots level—generally with a bottom up approach). "…the aim of conjunctive use and management is to maximize the benefits arising from the innate characteristics of surface and groundwater water use; through planned integration of both water sources, provide complementary and optimal productivity and water use efficiency outcomes."

(*Source* Evans et al. 2012).

Definition 4 "Conjunctive use of surface water and groundwater consists of harmoniously combining the use of both sources of water in order to minimize the undesirable physical, environmental and economic effects of each solution and to optimise the water demand/supply balance."

(*Source* Food and Agriculture Organization of the United Nations 1993).

The process of conjunctive use takes advantage of the interaction between the surface water and groundwater phases of the hydrological cycle and the natural movement of groundwater in planning the use of water from these two sources. The utilization of the water resources from the two sources are done in such a way that the economic and environmental benefits from each source are maximized. Thus the main objective of such a policy is to increase the yield, reliability of supply, and general efficiency of a water system by diverting water from streams or surface reservoirs for conveyance and storage in groundwater basins for later use when surface water is not available. Therefore, the evolution of a more planned conjunctive use of water resources offers great potential for increasing the water security and thereby improving the efficiency of supply for both irrigated agriculture and urban water supplies. Conjunctive use management will rely on water policies and regulations that are efficient in promoting the movement of access between the two resources at times required. In conjunctive use, groundwater is used more during the dry periods and conversely surface water is used at times when the availability from surface water sources is prominent such as from rivers and storage reservoirs.

The use of surface water during monsoons and the reliance on groundwater during dry periods ensures that water is available throughout all the periods and seasons in a year. This security in water availability encourages the farmers to expand their irrigated areas, by this means increasing the overall agricultural productivity. Moreover, the farmers tend to invest in high value crops and they will no longer have the insecurity regarding the amount spent on these crops. Another major benefit with the conjunctive use is that it reduces water logging in the wet seasons and salinization in the dry seasons, as the dependency on surface water is more during wet seasons and groundwater during dry seasons. The practice of surface irrigation without much consideration on groundwater often results in the problem of water logging and salinization in the command area due to increase in the groundwater levels caused by irrigation. The conjunctive use of water from two sources eliminates the salinity problems in shallow aquifers.

Since groundwater is abstracted and used, the buffer space in the sub soil is increased. This space acts as a cushion to heavy rainfall and thereby reducing the flood runoff. Thus the excess surface runoff is captured in the buffer space in the soil. The stored runoff volume then contributes to groundwater and in the later stages is extracted out for consumptive purposes. Thereby reduction in flood water volume and groundwater recharge is jointly made possible in a single approach. The interaction of various hydrological components need to be studied before implementing a conjunctive use approach. The emblematic movement of various hydrological components is shown in Fig. 23.10. The recharges to groundwater occur in many ways such as from the rainfall, streams, percolation ponds, dams and other recharge structures. The practice of conjunctive use is carried out to attain multiple objectives. Among the many objectives, the prominent one is to increase the total amount of supply from two sources, i.e., surface water and groundwater. Through the conjunctive use, there is substantial savings in the water that is lost by evaporation from reservoir surface, as a substantial amount of water will be filling the reservoirs due to surface water and groundwater interactions.

Groundwater can be replenished from streams by extending the duration of flows in the streams by means of dams or retarding the flows by levees. Conjunctive use can be employed in places where there is excess extraction of groundwater, surface irrigation schemes can be employed to reduce the depletion of groundwater levels.

23.4.2 Connection Between Surface Water and Groundwater

The connection between surface water and groundwater comprises of two major components—the degree of connection between the two resources and the time lag for extraction from one resource to impact upon the other. A highly allied resource would be one where the degree of

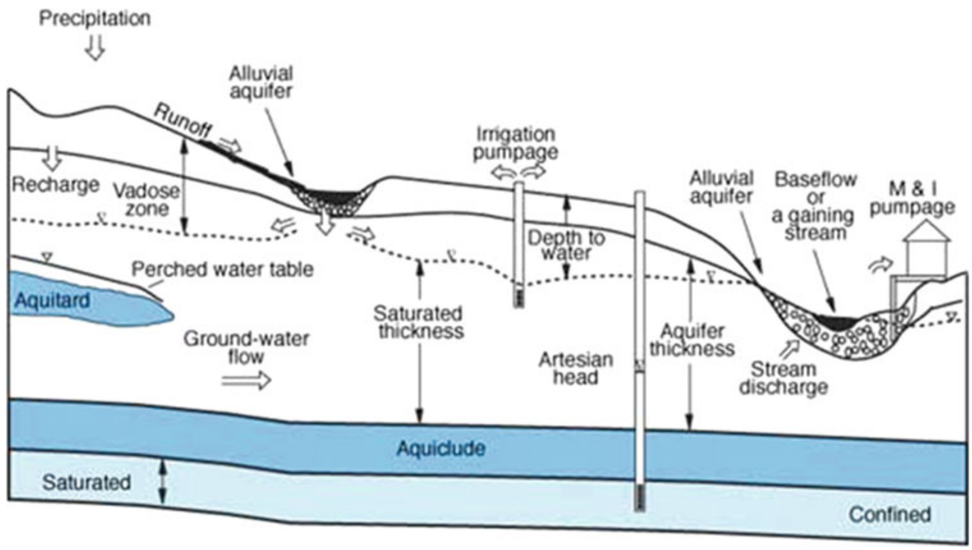

Fig. 23.10 Interaction of various hydrological components (*Source* www.kgs.ku.edu)

connection is high and the time lag for transmission of impacts is very fast. A losing stream is a one in which the groundwater gets replenished from the surface water sources and a gaining stream is the one in which the surface water body gets recharged from the groundwater source. The interaction of a stream with the underlying groundwater is shown in Fig. 23.11. A highly connected resource would be one where the degree of association is high and the time lag for transmission of impacts is very short. A fundamental tenet of connectivity understanding is that essentially all surface water and groundwater systems are connected and that it is just a matter of time for impacts to be felt across the connection.

The rate of flow between the river and aquifer will depend on the hydraulic conductivity of the aquifer and the hydraulic conductance of the river bed material. The major groundwater outflows include base flow into the surface stream network, direct evapotranspiration via capillary rise in areas where groundwater comes to the surface, evapotranspiration from trees where the roots touch the capillary fringe, discharge due to pumping, net outflow from the bottom of the aquifer. The types of aquifers involved in conjunctive use regimes that are spontaneous in nature are usually restricted to types that exhibit certain attributes. Generally, such systems are broad regional alluvial aquifers that either have good connection with associated large rivers or with irrigation command areas, both of which have the potential to provide a significant source of recharge. The types of aquifers and their example locations are discussed in Table 23.2.

In the conjunctive use system, both the surface water and groundwater resources are linked to each other. Therefore, the abstractions from groundwater will induce aquifer recharge from the available surface water resource in all hydraulically connected systems, in that way reducing the amount of surface water. The impression of groundwater extraction will be a function of time. The time taken for the groundwater to contribute to potential discharge sequentially depends on the hydrological formation of the aquifer. Similarly, when surface water is diverted from a connected system it can reduce the recharge to the underground aquifers. If surface water and groundwater are managed separately in connected systems, care must be taken to avoid 'double accounting' where the same volume of water potentially attributed to both the surface and groundwater resources. In cases where the two water resources are highly connected with short time lags, conjunctive management may be supported by a transparent water accounting framework that is able to be reported on for both surface and groundwater on an annual basis.

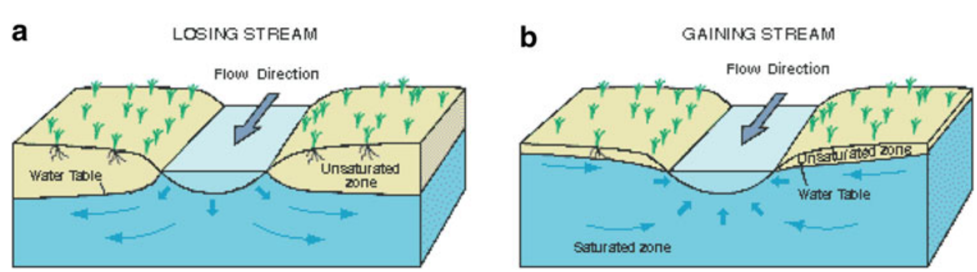

Fig. 23.11 Stream aquifer interaction (modified after Evans et al. 2012)

Table 23.2 Aquifer typology (Foster et al. 2010)

Aquifer type	Example location
Upstream Humid or Arid Outwash Peneplain	Indian Punjab—Indus Peneplain, Upper Oasis Mendoza—Argentina, Yaqui Valley, Sonora—Mexico
Humid but Drought Prone Middle Alluvial Plain	Middle Gangetic Plain—India, Middle Chao Phraya Basin—Thailand
Hyper—Arid Middle Alluvial Plain	Middle Indus Plain—Pakistan, Lower Ica Valley—Peru, Tadla—Morocco, Tihama—Yemen
Downstream Alluvial Plain or Delta with confined Groundwater	Ganges Delta—Bangladesh, Lower Oasis Mendoza—Argentina, Nile Delta, Egypt

In canal dominated irrigation command areas where the water table is below the level of the water level in the canal system or where the water table is shallow, the recharge may be dominated by irrigation-induced root zone drainage, and hence vertical unsaturated zone processes control the interaction process. Thus the canal distribution systems provide a significant reduction to groundwater extraction.

23.4.3 Types of Conjunctive Use

The use of surface water and groundwater conjunctively depends on the obtainability of resources and the scheme implemented varies from region to region on the basis of land topography and geology. Based on the variations in the method employed and the practices followed, conjunctive use can be of different types. They are discussed in the following section.

23.4.3.1 Planned Overdraft

The huge volume of water stored in the aquifers acts as a reserve and can be used as a source of water for several decades. But the major problem that comes to picture is the over extraction. If water is withdrawn from the aquifers without a proper strategy, then these aquifers can get exploited. A planned overdraft is required to ensure that the water is used prudently. To prevent the over exploitation of groundwater, the excess amount of water has to be taken from the surface water sources. This joint use of both the sources of water ensures that the resources are managed appropriately.

23.4.3.2 Use of Subsurface Storage

When the availability of surface water is more, then surface water is made use and groundwater is allowed to remain in storage. While sustaining average groundwater pumping, water resources availability increases without augmenting surface storage. During the dry years, where surface water is low, then the sub surface water is employed by increased pumping compared to other years. Whereas in wet years, the surplus surface water that is available is made use and the groundwater is left in storage.

23.4.3.3 Artificial Recharge

Artificial recharge has been used in the past to store surface flows or non-utilized surplus water that would otherwise be lost. In many countries the vadose zone is used as a buffer to store the excess surface water. Sometimes polluted water may be recharged to remove the pollutants as it passes through the soil media. The soil vadose zone acts as a filter media to the contaminated water. Artificial recharge can also be used to prevent land subsidence caused by groundwater table depletion and other environmental issues. The sewage effluent after treatment process can also be recharged into the aquifers. An example to this situation is the case in Los Angeles, California, where the sewage water reclaimed from a treatment plant is recharged into the wells, which acts as a hydraulic barrier to salt water intrusion in the coastal regions.

Artificial recharge of aquifers can also be achieved mainly through surface spreading, watershed management and recharge wells. Surface spreading is one of the simplest techniques in recharging phreatic aquifers. In this case water is spread in ponds or basins and is allowed to percolate into the ground. It is one of the cost effective method of artificial recharge. It requires large surface area to accommodate water, and there is chance of evaporation if the rate of recharge is slow. Surface spreading usually requires a diversion structure and an infiltration scheme. The diversion structures include earthen bunds that deflect the water into the fields. Even though the cost of building the bund is low, their overall maintenance and repair of the scheme is high. The infiltration basin consists of basins, channels or pits designed to retain water. The type of infiltration scheme depends on the type of land use in the region. The area of the basin may vary depending on the space availability. The area of the basins may range from 0.1 to 10 ha. Each basin should have its own water supply and drainage, so that each basin can be operated based on the necessity and as per schedule. Artificial recharge methods carried out through wells or infiltration ponds are quite expensive as the water that is recharged needs to be desilted in order to prevent clogging. After a particular period of time, the wells cannot be regenerated to the designated flow levels, in such cases the wells have to be replaced.

Spate irrigation is a traditional technique consisting of watering terraced fields by diverting flood flow into them. This technique usually contributes to the infiltration into the groundwater reservoirs. Check dams are structures build with a view of slowing down the velocity of water and thereby enhancing the percolation into the aquifers. Underground dams apply in shallow depth alluvial deposits to prevent groundwater from flowing away immediately after being stored. These structures consist of 1 to 1.5 m wide trench across the valley, which is filled with loose impermeable material. The drivers for the use of groundwater or surface water resources for irrigation are listed in the Table 23.3.

23.4.4 Planning and Management for Conjunctive Water Use

The runoff caused from precipitation, which supplies considerable discharge into rivers serves as a source for a particular season. The availability of water changes from season to season. Therefore, there is a requirement to save water during high supply period and use it latter. This can be achieved by storing the surplus water in dams or any other surface storage structures. But the surface storage structures often have limitations such as evaporation, sedimentation, environmental issues etc. The surface bodies are exposed to open air for several months in a year. The losses of water from the surface storage structures are proportional to the area exposed to open air. Another problem that affects the surface storage is sedimentation. There can be siltation and reduction in the storage capacity caused due to soil erosion. The soil vulnerability to erosion, and therefore the importance of the siltation problems in surface reservoirs, grows as the vegetation cover shrinks, so the more arid the climate, the less the vegetation cover, the higher the probability of sediment accumulation in the surface reservoirs. Surface reservoirs which are meant for water supply are highly affected by environmental impacts which may lead to adverse effect on humans. The water that is stored in the reservoirs needs to be conveyed to the demand regions through a proper distribution system. This distribution system can be canals, pipelines etc. and their construction is often expensive.

Storing and utilization of water from groundwater basins can be done by means of artificial recharge and extraction from aquifers. In places where groundwater discharge is slow due to the properties of geological stratum, the reduction in discharge force farmers and other communities to rely on surface water. The details of the conjunctive use policy based on different working policies are given in Table 23.4.

In conjunctive use policy, both the sources are harmoniously combined to minimize the undesirable physical, environmental and economic effects of each solution and to optimize the water demand/supply balance. So the conjunctive uses of both the resources are considered within a river basin such that the river and the aquifer represent the same segment of the system. Several aspects need to be considered before selecting the option of conjunctive use of surface water and groundwater. They are mainly determination of available storage beneath the ground surface, the potential discharge capacity of the aquifer as a measure of their productivity, amount of recharge to the aquifers both in terms of natural and induced recharge, the potential for artificial recharge into the aquifers and finally the economic and environmental benefits derived from the conjunctive use system.

Conjunctive use can be dominant, particularly in water-scarce areas and during the times of drought. The failure to integrate conjunctive water resources might result in overexploitation of groundwater. Conjunctive planning and management of water include water resources planning mechanisms touching various operational, administrative, institutional and political frameworks. Conjunctive water management requires balancing recharge with recovery and monitoring to validate the combined water management. Conjunctive water management employs the practice, where surface water and groundwater are utilized in amalgamation so as to improve water availability and reliability. But, it also comprises important components of groundwater management such as monitoring, evaluation of monitoring data to develop local management objectives, and use of monitored data to establish and enforce local management policies.

Before setting up the management plan, the initial requirements have to be fulfilled to ensure the sustainability of the project. For that the underground storage availability has to be determined. Conjunctive use will be successful if there is enough buffer space to accommodate the runoff. Dependability on groundwater hinge on the production capacity of the aquifer in terms of potential discharge. The productivity of groundwater wells in turn depends on the recharging capacity of the aquifer, which can be both natural and induced. This condition requires accurate hydrogeological investigations including geological mapping,

Table 23.3 Summary of drivers for sole use of groundwater or surface water resources for irrigation

Drivers of resource use	Groundwater resource	Surface water resource
Variable climate	A highly variable climate will typically favour users of groundwater resources, as groundwater characteristically provides a higher reliability of supply than surface water	
Poor surface water quality	Poor surface quality (often generated by the irrigation system itself) will favour groundwater use	
Poor groundwater quality		Surface water will remain dominant resource when groundwater quality is poor
Lack of adequate infrastructure	Gaps or failures in infrastructure (or in its operation and maintenance) that delivers surface water to users will favour the groundwater use	
Depth of groundwater resources'		Groundwater resources found at significant depths below the surface will incur significant pumping costs and hence often favour the use of surface water resources
Traditional Farming practices	Users of multi-generation farming practices that were established using a sole water supply are likely to be reluctant to incorporate a different water source into their traditional practices	Users of multi-generation farming practices that were established using a sole water supply are likely to be reluctant to incorporate a different water source into their traditional practices
Discovery of new groundwater resource	The discovery of a new groundwater resource will drive groundwater use; particularly in well-developed system where surface water allocation have been capped. This is especially so if there are fewer regulations on groundwater use	
Economic Value associated with production	Where economic return is significant, investment into obtaining additional water from groundwater resources is more likely to occur	If the economics in terms of farm income are distorted towards surface water use, farmers will be reluctant to incur additional cost to change water sources or use
Energy pricing	Subsidized energy costs of pumping can encourage groundwater use	
Technology Advances	Advances such as managed aquifer recharge mean that utilization of groundwater resources is often more feasible due to an increase in the volume of available water and security of the supply. Also advances in pumping technology can encourage groundwater usage	
Irrigation Education and Understanding	A lack of irrigator education and understanding of the benefits of conjunctive groundwater and surface water use can inhibit deviation from groundwater supply as a sole resource	A lack of irrigator education and understanding of the benefits of conjunctive groundwater and surface water use can inhibit deviation from surface water supply as a sole resource
Institutional Structures	Unless there is a genuine commitment at a national level to implement policies and allocate resources that will positively stimulate a change towards conjunctive use-surface water or groundwater	Unless there is a genuine commitment at a national level to implement policies and allocate resources that will positively stimulate a change towards conjunctive use-surface water

(continued)

Table 23.3 (continued)

Drivers of resource use	Groundwater resource	Surface water resource
	(whichever is currently favoured) will remain the primary water source for users	or groundwater (whichever is currently favoured) will remain the primary water source for users
Shallow Water Mitigation	Large volumes of irrigation recharge can lead to artificially high water table levels, which threaten surface and groundwater quality and the environment itself. Government incentives that encourage groundwater use as a mitigation measure ultimately drive groundwater use	

Table 23.4 Assessment of conjunctive use policy based on different parameters

Working principle	Shared use of groundwater and surface water resources
Capacity/Adequacy	Conjunctive use is often part of an overall water resources management based on water balance estimations. It may be used for both urban and rural areas. Its effectiveness differs due to different hydrogeological settings
Performance	High performance, which may have long-term impacts on water availability and quality
Self-help compatibility	Special knowledge is needed else groundwater sources may be exploited
O&M	On-going monitoring and adaptations are needed
Reliability	Only reliable if monitoring and coordination is done well
Main strength	Improves sustainability of water sources
Main weakness	High complexity

geophysics and reconnaissance drilling in order to determine the configuration and storage capacity of the underground reservoir. The ability of an aquifer to act as a storage reservoir can be determined from a number of parameters. The major criterion is that the aquifer material should be highly permeable such that it allows the free movement of water through the soil material. The vertical flow of water should not be restrained by less permeable layers, such as clay lenses. The depth of water table from the ground surface should not be more than 10 m. Aquifer transmissivity should be high enough that the water flows freely from the mount created by the recharge basin.

The quantum of groundwater for conjunctive use has to be decided based on a number of factors. Studies need to be carried out to analyse which of the two sources are cheaper in terms of economy in a particular area. The cost per ha required for the sources will determine the weightage given to groundwater for a particular area. The water supply requirements of an area have to be decided by considering the population growth. Various strategies are planned for conjunctive use, which includes allocation of certain parcels of land to a particular use and allocating surface and groundwater in time so that in a particular season, only surface water is used and in the other season groundwater is used. For the management of conjunctive use, the primary characteristics of surface water and groundwater need to be studied. The major factor is the response time of each resource. Surface water is quite quick, whereas there is lag in response of groundwater. The size of storage of groundwater is large, as the entire region in the vadose zone can be used to store the water. But the surface water storage units are restricted to reservoir capacity and other man—made structures. Another characteristic is the security of supply. The variability of monsoons over the years directly influences the surface water resources in monsoon dependent countries. Thus the reliability on surface water sources is less. On the other hand, groundwater is not much affected by the monsoon patterns, and therefore it is quite reliable. Ownership of the two sources also varies quite a lot. The surface water is considered as a public resource. Whereas land ownership and groundwater are highly correlated in some countries. The typical characteristics of surface water and groundwater are given in Table 23.5.

Conjunctive use is important in coastal areas subjected to very high groundwater abstractions. Higher pumping may result in the forward movement of seawater freshwater interface into the land. This can cause the fresh groundwater to turn saline, making it unfit for domestic uses. A planned

Table 23.5 Typical characteristic of groundwater and surface water (Evans et al. 2012)

S. No.	Characteristic	Groundwater	Surface water
1	Response time	Slow	Quick
2	Time lag	Long	Short
3	Size of storage	Large	Small
4	Security of supply	High	Low
5	Water quality	Poor	Good
7	Ownership	Private	Public
8	Flexibility of supply	Very flexible	Not flexible

conjunctive use strategy where a portion of the demand is met by surface water, lowers the risk of the problem. The demand to be met by each source of water has to be pre-determined by studies. Similarly, conjunctive use can prevent or reduce drainage problems in some areas because storage and water levels are controlled, with wells acting as vertical drains.

The surface water quality is more in the upstream side than groundwater, but quality deteriorates as it flows downstream. The dispersed runoff can be effectively captured by watershed management strategies. Many water conservation measures have been developed along the hill sides to prevent soil erosion and to reduce surface runoff, soil erosion and thereby increasing the infiltration into the aquifers to recharge them. In semi-arid regions, large programmes of soil and water conservation methods along with forestation are practiced to reduce siltation problems in the surface reservoirs resulting from soil erosion in the upper catchment. The primary objective of watershed management is to limit the soil erosion and thereby reducing the sediment accumulation in the surface reservoir downstream.

Another important method of watershed management is artificial recharge, which uses tube wells, shafts or connector wells to convey water to the aquifer. This method is employed in recharging confined and deep seated aquifers with poorly permeable layers between the surface and the aquifer. Since the recharge is done directly into the deep aquifers, there is less probability of evaporation losses. The major problem associated with artificial recharge is rapid clogging of the wells. The most economical way to conduct artificial recharge by injection is to use dual purpose wells, where cleaning of the aquifer can be performed during pumping period. The details of aquifer recharge planning strategies are given in Table 23.6.

The benefits of the optimized use of surface water and groundwater have been studied through theoretical modeling and studies of physical system. They are as follows:

- Economic gains.
- Increase in productivity.
- Energy savings.
- Increased capacity to irrigate larger areas.
- Water resource efficiency.
- Infrastructure development.
- Control on saltwater intrusion in coastal areas.
- Reduction in drainage problems.
- Additional flood control space in reservoirs.

Foster and Steenbergen (2011) emphasize that spontaneous conjunctive use of shallow aquifers in irrigation-canal-commands is driven by the capacity for groundwater to buffer the variability of surface water availability enabling:

- Greater water supply security.
- Securing existing crops and permitting new crop types to be established.
- Better timing for irrigation, including extension of the cropping season.
- Larger water yield than would generally be possible using only one source.
- Reduced environmental impact.
- Avoidance of excessive surface water or groundwater depletion.

The application of conjunctive use to regions with saline groundwater presents both challenges and opportunities. In such situations the major objective is to maintain both water and salt balances. In this context, system managers require great control and precision in canal water deliveries to different parts of the command to maintain an optimal ratio of fresh and saline water for irrigation (Murray Rust and Vander Velde, 1992). The command areas can be divided into separate zones for surface water and groundwater irrigation, depending upon the water quality and aquifer parameters.

Conjunctive water management policies add to drought proofing, it helps in reducing the evaporation losses from reservoirs. The variations in surface storage are more prominent compared to groundwater storage due to the sensitivity of surface water storage to the precipitation that varies with year. Therefore, the role of groundwater is

Table 23.6 Summary of types of aquifer recharge planning strategies (Foster et al. 2003)

Type	General Features	Preferred Application
Water harvesting	**Dug shafts/tanks** to which local storm runoffs are led by gravity for permeation **Field soil/water conservation** through terracing or contour ploughing or afforestation	In communities of fairly low-density population with leaky subsoil Extensively appropriate, particularly on sloping land in upper catchments
In-channel structures	**Check/rubber dams** to confine runoff by sediment retention and clear water **Recharge dam** with reservoir used for bed permeation to generate clear water **Riverbed baffling** to redirect surge and amplify permeation **Subsurface cut-off** by impervious membrane and/or puddle clay in furrow to impound base flow	In gullies with uncertain runoff frequency and high stream slope Upper valley with sufficient runoff and on deep water-table aquifer Wide braided rivers on piedmont plain On broad basins with thin alluvium overlying impervious bedrock
Off-channel techniques	**Artificial basins/canals** into which storm runoff is diverted with pre-basin for sediment removal **Land distribution** by overflow of riparian land occasionally cultivated with flood-tolerant crops	On superficial alluvial deposits of low permeability On permeable alluvium, with flood relief benefits also
Injection wells	**Recharge boreholes** into permeable aquifer horizons used alternately for injection/pumping	Storage/recovery of surplus water from portable treatment plants

prominent and powerful for drought mitigation, where surface water and groundwater are used conjunctively. The benefits can be listed as follows:

- Enhanced yield of past investments in surface water irrigation projects through increased irrigated area, improved water productivity, and expanded production, employment, and income.
- Improved sustainability of groundwater irrigation in regions of intensive groundwater use with inadequate availability of runoff for recharge.
- Enhanced long-term environmental sustainability of irrigated agriculture in salinity dominated environments by improving salt balances and sustaining the productivity of irrigated agriculture.
- Seawater intrusion in coastal areas caused by excess pumping of groundwater. This situation can be brought under control by encouraging the use of surface water resulting in conjunctive management.
- Can reduce drainage problems in some areas because storage and water levels are controlled, with wells acting as vertical drains.
- May provide flood-control space in reservoirs where a portion of the water supply storage has been transferred to groundwater basins

The main impediments to planned conjunctive use identified by Foster et al. (2010), as summarized from their work on examining a number of global examples of conjunctive use, are:

- The often disconnected responsibilities for water management between surface water and groundwater departments at various levels of government. This usually results in a failure to understand the integrative benefits of holistic resource management.
- Lack of information regarding conjunctive use management that can be used to influence and educate both politicians and the general public about conjunctive use benefits.
- Inadequate knowledge of the degree to which privately-driven groundwater use is practiced in irrigation commands, its benefits and its risks.

The constraints in conjunctive use management are lack of technical understanding, ineffective and incompatible institutional structures. To optimize the use of surface water and groundwater the factors that need to be considered are the difference in availability between the two water sources, cost of implementing particular conjunctive use policy including both capital and operating cost and the energy requirements involved. These are the major three factors that need to be considered to develop a planned conjunctive use system. Out of these the difference in availability of the water sources in terms of volume and timing between them is recognized and utilized in planning of conjunctive use policy.

23.4.5 Underground Storage and Production Capacity of the Aquifer

For the conjunctive use design, it is required to estimate the storage capacity of underground reservoirs in order to estimate the volume of water that can be recharged into the aquifers through recharge wells. To obtain a potential yield, the storage capacity of the underground reserve should be some significant fraction of the total surface runoff. An additional important factor that needs to be considered is the productivity of the wells. These wells should be able to discharge sufficient amount of water when in demand. There are different criteria to decide whether an aquifer is suitable for acting as an underground reservoir. The main reason is that there should be sufficient space between the water table and the ground surface to accommodate huge part of the surface runoff during the period which water is not needed. Preliminary studies must to be carried out to investigate the suitability of aquifers for underground storage. This includes accurate hydrogeological investigations including geological mapping, geophysics, reconnaissance drilling etc. The suitability of an aquifer for recharging may be estimated from the following parameters:

- Availability of a highly permeable material at the surface which allows the water to percolate easily.
- The depth of the water level from the ground surface should not be less than 5–10 m.
- The unsaturated zone should present a high vertical permeability, and vertical flow of water should not be restrained by less permeable clayey layers.
- Aquifer transmissivity should be high enough to allow water to move rapidly from the mound created under the recharge basin but should not be too high (as in karstic channels) so that water cannot be recovered.

An adequate transmissivity for recharge is also a good indicator of the aquifer capacity to produce high well discharge and therefore easily to return the water stored.

23.4.6 Problems and Constraints Related to Water Resources

A key characteristic of conjunctive use is that it usually aims to use the very large natural groundwater storage associated with most aquifers to 'buffer' water-supply availability against the high flow variability and drought propensity of many surface watercourses—making it especially important for the mitigation of climate change impacts, which in many scenarios will lead to increased intensity of droughts. The planning and management of water resources often come across various problems and constraints. The major constraints that occur in various countries are generalized as follows:

- Limitation in the available water resources arising due to lack of conservation, control and protection of the existing resources.
- Escalating acceleration of economic growth together with unmanageable rate of population growth, which is directly dictating excessive water utilization and environmental degradation.
- Careless deployment of upper catchment area of the rivers such as land conversion into industrial and human settlement leading to the detrimental condition hydro-ecology, together with their unwanted consequences, and hence, deprivation of appropriate balance of water resources ecosystem.
- Injudicious exploitation of surface water and groundwater sources lead to the acceleration of environmental degradation in addition to water related disasters such as flooding, droughts, and landslides, together with their related consequences for human health.

The hydrological settings also play a very important role in the conjunctive use program. The variation of the dynamics and constraints of conjunctive use with hydrogeological setting is given in Table 23.7.

23.4.7 Advantages of Conjunctive Use

Conjunctive use combines the advantages of groundwater storage with the surface water system. As a result, there is much greater water supply security by taking into consideration the natural groundwater storage. Larger net water supply yield can be achieved, greater than using one source alone. Timely delivery of irrigation water, since water can be deployed at any time of shortages especially due to lack of rainfall and canal water availability at critical times of crop growth cycle. Apart from these, environmental impacts are reduced by tackling land waterlogging, salinization, excess river flow depletion and aquifer exploitation. The conjunctive use policies have their own advantages, limitations and challenges. Among the advantages the main one is that the space between ground level and water table can be utilized to store surface water during the runoff time, which otherwise remain wasted. River is used to transport water from the aquifer to where it is needed when river discharge is too low on its own as often happens in summer. Thus conjunctive use can be implemented to reduce the abstractions from river, when the river flow is low, by using groundwater. Consequently, the problems such as water logging and groundwater overuse can be reduced leading to sustainable management.

Table 23.7 Variation of the dynamics and constraints of conjunctive use with hydrogeological setting (Foster et al. 2010)

Hydrogeological typology	Examples	Dynamics of conjunctive use	Constraints on conjunctive use
Upstream Humid or Arid Outwash Peneplain	Indian Punjab-Indus Peneplain, Upper Oases, Mendoza-Argentina, Yaqui Valley, Sonora-Mexico	Deep groundwater table with major groundwater recharge from rivers and unlined canals, where river flow reduces seasonally groundwater use predominates	In more arid areas widespread natural soil salinity which can be mobilized to groundwater during irrigation development and requires careful management
Humid but Drought-Prone Middle Alluvial Plain	Middle Gangetic Plain-India, Middle Chao Phyra Basin-Thailand	Shallow groundwater table and surface water and groundwater resources generally freely available	Excessive recharge in canal head-water sections can lead to serious soil water-logging/salinity and poor canal-water service levels in tail-ends sections causing excessive groundwater pumping
Hyper-Arid Middle alluvial plain	Middle Indus Plain-Pakistan, Lower Ica Valley- Peru, Tadla-Moroccon Tihama-Yemen	Major rivers and primary irrigation canals generate locally important fresh groundwater recharge/ lenses, in some cases further augmented by spate irrigation	Conjunctive use of groundwater important to counter rising water-table problems, and concomitantly reach higher cropping intensity, but extreme care needed to avoid saline-water encroachment
Downstream Alluvial Plain or Delta with confined Groundwater	Ganges Delta-Bangladesh, Lower Oasis Mendoza-Argentina, Nile Delta-Egypt	Irrigation predominantly from major rivers and associated canals but, where seasonal river flow reduction marked, supplementary groundwater irrigation can be important	Alluvial aquifers often semi confined by surficial clayey-silts(also sometimes with saline phreatic groundwater)—thus water well use constrained by recharge limitation and sometimes by saline-water mobilization

There are also limitations to the conjunctive use policy because of the high energy consumption for the operation of pumping wells, which can happen due to large fluctuations in water levels. The management plan developed for the region should be appropriate otherwise it will lead to additional expenses. Conjunctive use demands installation of appropriate recharge structures, which can also be expensive from the economic point of view. There may also arise administrative difficulties in defining appropriate rates for groundwater and surface water at the time of need. Also there should be people's participation involved for successfully executing the conjunctive use program.

Storing of the excess runoff to the ground is again a challenging issue by managing the aquifer recharge. Managed aquifer recharge is not a simple process and it is difficult to do on a usable field scale as it is difficult to absorb large volumes of flood water in a short time. This approach involves transferring water from surface to underground, which is done by spreading it over the surface and allowing it to percolate down or with the help of injection wells. Therefore, these methods work well in areas which are highly permeable where the land is inexpensive. The aquifer used should be an unconfined one.

Some of the major advantages are listed below.

- The total yield is increased as there is reduction in loss of freshwater sources to oceans and also reduction in evapotranspiration from reservoirs. Thereby reducing the losses, yield can be increased.
- The variations in runoff over a year can be balanced through conjunctive use, where there is too much water in some months and too little water in other months.
- There is security in the water supply close to consumers, in case if there is interruption of surface water by storing it in groundwater basin close to the users.
- Can operate with smaller surface-distribution system because of wide dispersion of wells.

- Proper demand management by ensured water supply during droughts and supply interruption. This becomes a valuable contribution to demand management.
- In some areas, it can reduce the drainage problems as storage and water levels are controlled by means of wells that act as vertical drains.
- Conjunctive management provides flood-control space in reservoirs in cases of huge downpour, where a portion of the surface water supply storage has been transferred to groundwater basins.

The potential benefits of using surface water and groundwater conjunctively and its implications on agricultural productivity, flood management and drinking water supply are given in Fig. 23.12. To maximize the benefits from conjunctive use it is necessary to create a balance between local recharge and groundwater.

The groundwater parameters that are to be considered in implementing conjunctive use and the related constraints and the management measures are listed in Table 23.8.

23.4.8 Models for Conjunctive Use of Surface Water and Groundwater

Optimization models and methods are effective tools for allocating water resources and providing decision supports. A number of optimization management models have been proposed for conjunctive use of surface water and groundwater (Sethi et al. 2002; Vedula et al. 2005). Irrigation is the largest water user in the world, accounting for about 70% of global water withdrawals and about 90% global consumptive water use (Döll et al. 2012). Karamouz et al. (2007) developed a methodology for conjunctive use of surface and groundwater resources in the southern part of Tehran, the capital city of Iran, with emphasis on water quality using Genetic Algorithms (GAs) and the Artificial Neural Networks (ANNs). The results of a groundwater simulation model are used to train the ANNs based simulation model and the model is then linked to the GA based optimization model to develop the monthly conjunctive use operating policies.

Azaiez and Hariga (2001) presented a single-period planning model for conjunctive use of surface water and groundwater for a multi-reservoir system, with stochastic inflow to the main reservoir and irrigation water demand. Barlow et al. (2003) developed a conjunctive management model through coupling numerical simulation with linear programming optimization model into a general framework to determine sustainable yield of the alluvial-valley stream-aquifer systems. Modifications were made by implementing dynamic optimization techniques to determine the surface and groundwater sources to manage the resources conjunctively. Karamouz et al. (2004) proposed a simulation-based dynamic programming optimization model for conjunctive surface water and groundwater planning and management in Iran. Management objectives of minimization of irrigation water supply shortages and pumping costs,

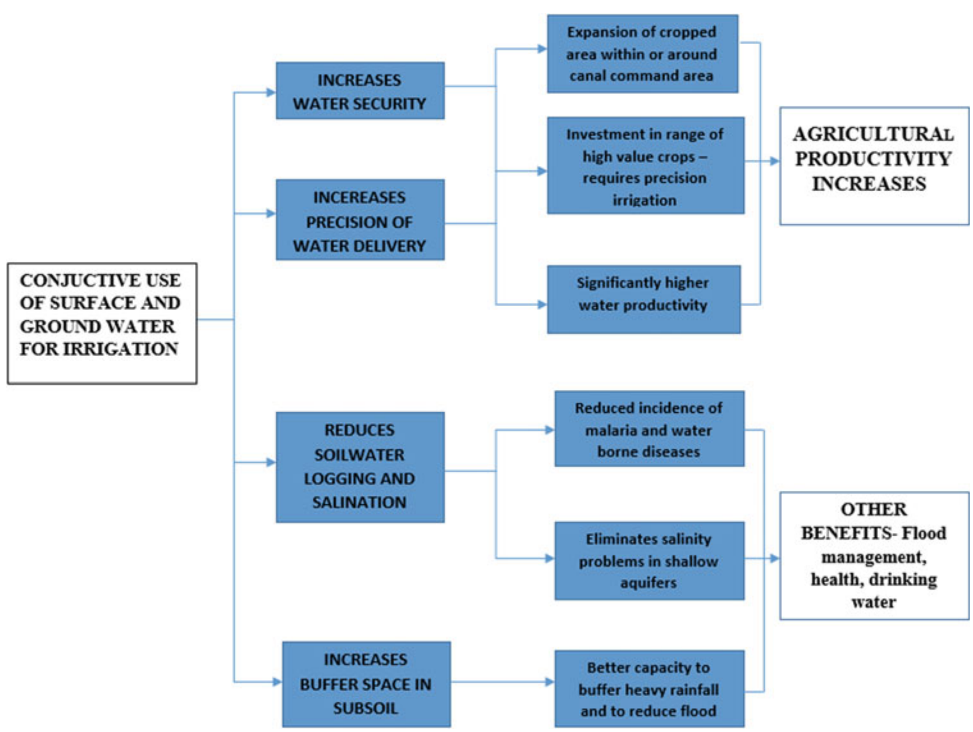

Fig. 23.12 Potential benefits of conjunctive use of surface water and groundwater (Foster et al. 2010)

Table 23.8 Management measures and instruments for conjunctive use of groundwater (Foster et al. 2010)

Groundwater parameter	Related considerations	Management measures and instruments
Aquifer characteristics	Storage capacity of shallow and intermediate depth aquifers critical	Preferable for surface water irrigation systems to avoid areas underlain by low permeability strata, which are likely to result in soil waterlogging and salinization unless elaborate and costly drainage provided
Recharge excess in local groundwater balance (rising groundwater table and soil waterlogging)	Balance needs to be struck between groundwater recharge and discharge by all mechanisms operative and any excess recharge used productively	Surface water diversion can be curtailed to reduce excess recharge to groundwater
		Private water well development may be stimulated through a range of incentives
		Land reclamation and drainage measures may be required to kick start intensive cultivation in a given area
Recharge deficit in local groundwater balance (falling groundwater table and saline encroachment)	Need for restoration of balance between discharge through water wells and groundwater recharge	Surface water resources may be diverted and reallocated with corresponding reduction in direct groundwater use
		Recharge enhancement measures could be introduced utilizing excess surface water flows through irrigation canals
		Promotes less water consuming crops on same irrigated area to reduce consumptive water use
Groundwater quality	Cautious analysis of any incipient groundwater salinity problems in and around area of irrigation development	Inhibition of further recharge and mobilization in areas with saline groundwater through selective irrigation canal lining
		Coastal areas experiencing excessive groundwater abstraction and saline intrusion may be supplied with additional surface water
		In certain instances like fish farming ponds, saline groundwater may be specially used so as to attain sustainable groundwater management

and control of average groundwater table fluctuations were considered. Khare et al. (2006) developed a linear programming model for conjunctive use management of surface water and groundwater resources in the Sapon irrigation command area in Indonesia. Net benefits from cropping activities were maximized considering water demand and availability. An increase of groundwater development was suggested to handle the surface water shortage problems.

More recently, Cheng et al. (2009) advanced a linear programming model to optimize the conjunctive use of surface water and groundwater for irrigation planning in Taiwan. Yang et al. (2009) presented an integrated multi-objective planning model for conjunctive surface water and groundwater management in Taiwan by considering multiple objectives of simultaneous minimization of fixed and operating costs. The model integrated a multi-objective genetic algorithm, constrained differential dynamic programming, and groundwater simulation model named ISOQUAD into a general framework. Safavi et al. (2010) proposed a simulation–optimization method for conjunctive use of surface water and groundwater on a basin-wide scale in Iran. The method incorporated an artificial neural network to simulate the variations of groundwater levels, and then used a genetic algorithm to solve the simulation-based optimization model.

Chang et al. (2013) developed a fuzzy inference system for conjunctively managing surface water and groundwater use by incorporating expert knowledge and operational policies with the fuzzy rules. Safavi and Esmikhani (2013) presented a simulation–optimization model for conjunctive use of surface water and groundwater in the Zayandehrood river basin in Iran. Surrogate models were developed by using support vector machines to replace surface water and groundwater simulation models in the optimization management model with the objective of minimizing water shortages for satisfying irrigation demands, subjected to a series of water-related constraints such as controlling cumulative water table drawdown and maximizing irrigation system's capacity.

23.4.9 Constraints in implementing conjunctive-use program

Some of the constraints in implementing a conjunctive use program are as follows:

- Inadequate water supply for recharging groundwater basins.
- Insufficient underground storage space to accommodate recharge water.
- Inadequate infiltration and percolation rates for basin recharge.
- Unavailability of land for recharge areas at affordable costs.
- Existing wells are not adequate to withdraw groundwater needed to meet demand during dry periods.
- New surface reservoirs or change in operation of existing reservoirs upstream from stream-diversion point or upstream from surface reservoirs used in conjunctive-use program could reduce quantity or degrade quality of water available for program.
- The quality of the available water may get altered by the change in land use pattern.
- Water rights and uses downstream from point of diversion from a stream used to recharge a groundwater basin must be protected. Also, natural stream recharge to downstream groundwater basins must be maintained.
- Groundwater levels should not be allowed to rise as part of recharge and storage activities to an elevation that would cause flooding of low-lying agricultural areas and building basements and inundation of the lower portions of refuse dumps and sanitary landfills. Without proper control, containment, or clean up measures, groundwater levels should not be allowed to rise and dissolve harmful chemicals in the vadose zone.
- In basins with adverse salt balances, quantity of surface water stored in groundwater basins as part of a conjunctive use may be restricted if it is inferior in quality to that of the native groundwater.
- A subsequent drought may occur before basin can be refilled following earlier surface water shortage. Periods between wet and dry periods may be seasons or many years.

These are some of the difficulties associated with the implementation of a conjunctive use plan in the field. One of the case studies of conjunctive management carried out in India is discussed below:

Box 23.1 Case Study: Benefits of Conjunctive Management in Madhya Ganga Canal Project, Uttar Pradesh, India (IWMI 2002)

The excess flood water during the monsoons was removed using lined canals. A simple modification to the existing structure can create positive impacts. The state of Uttar Pradesh, India had a network of earthen surface drains to control floods and waterlogging, which was constructed in the 1950s. After the 1950s, intensification of groundwater use created new opportunities for conjunctive management by building check structures at suitable intervals to promote groundwater recharge with monsoon floodwaters. In the course of a 10-year collaborative study, scientists from the International Water Management Institute (IWMI), Roorkee University, the Water and Land Management Institute, and the Uttar Pradesh Irrigation Department found that using these modified drains for monsoon flood irrigation produced the following benefits:

- A 26% increase in net farmer income.
- A decrease in average depth of groundwater from 12 m in 1988 to 6.5 m in 1998.
- Annual energy savings of 75.6 million kilowatt hours and pumping cost savings of Rupees 180 million.
- An increase in canal irrigation from 1,251 hectares in 1988 to 37,108 hectares in 1998.
- A 15-fold increase in rice cultivated area.
- A 50% reduction in conveyance losses in canals.

23.4.10 Institutional Requirements for Conjunctive Use

Conjunctive use and management of groundwater and surface water resources require strengthening of the institutional arrangements for water resource administration, coordination among the irrigation, surface water and groundwater management agencies, and gradual institutional reform learning from carefully monitored projects.

In alluvial regions the authority for water management are mainly concentrated in a surface water oriented agency, because of the relationship of surface water management measures to historical development like reservoirs and irrigation canals. This has led to little emphasis on complementary and conjunctive groundwater management, with responsibility for this resource in a minor department or completely separate minor agency. Therefore, reforms are required for strengthening groundwater management for improved conjunctive use policy and planning. Such agencies will need to promote changes in the participation of water users in water resource use and management to better respond to conjunctive use opportunities.

Conjunctive management is a complex plan where the predominant resource is groundwater. This is mainly because of divergent interests amongst some users, split government responsibilities and frequent lack of well-trained personnel. Moreover, the institutional requirements to implement management measures call for approaches that tend to be locality specific. There is an inevitable need for better information and proper communication on conjunctive use potential between private and public stakeholders. An Information and Communication effort from the appropriate water resource agency would facilitate the social learning and institutional development process and lead to the promotion of attitude changes and the acceptance of implementable regulations.

The implementation of conjunctive use management within existing commands, where existing infrastructure and historical governance are in place, rely on certain basic principles. They are listed as follows:

- Detailed knowledge of the characteristics of surface water and groundwater, existing system operation and demand of the crops should be taken into account while planning a conjunctive use policy.
- The primary aim should be given to optimization of water supply and demand balance, irrespective of existing institutional, governance and regulatory models.
- The combined surface water/groundwater system and their use should be managed so as to optimize net economic, social and environmental benefits taking into account national energy, food security, population and poverty reduction, sustainability and climate change policies and programs.
- Stakeholder participation should be encouraged.

From an operational point of view, some key guidelines for implementing conjunctive management include:

- A technically robust understanding of stream-catchment-aquifer interactions.
- A water balance that is inclusive of connectivity between the surfacewater and groundwater systems.
- Technical assessment techniques commensurate with the understanding of the hydrological system and with explicit recognition as to the limitations to the validity and applicability of information.
- A strategic monitoring program for the catchment including the alignment of groundwater and surface water monitoring. Monitoring regimes should recognise the differences between assessment monitoring and management monitoring. Management monitoring refers to the monitoring of management rules and processes whilst assessment monitoring refers to monitoring of the technical or scientific aspects of stream-aquifer interactions (Fullagar 2004).

In summary, conjunctive use planning is the structured water planning process whereby the different characteristics (technical, economic, social and institutional) of groundwater and surface water are compared and weighed against each other so that the optimum use of the two water sources is achieved. The fact that this rarely occurs throughout the world is testament to the entrenched water institutional structures and the very poor understanding of fundamental natural and technical processes.

23.4.11 Feasibility of Conjunctive Water Management Projects

The feasibility of a project depends on the hydrogeological constraints, source of available water, the conveyance system employed and the recharge and extraction facilities. Among the hydrologic conditions, the major ones include the location of recharge zone for the corresponding aquifer from which pumping is done. Similarly, the mechanism of recharge and the rate at which it is given also play a major role. Apart from that the characteristics of sub soil such as infiltration capacity, porosity, hydraulic conductivity, and specific yield also play a major role in deciding the feasibility of a conjunctive use project.

Water source and the mode of conveyance to the recharge location is another influencing factor. Water sources include imported water, local runoff, and treated wastewater. This water is used for storage in groundwater. Conveyance is necessary to transport the water from source to recharge location and the systems include lined and unlined canals, pipelines, streams and transport facilities by trucks. The five project feasibility considerations of conjunctive management —hydrogeologic feasibility, available groundwater storage capacity, groundwater source, conveyance, recharge and extraction facilities, and pre- and post-treatment facilities (under certain circumstances)—are the fundamental physical elements that are indispensable for conjunctive management to be functional. If any of these physical elements are missing, it will make conjunctive management impractical and unworkable.

The development components that come into picture while considering a conjunctive management project are discussed below.

23.4.11.1 Groundwater Planning and Management

Groundwater planning is the process to decide what needs to be accomplished to preserve the natural resource. Groundwater management denotes the set of activities that direct how to implement management actions identified during the planning step as contained in the groundwater management plan. The strategy aims to improve specific aspects of the management of groundwater resources in individual basins or portions of basins across a region or throughout the state. The improvements pertain to many aspects of groundwater management, including implementing programs or projects to manage and protect groundwater, characterizing and increasing knowledge of individual groundwater basins, identifying basin management strategies or objectives, planning and conducting groundwater studies, and designing and constructing conjunctive management projects.

23.4.11.2 Project Construction and Operation

Project construction and operation may include construction and operation of treatment facilities, conveyance facilities, or spreading basins as well as installation and operation of monitoring, production, and injection wells, and drilling of test holes.

23.4.11.3 Institutional Structures

As with other types of projects, conjunctive management projects must also adhere to local ordinances in addition to state and federal laws and regulations. Institutional structures include laws, regulations and ordinances, contract and agreements, political support, public private partnership, governance.

23.4.11.4 Funding

Funding sources include state and federal grants and loans, state and local bonds, state and local taxes, assessments, and fees, and public–private partnerships. As with other types of projects, a conjunctive management project also has associated cost components, and financing and economics issues. As a result, available sources of funding have to be identified and secured to successfully plan, design, and implement a conjunctive management project.

23.4.11.5 Organizational Capacity Building

Organizational capacity building is the process of equipping entities, usually public agencies, with certain skills or competences, or upgrading performance capability by providing assistance, funding, resources, and training. This is important for the continued operation and long-term success of conjunctive management projects. The five project development components—groundwater planning and management, project construction and operation, institutional structures, funding, and organizational capacity building—bring a conjunctive management project to fruition.

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S. Mohan is currently serving as Professor in Environmental and Water Resources Engineering, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, TamilNadu. Dr Mohan's area of interest includes Environmental Engineering, Contaminant Transport Modeling, Wastewater Treatment, Environmental Impact Assessment, Water Resource Systems and Sustainability Engineering. He has guided 21 PhDs and published more than 150 papers in reputed journals. He has overall 32 years of rich experience in teaching, research and consultancy

Neenu Kuipally is currently a Ph.D., Research Scholar in the Environmental and Water Resources Engineering, Department of Civil Engineering at Indian Institute of Technology Madras. Her research interests include Groundwater Modeling, Particle Tracking and Groundwater Management. She has worked on various groundwater modeling environments such as MODFLOW, MT3DMS, SEAWAT and GMS during her academic period of study

Storage Reservoir Operation and Management

24

Stephan Hülsmann, Karsten Rinke, Lothar Paul, and Cristina Diez Santos

Abstract

Reservoirs provide diverse water-related services such as storage for energy production, water supply, irrigation, flood protection and provision of minimum flow during dry periods. When reservoirs are meant catering for multi-purposes, trade-offs and synergies between services provided need to be considered through their proper management and operation. This chapter reviews multipurpose multiunit reservoir systems including their optimum management and tools and decision support systems available for that.

Keywords

Integrated reservoir management • Ecotechnology • Watershed management • Modelling tools • Sedimentation • Nutrient control • Multiunit • Multipurpose

S. Hülsmann (✉)
United Nations University Institute for Integrated Management of Material Fluxes and of Resources, UNU-FLORES, Dresden, Germany
e-mail: stephan.huelsmann.dd@gmail.com

Global Change Research Institute CAS (CzechGlobe), Brno, Czech Republic

K. Rinke
Department of Lake Research, Helmholtz-Centre for Environmental Research (UFZ), Magdeburg, Germany
e-mail: karsten.rinke@ufz.de

L. Paul
Neunzehnhain Ecological Station, TU Dresden, Lengefeld, Germany
e-mail: lopapo@t-online.de

C. D. Santos
International Hydropower Association (IHA), Sutton, London, UK
e-mail: Cristina.diez-santos@hydropower.org

Abbreviations

ATT	Arbeitsgemeinschaft Trinkwassertalsperren
AWWA	American Water Works Association
DOC	Dissolved Organic Carbon
DSS	Decision Support System
EDF	Électricité de France
EUR	Euro
FFH	Flora-Fauna-Habitat
ICOLD	International Commission on Large Dams
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
MRC	Mekong River Commission
RT	Retention Time
SDG	Sustainable Development Goals
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WWC	World Water Council
WWF	World Wildlife Fund
WWTP	Wastewater treatment plants
ZAMCOM	Zambezi Watercourse Commission
Zmix	Mixing depth in stratified water bodies
n.d.	Not dated

24.1 Introduction

The need to allocate and distribute water to specific uses and services and the respective users has inspired mankind to construct various types of water storage systems and the associated distribution infrastructure. In fact, it can be argued that water resources management is intimately linked to human civilization (Yevjevich 1992), with first dams and

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impoundments built millennia ago. In this chapter we will focus on reservoir systems built within or along rivers using dams. Such systems, due to technological requirements, have been built since the first half of the last century. We consider particularly, but not exclusively, those categorized as large reservoirs according to the definition of the International Commission on Large Dams ("International Commission on Large Dams (ICOLD)," (n.d.)), i.e. those "with a height of 15 m or greater from lowest foundation to crest or a dam between 5 and 15 m impounding more than 3 million cubic metres".

Reservoirs are essential for various water related services, including storage for energy production, water supply, irrigation, but also transportation, recreation, flood protection and ensuring minimum flow during dry periods. Their energy storage capacity offers opportunities to facilitate the integration of other renewable energy sources with intermittent power supply. Overall, they are thus essential for achieving various Sustainable Development Goals (SDGs, (United Nations 2015), particularly SDG 2 (zero hunger), 6 (clean water and sanitation), 7 (affordable and clean energy), but also SDG 8 (decent work and economic growth) and 9 (industry, innovation and infrastructure) (van der Bliek et al. 2014).

Most reservoirs have been built for one main purpose, i.e. providing water for one particular use, with other uses having a less dominant role. Based on data from the ICOLD database 74% of registered dams (38,452 in total, status 2015) are single purpose dams, about half of them serving irrigation, hydropower being the only use in 20% of these single-purpose reservoirs, followed by water supply (13%) and flood control (9%) (Branche 2015). In the case of consumptive uses (irrigation, water supply), but also concerning flood control, it can be generalized that most reservoirs were built for managing a temporal and/or spatial mismatch of water requirements and water availability, e.g. for irrigation during dry periods by absorbing excess water for later use. The primary use, according to the needs of people in the region was typically reflected in the location and main features of the respective reservoirs (Table 24.1). Multipurpose reservoirs are, however, more and more becoming the norm and during rehabilitation of older dams in many cases additional uses or a shift in priorities is considered (see Sects. 24.2 and 24.6).

These systems bear many similarities, but also considerable differences compared to natural lakes which need to be considered for effective management (Jorgensen et al. 2005). The type and extent of differences depend on the specific construction type and uses of reservoirs, but also on changing hydrologic conditions. Basically, damming a lotic system (river) turns it at least partly into a lentic or lacustrine, thus lake-type system. This shift will be more pronounced the longer the retention time and the deeper the reservoir and typically results in vertical differentiation of the water body related to thermal stratification (see below and Fig. 24.1). Typically, reservoirs also have a characteristic longitudinal differentiation: the inflow region more or less retains its lotic (riverine) characteristic, while after a transition zone the main body of water, typically close to the dam, shows more lacustrine characteristics. Important features of reservoirs which have decisive implications for reservoir management include:

1. Size of watershed in relation to area of the water body
   This ratio strongly depends on the location of the reservoir within the river system and is higher, the further downstream the reservoir is. Compared to natural lakes the ratio is typically high—with strong implications for the theoretical water retention time and the import of matter.
2. Theoretical water retention time (RT)
   The value of RT is computed as V/Q based on the average values of volume (V) and inflow (Q). RT is indeed a theoretical value since depending on the mixing/stratification conditions certain layers of water may pass through the reservoir much more quickly than others. Compared to natural lakes RT is typically much lower in reservoirs.
3. Import of matter
   Given the relatively large size of the watershed and low values of RT the import of matter into reservoirs is higher than in lakes—and among the major concerns and target command variable of reservoir management, which generally aims at reducing the import. This concerns sediment load in a range of particle sizes, leading to a

Table 24.1 Typical features of reservoirs serving various purposes

Primary use	Size	Depth	Retention time
Drinking water supply	Small–medium	Deep	High
Hydropower	Medium–large	Deep	Variable
Pumped storage	Small–medium	Deep	Extremely variable
Irrigation	Small–medium	Shallow	High
Navigation	Large	Deep	Short
Flood protection	Small–medium	Shallow	Short/variable

Modified from Straskraba et al. (1993), Jorgensen et al. (2005)

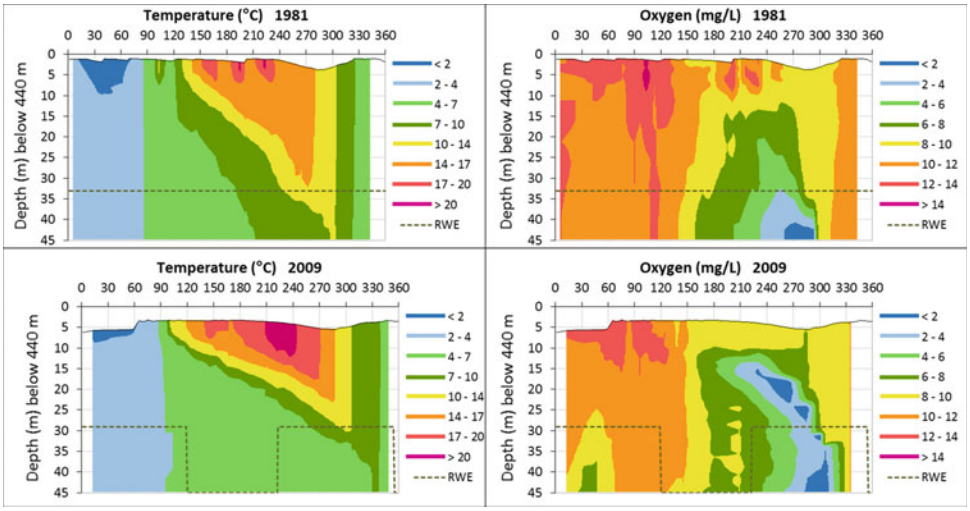

Fig. 24.1 Examples of stratification patterns in Saidenbach Reservoir (mainly serving drinking water provision and flood protection) in Saxony, Germany. Left panels display temperature, right panels show oxygen concentrations. The x axes give day of the year. The dashed line (RWE) indicates the depth of raw water withdrawal. 1981 represents a relatively cold year, thermal stratification lasted from May through October. High water withdrawal resulted in strong exploitation of the hypolimion, where oxygen deficits developed towards the end of the stratifying period. 2009 represents a warm year, stratification lasted from April through Mid-November. Exploitation of the hypolimion was less pronounced due to low water withdrawal rates, which resulted in extension of oxygen deficits higher up in the water column

loss of storage volume, the import of nutrients (mainly nitrogen in various forms and phosphorus) causing eutrophication, dissolved organic carbon and further pollutants from point or non-point sources.

4. Morphometry
   The typical longitudinal gradient in water depth, increasing towards the dam, is a clear difference to natural lakes and provides management options via withdrawal regimes.
5. Outlet characteristics/water withdrawal regimes
   Natural lakes have, if at all, a surface outflow. The fact that maximum water depth in reservoirs is typically close to the dam provides the opportunity to withdraw water from various depths. All reservoirs possess a bottom outlet, a spillway for flood relief and typically selected outlets in respective depths (Fig. 24.2), depending on the purpose. During rehabilitation of dams in many cases both the withdrawal capacities as well as the number of outlets in several depths were increased.
6. Water level fluctuations
   Water demands for various uses result in higher water level fluctuations in reservoirs than in lakes. This implies that typical shoreline vegetation zones found in lakes such as reed belts are not or poorly developed in reservoirs, which means buffer zones and habitats for many organisms are largely lacking. Barren shorelines are also prone to sediment resuspension resulting in sediment focusing, the accumulation of sediments in the deepest water layers.

All these factors have important effects on water quantity as well as quality in terms of physico-chemical characteristics, the biological structure and respective ecosystem services. Management options will be discussed in Sect. 24.4. Basic interrelations and impact on water quality is outlined below.

A basic feature of lacustrine systems is their tendency to stratify, leading to a distinction into hydrologically shallow (non-stratified) or deep (at least temporally stratified) reservoirs. Given RT is high enough, besides depth the wind fetch is a decisive factor which determines whether a reservoir stratifies or not. Most large reservoirs fall into the deep/stratifying category. Deep reservoirs in the temperate or subtropical zone display seasonal stratification with high density differences along the vertical axis, typically based on thermal differences, while tropical systems normally stratify only weakly due to low density gradients. Under conditions of thermal stratification, a warm epilimnion establishes in the upper water layers and is separated from the deep and colder hypolimnion. The mixing depth Z_{mix}, characterizing the transition between both layers, is a key variable determining physico-chemical and biological processes in the water body. Figure 24.1 provides examples of stratification patterns of a reservoir located in the temperate zone (Germany) which can be classified as dimictic (two mixing periods per year): two brief periods of complete mixing in spring and autumn can be distinguished from a long stratification period in summer and shorter period of inverse stratification in winter, when the coldest water layers are close to the surface

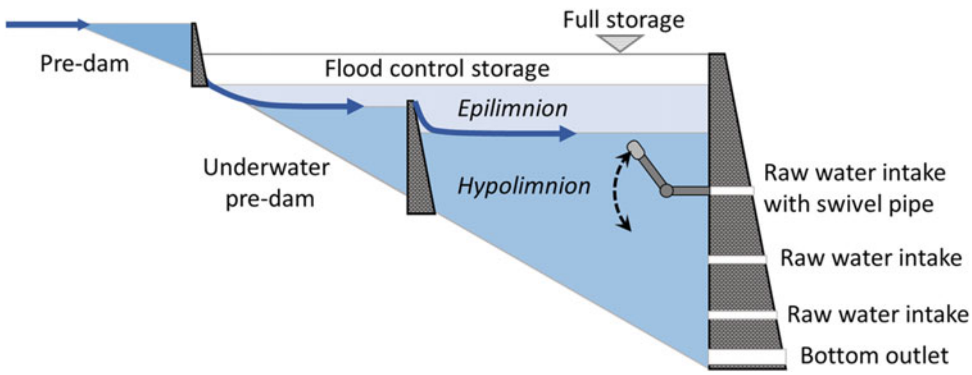

Fig. 24.2 Schematic longitudinal cross-section of a drinking water reservoir serving also for flood protection and exhibiting thermal stratification. Several potential technical measures which increase management options are indicated: a pre-dam for sediment and nutrient control, supplemented by an underwater pre-dam serving the same purpose; various options for water withdrawal in the main dam provide opportunities to (i) adapt water withdrawal depth for water quality management within the reservoir as well as in the downstream river and (ii) to increase withdrawal capacities for more efficient flood management

under ice. The interaction of stratification with water withdrawal regimes and climatic impacts will be explained in Sect. 24.4.

Another key variable is the vertical gradient in light conditions, allowing photoautotrophic organisms, mainly phytoplankton, to grow, produce oxygen and take up CO_2 in the euphotic zone, while below a critical depth organic substances and oxygen are consumed and CO_2 is produced. This may lead to anoxic conditions in the hypolimnion (see Fig. 24.1) with respective consequences for the vertical distribution of organisms and chemical processes. A detailed discussion of water quality implications of stratification is given in Jorgensen et al. (2005). A comprehensive overview of the main elemental cycles within the water body of lakes and reservoirs is provided in Uhlmann et al. (2011). The relatively higher eutrophication potential of reservoirs compared to lakes (due to larger size of watershed and high rates of matter import) implies that much organic material is produced, leading to water quality deteriorations and to high authochthonous sedimentation, which adds to the allochthonous sedimentation. One major concern of integrated reservoir management and operation is thus on limiting the import and the internal production of matter due to its impacts on storage capacities and on water quality, which may limit certain uses and services provided by reservoirs.

In this sub-section we first explore the interrelations between concurring and partly competing uses of multipurpose reservoirs as well as potential for synergies. After outlining specific challenges of reservoir management we put ample emphasis on discussing management options and tools, finishing with some general conclusions.

24.2 Trade-Offs and Synergies Between Services Provided by Multi-purpose Reservoirs

Water and the associated storage infrastructure often and increasingly serve multiple uses: water is needed for irrigation for crop production, for domestic and industrial use, aquaculture, energy production and storage, ecosystem services, recreation and navigation. In addition, storage capacity is required for flood control and drought management. All of these concurring and partly competing water uses need to be considered to maximize co-benefits, minimize trade-offs and deliver services in a synergetic way. This balancing needs to take the temporal variability of water demands as well as site-specific priorities into account.

Different water uses vary considerably in terms of both variability and predictability of water demands (Table 24.2). For example, the daily and seasonal variability for hydropower can be quite stable and highly predictable. However, if hydropower is mainly or additionally used to buffer the erratic energy provision from intermittent renewables such as wind and solar energy, variability can be much higher and predictability rather low. This function of water as energy storage can support the integration of other renewable energy sources and is expected to become increasingly important (Harby et al. 2013; Hülsmann et al. 2015). Water demands for domestic purposes and industrial use are typically varying both daily and seasonally in a predictable way. Water providers are facing the challenge that demands for specific domestic uses (e.g. bathing, gardening) increase particularly at times of limited water supply during summer periods (Rathnayaka et al. 2015) and is expected to increase with global warming (Wang et al. 2017). The same holds true for irrigation. While the general demand during growing seasons is well predictable, the actual water demand depends on the actual weather conditions and is particularly high when supply is low. Making discharges to supplement river downstream from reservoirs is a widespread management practice in central Europe where reservoirs are used to keep the discharge in downstream rivers above a critical level in order to provide the river ecosystems with a certain dilution potential. This becomes important when these rivers receive effluents from wastewater treatment plants (WWTP), e.g. in urban areas, and tolerable pollution loads are defined by the immission principle (in contrast to the emission principle which focuses on thresholds of pollution).

The relations between these various uses differ according to the actual combination in single systems. A specific case which is always in a competitive relation to other uses is flood control since it requires empty space instead of a filled reservoir. Typically, in respective reservoirs a specific portion of the available volume is reserved as flood control space (Fig. 24.2). This space can be adapted based on shifting priorities. A centennial flood in Saxony, Germany, in 2002 resulted in adapted management plans and increased flood control space of reservoirs in the region, thus limiting the maximum available water for other uses, most importantly drinking water supply (Sieber and Socher 2003).

Consumptive uses such as water for domestic or industrial use or for agriculture (irrigation) are clearly competitive. Under conditions of water scarcity allocation would have to follow given priorities which can be adapted and may change according to specific seasonal conditions. In many cases and many regions, the number of concurring uses of multifunctional reservoirs is limited due to specific conditions and requirements of that region. For example, in Germany many reservoirs are located in the central mountains mainly serving as drinking water reservoirs ("Arbeitsgemeinschaft Trinkwassertalsperren e.V." (n.d.)), for flood protection and some hydropower. In those areas, typically neither industrial use nor irrigation plays a role. In a recent collection of 12 case studies of multipurpose reservoirs only three systems serve both water supply and irrigation (Branche 2015). More common are combinations of hydropower and irrigation or hydropower and flood control.

Hydropower differs from other uses since water is not directly consumed and at least theoretically the water driving turbines can still be used for other purposes, thus offering opportunities for synergies. In many cases, these opportunities were, however, not realized. Considering the multiple uses of multipurpose hydropower reservoirs in a comprehensive way was the aim of an initiative by Électricité de France (EDF) and the World Water Council (WWC). The SHARE concept (Branche 2015, 2017) was proposed as framework to address the issue of competing water uses in reservoirs where hydropower is one of them. In this context SHARE stands for shared vision, shared resources, shared responsibilities, shared rights and risks and shared costs and benefits. It also stands for **S**ustainability approach for all users, **H**igher efficiency and equity among all sectors, **A**daptability for all solutions, **R**iver basin perspective for all and **E**ngaging all stakeholders. Twelve case studies from all continents were analysed, the respective reservoirs served at least two, typically three or more purposes. A general outcome of this analysis was that besides the mentioned general principles which should be applied as far as possible, the decision how to allocate water between the different uses and users is always case-specific. While generalisations about the "how to" are thus not possible, the case studies do provide valuable indications about suitable institutional arrangements, e.g. basin committees (see also Sect. 24.2) and about management tools, ranging from planning documents and guidelines to tariff systems and data sharing policies and platforms (see Sect. 24.9).

The case studies analysed within the SHARE initiative provide various examples of co-benefits and synergies. In the Durance-Verdon basin in France application of the methodology showed that the non-power benefits due to the multi-purposes reservoirs were considerably higher than hydropower benefits alone. This case study represented one of the examples covering virtually all uses, thus being indeed multifunctional. Drinking water provision, irrigation and tourism were important uses creating benefits, including jobs in the region. It is worth mentioning that via integrated management water demand by irrigation was decreased

Table 24.2 Variability and predictability of water/storage demands from different uses; in case of flood control the demand is on available storage capacities

Use	Variability	Predictability
Hydropower	Baseload + peaks (daily)	High
Energy (pumped) storage	High	Low
Domestic and industry	Daily and seasonally	High
Irrigation	High: seasonal/erratic	High/low
Ecosystem services	Low	High
Flood control	High	Low

considerably, indicating that governance structures and implemented management schemes, including tariff systems and economic incentives, effectively supported resource use efficiency. Also other cases examined within the SHARE initiative give evidence that hydropower can be linked to consumptive water uses in a rather synergetic than competitive way, e.g. with irrigation (Lake Arenal, Cost Rica; Olmos Project, Peru; Kandadji Project, Niger; Pancheswar Project, Nepal/India; Arthurs Lake, Australia). Further examples exist demonstrating that improved management can indeed result in increased energy yields for hydropower and enhanced ecological conditions (Ding et al. 2018). However, in other cases, such synergies are not (yet) realized and non-hydropower uses such as irrigation are rather considered as threat to energy security, particularly in times of climate change (e.g. Spalding-Fecher et al. 2014).

Case studies within the SHARE initiative also give evidence that further non-consumptive uses of multipurpose reservoirs typically provide opportunities for co-benefits or even synergies. This includes navigation, which is an important use e.g. in the Three Gorges Dam, China. A ship lock built around the dam resulted in a fourfold increase in navigation and a reduction of transport costs, facilitating socio-economic development in the upstream region. Navigation is only relevant in large systems and theoretically would interfere with drinking water supply, which is, however, typically not relevant in respective systems. The high water quality demand of drinking water supply also restricts certain recreational uses such as bathing. The outlet of a minimum ecological flow, while competitive at first sight, should ultimately be valued positively or at least less costly. The volume of water released, compared to other (main) uses is typically rather small (but see Sect. 24.6). More importantly, maintaining ecological flow is essential for reducing environmental impacts and enhancing overall sustainability. Moreover, it offers opportunities for water quality management (see Sect. 24.6). Via controlled flooding the water release to the river system may substantially contribute to sedimentation management, thereby benefitting the reservoir as well as the river system (see Sect. 24.9).

In general, competition between consumptive uses including hydropower is less severe the larger the volume of water. Large systems also dampen the competition with flood control since they may offer ample flood control space, while still ensuring other services, exemplified in the Three Gorges Dam, China. While hydropower represents the most direct economic benefit, flood control was a more important motivation for planning the project and has proven effective during a major flood event in 2010, some years after the completion of the project. Earlier floods had disastrous impacts within the region.

When considering synergies and benefits, the economic dimension cannot be ignored. One of the most comprehensive evaluations of the hydropower sector's macroeconomic contribution was conducted in 2015 with a focus on Europe (DNV-GL 2015). It found that the European hydropower sector generates major revenues for governmental budgets at national, regional and local levels. The sector supports 100,000 jobs and direct tax contributions were estimated at EUR 15 bn annually, where the value created was EUR 38 billion per year with projections of up to EUR 90 billion by 2030. Moreover, associated benefits (flood mitigation, supply drinking water, water for irrigation, industrial needs, tourism, etc.) multipurpose functions of hydropower represent an additional annual economic value of EUR 10–20 bn. Due to climate change these benefits can be expected to further increase in the future. The International Renewable Energy Agency (IRENA), assessed in its recent review on the jobs created by renewable energies that large hydropower utilities employed 1.5 million people (direct jobs), with around 60% of those in operation and maintenance (IRENA 2017). However, small hydropower employment is challenging to assess since certain activities in the supply chain are shared with large hydropower and a significant portion of jobs are informal. For a truly comprehensive economic assessment future studies need to estimate also ecological as well as socio-economic costs of reservoirs (see also Sect. 24.10).

Under conditions of increasing water scarcity achieving co-benefits and synergies between hydropower and other uses becomes more challenging. For the Zambezi Basin it has been assessed that climate change scenarios put the economic profitability of planned reservoirs at risk (Spalding-Fecher et al. 2014). Increasing demands for irrigation, if prioritized, will decrease hydropower capacities and respective revenue and this increasing trade-off needs to be considered in planning.

In pumped storage systems trade-offs with other uses may be enhanced. With regard to water quantity, to remain functional the amount of water released from the lower reservoir for other uses has to be restricted. With regard to water quality, pumped storage may have an effect particularly if the ratio between epi- and hypolimnion is reduced. Whether this scenario applies depends on various factors such as inlet/outlet depths and the volume ratio of the pumped water compared to the total volumes in the upper and lower basin. Given that the upper basin is typically relatively small, shallow and fully mixed, warmed up water from the upper basin may also increase the volume of the epilimnion in relation to the hypolimnion. Pumping may also lead to increased resuspension of sediments, which increases turbidity. The resulting water level fluctuations also enhance resuspension besides the earlier described effects on physico-chemical characteristics and biological structure.

24.3 Challenges of Reservoir Management and Operation

As explained in Sect. 24.3, balancing competing water uses and allocating water appropriately, while at the same time considering water quality is by itself a challenging task. It becomes even more so under conditions of Global Change and in transboundary settings since in general water demands are expected to increase while water availability is projected to decline in various regions and/or to become more erratic in its occurrence.

24.3.1 Global Change

Major aspects of global change are the growing human population, its increasing concentration in urban centres, changing land use, and climate change. All factors pose specific challenges on water demand, supply and quality.

24.3.1.1 Increasing Water Demand

The growing population in the first place implies a growing demand for water, food and energy, considering that the production of food and energy requires high amounts of water. Water storage thus becomes increasingly important under conditions of global change, requiring solid knowledge of existing storage capacities (Lehner et al. 2011). Current scenarios estimate an increase in water demand for domestic use by 50–250% (range obtained from ensembles of global domestic water withdrawal projections from the three global water models) and an increase in industrial water withdrawal of >100% by 2050 compared to 2010 (Wada et al. 2016). Also irrigation water demand, the largest consumer of freshwater resources at a global scale, is projected to increase (Wada et al. 2013). Therefore, storage capacities have to increase at a global level, but in particular in regions facing at least sporadic water scarcity. Given the need to decarbonize the energy supply, much of the electricity demand increase due to population increase, growing economy and rapid industrialization will require to be supplied by hydropower (IHA 2017a), which is indeed reflected in a boom in hydropower development (Zarfl et al. 2015). Site selection and river basin planning is essential to ensure multiple benefits and address sustainability issues, see Sect. 24.9. However, besides improving the supply side by implementing new multipurpose reservoirs, increasing water use efficiency and hence reducing water demand should be considered wherever possible.

24.3.1.2 Climate Impacts on Water Availability

Climate change is generally expected to increase variability and decrease predictability of precipitation, but predictions at the local scale are diverse and face a higher level of uncertainty. In many regions trends of increasing precipitation have been reported, but in others precipitation declined and/or became more erratic. Similarly, projections partly show increases, while in other regions declining precipitation is predicted. Although uncertainties in forecasting rain intensity are high, some evidences indicated that wet areas get even wetter and dry regions are getting drier (IPCC 2013). The consequences for the reservoir sector are straightforward, as these water bodies can buffer water resources and store water volumes for times of high water demand. Accordingly, reservoirs will gain more importance for the reliable provision of water resources in large parts of the world. But the management of these reservoirs will also become more complicated. This is particularly relevant for multipurpose dams as existing trade-offs, e.g. between flood protection and water provisioning or between irrigation and hydropower, will become more intense (e.g. Spalding-Fecher et al. 2014).

24.3.1.3 Declining Water Quality and Ecological Responses to Climate Change

Changed hydrologic conditions in conjunction with increasing temperatures affect the import of matter into rivers and reservoirs, including sediment load, nutrients and dissolved organic carbon (DOC). The latter phenomenon has been frequently observed in the last decades in northern temperate systems (Monteith et al. 2007). This trend also affected many reservoirs and appeared to be particularly problematic in drinking water reservoirs, where intensified DOC transport from the catchment into the water body has been reported (Musolff et al. 2017). High DOC concentrations interfere with drinking water production by the formation of disinfection by-products and impairing flocculation steps. Flash floods, moreover, have the potential to mobilise high nutrient loadings, particularly from agricultural catchments and induce massive nutrient spills into the receiving water bodies. A drastic heavy rain event induced, for example, massive nutrient loading and consequent algal blooms in Lake Erie in 2011 (Michalak et al. 2013).

In line with general warming trends reported (IPCC 2013), water temperature has been found to increase in many lakes and reservoirs worldwide (O'Reilly et al. 2015). While warming of shallow lakes directly follows the warming of the atmosphere (Mooij et al. 2008), the situation is much more complex in deep lakes where it interacts with stratification patterns, lake temperatures and stratification patterns being only loosely related (Kraemer et al. 2015). Reservoirs may react differently to warming than lakes because reservoir management can influence heat storage and surface temperature. This refers mostly to the withdrawal management (epilimnetic vs. hypolimnetic), which substantially affects water temperatures (Kerimoglu and Rinke 2013). Figure 24.1 provides an example of stratification pattern in a dimictic reservoir in two years which differ strongly in hydraulic conditions and withdrawal regimes (Saidenbach Reservoir, Germany). 1981 was a year with a relatively cold summer, but high hypolimnetic water withdrawal, resulting in depletion of the hypolimnetic layer during the summer period. 2009 was a warm year with a long-lasting stratification period. Nevertheless, due to lower withdrawal rates, the hypolimnion was retained—albeit reduced—throughout the stratification period and zones with low oxygen extended relatively high up in the water column. This example demonstrates both the relation between temperature and oxygen budgets and the interplay between physical stratification and water withdrawal regimes.

Stratified water bodies are particularly sensitive to climate warming because warming prolongs the period of stratification during summer and thereby extends the growing season for phytoplankton as exemplified also in Fig. 24.1. Improved conditions for phytoplankton growth, particularly favouring problematic groups such as cyanobacteria ("blue-green algae") which may be toxic and bloom-forming, will negatively affect water quality (Paerl and Huisman 2009; Wagner and Adrian 2009; Kasprzak et al. 2017). With regard to physical aspects, warming may change mixing regimes of lakes and turn originally dimictic lakes into monomictic (only one mixing period per year) lakes (Kirillin 2010). More stable stratification may hamper complete mixing in large, monomictic lakes, i.e. turning monomictic systems into oligomictic systems (Rempfer et al. 2010). These changes go along with increasing risks of hypolimnetic anoxia (Fang and Stefan 2009) and corresponding negative consequences on water quality.

Rising temperatures and changing mixing regimes also affect the biological communities in lakes and reservoirs. Among primary producers, Cyanobacteria benefit strongly from climate warming. This group has high competitive abilities under conditions of high stratification intensity, warm temperatures and high phosphorus loads (Carey et al. 2012). They are further promoted by low nitrogen availability due to their ability to fix nitrogen. Cyanobacterial blooms are harmful because several cyanobacteria species produce toxins and hence considerably reduce water usability. In fact, the boosting effect of climate change towards cyanobacterial blooms is one of the major threats for water resources (Paerl and Huisman 2009). Another striking effect of climate change is arising from shifting biogeography, i.e. the invasion of warm-tolerant species into previously colder regions. This may be exemplified by the invasion of the tropical cyanobacteria *Cylindrospermopsis* into temperate lakes (Wiedner et al. 2007).

There are a number of further effects of climate change on aquatic ecosystems, including shifts in phenology (seasonal occurrence and abundance patterns), potentially leading to mismatches in food chains, changes in body size and biomass of organisms and populations and changes in biodiversity and in biogeochemical cycles (see Sommer et al. 2012), potentially impacting overall water quality. Due to the heat storage capacities of water and the complex patterns of temperature stratification, effects on food web interactions are not necessarily direct and straightforward and result in phase-specific warming trends and subsequent instantaneous or time-delayed ecological responses as demonstrated in a comparative study of water bodies in the temperate region (Wagner et al. 2012).

Looking at impacts of climate change on aquatic systems from a user perspective, Mooij et al. (2005) identified some management options to mitigate them, including nutrient load, residence time, water level, compartmentalization and harvest. Some of the proposed measures are, however, only feasible in shallow lakes and reservoirs, e.g. compartmentation, while, e.g., harvesting (macrophytes, fish) is at least much more difficult to perform in large and deep water bodies. The main conclusion was that management measures aimed at confining eutrophication and rehabilitating eutrophied systems, in particular controlling external nutrient loading, should be enhanced, given that climate change is expected to exacerbate eutrophication (Moss et al. 2011). This becomes particularly pressing since the earlier mentioned population growth and urbanization and the resulting increasing water demand implies increasing water quality issues from point and non-point sources (UNEP 2016). Potential management options targeting water quality are discussed in Sect. 24.5.

24.3.2 Transboundary Systems

From a systems perspective, the most appropriate boundary for reservoir management is the watershed. In practice, river systems are often managed in compartments reflecting national and sub-national borders. From 286 global transboundary rivers systems ("Transboundary Waters Assessment Programme—RIVER BASINS COMPONENT" (n.d.)) roughly two thirds do not have a cooperative management framework (SIWI (n.d.)). The lack of such a framework does not necessarily mean that there is no cooperation between basin countries. Conversely, the existence of a legal framework does not prevent or resolve all conflicts about water use and allocation, a prominent example being the Grand Ethiopian Renaissance Dam (Hussein 2017), which is dealt with in the context of the Nile Basin Initiative (Paisley and Henshaw 2013). Despite all difficulties, this example clearly offers many opportunities for cooperation and positive developments in the region (Yihdego et al. 2018). Overall, water diplomacy can be considered effective in solving conflicts about water use as well as other issues and facilitating cooperation (Delli Priscoli and Wolf 2009). River basin commissions provide a framework for data and information sharing and developing and implementing integrated management concepts including coordinated reservoir management for various uses such as drought and flood risk management or hydropower, overall facilitating benefit sharing.

It has been proposed that the Nexus Approach to manage the water, energy and food sectors (Hoff 2011) provides a valuable tool for transboundary water management (de Strasser et al. 2016) since it enforces an integrated perspective on the system and widens opportunities to share the various benefits of the river in general and of reservoirs in particular. Various examples from transboundary systems with reservoirs in which hydropower is among the main purposes indeed demonstrate how cooperation between countries can be enhanced (Kouangpalath and Meijer 2015).

A recent comprehensive assessment of transboundary rivers categorized 41 out of 286 to be at high or very high risk considering environmental, human and agricultural water stress, while certain risks, e.g. by pollution is high in most (218) basins (UNEP-DHI and UNEP 2016). Multipurpose reservoirs were considered essential for mitigating risks posed by increasing water demands and climate change if planned and operated carefully. Associated conflicts require a systematic approach in which appropriate software and decision support systems can play a decisive role (Nandalal and Simonovic 2003).

24.4 Specific Features of Multi-unit Systems

In many river systems worldwide several reservoirs have been established, leading to a cascade of reservoirs, prominent examples are known from Brasil (Paranapanema River with 11 reservoirs), the Czech Republic (Vltava River with 9 reservoirs) and Sri Lanka (Mahaweli River with 7 reservoirs). For the management of each single reservoir issues discussed in the previous sections need to be considered, while the system perspective requires to pay specific attention to cascade effects. While the upper reservoir of the cascade functions like a single reservoir, the next and lower reservoirs are all influenced by the upper one. Adverse effects of management measures in an upstream reservoir would be amplified in the downstream reservoirs, e.g. epilimnetic water withdrawal in an upstream reservoir would result in significantly warmed water bodies below with respective implications for stratification/mixing regimes and system metabolism (compare Fig. 24.1), potentially limiting specific uses. For specific functions, e.g. hydropower, the whole system might be operated as one unit, but in terms of physical, chemical and biological structure and functioning each reservoir behaves in a unique way and is influenced by the inflow, which requires adopting a systems perspective.

Basically the same holds for linked reservoir systems (termed multi systems in Straskraba et al. (1993)), which connect sub-basins of larger watersheds or even (originally) completely distinct and separate watersheds by artificial interbasin channels or tunnels. Such cross-basin systems in addition have to consider (during planning and operation) the overall water balances of the connected systems as well as the translocation of substances and organisms. Transferring water between watersheds may cause specific problems due to hydrochemical differences or the transfer of non-native or problematic organisms. Clearly, the more interconnected units there are and the more diverse their characteristics, the higher the demands in system integration and management, requiring careful planning as well as operation.

24.5 Management Options and Tools

A systems perspective on reservoir management implies that the focus has to be on the entire watershed. It has to consider the fact that water quantity and water quality management are closely linked (Jorgensen et al. 2005). These authors, consequently, emphasised the need for integrated reservoir management (Chapter 7 in Jorgensen et al. (2005)), representing a specific case and practical implementation of Integrated Water Resources Management (IWRM). The different management options, focusing in particular on water quality measures, are comprehensively addressed in Chap. 4 of that book. Addressing water quality management, in particular for domestic use, in a systematic manner, from watershed to reservoir management and subsequent steps of water treatment, has been referred to as multi-barrier system, which is a common approach to providing safe drinking water (American Water Works Association (AWWA) 1997; Castell-Exner 2010).

Taking a broader perspective on resources management and emphasizing the close linkage of water with energy and food security, the approach that integrates management and governance across sectors and scales has been termed a nexus approach (Hoff 2011; Allan et al. 2015). Taking a resources perspective, it turns into a nexus approach to managing water, soil (basis for food and biomass production) and waste (recycling of nutrients and organic matter, reuse of grey water (return flow from showers and other uses), etc.) (Hettiarachchi and Ardakanian 2016). This dimension of the nexus approach also emphasizes that it is not only the water quantity, which needs to be managed, but also the water quality (strongly driven by land-use and waste management), since many of the water uses require a certain water quality standard. These inter-linkages make reservoirs an ideal showcase for adopting and applying a nexus approach and an essential tool for building resilience and reduce risks arising from global change (Matthews and McCartney 2017).

24.5.1 Watershed Management

Addressing reservoir management from a systems perspective certainly requires looking at the watershed. Basic principles of watershed management are comprehensively outlined in Jorgensen et al. (2005). Here we focus on main points, relevant updates and emerging issues.

Measures against erosion are important components of watershed management, particularly in reservoirs with a high sediment load (Morris and Fan 1998). Erosion intensity depends on geomorphologic properties like slope and soil type and climatic factors but is also strongly affected by land use and vegetation cover. The governmental Grain-for-Green programme in the Chinese Loess plateau induced large scale land use conversions from agricultural land to grasslands and forests and lead to significant reduction in erosion intensity (Feng et al. 2010). In defined areas susceptible to soil erosion arable land was retired form agricultural use and farmers got financial incentives for the back-conversion to natural vegetation. Similar positive experiences with land use conversions as a measure against soil erosion were made in the Ethiopian highlands (Tamene and Vlek 2007).

Land use within the watershed does, however, not only affect water quality via erosion and export of nutrients, agrochemicals etc. It also has profound effects on water yield. The mentioned example of the Chinese Loess plateau, while being successful in reducing sediment load had substantial trade-offs with regard to water yield, which was significantly reduced in afforested watersheds, a major factor being enhanced evapotranspiration (Zhang et al. 2015). Investigations in the Three Gorges Region in China indicate that effective land-use management may result in strong reduction of sediment loads without negative effects on water yield (Bieger et al. 2015): Despite resettlement and relocation of agricultural land to upstream parts of the region, forested areas slightly increased and large areas of cropland were converted to orange orchards. Overall, this resulted in reduced soil erosion while streamflow was only marginally affected.

Watershed management is essential also for minimizing import of other substances and materials from point and non-point sources, particularly for eutrophication control. Within the context of integrated management in the sense of a Nexus Approach it should embrace the aspect of multifunctionality (Zhang and Schwärzel 2017). With regard to wastewater management nature-based solutions, such as constructed wetlands should be a preferred option, since they also offer opportunities for multifunctional use (Avellan et al. 2017).

24.5.2 Ecotechnology (Biomanipulation)

Nature based solutions cannot only be applied in the watershed, but also within the reservoir. The concept of ecotechnology (Benndorf 2005) encompasses various options, relevant for reservoirs is mainly food web manipulation, also termed biomanipulation, as means to control eutrophication. Its principles and application in lakes and reservoirs is discussed in Chap. 4 of Jorgensen et al. (2005). Briefly, the method makes use of interactions between adjacent trophic levels (producers: phytoplankton and the various levels of consumers: herbivorous zooplankton, planktivorous fish, piscivorous fish). By manipulating the food web top down by enhancing piscivorous fish, the next lower trophic level, planktivorous fish, is reduced, resulting in enhanced densities of herbivorous zooplankton which reduces phytoplankton. In this context, not only size-relations between, but also within each trophic level are of high importance. Classical studies during the 1960ies (Hrbácek et al. 1961; Brooks and Dodson 1965) revealed that planktivorous fish are highly size-selective and will thus eliminate predominantly large-sized zooplankton species, mainly of the genus *Daphnia*. The resulting zooplankton community thus consists of small sized species which are less efficient in grazing on phytoplankton. If released from fish predation, *Daphnia* will quickly gain dominance in the zooplankton community and exert a strong top-down control on phytoplankton.

The simplified mechanism of a trophic cascade is, however, rarely realized under natural conditions, mainly because bottom-up mechanisms (besides compensatory mechanisms such as predator avoidance) simultaneously play a role. Increasing nutrient availability by anthropogenic eutrophication will enhance phytoplankton production and may ultimately lead to a decoupling of the top-down trophic cascade at the zooplankton-phytoplankton link. Conclusive and sustained effects of biomanipulation on water quality can therefore only be expected under specific conditions mainly set by nutrient loading (trophic state) and are more likely in shallow systems (Benndorf 1995; Benndorf et al. 2002). Below, we focus mainly on results obtained in deep systems, which are more relevant for large reservoirs.

A comparative analysis of two long-term biomanipulation experiments in moderately deep and stratified systems (Kasprzak et al. 2007) confirmed that a sustained reduction of phytoplankton biomass via top-down control can only be achieved below a certain threshold level of nutrient loading. Under such conditions, besides direct grazing effects reducing the edible fraction of phytoplankton, indirect top-down effects may become effective which reduce the availability of phosphorus (P) for phytoplankton growth. The main mechanisms behind this top-down induced bottom-up effect should be enhanced P-sedimentation and P-incorporation into zooplankton (mainly genus *Daphnia*) biomass, as concluded by Benndorf et al. (2002). The importance of this mechanism was confirmed in application of biomanipulation in two reservoirs (Scharf 2008, 2010), confirming the potential for achieving additive effects by combining external nutrient control with food web management. Results from an enclosure experiment under natural conditions propose that enhanced P-sedimentation is associated with high densities of zooplankton (*Daphnia*) and should be the dominant mechanism reducing P availability for phytoplankton growth (Pitsch et al. 2012). If the nutrient levels are too high the described indirect effects are overruled by continuous external and internal P-loading. The effects of enhanced grazing in this case are short-termed, e.g., confined to a limited period of a clear water phase during the early growing season in temperate regions. When considering the complete growing season, total phytoplankton biomass is not or hardly reduced, but its size structure is shifted to large and slow-growing species which are inedible for zooplankton. However, the occurrence of a clear water phase and a shift in phytoplankton community structure may still be considered a (partial) success.

The second major conclusion of Kasprzak et al. (2007) was that manipulation the fish stock by reducing planktivorous fish via intense fishing might not be sustainable and sufficient. That study concluded that fish stock management has to comprise stocking and protecting piscivorous fish to achieve a share of 30–40% of total fish biomass. Earlier comparative studies recommended a massive reduction of planktivorous fish by at least 75% and a concomitant control of benthivorous fish and of fish recruitment (Hansson et al. 1998). For the latter factor, besides enhancing top down control by piscivorous fish, water level management can be used to control recruitment of certain planktivorous fish species (Kahl et al. 2008).

The apparent need for establishing and maintaining a diverse community of piscivorous fish poses a challenge since at least in the temperate region the predominant recreational sport fisheries are typically targeting piscivorous fish. Successful biomanipulation thus critically depends on close involvement and cooperation with local fisheries. The example of Bautzen Reservoir, Germany (Benndorf et al. 2002; Kasprzak et al. 2007) shows that this cooperation may work, including self-imposed catch restrictions by the recreational fishery stakeholders to ensure sustainability of catches. In other cases, establishing piscivorous fish in the presence of recreational fishery proved difficult, e.g. in Saidenbach Reservoir, Germany (Hülsmann et al. 2006). Co-management of ecosystems and fisheries seems feasible if clear guidelines are implemented (Mehner et al. 2004).

A management tool which certainly cannot be recommended is stocking with exotic fish species. A prominent example is stocking with filter-feeding carp, e.g. silver carp (*Hypophthalmichthys molitrix*) in various systems outside Asia, expected to have positive effects by feeding on (large) phytoplankton. The resulting effects were, however, rather negative, since these fish were found to have profound effects on zooplankton and negatively affected water quality (Radke and Kahl 2002; Lin et al. 2014). Moreover, they were found to be invasive in some systems ("Invasive Species: Aquatic Species—Silver Carp (Hypophthalmichthys molitrix)" (n.d.)).

Most biomanipulation experiments were performed in temperate systems with relatively uniform composition of fish and zooplankton communities and these results may not be applicable and relevant for tropical reservoirs. For example, it had been hypothesized that the general dominance of smaller-sized grazers in the zooplankton communities of tropical systems might be due to physiological constrains. A systematic comparative study revealed, however, that fish predation is the main factor limiting large-sized zooplankton species to develop and persist in tropical systems (Iglesias et al. 2011). A more complicating factor is the higher diversity of the fish community, the frequent occurrence and dominance of omnivorous fish and year-round productivity, e.g. more than one spawning per year, which weaken the trophic cascade in tropical systems (Lazarro 1997). In general, in warm(ing) lakes predation on zooplankton seems to be enhanced, making biomanipulation a less suitable management tool (Jeppesen et al. 2010).

In conclusion, biomanipulation cannot be considered a routine, "ready to use" method for water quality control. Uncertainties about its applicability and effectiveness exist in particular in large and deep tropical reservoirs. In temperate systems there is sufficient evidence to conclude that it may complement other means of nutrient control, particularly those controlling import from the watershed. It offers opportunities for synergies between fisheries and water quality management.

24.6 Reservoir Operation and Infrastructure Design

Measures for prevention and control of pollution at its point sources in the drainage basin of lakes and reservoirs are most sustainable and have highest priority. However, it is not possible to completely prevent pollution from non-point sources. Additional stabilization and improvement of the water quality is necessary and can be achieved by therapeutic in-lake measures and by optimized water quantity management that aim at:

- further reduction of import (pre-dams, phosphorus elimination plants, circumvention of inlets),
- enhanced removal of imported material from water to sediment (longitudinal segmentation, Phosphorous-precipitation, biomanipulation—see Sect. 24.5),
- limitation of phytoplankton growth and controlling release of problematic substances, mainly phosphorus, iron and manganese from internal pools by artificial mixing, hypolimnetic aeration or destratification; these measures are extensively discussed by Jorgensen et al. (2005) and only briefly addressed here,
- increased export (regulation of raw water withdrawal and release of compensation water) of nutrients and other harmful substances.

24.6.1 Pre-dams

Compared to natural lakes, reservoirs are strongly flushed stagnant water bodies with low retention time. Therefore, the load of inflowing dissolved and particulate substances related to surface area is high and pre-dams situated upstream the mouths of tributaries were built (see Fig. 24.2). They allow settling of particles and substances attached to them (e.g. coliforms and other potentially harmful microorganisms, heavy metals and DOC) and thus protect drinking water reservoirs from fast siltation. Furthermore, they enhance the elimination of dissolved nutrients by their incorporation into and sedimentation of phytoplankton cells (Paul 2003). Based on a modelling approach for phosphorus elimination (Benndorf and Pütz 1987), a technical standard on effects, design and operation of pre-dams was issued in Germany (DWA 2005). It also comprises rules for keeping pre-dams functioning, which requires regular removal of sediments.

Pre-dams are usually permanently fully filled and their efficiency depends strongly on retention time. High flushing rates during flood events severely reduce the elimination of suspended particles and phosphorus. The P-removal is likewise limited in dry periods with very high retention times due to probably dominating phytoplankton species with low settling rates under such conditions. Thus, the performance of pre-dams can be optimized by the installation of technical measures that allow adapting the pre-reservoir's fill level and retention time depending on discharge (Paul and Pütz 2008).

The temperature increase of tributary water in pre-dams and the resulting near-surface entrainment into the reservoir in summer may have negative implications since nutrients and algae grown in the pre-dam flow directly into the euphotic layer and may inoculate or maintain a phytoplankton development in the main basin of the reservoir. This effect may gain influence in the context of climate change. The trophic state of pre-dams is relatively high. Thus, further warming may favour the import of cyanobacteria into the reservoir and initiate mass growth of eventually harmful phytoplankton species.

24.6.2 P-Elimination Plant at the Main Inflow

The reduction of P-loading from inflowing water by chemical P-precipitation is most efficient in properly designed P-elimination plants such like installed at the Wahnbach Reservoir, Germany and in several lakes (Klapper 2003). Their efficiency depends strongly on how they are able to treat flood flows.

24.6.3 By-Passing of Tributary Water

Generally, while being effective with regard to sediment and nutrient control, pre-dams cannot significantly reduce the import of DOC into reservoirs especially in cases of high discharges that determine to a great extend the annual loading. The inflow of extremely high DOC concentrations into the heavily organically contaminated Carlsfeld drinking water reservoir in Saxony (Southeast Germany) was significantly diminished by the construction of an upstream buffer dam and a bypass around the reservoir. At high run-off, the buffer dam is filled with DOC-rich water from the rising limb of the flood and subsequently released through the pipeline to the river downstream of the reservoir. A similar solution but with the purpose to reduce the import of turbidity and nutrients was realized at the Klingenberg Reservoir near Dresden. A 3 km long tunnel connecting the pre-dam with the river downstream of the reservoir was constructed that enables circumventing up to 30 m^3/s, which represents the downstream capacity. However, it must be taken into account that those installations are unable to fully control high flood events.

24.6.4 Longitudinal Segmentation

Underwater pre-dams were built downstream of the tributaries mouths in the main basin of the Saidenbach Reservoir (see schematic view in Fig. 24.2). Their dam crests are several metres below the surface of the entirely filled reservoir and usually overflown. In those cases, their P-elimination capacity is considerably lower than in conventional pre-dams of respective size (Paul 1995). Nevertheless, they may prevent hydraulic short circuiting of the inflows and form small hypolimnetic volumes during summer stratification, which allow particles to settle that otherwise would be dragged far towards the main reservoir basin. However, their most precious effects are relevant in dry years, when the fill level of the reservoir falls below the dam crests and the water quality is generally critical due to the unfavourable high ratio between epi- and hypolimnion volumes. Now the underwater basins become real pre-dams and improve the elimination of nutrients and turbid matter. Furthermore, they prevent the riverine sediments of falling dry, which otherwise would be washed into the hypolimnion by inflows and wind waves and produce tremendous turbidity and oxygen depletion. Effects similar to those observed in conventional pre-dams can be achieved by submerged overflown flexible curtains installed in the riverine part of stably stratified dams or lakes (Paul et al. 1998). Hanging down from just below the surface to slightly below the metalimnion, they prevent the direct inflow of tributary water into the main basin of the reservoir and interrupt hydraulic circuiting.

24.6.5 Phosphorus Precipitation

Phosphorus precipitation by adding P binding chemicals is an approved method to artificially increase P retention in lakes with long residence time and/or large mobile sediment P pools. Similar to biomanipulation these measures are only sustainable after substantial control of the external P sources (Hupfer et al. 2016). The application of this technique in reservoirs with high flushing rates is usually ineffective. In the highly eutrophic Bautzen Reservoir (Germany), however, internal dosing of iron compounds in combination with local water column destratification was deployed in order to reduce the P concentration and finally control acute blooms of cyanobacteria (*Microcystis*) (Deppe and Benndorf 2002).

24.7 Hypolimnetic Oxygenation and Destratification

Phosphorus, manganese, iron and many other redox-sensitive substances impairing the water quality and the ecosystem stability are released from the sediments under anaerobic conditions in the hypolimnion of stratified reservoirs as consequence of strong oxygen depletion (Müller et al. 2012). Different technical solutions were developed to enrich deep water layers with atmospheric or pure technical oxygen (Singleton and Little 2006). Complete destratification during the entire stagnation period is usually no option in drinking water dams because it would destroy the hypolimnion from which the raw water is preferably withdrawn. It may be applied during the mixing phases to promote intensive oxygenation down to the deepest layers of the reservoir or in the end of summer in order to avoid extreme reductive conditions in the remaining small hypolimnion by inducing earlier full mixing and re-aeration down to the bottom. However, hypolimnetic oxygenation and destratification have little or no effect on the internal phosphorus loading if the external P import is the dominant factor for P-availability (Gächter and Wehrli 1998). Moreover, the applicability of this technical option is restricted to rather small reservoirs and not feasible in large water bodies.

24.8 Regulation of Raw Water Withdrawal and Release of Compensation Water

Appropriate management of water quantity can substantially stabilize or even improve the raw water quality in reservoirs and reduce the costs of water treatment for drinking water provision (Arbeitsgemeinschaft Trinkwassertalsperren (ATT) 2009). In deep stratified systems, raw water is usually taken from hypolimnetic layers (see Fig. 24.2). Thus, the quantity of raw water available during summer stagnation is determined by the volume of the hypolimnion formed at the beginning of the stratification period. This quantity as well as the ratio between hypolimnion and epilimnion volumes is greatest when the reservoir is completely filled, which promises the best hypolimnion water quality. The implementation of a flood storage reduces the active storage and in particular the hypolimnion volume. Thus, the availability of raw water with the potentially best water quality is restricted in drinking water reservoirs with flood control function (see Sect. 24.2).

The duration of the summer stagnation may be shortened in reservoirs with high raw water demand due to early depletion of the hypolimnion. Ironically, this especially applies to rainy summers, when large amounts of water have to be released from the deep water layers of the reservoir just to prevent the filling of the flood storage as long as possible. Large water masses up to the downstream capacity can usually only be withdrawn via the bottom outlets. So, heavily polluted inflowing water is stored while hypolimnetic water of good quality has to be released. To overcome this calamity, some German drinking water reservoirs (e.g., Klingenberg, Saidenbach, Aabach) have been upgraded with additional outlet structures at the level of the active storage that enable surface water up to the quantity of the downstream capacity to flow out. In this way floods can be partially ducted through the reservoir.

The existence of several raw water intakes at different depths is state of the art (e.g., Klapper 2003, see Fig. 24.2). They allow choosing the raw water withdrawal layer under consideration of the vertical distribution of water quality. Greatest flexibility offer swing pipe systems as for instance installed in the reservoirs Esch-sur-Sure in Luxemburg or Cranzahl and Leibis-Lichte in East Germany.

Not only compensation water to ensure environmental flow but also raw water should preferably be released as often and long as possible from the deepest intake available during stratification in drinking water reservoirs. Usually these are the bottom outlets. Oxygen depletion is most likely highest near the bottom of the reservoir. Continuous withdrawal of these water layers may at least delay the occurrence of anoxic conditions at the sediment–water-interface. Additionally, water with potentially high concentrations of nutrients re-mineralised from settling organic matter or remobilised from the sediments is exported. This is comparable with the deep water abstraction from natural lakes, which, however, is much less effective in waters with long retention time (Klapper 2003). If raw water can be withdrawn via the bottom outlet, compensation water may eventually entirely or partially be released from epilimnetic layers, thus saving water of good quality for raw water supply.

In the context of technical reservoir operation also pumped storage facilities, their technical implementation and management should be considered. As outlined in Sect. 24.2 the respective pumping/release and the associated water level fluctuations and potential effects on thermal structure may negatively influence water quality.

24.9 Managing and Reducing the Environmental Impacts of Reservoirs

Negative impacts of reservoirs are well known and one of the major threats to aquatic biodiversity and ecosystem functioning. A comprehensive list of negative environmental, social and economic effects of reservoirs is given by Branche (2017). The analysis of the respective case studies focused largely on economic and social issues, however. Here we focus on environmental impacts, which are the major reason why damming has a largely negative perception among many environmental agencies and NGOs. However, they typically do acknowledge that reservoirs are essential for water security, flood protection as well as providing "green" energy and that negative impacts can be minimized if properly planned and managed (WWF 2013; The Nature Conservancy 2015). Avoiding or at least minimizing these impacts is best realized if considered during the planning phase of reservoirs (see below). A number of mitigation options can be implemented during dam building or during refurbishment of existing dams and by applying specific management measures (Table 24.3). In general, they aim at maintaining ecological and hydrological integrity and connectivity as far as possible.

Damming creates an insurmountable barrier for many aquatic species, which is problematic in particular for organisms with obligatory migration between different habitats during their lifetime. The most prominent example is salmonid fish species, e.g., the Atlantic Salmon (*Salmo salar*), which require the entire rivers system to be accessible. But also other (mostly smaller) fish species which "only" migrate within the river will be impaired by damming due to habitat fragmentation and lack of gene flow between sub-populations. Overall, damming represents a major threat to fisheries (e.g., Stone 2016). Invertebrates can also be affected, but mostly less severe since they typically have more effective means of dispersal. Fish ladders, passes or even elevators have been introduced to allow re-colonization and connectivity. The effectiveness of these systems depends on proper design (Katopodis and Williams 2012).

The switch towards a stagnant water body after damming on the other hand favours lake-type ecological communities. In case of high temperatures and high nutrient loading this may lead to mass developments of pest species such as cyanobacteria, which can be toxic. In other cases, particularly in the tropics, excessive growth of submerged or floating leaved vegetation was observed. They cause various ecologic, technical and health-related problems and are difficult to control (ICID 2002), requiring an integrated management approach.

In the past (and still today), economic aspects in terms of hydropower production, raw water supply, and flood control determined water management. The amount of compensation water was usually more or less constant throughout the year and as low as the minimum flow necessary to principally maintain basic ecological requirements. Besides the mostly unrecoverable interruption of the longitudinal penetrability, the ecological conditions (especially seasonal flow dynamics, temperature, pH, oxygen and nutrient concentrations) in the downstream reaches of reservoirs were far from natural and completely different from those upstream. The stream ecosystem below the dam was seriously distorted.

Reduced flow dynamics downstream of a reservoir, while negatively affecting aquatic species relying on high flow and turbulence (rheophilic species) can intensify primary production. River eutrophication has various negative impacts

Table 24.3 Environmental problems associated with reservoirs, their impacts and potential solutions in reservoir management

Problem	Negative impact	Potential solutions	Examples (reference)
Barrier for organisms	Extinction of migratory species	Installation of passage infrastructures	Various systems worldwide (Katopodis and Williams 2012)
Excessive growth of pest species such as cyanobacteria or submerged or floating leaved plants	Toxicity, clogging of infrastructure, providing habitats for disease vectors	Water quality management, harvesting, biological control etc.	Bautzen Reservoir (Deppe and Benndorf 2002; ICID 2002)
Reduced flow dynamics	Intense primary production (=eutrophication), sediment colmatation	Implementation of dynamic flow regime	Leibis-Lichte, Germany (Peters et al. 2000)
Temperature disruption	Changing communities downstream	Near-natural temperature release from variable water depths	Große Dhünn Reservoir (Schultze et al. 2016)
Reduced sediment transport	Bed scavenging downstream, coastal erosion	Increased outlet capacities, Controlled flooding	Sanmenxia Reservoir (Wang et al. 2005) Aabach Reservoir (European Commission 2014)

on the ecosystem (Hilton et al. 2006) and may exacerbate the sediment compacting and colmatation, which takes place due to low flow.

Recently these aspects gain importance in reservoir management and two main measures are discussed: (1) hydrologic homogenization of the water release, and (2) adaptation of the outflowing water quality (Arbeitsgemeinschaft Trinkwassertalsperren (ATT) 2009). Homogenisation (or dynamisation) of the discharge means adapting the outflow variability in time to that of the inflow, but in a ratio considerably lower than unity (e.g. 1:10). This is, however, ecologically sound only when the downstream hydromorphological conditions are intact as shown exemplarily for the Aabach drinking water reservoir (North Rhine Westphalia, Germany) (European Commission 2014). Additionally, a flushing surge (artificial flood) is generated at this dam each year at the end of the summer stagnation to initiate substrate transport, sideward erosion and the reformation of bed structures typical for the downstream reach of the specific river.

An even more stringent discharge regime is to be realized at the Leibis-Lichte Reservoir in Thuringia, Germany (Peters et al. 2000) due to ecological flow requirements in the river reach downstream of the drinking water dam that is under protection according to the European FFH-Guidelines (FFH—Flora-Fauna-Habitat). Storage of water only takes place at medium inflow when discharge is higher than a fixed minimum threshold (Q1) and lower than an upper threshold (Q2). Discharges lower than Q1 and higher than Q2 have to be released 1:1 from the reservoir up to the downstream capacity. Storage also occurs in situations of flood control at flow rates higher than the downstream capacity. Moreover, the temperature of the water withdrawn must not differ by more than 2 °K from the stream's temperature upstream of the dam. Thus, the water is released from layers with the appropriate temperature via depth-variable intakes equipped with swivel pipes (Schultze et al. 2016).

Similar considerations were motivation for upgrading the Große Dhünn drinking water dam with a swivel pipe system ("Thermorüssel"—thermo-trunk; Schultze et al. 2016) that allows releasing water of near-natural temperature every time of the year. This provides habitat conditions needed in the downstream river for the reestablishment of a species rich fish fauna characteristic for the upper-middle section of (low) mountain rivers ("grayling region", named after a characteristic fish species), which is required to reach a good ecological status according to the European WFD.

As mentioned in Sect. 24.5, sedimentation is a major threat to reservoirs, but the lack of sediments in the downstream river system including the delta is just as problematic. The sediment deficit induces bed scavenging and scouring downstream and may lead to increased coastal erosion particularly in times of sea level rise due to global warming. The example of Sanmenxia Reservoir in China demonstrates that even very high sediment load can be managed and a balance between sediment in- and outflow be achieved by optimizing outlet capacities and the water withdrawal regime (Wang et al. 2005).

24.10 Planning of Multi-purpose Reservoirs

Site selection and river basin planning are very important to maximise the benefits of multipurpose reservoirs and minimize adverse effects on the river ecosystem and local communities. The Hydropower Sustainability Assessment Protocol provides a methodology for a sustainable assessment of hydropower projects across more than 20 sustainability topics, encompassing environmental, social, technical, financial and economic aspects (International Hydropower Association 2010). It rests on a multi-stakeholder-agreed definition of basic good practice and proven best practice for each of the topics, and provides accompanying definitions and guidance.

The Sustainability Assessment Protocol was launched at the IHA world congress in 2011. Since then, it has become broadly recognised as the primary tool for evaluating sustainability performance, having been implemented worldwide (IHA 2017b). It is a reference framework that enables the development of a full sustainability profile of a hydropower project. Official assessments are carried out by a team of accredited assessors, experts in the fields of sustainability and hydropower, who assess the sustainability performance of a project against over 20 topics. An assessment can be carried out from early stage development and through the implementation and operation stages. Each topic is assessed against six measures: assessment, management, stakeholder engagement, stakeholder support, conformance and compliance, and outcomes. The results are presented in a form of a spider diagram displaying the results clearly and unambiguously with a score from 1 to 5 with 3 being equivalent to basic good practice and 5 being equivalent to proven best practice.

The protocol is governed by a multi-stakeholder body, using a consensus approach. This governing body includes representatives of social and environmental organizations, governments, financial institutions and the hydropower sector, meeting four times a year to guide the Protocol's work programme. The International Hydropower Association acts as the management entity for the Protocol's day–to-day operations, covering tasks such as overseeing training and accreditation, liaising on assessment, and co-ordinating governance activities.

Site selection and optimal location also promise higher rates of return on investments (The Nature Conservancy 2017): Adopting a system-scale planning process (Hydropower by Design) "can identify strategic and sustainable hydropower systems that deliver economic value to countries, financial value to developers and greater environmental values from rivers". When the planning is done at a basin level, the benefits can be shared at a local, national and transboundary levels (Sadoff and Grey 2002). At a local level, it can help distribute electricity, revenues, and economic benefits from hydropower operation across a broader set of beneficiaries. It can involve the sharing of gains from resource development among residents and stakeholders. Hydropower production and interconnection could expand productive opportunities, increase the profitability and the economic interactions among riparians, reducing the tensions that may arise among them.

24.11 Modelling Tools and Decision Support Systems

Modelling tools have become indispensable for managing environmental systems and this is also true for lakes and reservoirs (Jorgensen et al. 2005, Chap. 5). From a scientific perspective they mainly serve for systems understanding by confronting model output with empirical data. From a management perspective they are mainly used for data integration and assessing management options and the impact of drivers. The importance of clearly defining the scope and objective of any modelling exercise thus cannot be overemphasized for model development (Jakeman et al. 2006), but also for the choice of existing models. While many such tools are available, it may be challenging to find the most suited one, since there is no single best option depending on (i) the water uses to be considered, (ii) specific issues and challenges within the watershed and (iii) the availability of data. In order to facilitate the choice of the best-suited model (or ensemble of models) a web based interactive data base of modelling tools has been proposed and developed (Mannschatz et al. 2016). Aiming for integrated management implies that the respective modelling tools have to address a certain degree of complexity. The diversity of existing models may ultimately increase systems understanding via ensemble approaches and linking of models (Janssen et al. 2015), but this kind of studies are still rare.

Any management-oriented environmental model relies on respective input data. Therefore, appropriate monitoring schemes, providing data on water quantity and water quality need to be implemented. Increasingly automated systems providing data in high temporal resolution are available (Marcé et al. 2016). Sophisticated water discharge monitoring at high temporal resolution is common, but a comparable monitoring effort for water quality variables is by far rarer. These differential monitoring efforts for water quantity and water quality may constitute another reason why the management of water quantity is far more advanced among reservoir operators than the management of water quality.

The basis of a sophisticated water quality monitoring would be the assessment of the physical structure by chains of temperature loggers or profiling systems. Profilers also facilitate the measurement of further water quality variables by appropriate sensors, e.g. for pH, oxygen or algal abundances. From a systems perspective, a comprehensive water quality monitoring also has to include the water quality of the inflows in order to gain information about matter fluxes from the catchment into the water body. The Rappbode Reservoir Observatory, installed at Germany's largest drinking water reservoir, provides a showcase of such a monitoring system for inflows and reservoirs in combination (Rinke et al. 2013), but so far represents rather an exceptional case. In case of limited monitoring data, global databases (Sharma et al. 2015) may at least partly fill gaps and help finding reasonable input data for models.

In the best case monitoring data is directly fed into a model framework (see Hipsey et al. 2015). This should allow visualization and prediction of the outcome of applying management options, of global change scenarios or even enable the utilization of models for operational decisions. The application of models in reservoir management is a very wide field and includes hydrological catchment models, partly combined with geochemical routines for matter fluxes, as well as models of the water body over a wide range of complexity and spatial resolution. In scenario-based simulations, catchment models are used for predicting future changes in, for instance, hydrology (Matonse et al. 2013) or sediment load (Mukundan et al. 2013) due to climate change. These forecasts are highly relevant as the usual lifetime of reservoirs (100+ years) overlaps with the relevant timescales of climate change and in some cases the installed infrastructures may require extensions in order to guarantee a safe and efficient operation in future. Planned reservoirs or those under construction also require reliable information about expected hydraulic and sediment loads from their catchments. It makes sense to extent this framework also for future nutrient loads.

The simulation of reservoirs including hydrodynamics, biogeochemistry and ecological dynamics can be an important tool for reservoir management. There is no distinction between reservoir models and lake models and existing model codes are suited for either of them (Jorgensen et al. 2005). A key feature of these models is their dimensionality. One-dimensional models account only for the dynamics along the vertical axis and aim at reproducing the major vertical gradients involved in stratification as well as biological and chemical features. Two-dimensional models additionally account for the longitudinal dimension, i.e. the spatial axis from the dam towards the inflow section. A 2D-model makes sense in a reservoir because systematic gradients (riverine-lacustrine) are expected along the longitudinal axis (e.g. Sadeghian et al. 2017), as an example for sediment transport. A realistic spatial representation of the reservoir basin and its water body requires a 3D-model, where complex hydrodynamic features (e.g. internal waves, see Bocaniov et al. 2014) can be simulated in great detail. The appropriate choice for the model dimensionality is a key step when initializing a model project. A 3D model is always most powerful in terms of spatial representation and allows for a high-quality representation of hydrodynamics, but also has high requirements for input data and computational power. A 1D-model is very easy to handle, can be set up within a day by a skilled person, and has extremely short computation times, which can be a big advantage when large ensembles have to be computed in a reasonable time. According to the concept of maximum parsimony, models should be kept as simple as possible for a given study aim. In the past years, a number of models have been implemented as open source models and are now developed by a community of researchers and freely available via the internet (Trolle et al. 2012). This is a highly valuable prerequisite for improving and analysing reservoir management in developing countries where the responsible authorities often cannot afford to let model studies be conducted by professional engineering consultants.

Besides using models in scenario-based simulations, e.g., for analysing future trends or alternative management strategies, models could also be directly embedded into reservoir operation when they are running online and in real-time. The technical realisation of implementing models into reservoir operation has a long history (compare review papers by Yeh 1985; Rani and Moreira 2010). These models are highly diverse in terms of spatio-temporal details and in terms of modelling approaches such as dynamic programming, fuzzy logic, neural networks or simulation tools (Loucks and Van Beek 2017). The classical field of model-based reservoir operation is water quantity management, i.e. identifying the optimum storage adjustments in face of flood events, can be addressed using different modelling approaches, while each of them has its pros and cons (Uysal et al. 2016).

A more demanding approach is to realise model-aided reservoir operation that also includes water quality aspects. In a recent study by Weber et al. (2017), an operational reservoir model was developed in order to identify optimal withdrawal strategies. The model is based on a one-dimensional lake model simulating thermal stratification and dissolved oxygen dynamics. This model is operationalised for the determination of optimal withdrawal depths for the water outlet into the downstream river in order to establish a natural temperature regime within the downstream river. Besides the downstream temperature regime, two further criteria came into play in this application: (i) sustaining a high dissolved oxygen concentration in the deep layers of the reservoir and (ii) minimizing the loss of hypolimnetic raw water suited for drinking water production. In a case study in a German drinking water reservoir it was shown that the thermal regime of the downstream river could be completely restored, i.e. the "thermal footprint" of the reservoir disappeared, without running into risks of hypolimnetic anoxia or supercritical loss of raw water.

Various implementations of data-modelling frameworks which explicitly were designed as Decision Support Systems (DSS) support the management of single large lakes, such as lake Constance (Lang et al. 2010) or in complex watersheds (e.g. the Zambezi: "ZAMCOM—Zambezi Watercourse Commission" (n.d.); or the Mekong: MRC (n.d.)). Such DSS should not only be able to support the reservoir operation and watershed management, but already support reservoir planning (McCartney and King 2011), following key principles of DSS:

– Facilitate examination of the wider social and ecological context of conflicts enabling mitigation measures and compromises to be found,
– Enable integration of more and diverse sources of information from different scientific disciplines,
– Sharpen the focus on stakeholder involvement in decision-making so that all stakeholders participate from early on in the process,
– Facilitate negotiation-based approaches to decision-making that hopefully lead to increased cooperation and consensus building between different stakeholders.

Used in this way, DSS may not only facilitate integrated and sustainable resources management, but also help in mitigating and ultimately solving water-related conflicts in transboundary settings (see Sect. 24.3).

The future perspectives in model-based management of water resources was illustrated by the seminal paper of Hipsey et al. (2015). They propose a comprehensive network that integrated historical and online observation data, data driven modelling tools and dynamic simulations using integrated models. This framework enables the assimilation of measurements into ongoing model simulations and automated routines for assessing the uncertainty of forecast. Moreover, parameter identification is taking place based on existing model outputs and data so that the model configuration can evolve to more reliable settings for a given system.

24.12 Conclusions

- Multipurpose reservoirs are increasingly important under conditions of global change and for achieving SDGs.
- Trade-offs between partly competing water uses may be diminished via an integrated management approach. In particular hydropower, as a non-consumptive use, provides opportunities for synergies with other uses.
- Global change is expected to intensify trade-offs between competing water uses, making the adoption of integrated management even more pressing.
- Water quality issues are also expected to be exacerbated by climate change, requiring increased efforts to implement effective water quality management.
- In transboundary settings multipurpose reservoirs offer increased opportunities for benefit sharing and cooperation and may therefore facilitate resolving water conflicts.
- The management of multipurpose reservoirs requires adopting a systems perspective, making watershed management an essential element concerning both water quantity as well as quality.
- Food web manipulation (biomanipulation) within multipurpose reservoirs may effectively support water quality management, at least in the temperate region.
- Various technical measures within the reservoir (or at the inlet) as well as management operations such as withdrawal management can be applied for water quality management considering both the reservoir itself as well as the downstream river.
- Negative environmental impacts of reservoirs can be reduced by proper planning and site selection and by adopting specific management measures, which partly requires refurbishing the technical infrastructure.
- Modelling tools are indispensable for integrated management of water quantity and quality and appropriate water allocation to various uses. They should be integrated into frameworks spanning from the collection of monitoring data to model simulations and assessment of management options.

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Stephan Hülsmann lead the Systems and Flux Analysis considering Global Change Assessment unit at the United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES) and is affiliated to the Global Change Research Institute CAS (CzechGlobe), Czech Republic. He obtained his Ph.D. at Technische Universität Dresden (integrated water quality management in reservoirs). His research interests are integrated resources management, and responses of aquatic systems to stressors such as eutrophication and climate change.

Karsten Rinke is a limnologist heading the Department of Lake Research at the Helmholtz-Centre for Environmental Research (UFZ) in Magdeburg, Germany. His main research topics include plankton ecology, reservoir management, water quality monitoring, and lake ecosystem modelling. He graduated and received his Ph.D. from Dresden University of Technology and was afterwards on a researcher position at the University of Konstanz before he took over his current position at UFZ.

Lothar Paul graduated at the University of Leipzig, Germany in physics. After working for 4 years in an electronics company, he accepted an assistant position at the Neunzehnhain Ecological Station of the University of Technology, Dresden and took over its directorship in 1980. He received his Ph.D. in 1985 in the field of limnology. As teacher and researcher, he concentrated on applied aspects of limnology and management of drinking water reservoirs until—and beyond—his retirement in 2016.

Cristina Diez Santos is Senior Hydropower Analyst at the International Hydropower Association, focusing on the river basin development and sediment management work programmes. Cristina holds a master degree in civil engineering specialized in hydraulics and a master of advanced studies in sustainable water resources from ETH Zurich. She has experience in hydropower development and water—energy nexus, working with over 35 countries, with international financial institutions, the private and public sectors and NGOs.

25 Complexity in Water Management and Governance

Sabrina Kirschke and Jens Newig

Abstract

Water management is often facing complex problems, which are particularly challenging to address. But while the term 'complexity' has increasingly been used, the concept and its implications for management and governance have often remained unclear. Building on both conceptual and empirical research, this chapter sheds light on complexity in the water field from a management and governance perspective. Analytical concepts of complexity are described and distinguished from related concepts such as 'wicked' and 'uncertain' problems. Further, three types of approaches to address complex problems are discussed, characterized by various understandings of complexity, governance approaches, and emphasis put on inputs (processes) and outputs (results). The chapter provides examples of addressing complex problems, including installing an Integrated Water Resources Management, implementing a Nexus approach to environmental resources and sectors, and addressing poor water quality within the European Water Framework Directive. The chapter concludes on the future role and design of governance research in addressing complex water management problems.

Keywords

Complexity • European Water Framework Directive • Integrated Water Resources Management • Nexus • Uncertainty • Water quality • Wicked problems

S. Kirschke (✉)
United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany
e-mail: kirschke@unu.edu

J. Newig
Leuphana University, Lüneburg, Germany
e-mail: newig@uni.leuphana.de

Abbreviations

IWRM	Integrated Water Resources Management
NGO	Non-Governmental Organization
WFD	Water Framework Directive

25.1 Introduction

The role of complexity in management and governance has been discussed increasingly in the field of water (e.g., Pahl-Wostl 2007; Metz and Ingold 2014; Dunn et al. 2017). Water problems are often regarded as complex not only in a biogeophysical and technical sense but also from a management and governance perspective. Such complexity is assumed to hinder the design and implementation of effective measures to address water problems. One recent example is the pollution of freshwaters with contaminants of emerging concern such as pesticides or pharmaceuticals. While there exist some technologies to reduce such pollutants in wastewater, designing and implementing solutions is challenging given the high number of different contaminants, various effects on socio-ecological systems, as well as diverging interests regarding solution options.

While the role of complexity in water management and governance has gained wide attention in policy debates, the role of complexity in research on water management and governance is still a niche topic as compared with water-related complexity research more generally. However, the role of complexity for water management and governance has also gained momentum in the academic literature. In the field of water, the number of SCOPUS-listed publications on 'complexity,' 'management,' and 'governance' has, in fact, increased significantly since 2000. The annual number of publications on complexity and water has risen from 368 publications in 2000 up to 2631 publications in 2020. Many of these publications explicitly refer to the management of complexity, with 57 publications in 2000 up

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to 578 publications in 2020. A smaller number of publications directly relate to governance, with an increase from 2 publications in 2000, up to 56 in 2020 (see Fig. 25.1).

But while the increase of discussions at both the political and academic level has gained momentum, the term 'complexity' also risks conceptual stretching, resulting in limited usefulness from an analytical point of view. While most practitioners and researchers would—intuitively—agree that water problems are complex, the understanding of the complexity and its implications for problem-solving, including management and governance, have been mostly unclear (e.g., Kirschke et al. 2017a, b).

This chapter sheds light on this debate, building on previous work on the role of complexity in water management and governance. It starts by introducing the basic concept of complexity, distinguishing it from related concepts such as 'wicked' and 'uncertainty' problems (Sect. 25.2). Then it discusses various strategies to address complex problems from a management and governance perspective (Sect. 25.3). The next chapter then provides examples of addressing complex problems related to (i) an Integrated Water Resources Management, (ii) the Nexus approach in environmental management, and (iii) addressing poor water quality within the European Water Framework Directive (Sect. 25.4). Section 25.5 concludes on the role of governance research in addressing complex water problems.

25.2 Understanding the Complexity of Water Management Problems

Complexity has become a prominent concept in the field of water management. Both researchers and practitioners state that water management problems such as urban water management (Dunn et al. 2017), the pollution with contaminants of emerging concern (Metz and Ingold 2014), and diffuse water pollution (Kirschke et al. 2019a) are particularly complex.

Complexity can be defined in different ways. In most general terms, problem complexity is understood as 'a predictor of how challenging problem solving is' (Kirschke and Newig 2017, p. 3). Research traditionally describes the number of interconnected and dynamically evolving factors as a vital sign of complexity. In social science, additional structures such as conflicting interests between stakeholders and informational uncertainties play an increasing role. Kirschke et al. (2017b, p.2) differentiate five dimensions of complexity:

1. Goals, including their number and relationship with each other,
2. Variables, referring to the number of (non-constant) factors that characterize the problem setting, which potentially influence goal achievement, and which therefore should be considered in decision-making,
3. Dynamics of these variables, meaning how strongly their values change over time,

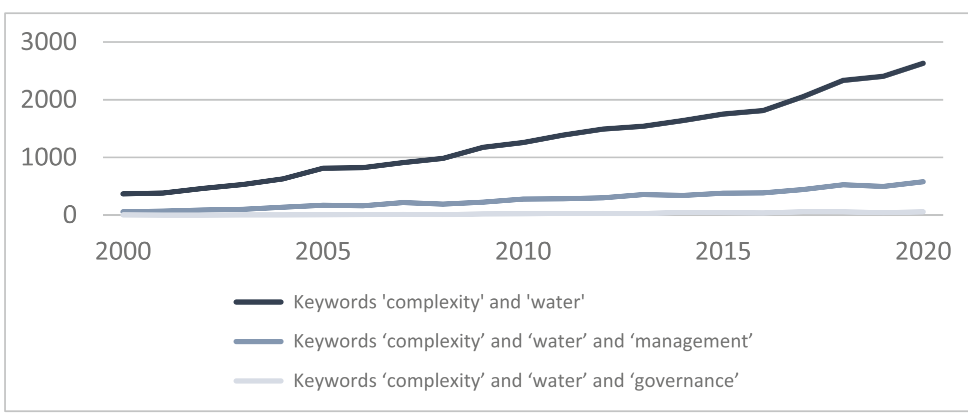

Fig. 25.1 Number of SCOPUS-listed publications in the field of complex water problems. Source: Own representation

4. Interconnections of the variables, describing the extent to which the variables are interrelated, and
5. Informational uncertainty, referring to how much information is missing for problem-solving.

Water research has identified multiple sources of complexity, including a variety of goal conflicts, natural, technical, and social influencing factors, their dynamics, interconnections, as well as data, information, and normative uncertainty as given in Table 25.1.

While water managers typically have to consider the diversity of influencing factors illustrated in Table 25.1, scholars also differentiate various degrees of problem complexity, contrasting complex problems with simple or complicated problems. For each of the above-listed dimensions, Kirschke et al. (2017b, 2019a, b) distinguish different degrees of complexity, ranging from simple to complicated to complex problems. Complexity may thus be understood as a multidimensional concept between two extremes: very simple problems up to very complex problems as shown in Fig. 25.2. Simple problems are defined by a lack of goal conflicts, a small number of static factors which are barely interconnected, as well as certainty in decision-making (see small pentagon in Fig. 25.2). The upgrades of wastewater treatment plants in some developing countries may be an example of that. Complex problems, on the other hand, are instead coined by multiple conflicts, a variety of highly dynamic and interconnected factors, as well as substantial uncertainty (see large pentagon in Fig. 25.2). A recent example is pollution with contaminants of emerging concern.

Research further contrasts complex problems with other types of problems, which highlight barriers to problem-solving. Water management and governance problems have often been described as 'wicked' (e.g., Patterson et al. 2013; Grafton 2017; Shortle and Horan 2017; Markowska et al. 2020), or 'uncertain' (e.g., Newig et al. 2005; Sigel et al. 2010; Höllermann and Evers 2017). But while the three concepts of 'complexity,' 'wickedness,' and 'uncertainty' share many similarities by highlighting structural barriers to problem-solving, the concepts also differ from each other, thus shedding light on specific types of barriers.

The term wickedness mainly goes back to Rittel and Webber (1973), who highlight ten dimensions of problems, which hinder the planning and addressing of public policy

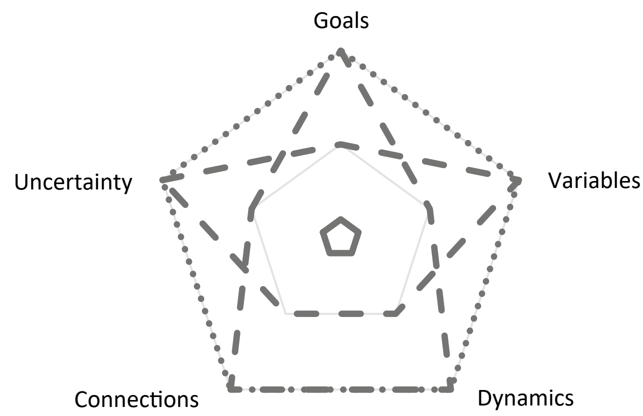

Fig. 25.2 Variations of problem complexity across five dimensions. Depicted are four generic examples of complex problems (dotted lines, large pentagon), complicated problems (dashed lines; two examples of medium pentagons), and simple problems (solid lines; small pentagon). Medium degrees of complexity may include elements of simple or complex problems as well (a combination of dotted and dashed lines) (*Source*: Kirschke et al. (2017a))

Table 25.1 Sources of complexity in the water field

Complexity dimensions	Arguments for complexity
Goal conflicts	Conflicts between stakeholders using water or affecting the quality of freshwater resources, such as agriculture, industries, mining companies, wastewater treatment facilities, environmental organizations, tourism
Variables	Natural conditions (e.g., water, soil, climate conditions), local conditions (e.g., property rights, technical and financial capacities, population structure), governance conditions (e.g., responsibilities, regulations), social and cultural framework conditions (e.g., interests of stakeholders, cultural background), variety of solutions (different technical measures and governance strategies to address problems)
Dynamics	Linear and exponential dynamics of conditions (e.g., climate change, demographical and economic development), development of solution options (e.g., technological and management innovations)
Interconnections	Interconnections between different variables, including effects of technical solutions depending on natural, local, and further governance conditions
Uncertainty	Lack of data and information regarding the structure, dynamics, and interconnections of various variables, unclear effects of solutions on problems, normative uncertainty

Source: Adapted from Kirschke et al. (2017a, 2019a) problems. The concept of wickedness has, just as the concept of complexity, gained massive momentum in public policy research (Dunn 2018). While the two concepts have many overlaps and are often used interchangeably, one important difference is suggested: While both concepts highlight conflicting goals and interests of stakeholders, wicked problems put a stronger emphasis on the differing values underlying such problems. As Rittel and Webber (1973, p.162) state, 'solutions to wicked problems are not true-or-false, but good-or-bad,' which also questions the role of science in addressing wicked problems. Wicked problems may thus be different to (more technically understood) complex problems, in which science may support conflict solving by providing evidence for the effects of actions.

Uncertainty problems are closely related to complex problems. In addition to the more classical data and information uncertainty addressed in science, social science research puts particular emphasis on uncertainties in decision-making, including, for example, uncertainties concerning conflicting interests of stakeholders. Dewulf and Biesbroek (2018), for example, differentiate 'nine lives of uncertainty,' which encompass these different strands of literature. Again, essential similarities and differences between the concept of complexity and uncertainty are assumed. While both concepts address conflicting interests or lacking data, the concept of complexity may instead describe the current state (existence of conflicts, lack of data), rather than the effects (normative uncertainty resulting from the presence of conflicts and the lack of data).

25.3 Addressing Complex Water Problems

Complexity, including its different dimensions and sources, may hamper solutions to problems significantly, and even questions the solvability of problems. One reason is the variety of interests on the part of stakeholders. While simple problems entail that there is agreement on a specific target, complex problems are coined by conflicting views on goals. Moreover, the interconnections of dynamic social, ecological, and technical factors can result in (delayed) adverse side effects of activities meant to address complex problems.

One example is the complex problem of groundwater pollution from agriculture. The pollution of groundwater with nutrients may trace back to intensive agricultural uses. Thus, more sustainable ways of agricultural production, such as extensification practices, can reduce the pollution of groundwater. However, such new agricultural practices may conflict with other societal goals such as food production against hunger, a stable income of farmers, and so forth. Further, even if pollution is reduced, effects may only be visible after long time frames, which may also decrease the willingness to take action against pollution.

Complexity research has dealt differently with these challenges of complex problems. We observe three partly intertwined types of approaches characterized by various understandings of how complex water management problems should be dealt with. These types can differ along three dimensions as given in Table 25.2, namely (i) input- vs. output orientation, (ii) the specific understanding of complex problems, and (iii) the type of governance approaches discussed.

Type 1 strategies are typically characterized by a strong output orientation, meaning that the focus of research and practice is on achieving effective solutions to complex problems. The starting point is an understanding of complex water management problems as (complex) technical problems, which can be solved by (complex) technological innovations. Examples are the building of large dams for providing water for drinking and irrigation, as well as large-scale wastewater treatment plants for addressing water pollution. Governance-wise, such approaches follow hierarchical (i.e., top-down) planning approaches in which solutions to water scarcity and pollution problems are designed and agreed upon centrally. However, while significant investments have often accompanied top-down approaches, the construction works have often been delayed due to a lack of acceptance at the local level. Also, constructions have often been decayed due to lack of funding or capacity for maintenance.

In contrast to type 1 strategies, type 2 approaches typically focus on a strong input orientation, meaning that science and practice put more emphasis on the knowledge and interests of local stakeholders rather than on clear-cut solutions. The starting point is an understanding of complex water management problems as complex social problems, coined by many different interests and fields of knowledge. Output-wise, type 2 approaches question optimal solutions, and instead argue for constant adaptation to new situations (Chaffin and Gunderson 2016), aiming at small wins rather than grand solutions (Termeer and Dewulf 2019). Implementing such a management approach in complex situations also calls for new governance arrangements and strategies. Research has come up with several strategies aiming at increasing small wins in complex cases. These strategies can be best summarized under the notion of 'diversity.'

The 'diversity' approach mainly calls for a strong involvement of stakeholders in problem-solving processes (Duit and Galaz 2008). Researchers that are arguing in this direction call for involving many different types of actors (e.g., public, private, and civil society sector), representing different scales (e.g., from local to global), and sectors (e.g., water, agriculture, and various industrial sectors) in decision-making. Also, researchers call for inter- and transdisciplinarity, i.e., the involvement of different types of disciplines (e.g., natural, technical, and social sciences), as

Table 25.2 Three types of strategies to address complexity in management and governance

	Type 1	Type 2	Type 3
Input- vs. output orientation	Output orientation	Input orientation	Effect of inputs on outputs
Understanding of complexity	Technical complexity	Social, natural, and technical complexity	Different types of complex problems
Dominant governance approaches	Top-down decision-making	Bottom-up decision-making	Different types of strategies

well as the close interaction between science and practice (e.g., Head and Xiang 2016; Brugnach and Özerol 2019). Popular governance concepts that are related to this approach are forms of collaborative, deliberative, and network governance (e.g., Imperial 2005; Head 2014). Hierarchic and evidence-based policy-making are generally questioned.

Such participatory approaches mostly build on the assumption of limited knowledge of individual decision-makers. While individuals may have an important knowledge in one specific area, they may not understand the different implications of actions for other fields of science and practice. The management of a wastewater treatment plant, for instance, may be located on a local scale. Still, it also depends on decisions at the national and global levels and effects the whole basin. The involvement of representatives of these different scales may then improve the knowledge base for making relevant decisions regarding the wastewater treatment plant. However, while participation has been widely promoted in water governance research, research has also shown that participation does not always result in better environmental outcomes (Koontz and Thomas 2006; Newig and Fritsch 2009).

Building on the experiences of type 1 and 2 strategies, type 3 approaches more strongly combine input and output orientations in addressing complex problems. Following a policy design approach, respective approaches put a stronger emphasis on the effects of participation and other influencing factors on complex problem-solving.

The starting point is the acknowledgment that complex problems are indeed complex in many regards, including technical, natural, and social dimensions. In contrast to type 2 approaches, however, this type of approach puts a stronger emphasis on a differentiated analytical understanding of complex problems. This new understanding also results in a diversity of complex water-related problems, such as more complex diffuse pollution problems and less complex technical water management problems.

Given the variety of problem types, type 3 approaches emphasize the diversity of governance arrangements, policies, and instruments, as well as their effects on small wins in complex situations.

In terms of governance arrangements, research analyses the effects of diverse influencing factors on designing solutions to complex problems. Building on the results of type 2 approaches, participation plays a central role in collecting knowledge for solutions, thereby also affecting better outcomes. However, participation, and particularly deliberation, is no panacea, but may also be time-consuming and prone to reinforcing existing interests and thus may also have adverse effects on adaptive decision-making. Moreover, additional factors may influence the design of small-win-solutions to complex problems. Hard law, for instance, may increase the willingness to take actions in a complex situation, but may also hamper adaptive decision-making (e.g., Kirschke and Newig 2017).

Further, research analyses policy mixes rather than one-fits-all solutions to complex problems. Emphasis is put on the coherence of water policies with related policies. A prominent example is research on the nexus of sectors (e.g., water, energy, and food) and resources (e.g., water, soil, waste) (e.g., Nilsson et al. 2012; Kurian 2017; Schaub 2019). Also, research suggests a diversity of governance strategies meant to address complex problems, amongst them economic incentives, information and persuasion, and regulations, calling for a mix of different governance strategies according to context (e.g., Kirschke et al. 2019b).

However, while type 3 debates can build on previous work in water management and governance research and public policy analyses more generally, the benefits of this analytical approach to complex problem-solving are still to be defined. Open questions mostly relate to the effects of various policy mixes on policy outcomes depending on problem types (e.g., Capano and Howlett 2020).

25.4 Examples of Addressing Complex Water Problems

Complex water management problems are a global phenomenon. This section provides examples of how complex water problems are being addressed, considering different levels—from globally applied concepts such as an Integrated Water Resource Management (IWRM) and the Nexus of resources and sectors, down to rather specific water pollution problems in Europe.

25.4.1 Integrated Water Resources Management

A broad example of addressing complex water management problems is the implementation of IWRM. IWRM generally describes ‘a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems’ (GWP 2000, p. 22). While having different origins, the concept mainly goes back to the Dublin principles adopted at the International Conference on Water and the Environment in Dublin 1992. Since then, the concept has been widely investigated and has also guided water management and governance globally (Mukhtarov 2008; Ibisch et al. 2016).

Research has shown that implementing an IWRM is a complex endeavor (e.g., Pahl-Wostl 2007; Pahl-Wostl et al. 2012). First, IWRM usually comes together with a set of conflicting goals regarding water uses. Research has identified various water using stakeholders and sectors (e.g., agriculture, urban wastewater, industries, mining, etc.), which partly have conflicting interests (e.g., concerning water treatment). Second, the concept puts special emphasis on integrating various types of waters (groundwater and surface waters), resources (e.g., water and land), sectors (e.g., agriculture, industry, water), under various framework conditions (e.g., demographic change, climate change). IWRM thus includes a high number of interconnected and dynamic factors. Also, several authors have emphasized that uncertainty prevails concerning what should be integrated and how this should be done (e.g., Biswas 2008; Hering and Ingold 2012; see also commentaries on IWRM in Chapter 12 and Sect. 3.4).

To address such complex problems, a diversity of governance strategies has been suggested, with special emphasis given on participation and basin organizations (e.g., GWP 2000). Participation of different types of stakeholders (e.g., from the public and private sector, and civil society), from different sectors (e.g., agriculture, industries), and scales (e.g., local, basin, national, international) has been key to the IWRM concept and its implementation, and as a tool for adaptive management. However, research and practice have also emphasized the need for an adequate design of participatory processes for effective outcomes (e.g., Anderson et al. 2008; Kirschke et al. 2016). In terms of organizational structures, the river basin approach and the establishment of river basin organizations have been promoted to implement IWRM. In consequence, many river basin organizations have been established to foster integrated management approaches. However, the organizational shifts towards basin organizations have also been seen critically, and the role of the specific designs of such organizations according to capacities and contexts has been highlighted (e.g., Moss 2003; Dombrowsky et al. 2014; Hidalgo-Toledo et al. 2019).

While changes in politics (participation) and polity (organization) have certainly advanced IWRM debates, the effects of these approaches are also ambivalent. On the one hand, reports see some progress in the implementation of an IWRM (UN Water 2012). On the other hand, there is also much skepticism (e.g., Biswas 2008). Against this background, research has increasingly called for more pragmatism, even proposing a light approach of IWRM, adapting the level of integration to the respective case-specific conditions (e.g., Butterworth et al. 2010; Hering and Ingold 2012).

25.4.2 Nexus Approach to the Management of Environmental Resources and Sectors

Another example of addressing complex water problems is the Nexus approach to environmental resource management. In Nexus-related research, academics consider the interrelationships between various sectors (e.g., water, agriculture, energy, climate, health) or resources (e.g., water, soil, and waste). While there are some similarities with the IWRM concept, there are also some important differences, such as lacking water centricity and the emphasis put on the integrated management of specific sectors or resources (e.g., Benson et al. 2015; Hagemann and Kirschke 2017). The Nexus approach has been increasingly advocated since 2011 when the Bonn Nexus conference on water, energy, and food took place in Germany (Hoff 2011). Since then, research has provided an increasing number of examples for nexus problems and areas, amongst them the safe use wastewater in agriculture (e.g., Hettiarachchi et al. 2018), or multifunctional land-use systems (e.g., Zhang and Schwärzel 2017).

Research has shown that Nexus problems are quite complex. First, there exists, just as in the field of IWRM, conflicting interests between different types of stakeholders. Considering the water-energy-food nexus, for instance, environmental NGOs can be just as concerned as farmers, mining companies, and consumers. Second, nexus problems typically involve many interconnected and dynamic social, environmental, and technical factors. Third, uncertainty often exists concerning goals and measures. One example is the integrated management of water and soil in the Loess Plateau in Northwest China. The management of these resources is complex in the sense that severe conflicts related to resource allocation and management exist, a large number of social and natural factors influence decision-making, and there is a lack of reliable data related to the problem (Kirschke et al. 2018).

To address such complex nexus problems, research suggests different management and governance strategies, including participatory governance arrangements, institutional prerequisites, and strategies for implementing solutions (e.g., Kurian and Ardakanian 2016; Urbinatti et al. 2020). A particularly important role play the concepts of trade-offs, synergies, and policy coherence. Research generally calls for coherent policies along with goals and instruments at the level of measures and governance strategies (e.g., Nilsson et al. 2012; Kurian 2017).

However, just as for IWRM, the effects of Nexus research and practice are yet to be defined. On the one hand, Nexus approaches have the potential to enable both more targeted and integrative thinking and practice, resulting in increased policy coherence and, thus, also better solutions to complex problems (see Chapter 17, presenting a comprehensive overview of the application of the nexus concept in the Gulf Region; and Sects. 3.4 and 9.4, addressing some fundamental issues related to nexus considerations). On the other hand, some researchers also question the relevance of applying a Nexus approach for integrated solutions to complex resource management problems (e.g., Wickelns 2017). Also, research calls for strengthening the relevance of nexus research by further clarifying relevant scales for its application (e.g., Lawford et al. 2013; Avellán et al. 2017; Weitz et al. 2017).

25.4.3 Addressing Poor Water Quality Within the European Water Framework Directive

One rather specific example of addressing complex water management problems is the implementation of the European Water Framework Directive (WFD) (Directive 2000/60/EC)—a major regulation for water quality management in the European Union. The Directive came into force in 2000, aiming at achieving a good ecological and chemical status of European freshwaters by 2015. To this end, the member states of the European Union had to (i) monitor the state of freshwaters and to (ii) design and implement river basin management plans and programs of measures. If water quality goals had not been achieved by 2015, EU member states could make adjustments to achieve the Directive's goals until the end of 2027 (e.g., Richter et al. 2013).

Research has shown that achieving the goals of the WFD is a very complex endeavor. This particularly relates to diffuse pollution problems, such as the pollution with nitrogen from agricultural sources (e.g., Wiering et al. 2018; Kirschke et al. 2019b). However, water problems are also diverse, with some point source pollution problems being less complex than selected diffuse pollution problems. One example is an analysis of 37 types of water pollution problems in Germany, targeted by the German federal states to implement the WFD's goals (Kirschke et al. 2017b). These problems relate to various types of waters (groundwater and freshwaters), and pollution sources (e.g., agriculture, mining, industries, urban wastewater treatment plants, stormwater). Based on semi-structured interviews with experts from science and practice, research has shown that these pollution problems are complex to different degrees (Kirschke et al. 2017b, Fig. 25.3), with some clusters of problems being rather tame or wicked, and others being characterized by system complexity and uncertainty (Kirschke et al. 2019a, Fig. 25.4).

To address such complex problems, the WFD obliges European member states to a participatory approach, including the sharing of information and commitments to including stakeholder's recommendations into planning (Art. 14, Directive 2000/60/EC). According to the Directive's requirements, such participatory arrangements are typically implemented at the basin level. Still, they may also be extended to lower and larger scales, such as the water body and national level. Moreover, participatory arrangements follow different formats, such as written information and recommendation transfer and roundtable discussions.

Also, EU member states can choose different governance strategies to address specific water quality problems. While there exists a diverse set of governance strategies, such as economic incentives, information and persuasion, and regulations, such strategies are used to various extents. Concerning the complex problem of agricultural pollution of freshwaters in Germany, for instance, information and persuasion mechanisms are predominant. In contrast, hard law and economic incentives are only used to a limited extent (Kirschke et al. 2019b). Coming to the emerging field of micro-pollution, recent analyses show some reluctance by the German population to apply market-based instruments (Tosun et al. 2020).

While the implementation of the WFD is entering its third stage, the governance approach by European member states may not necessarily be effective. Generally, the targets of the WFD are barely met. In terms of the example in Germany, an analysis of the solution to the 37 pollution problems shows that complexity significantly hindered the solutions to complex problems (Kirschke et al. 2017b). While there are some advances in problem-solving, major water quality problems are particularly challenging to address. One example is the pollution of freshwater resources from agriculture, where goal conflicts between different parties have significantly hindered the solution of problems of rather high complexities (Kirschke et al. 2019b; Schaub 2019).

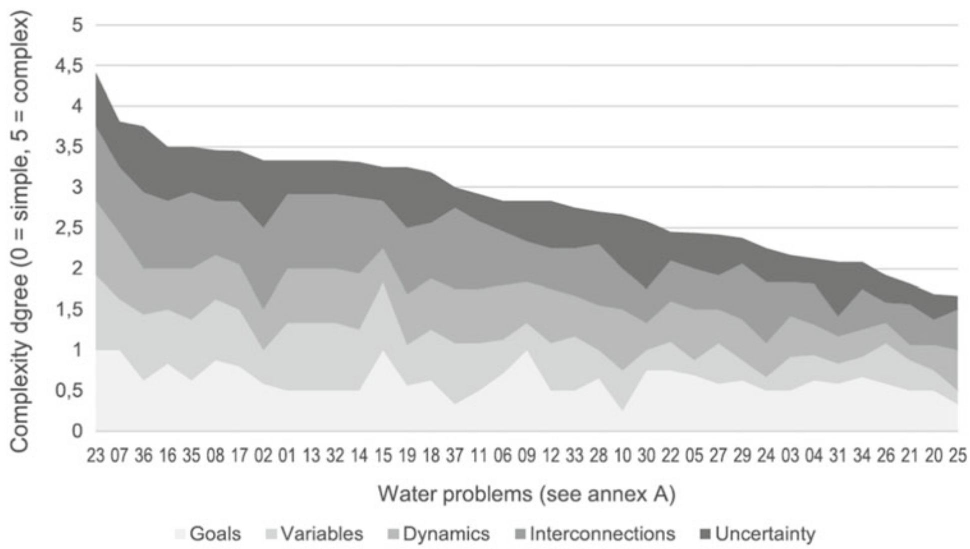

Fig. 25.3 Cumulative complexity degrees per type of problem. The total complexity of a problem (0–5) is the sum of individual degrees of the five dimensions of complexity (0–1), measured based on 65 expert interviews (*Source*: Kirschke et al. 2017b)

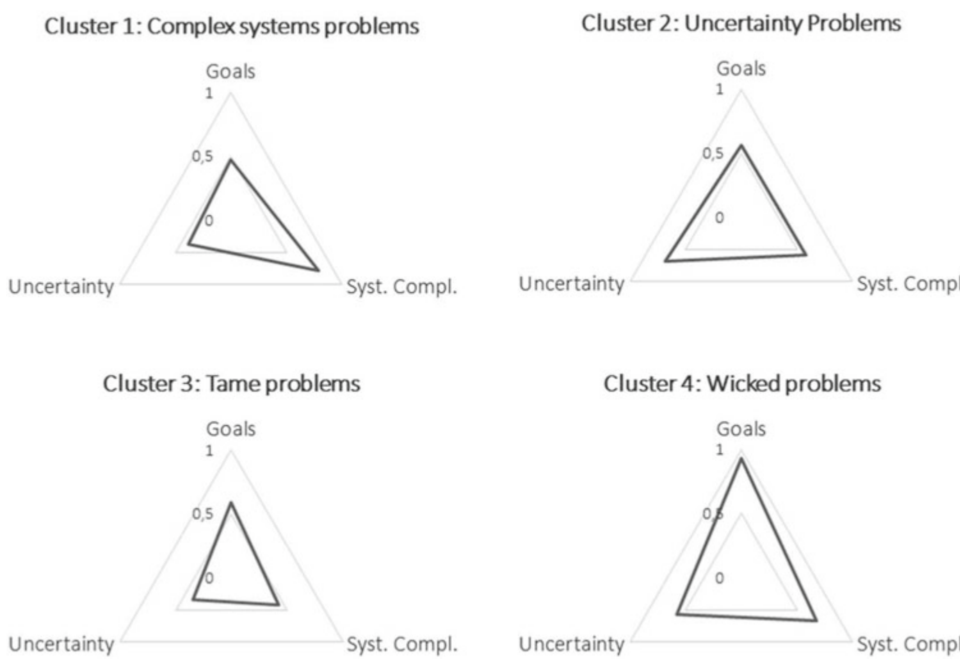

Fig. 25.4 Four clusters of water quality problems. Depicted are clusters of 'complex system', 'uncertainty', 'tame' and 'wicked' problems, based on three factors of complex problems (goals, uncertainty, and system complexity), with system complexity encompassing variables, dynamic, and interconnections (*Source*: Kirschke et al. 2019a).

25.5 Conclusion

Complexity research has gained momentum in the field of water management and governance. Two types of conclusions shall be highlighted: First, the understanding of complexity has moved from a rather technical or natural science perspective to an understanding of complex problems as integrated social-ecological problems. This goes hand in hand with more advanced analytical understandings of complexity, encompassing various dimensions and sources, helping to relate better the concept of complexity to other concepts such as wickedness and uncertainty. Second, the role of governance in addressing complex water management problems has moved from hierarchic and participatory decision-making approaches to more complex analytical frames, considering various influencing factors for generating small wins in complex situations. Future research may deepen analyses of effects of various governance arrangements and strategies on addressing different types of complex water problems, including water quality and scarcity problems, as well as their interlinkages with other resources (e.g., soil and waste) and sectors (e.g., agriculture, energy, health, biodiversity, etc.). Given the variety of problems and the myriad of potential influencing factors, research may follow mixed methods designs, as public policy research in the field of complex and wicked problems suggests (Mertens 2015). Particular emphasis will also have to be put on the long-term effects of management and governance strategies on sustainability in its social, ecological, and economic dimensions (e.g., Pahl-Wostl 2020).

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Sabrina Kirschke is senior research associate at United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), in Dresden, Germany. As a political scientist, she contributes to the research, academic, and capacity development activities in water resources management within the resource nexus.

Jens Newig is full professor and heads the Institute of Sustainability Governance at Leuphana Universtiy Lüneburg, Germany. Dr Newig has led several funded projects and published widely on sustainable water governance, with a particular focus on governance implications of the EU Water Framework Directive.