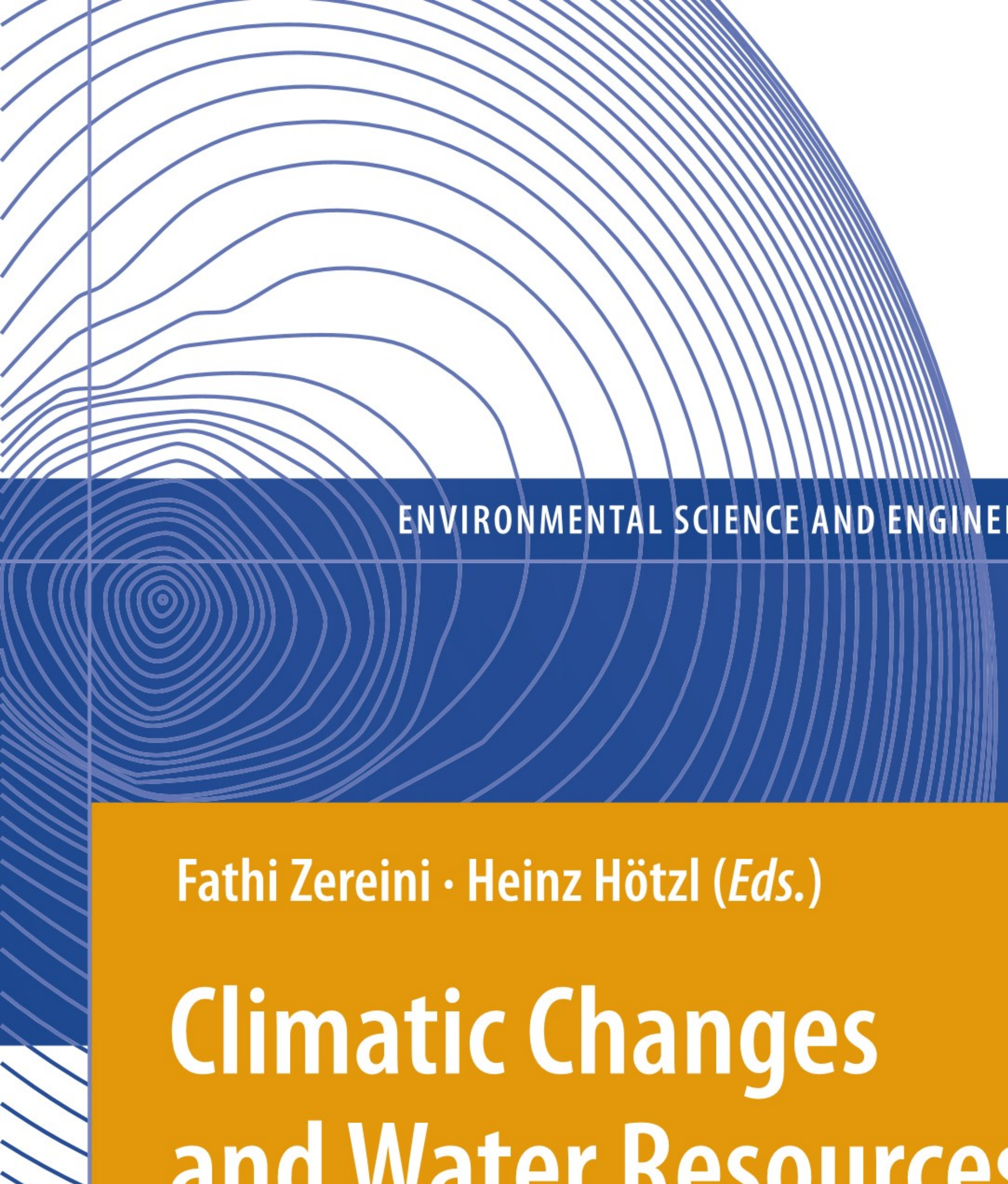


ENVIRONMENTAL SCIENCE AND ENGINEERING

Fathi Zereini · Heinz Hötzl (*Eds.*)

Climatic Changes and Water Resources in the Middle East and North Africa

Springer

Environmental Science and Engineering
Subseries: Environmental Science

F. Zereini · H. Hötzl (Eds.)

Climatic Changes and Water Resources in the Middle East and North Africa

Springer

Editors

Prof. Dr. habil. Fathi Zereini
Institute for Atmospheric and
Environmental Sciences
Goethe-University, Frankfurt
Altenhöferalle 1
D-60438 Frankfurt am Main
Germany
zereini@iau.uni-frankfurt.de

Prof. Dr. Heinz Hötzl
Universität Karlsruhe
Inst. Geologie
Kaiserstr. 12
76131 Karlsruhe
Germany
heinz.hoetzl@agk.uka.de

ISBN: 978-3-540-85046-5 e-ISBN: 978-3-540-85047-2

Environmental Science and Engineering ISSN: 1863-5520

Library of Congress Control Number: 2008932570

Cover Design: Integra Software Services Pvt. Ltd.

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Preface

This publication on „Climatic Change and Water Resources in the Middle East and North Africa“ is dedicated to high-priority topics related to the impact of climate change on water resources in a water scarce region. Many aspects of climate change and its impact on the global hydrological cycle have been investigated, presented and published. However, the quantification of this influence is still very uncertain due to lack of understanding the complex system and the detailed interactions. Hence, process-oriented interdisciplinary research is necessary to overcome this problem.

The German-Arab Scientific Forum for Environmental Studies organizes every second year a scientific forum as a platform for the exchange of information and presentation of research findings. As a result of this scientific forum, many scientists have taken the opportunity to contribute to this book giving an overview about their research regarding this topic. Naturally this book is divided into three chapters:

Global climate change- sources and impacts on the water cycle.

Impact of climate change on water resources.

Water resources and water management.

Global climate change due to greenhouse gases in the atmosphere is influencing the world water cycle resulting in changes in precipitation patterns, temporally and regionally. In the first chapter several authors present their research results dealing with this relationship.

First of all an overview about the dynamics of the climate systems in scope of the earth history is given and the influence of the temperature rise on the atmospheric circulation and thus on the global water cycle is discussed. However, for the prediction of the future development, observations of the regional precipitation trends are important. Hence, the regional climate trends in the Middle East and North Africa have been investigated either by applying climate models or statistical analysis.

The effects of climate changes on water resources in chapter two are also related to regions of the Middle East and North Africa. This chapter begins with a focus on climate changes and the resulting discharge conditions in the Arabian Peninsula in Quaternary, complimented by the paleo-climate for Holocen and Neolithicum. The impact of climate change on water resources in the region is discussed and a short term hydrologic drought in Lebanon is proposed as a superposition of climate and anthropogenic effects. It is assumed that changes in precipitation average and events will cause a higher number of floods in the future and require new management options for sustainable ground water exploitation.

The influence of the climate change on the world water cycle is distressed by increasing water demands due to population growth and urbanization. Thus, integrated water resources management has become an eminent steering mechanism in the optimization of solutions to this problem.

Chapter three of this book comprises 14 contributions related to this topic. New concepts in water management, in technologies of water exploitation or details of water resources management including water protection are presented and discussed. Other contributions focus on linked eco-hydrological processes in Lake Kinnereth, ecological effects in soils, the relevance of groundwater during droughts, groundwater degradation by sea water intrusion in the coast of greater Beirut, Lebanon, the desiccation of the Dead Sea and the interaction between population dynamics and water supply systems.

All topics of this book are complimentary and contribute to a comprehensive understanding of the interactions between global climate change, world water cycle and water resources. New and innovative water management concepts are necessary to overcome some of the problems that might arise within this development.

All over, a valuable and meaningful interdisciplinary mixture of topics has been combined in this book and is of great interest to many scientists.

In this context, I wish this publication a friendly and successful acceptance in the scientific world.

Aachen March 2008 Prof. Dr. Rafig Azzam

Preface of the Editors

Changes to the earth's climate have a direct effect on the global hydrological cycle and hence on water. The rise of temperatures may exacerbate existing water shortages, impair water quality or enhance the frequency and intensity of floods and droughts. In particular countries in the transition zone from wet to dry arid climatic conditions have experienced water-related problems, such as uneven distribution of water resources and year-to-year variability. These changes in water resources and water-related extreme events are likely to affect social and economic developments.

Water resources are one of the highest-priority issues with respect to climate change impacts and adaptation in the Middle East and North Africa. While many aspects of climate variations and their impact on water resources have been presented and published, the information is still greatly dispersed and lacks a general overview. In order to support exchange on this issues the *German-Arab Scientific Forum for Environmental Studies* organised in 2006 a conference on this topic. The resulting report provides a broad overview of this important issue. It highlights the current knowledge about climate variations and change, discusses the impact on water resources systems, characterizes its predictability, and provides examples of its use in water resources management, planning, and design.

This book „*Climatic Changes and Water Resources in the Middle East and in North Africa*“ is the first to comprehensively present and discuss the results of scientific research on *Impact of climate change on water resources in this regions* from a variety of disciplines. The subject is described and discussed in three main chapters and different case studies. The three main chapters are (1) Climatic changes – their sources and effects on the water cycle, (2) Impact of climate change on water resources, (3) Water resources and water management.

These chapters are further split up into 26 sections. A total of 64 individuals from Germany, Israel, Italy, Jordan, Lebanon, Morocco, Palestine, Syria, Tunisia, and UK have made contributions to this book.

The editors would like to thank the authors and reviewers for their contributions and cooperation in terms of the successful completion of this book. Many thanks go to Prof. Dr. R. Azzam from the Department of Engineering Geology and Hydrogeology, RWTU-Aachen University and Dr. A. Margane from Federal Institute for Geosciences and Natural Resources (BGR), Germany for their support. We would further like to thank Prof. Dr. Broder J., Merkel from the Geology Department, University of Freiberg, Germany, Prof. Dr. Christian-D. Schönwiese from Institute for Atmosphere and Environment, J.W. Goethe University, Frankfurt, Germany, and Dr. A. Shaban from National Council for Scientific Research, Remote Sensing Center, Beirut, Lebanon.

We are especially grateful to Mrs A. Oelschläger from Springer, who made this publication possible. We would also like to extend our gratitude to Mr. H.-H. Dülfer from the Institute for Atmospheric and Environmental Studies, Goethe University Frankfurt am Main.

Frankfurt am Main, Karlsruhe, March 2008

Prof. Dr. Fathi Zereini
Prof. Dr. Heinz Hötzl

Contents

List of Contributors

Abdallah, A
The Arab Center for the Studies of Arid Zones and Dry Lands – ACSAD,
POB 2440; Damascus,
Syria
www.acsad.org

Ait Boughrous Ali
Département de Biologie, Laboratoire d'Hydrobiologie,
Ecotoxicologie et Assainissement,
Faculté des Sciences Semlalia,
BP 2390, Marrakech
Morocco

Al-Sibai, M
The Arab Center for the Studies of Arid Zones and Dry Lands – ACSAD,
POB 2440; Damascus
Syria
www.acsad.org

Arkadan Abdul-Rahman M Dr
Lebanese University, Faculty of Sciences
e-mail: ararkadan@hcu.edu.lb

Benaabidate Lahcen, Prof Dr
Faculy of Sciences and Technology,
Laboratory of Georesources and Environment,
Fez
Morocco,
e-mail: benaabidate@yahoo.fr

Benbouziane, A
Secrétariat d'Etat auprès du Ministère de l'Aménagement du Territoire de l'Eau et de l'Environnement,Chargé de l'Eau,
Rabat
Morocco

Borgstedt Ariane
Bundesanstalt für Geowissenschaften und Rohstoffe,
Stilleweg 2, 30655 Hannover
Germany

Ben-Hur Memi
Institute of Soil, Water and Environmental Science,
The Volcani Center, POB 6
Bet Dagan, 50250
Israel
e-mail: meni@volcani.agri.gov.il

Born K, Dr
Institute for Geophysics and Meteorology, University Cologne
Kerpener Str 13,
D-50923 Köln
Germany

Boulanouar Mohamed
Département de Biologie, Laboratoire d'Hydrobiologie,
Ecotoxicologie et Assainissement,
Faculté des Sciences Semlalia,
BP 2390, Marrakech
Morocco

Busche, H
Institute of Geography, University of Bonn,
Meckenheimer Allee 166
53115 Bonn, Germany

Christoph, M, Dr
Institute for Geophysics and Meteorology,
University Cologne; Kerpener Str 13,
D-50923 Köln
Germany

Droubi Abdallah, Dr
The Arab Centre for the Study of Arid
Zones and Dry Land (ACSAD)
PO Box 2440; Damascus
Syria
e-mail: droubi@scs-net.org
www.acsad.org

El Alami El Filali Asma
Département de Biologie, Laboratoire
d’Hydrobiologie,
Ecotoxicologie et Assainissement,
Faculté des Sciences Semlalia,
BP 2390, Marrakech
Morocco

El-Fadel Mutasem, Prof Dr
School of Civil Engineering and the Environment, University of
Southampton
UK
e-mail: mfadel@aub.edu.lb

El-Naser Hazim, Dr
Amman
Jordan
e-mail: hazim.el-naser@osd.com.jo

Fink, A H, Dr
Institute for Geophysics and Meteorology,
University Cologne,
Kerpener Str 13,
D-50923 Köln
Germany

Friedrichsen Hans
Institute for Geological Sciences,
Freie Universität Berlin, Germany
Malteserstr 74-100
12249 Berlin
Germany

Fryar Alan Ernest
University of Kentucky at Lexington,
e-mail: alan.fryar@uky.edu

Gaaloul Noureddine, Dr
National Research Institute for Rural Engineering, Water and Forestry (INRGREF)
Rue Hedi Karray
BP10, 2080 Ariana, Tunisia
e-mail: gaaloul.noureddine@iresa.agrinet.tn

Gophen Moshe, Prof Dr
Senior Scientist - MIGAL,
Galilee Technological Center, and
Kinneret
Limnological Laboratory
POB 831 Kiryat Shmone (11016)
Israel
e-mail: gophen@migal.org.il

Hammerschmidt Konrad
Institute for Geological Sciences,
Freie Universität Berlin, Germany
Malteserstr 74-100
12249 Berlin, Germany

Heckl Andreas
Institute for Meteorology and Climate
Research (IMK-IFU),
Forschungszentrum Karlsruhe,
Kreuzeckbahnstraße 19,
82467 Garmisch-Partenkirchen
Germany

Hennings, V
Federal Institute for Geosciences and
Natural Resources – BGR,
Stilleweg 2; 30655 Hannover
Germany
www.bgr.bund.de

Hötzl Heinz, Prof Dr
Department of Applied Geology, University Karlsruhe,
Kaiserstr 12, 76128
Karlsruhe
Germany
e-mail: hoetzl@agk.uka.de

Huber, M
Federal Institute for Geosciences and
Natural Resources – BGR,
Stilleweg 2;
30655 Hannover
Germany
www.bgr.bund.de

Hummel Diana, Dr
Institut für sozial-ökologische Forschung (ISOE),
Hamburger Allee 45
60486 Frankfurt/Main
Germany
e-mail: hummel@isoe.de

Issar Arie S, Prof Dr
Ben Gurion University of the Negev,
Israel; J Blaustein Institutes for Desert
Research
Israel
e-mail: Issar@bgu.ac.il

Khalif Nidal
Ministry of Water and Irrigation (MWI)
PO Box 2412; Amman 11183, Hashemite
Kingdom of Jordan

Klose Stephan, Dr
Institute of Geology, University of Bonn,
Nussallee 8,D-53115 Bonn
Germany

Knippertz, P
Institute for Physics of the Atmosphere,
Johannes Gutenberg University,
55099 Mainz
Germany

Kunstmann Harald, Dr
Institute for Meteorology and Climate
Research (IMK-IFU),
Kreuzeckbahnstraße 19
82467 Garmisch-Partenkirchen
Germany
e-mail: harald.kunstmann@imk.fzk.de

Lahmouri Abdeddaim
Secréterait d'État chargé de l'Eau,
Ministère d'Aménagement du Territoire
de l'Eau et de l'Environnement,
Rue Hassan Benchekroun, Agdal Rabat,
Royaume du Maroc

Lange Torsten, Dr
Geoscientific Centre of the University of
Göttingen,
Department of Applied Geology,
Goldschmidtstrasse 3,
37077 Göttingen
Germany;
e-mail: tlange@gwdg.de

Marei Amer
Department of Applied Earth and Environmental Sciences,
Al Quds University,
East Jerusalem
Palestine

Margane, Armin, Dr
Federal Institute for Geosciences and
Natural Resources (BGR)
Stilleweg 2
D-30655 Hannover
Germany
e-mail: armin.margane@bgr.de

Maroun Rania, MS
Research Associate, Water Resources
Center,
American University of Beirut,
Beirut
Lebanon

Messana Giuseppe
Istituto per lo Studio degli Ecosistemi del
CNR; ISE-CNR,
Sede di Firenze;
Via Madonna del Piano 10;
50019 Sesto F no, Firenze
Italy
e-mail: messana@ise.cnr.it

Messouli Mohammed, Dr
Département de Biologie, Laboratoire
d'Hydrobiologie,
Ecotoxicologie et Assainissement,
Faculté des Sciences Semlalia,
BP 2390 Marrakech
Morocco;
e-mail: messouli@gmail.com

Mosbrugger Volker, Prof Dr Drhc
Senckenberg Research Institute and Natural History Museum
Senckenberganlage 25
60325 Frankfurt am Main
Germany; e-mail:
volker.mosbrugger@senckenberg.de

Löwner Ralf
GeoForschungsZentrum Potsdam (GFZ),
Germany,
e-mail: loewner@gfz-potsdam.de

Obeissi, M
The Arab Center for the Studies of Arid
Zones and Dry Lands – ACSAD,
POB 2440; Damascus
Syria
www.acsad.org

Oroud Ibrahim M, Prof Dr
Mu’tah University,
Kerak
Jordan
e-mail: ibrahimoroud@yahoo.com

Oulidi Hassane Jarar
Faculty of Sciences Dehar Mehraz,
Morocco,
e-mail: jararhassane@yahoo.fr

Paeth, H
Institute for Geography, University Würzburg, Germany
Am Hubland
97074 Würzburg
Germany

Reichert Barbara, Prof Dr
Institute of Geology, University of Bonn,
Nussallee 8,
D-53115 Bonn
Germany
e-mail: b.reichert@uni-bonn.de

Rimmer Alon
Kinneret Limnological Laboratory, Israel
Oceanographic & Limnological
Research Ltd,
PO Box 447, Migdal 14950
Israel

Saadeh Mark, MS
SANA Engineers, Beirut
Lebanon
e-mail: Saadeh_mark@yahoo.com

Salameh, Elias, Prof Dr
Dept of Env And Applied Geology
University of Jordan,
POB 9999 Webdeh, 1191
Amman
Jordan
e-mail: Salameli@ju.edu.jo

Schelkes, Klaus , Dr
Federal Institute for Geosciences and
Natural Resources (BGR)
Stilleweg 2; D-30655 Hannover
Germany
e-mail: k.schelkes@bgr.de

Schmidt Gerhard
Federal Institute for Geosciences and
Natural Resources (BGR)
Stilleweg 2; D-30655 Hannover
Germany
e-mail: Gerhard.Schmidt@bgr.de

Schönwiese Christian-D, Prof Dr
JW Goethe University, Institute for
Atmosphere and Environment,
POBox 111932
60054 Frankfurt/M, Germany
e-mail: schoenwiese@meteor.uni-frankfurt.de

Shaban Amin, Dr
National Council for Scientific
Research, Remote Sensing Center,
Riad El-Solh St,
PO Box 11-8281, Beirut
Lebanon
e-mail: geoamin@gmail.com

Schulz Oliver, Dr
Institute of Geography, University of
Bonn,
Meckenheimer Allee 166
53115 Bonn
Germany
e-mail: oschulz@uni-bonn.de

Speth, Peter, Prof Dr
Institut für Geophysik & Meteorologie,
Universität zu Köln,
Kerpener Str 13, D-50923 Köln
Germany
e-mail: speth@meteo.uni-koeln.de

Subah Ali
Ministry of Water and Irrigation
(MWI)
PO Box 2412; Amman 11183, Hashemite Kingdom of Jordan
e-mail: Ali_Subah@mwi.gov.jo

Suppan Peter, Dr
Institute for Meteorology and Climate
Research (IMK-IFU),
Forschungszentrum Karlsruhe,
Kreuzeckbahnstraße 19
82467 Garmisch-Partenkirchen
Germany
e-mail: peter.suppan@imk.fzk.de

Toll Mathias
University of Göttingen; Department of Applied Geology;
Goldschmidstraße 3;
D-37077 Göttingen
Germany
e-mail: Mathias.Toll@geo.uni-goettingen.de

Weise Stephan M, Dr
Department of Isotope Hydrology,
UFZ Centre for Environmental Research,
Leipzig-Halle
Germany
e-mail: stephan.weise@ufz.de

Wolfer Johannes, S*enior Hydrogeolist*
Federal Institute for Geosciences and Natural Resources – BGR,
Stilleweg 2; 30655 Hannover
Germany
e-mail: j.wolfer@bgr.de

Yacoubi-Khebiza Mohamed
Département de Biologie, Laboratoire d'Hydrobiologie,
Ecotoxicologie et Assainissement,
Faculté des Sciences Semlalia,
BP 2390, Marrakech
Morocco

Zahra, S
The Arab Center for the Studies of Arid Zones and Dry Lands – ACSAD,
POB 2440; Damascus
Syria
www.acsad.org

Zereini Fathi, Prof Dr habil
Institute for Atmospheric and Environmental Sciences
JW Goethe-University, Frankfurt
Altenhöferallee 1
D-60438 Frankfurt am Main
Germany
e-mail: zereini@iau.uni-frankfurt.de

List of Referees

Ahrens Bodo, Prof Dr
Institute for Atmospheric and Environmental Sciences
JW Goethe-University, Frankfurt
Altenhöferallee 1
D-60438 Frankfurt am Main
Germany
e-mail: Bodo.Ahrens@iau.uni-frankfurt.de

Azzam Rafig, Prof Dr
Department of Engineering Geology and Hydrogeology
RWTH Aachen University
Lochnerstr 4-20
5206 Aachen, Germany
e-mail: azzam@lih.rwth-aachen.de

El-Fadel Mutasem, Prof Dr
School of Civil Engineering and the Environment, University of Southampton, UK,
e-mail: mfadel@aub.edu.lb

Gaaloul N Dr
National Research Institute for Rural Engineering, Water and Forestry (INRGREF)
Rue Hedi Karray, BP10, 2080 Ariana
Tunisia
e-mail:
gaaloul.noureddine@iresa.agrinet.tn

Hötzl Heinz, Prof Dr
Department of Applied Geology,
University Karlsruhe, Kaiserstr 12, 76128
Karlsruhe, Germany
e-mail: hoetzl@agk.uka.de

Kluge Thomas, Dr
Institut für sozial-ökologische Forschung (ISOE),
Hamburger Allee 45
60486 Frankfurt/Main
Germany

Margane, Armin, Dr
Federal Institute for Geosciences and Natural Resources (BGR)
Stilleweg 2
D-30655 Hannover, Germany
e-mail: armin.margane@bgr.de

Merkel Broder J, Prof Dr
Geology Department - Chair of Hydrogeology
University of Freiberg
Gustav Zeuner Str12
D-09596 Freiberg
Germany
e-mail: merkel@geo.tu-freiberg.de

Messouli Mohammed, Dr
Département de Biologie, Laboratoire d'Hydrobiologie,
Ecotoxicologie et Assainissement,
Faculté des Sciences Semlalia,
BP 2390, Marrakech, Morocco
e-mail: messouli@ucam.ac.ma

Reichert Barbara, Prof Dr
Institute of Geology, University of Bonn,
Nussallee 8,
D-53115 Bonn, Germany
e-mail: b.reichert@uni-bonn.de

Richard Knoche, Dr
Institute for Meteorology and Climate Research (IMK-IFU),
Forschungszentrum
Kreuzeckbahnstraße 19
82467 Garmisch-Partenkirchen
Germany
e-mail: hans-richaed.knoche@imk.fzk.de

Salameh Elias, Prof Dr
University of Jordan
Amman 11942
Jordan
e-mail: salameli@ju.edu.jo

Schelkes, Klaus, Dr
Federal Institute for Geosciences and Natural Resources (BGR)
Stilleweg 2
D-30655 Hannover, Germany
e-mail: k.schelkes@bgr.de

Schmidt Gerhard
Federal Institute for Geosciences and Natural Resources (BGR)
Stilleweg 2
D-30655 Hannover
Germany
e-mail: Gerhard.Schmidt@bgr.de

Schönwiese Christian-D, Prof Dr
JW Goethe University, Institute for Atmosphere and Environment,
POBox 111932
60054 Frankfurt/M
Germany
e-mail:
schoenwiese@meteor.uni-frankfurt.de

Schulz Oliver, Dr
Institute of Geography, University of Bonn,
Meckenheimer Allee 166
53115 Bonn
Germany
e-mail: oschulz@uni-bonn.de

Shaban Amin, Dr
National Council for Scientific Research,
Remote Sensing Center,
Riad El-Solh St,
PO Box 11-8281,
Beirut
Lebanon
e-mail: geoamin@gmail.com

Suppan Peter, Dr
Institute for Meteorology and Climate Research (IMK-IFU)
Kreuzeckbahnstraße 19
82467 Garmisch-Partenkirchen
Germany
e-mail: peter.suppan@imk.fzk.de

Toussaint Benedikt, Prof Dr
D-65232 Taunusstein
e-Mail: b_toussaint@webde
www.hgc-toussaint.de

Wolfer Johannes, S*enior Hydrogeolist*
Federal Institute for Geosciences and Natural Resources – BGR,
Stilleweg 2
30655 Hannover
Germany
e-mail: j.wolfer@bgr.de

Zereini Fathi, Prof Dr habil
Institute for Atmospheric and Environmental Sciences
JW Goethe-University, Frankfurt
Altenhöferallee 1
D-60438 Frankfurt am Main
Germany
e-mail: zereini@iau.uni-frankfurt.de

1 Global Climate Changes – Sources and Impacts on the Water Cycle

The Earth's climate has changed many times during the planet's history, with events ranging from ice ages to long periods of warmth. During the last centuries natural factors such as volcanic eruptions or the amount of energy released from the sun have affected the Earth's climate on a smaller scale. Beginning since the 19th century, due to human activities associated with emissions of carbon dioxide and other greenhouse gases the composition of the atmosphere has changed. The scientific community has reached consensus that this changes cause a warming of the atmosphere and therefore influencing the Earth's climate. Continuation of greenhouse gas emissions can result in additional warming over the 21^{st} century up to 4.5 °C by 2100. This warming will have severe consequences for the water cycle of the world, because with the warming will come changes in precipitation patterns with increased risk of droughts and floods.

The assessment of the influences of climate changes on the global hydrological regimes and water resources are still very uncertain due primarily to the complex meshing systems as well as to an inadequate understanding of the water cycle in the oceans, atmosphere and biosphere. For assessing the effects water-balance calculations are necessary, including temporal and spatial changes in the relevant hydrologic parameters. Empirical knowledge would have to be replaced increasingly by improved process understanding. Overcoming this problem requires new ways in a field traditionally divided amongst several disciplines. In order to improve the assessment general circulation models are applied nowadays to simulate climate-change scenario and to evaluate possible future changes. Although there is variation between scenarios, the results suggest that average annual runoff will increase in high latitudes and in the equatorial regions, but will decrease in mid-latitudes and most subtropical regions. The selected scenario produces changes in runoff which are often closely related to the initial conditions, but there are important regional differences. The study also showed that different indications of the impact of climate change on water resource stresses could be obtained using different projections of future water use.

In this introductory chapter of the book several authors contribute to the basic relationship between climate changes and the world water cycle. In the first contribution Mosbrugger refers to the earth history providing abundant information on the dynamics of the climate systems. The geological past clearly indicates that global warming is typically linked with more humid conditions, which is in contrast to several younger prediction and assumption. Schönwiese is focusing on climate change in terms of temperature rise and, in turn, with the resulting consequences for atmospheric circulation and the water cycle. Detailed global and regional precipitation trend analysis of the last hundred years show that there is no confident prove of increased intensity of the global water cycle, however, complicated precipitation trend patterns can be observed on a regional basis indicating the influence of other factors. In order to understand recent changes and to predict next developments in the Mediterranean region Born et al. (Marocco) and Suppan et al. (Near East) are applying regional climate modelling. The analysis points to a continuation of the trend of the last hundred years. Although differences in long-term variability between observations and model data can be seen, a change of climates towards warmer and dryer conditions can be assessed from the simulations. Arkadan refers by statistical analysis from precipitation data in Lebanon on a certain cyclicity, however, are in doubt, whether the observation period are enough to confirm the control of the prevailed climatic conditions by this cyclicity.

1.1 Climate Change and Water Cycle — Some Lessons from the Geological Past

Volker Mosbrugger
Senckenberg - Forschungsinstitut und Naturmuseum
Senckenberganlage 25
60325 Frankfurt am Main

1.1.1 Introduction

Since the 4. Assessment Report of the International Panel on Climate Change (IPCC-4.AR), presented to the public in early spring 2007, there can be no doubt: global climate is changing, at least partly because of human activities. To predict the future climate change expected to occur over the next 100 years highly sophisticated climate models (or rather earth system models) are used. According to these models global warming will be between 1° and 6.3° C in 2100, depending on the scenario (Fig. 1.1.1). Meanwhile there is a considerable political movement –

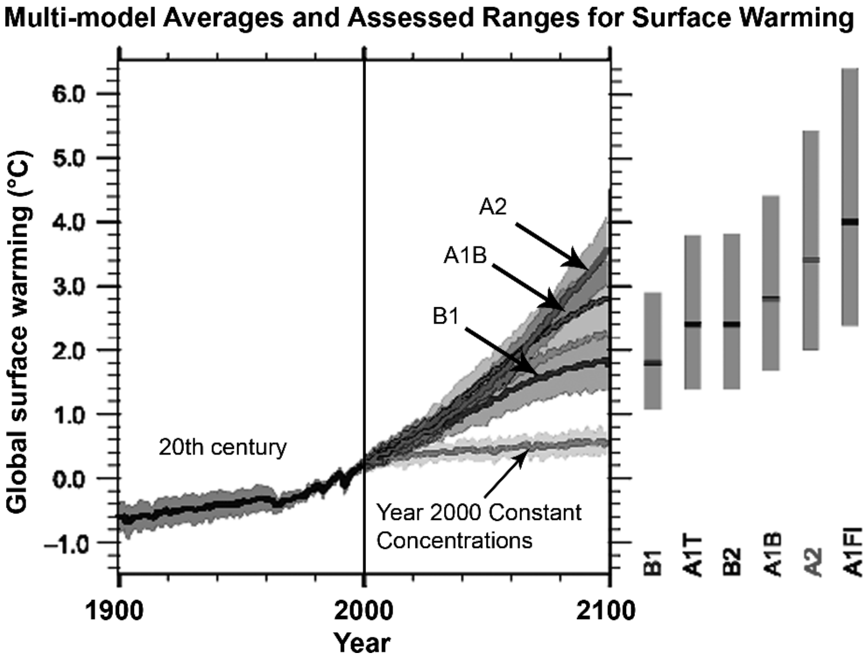


Fig. 1.1.1. Prediction of global warming until the year 2100 (from IPCC 2007).

strongly promoted by the Federal Government of Germany – to keep global warming until 2100 below 2° C although many scientists estimate that it is already too late to reach this goal.

The question arises how reliable all these model predictions are. In fact, the performance of these climate (or earth system) models is highly impressive when modelling the well-documented climate change that occurred over the last 150 years. On the other hand all models have their imperfections. For instance, recent climate models still suffer from insufficient representations of the cloud dynamics, of soil processes or of biosphere-atmosphere interactions (see for instance IPCC 2007). Moreover, all models have to use the technique of parameterization with the inherent problem that these parameterizations are adapted to certain situations and are valid only within specific boundary conditions. Hence, it is to be expected that model predictions for climate states far away from the present-day situation have higher uncertainties. It is therefore not surprising that today not a single climate (or earth system) model can simulate an extreme greenhouse world with almost no polar ice as it existed in the Eocene about 50 million years ago (see Figs. 1.1.2 and 1.1.3).

In fact, the past climate history is a strong tool to test and validate climate (earth system) models and their predictions for future climate change. Reliable climate models should be able to realistically simulate past climate states which are well different from the present-day situation. Moreover, the earth history provides us with climate states which are similar or analogous to the expected future climate (e.g. global warming due to high CO_2) and allow to validate model predictions. Thus, even when only interested in future climate change the climate history of the geological past may teach us some lessons. This will be briefly illustrated using four examples covering the natural climate dynamics of the last 50 million years.

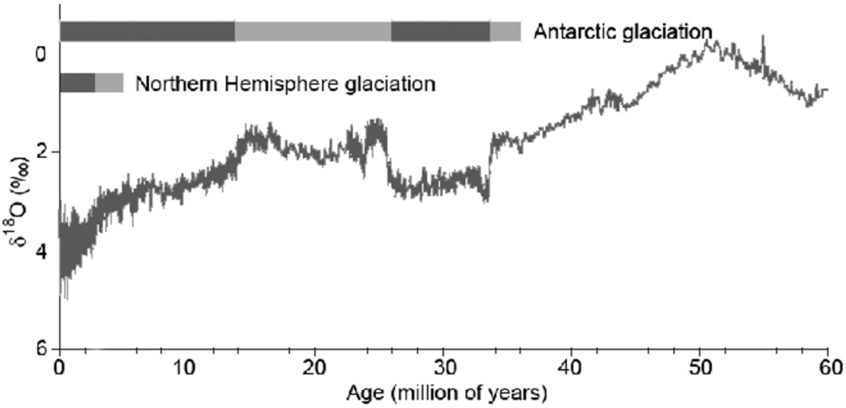


Fig. 1.1.2. Global climate change over the last 60 million years as documented in the marine record (redrawn from Billups 2005 after Zachos et al. 2001).

1.1.2 Global warming, seasonality and rainfall

Over the last 60 million years the earth experienced a significant cooling well documented in the marine record (Zachos et al. 2001; Fig. 1.1.2). The Early Eocene period around 50 Ma ago represents the warmest periods with temperate deciduous forests up to 80° latitude north and (virtually) no ice at the poles. Then overall cooling starts, presumably linked to uplift of mountain chains and plateaus (such as the Himalayas and Tibet). An Antarctic ice shield developed near the Eocene/Oligocene boundary and North Hemispheric ice sheets appeared in the Upper Miocene around 6 to 8 Ma ago. In the Pliocene (5-2.5 Ma ago) cooling continued and the Quaternary (2.5 Ma ago to today) was characterized by rapid climatic changes between glacial and interglacial phases with the present-day Holocene representing the last interglacial.

More recently it became possible to reconstruct this Cenozoic climate also over land in quantitative terms. Fig. 1.1.3 illustrates the climatic changes in NW Germany over the last 50 Ma as represented by four different climate parameters, i.e. mean annual temperature (MAT), mean temperature of the coldest month (CMT), mean temperature of the warmest month (WMT) and mean annual precipitation. When comparing Figs. 1.1.2 and 1.1.3 it becomes evident that all in all the temperature change in NW Germany over the last 50 Ma largely follows the global climate change documented in the marine record. Both, the marine and the continental record show a similar overall cooling pattern with, for instance, a steep end-Eocene cooling, an end-Oligocene warming and a mid-Miocene temperature optimum followed by a gradual cooling.

The continental record, however, provides additional information concerning changes in seasonality and rainfall. As is evident from Fig. 1.1.3, the change in winter temperature is much more pronounced than the change in mean annual temperature, and the summer temperature changes are relatively small as compared to the mean annual temperature. Hence, the global climate cooling since the Early Eocene is more pronounced in winter temperature than it is in mean annual temperature or in summer temperature. Moreover, the precipitation data indicate that the overall Cenozoic cooling is linked with a reduction in rainfall.

Thus, if we read Fig. 1.1.3 backwards, i.e. from the present-day to the past, it teaches us some interesting lessons. First of all, over the last 50 Ma global warming is typically linked with an increase in rainfall, at least in temperate zones. Secondly, global climate change (i.e. warming or cooling) is generally more pronounced in winter temperature than in summer temperature. Correspondingly, warming induces a reduction in seasonality and cooling an increase in seasonality. We may expect that this same pattern holds true for the global warming occurring over the next 100 years.

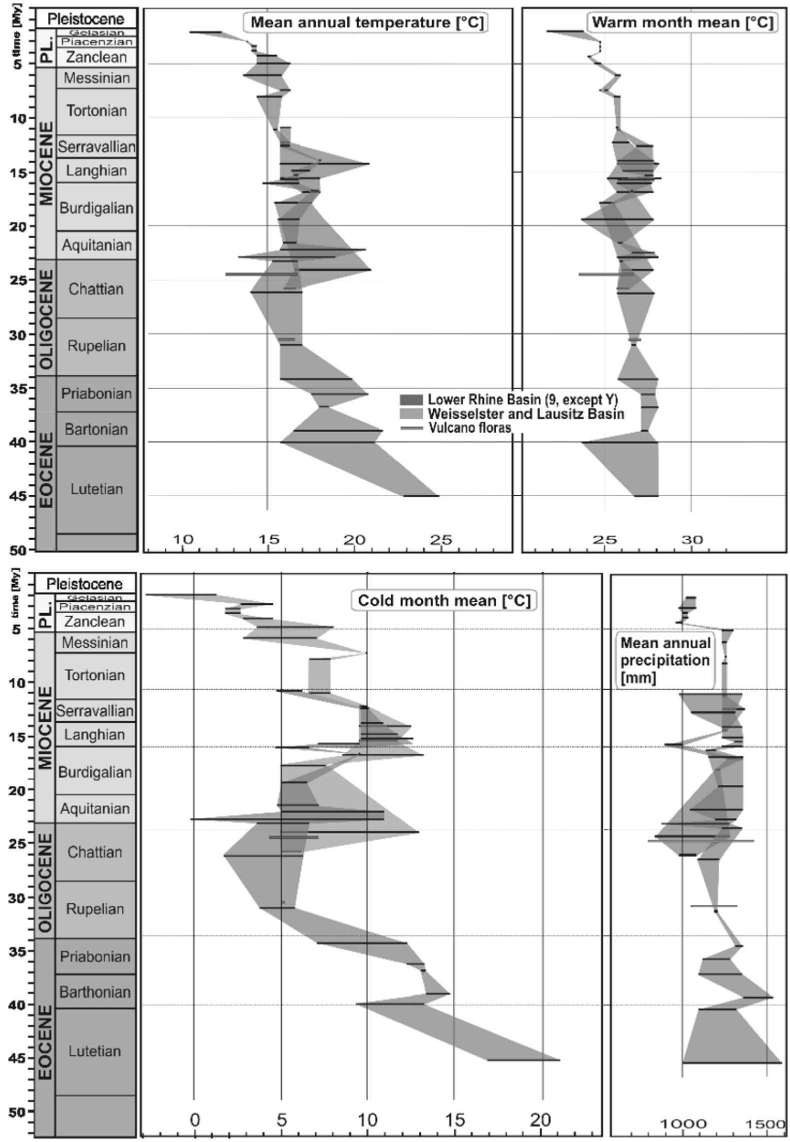


Fig. 1.1.3. Climate change in NW Germany over the last 50 million years (after Mosbrugger et al. 2005).

1.1.3 Global warming and the Gulf Stream

Another possible lesson from the past concerns the future of the Gulf Stream. The Gulf Stream is a warm Atlantic ocean current that transports considerable energy

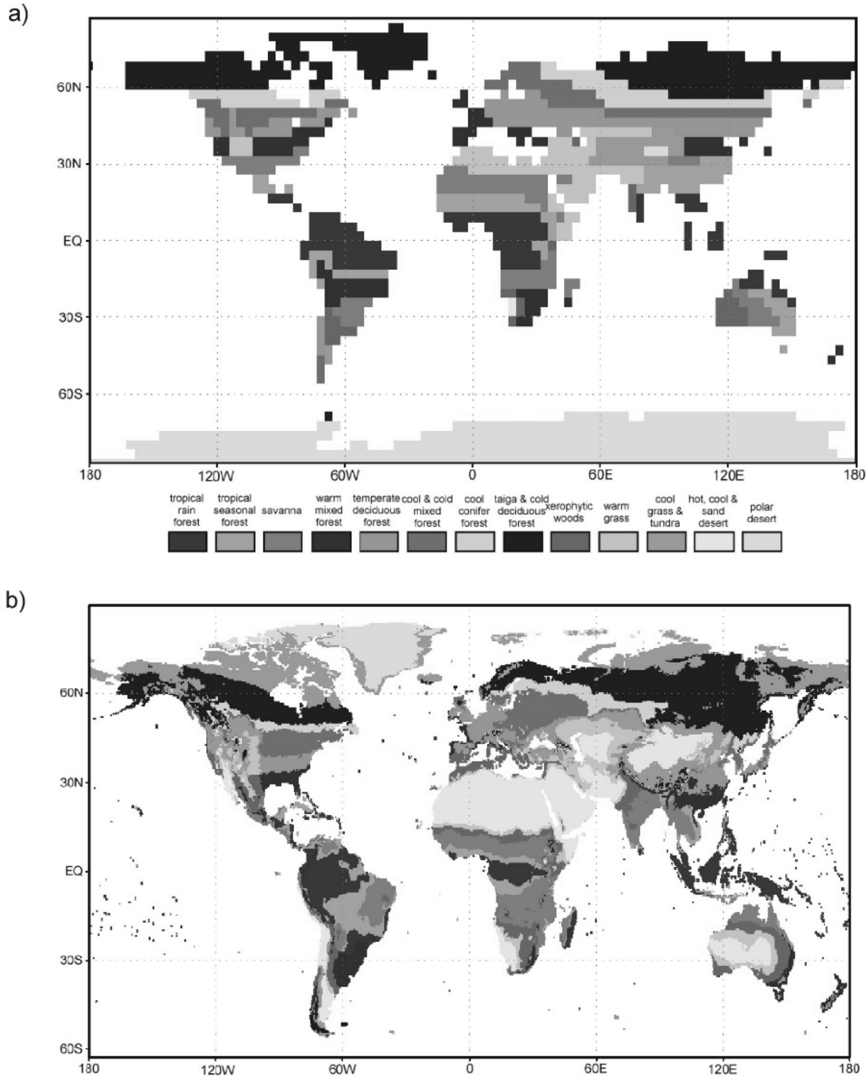


Fig. 1.1.4. Vegetation distribution a) in the Upper Miocene (8-10 Ma ago) and b) today (from Micheels et al. 2007).

(about 1.4 petawatts) from the low latitudes of Florida and the Gulf of Mexico to the high latitudes of the North Atlantic. It is responsible for the considerable temperature difference existing between the West and East coast of the North Atlantic. For instance, Bergen in Norway and Prins Christian Sund in Southern Greenland are both located at around 60° latitude North, but Bergen enjoys a mild climate with about 8° C mean annual temperature whereas the mean annual temperature is 0.6° C in Prins Christian Sund. Because the temperature gradient between Equator and North Pole is one of the drivers of the Gulf Stream several modelling studies predicted that global warming should lead to a weakening of the Gulf Stream and hence to a cooling of considerable parts of Europe (e.g. Rahmstorf 1997, 2003).

The Cenozoic climate history tells a different story. So far all proxy-data show that global warming also means warming of Europe; no past situation is known with a global climate warmer than today and a Western or Northern European climate cooler than today. This is clearly documented not only by the climate evolution in NW Germany over the last 50 million years (Fig. 1.1.3) but also by a global vegetation map of the Upper Miocene (8-10 Ma) shown in Fig. 1.1.4. The Upper Miocene is a phase with a considerably warmer climate than today (cf. Figs. 1.1.2 and 1.1.3) and the vegetation in Western and Northern Europe also clearly reflects a warmer climate.

Although past climate data indicate that a globally warmer climate also implies a warmer Europe, they say nothing about the strength of the Gulf Stream. In fact, it might well be that the Gulf Stream is indeed weaker in a globally warmer climate but that the effect of a weaker Gulf Stream is compensated by other processes such as a more intense latent heat transport, i.e. energy transport through the water cycle (Mosbrugger et al. 2005, Mosbrugger & Micheels 2007; see also below).

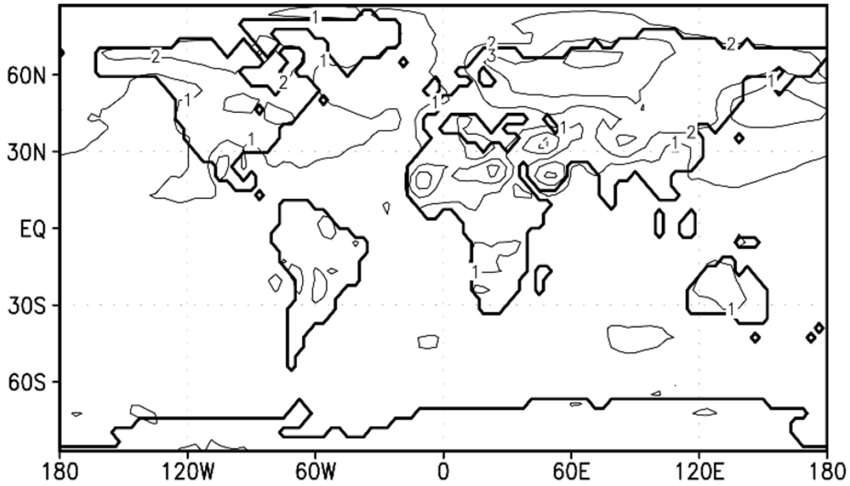
Thus, taking the lesson from the earth history seriously one would predict that the expected global warming will also lead to a warmer and all in all more humid Europe. It is interesting to note that meanwhile also modelling studies come to the same result and that recent measurements do not yet indicate a weakening of the Gulf Stream (Kerr 2006).

1.1.4 Global warming and forests

One of the most important mitigation strategies to compensate for the anthropogenic CO_2 emission is to plant forests since growing forests or biomass extract CO_2 from the atmosphere. Correspondingly, forests also play a major role in the emission trading business. Here again, the earth history may help to better understand the overall climatic effect of forests.

Fig. 1.1.4 shows the vegetation distribution of today as well as the vegetation distribution about 8 to 10 Ma ago, during a period of globally warmer climate (Figs. 1.1.2 and 1.1.3). A quantitative comparison reveals that during the Upper Miocene there existed about 25 % more forests than today (Micheels et al. 2007), the additional forests being located in particular in the high northern latitudes and in the subtropical zone. To investigate the climatic effect of these additional 25 % of forests a modelling study was performed (Mosbrugger & Micheels 2007).

5a Tortonian with palaeovegetation vs. Tortonian with modern vegetation
Difference of temperature



5b Tortonian with palaeovegetation vs. Tortonian with modern vegetation
Difference of precipitation

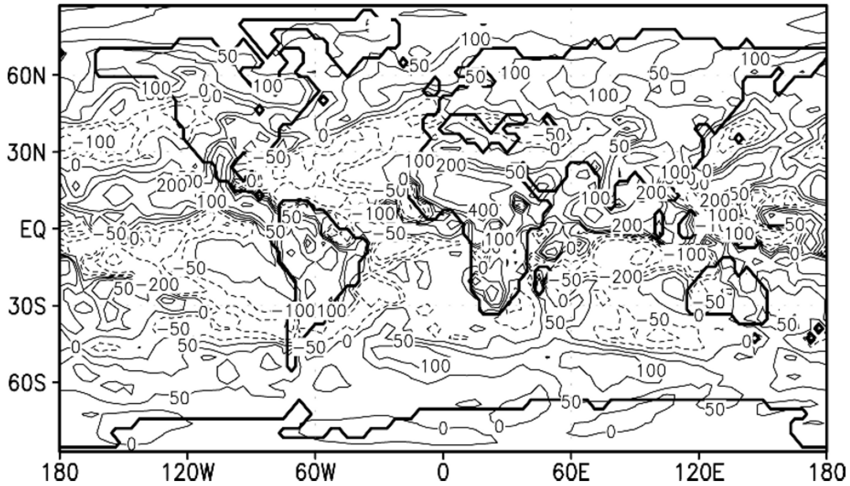


Fig. 1.1.5. Modelling experiment for the Upper Miocene (from Steppuhn et al. 2006, Mosbrugger & Micheels 2007). Further explanations in the text.

In this study we first simulated the Tortonian (Upper Miocene, 10-8 Ma ago) climate with the AGCM ECHAM coupled to a mixed-layer ocean model and using the vegetation distribution of Fig. 1.1.4a (Mosbrugger & Micheels 2007). Then we repeated the same model experiment but with the present-day vegetation distribution (Steppuhn et al. 2006). The difference between the two runs is shown in Fig. 1.1.5a and directly reflects the effect of the additional 25 % of forests on temperature and precipitation. Obviously, the additional forests cause a significant warming which in some regions such as Siberia may reach 4° C (Fig. 1.1.5a). The changes in the precipitation pattern caused by the additional forests are particularly interesting (Fig. 1.1.5b). In some regions precipitation increases by more than 100 mm/a, in others it decreases by the same amount but all in all there is a global increase in mean annual rainfall by 35 mm/a. Thereby a peculiar pattern becomes evident for the Atlantic: while precipitation in low latitudes decreases, precipitation in high latitudes increases. This obviously indicates that the latent heat transport was increased by the additional forests: more water evaporated in the low latitudes, more water precipitated in the high latitudes.

What is the lesson from this case study? First of all, changing the vegetation and the terrestrial biomass does not only influence the atmospheric CO_2 concentration, it also impacts temperature and precipitation by influencing albedo and water cycle. An increase of forest cover may indeed induce additional warming and rainfall and enhance latent heat transport. Thereby it is important to note that the climatic effects of changes in vegetation are not restricted to those regions where changes occurred. This lesson needs to be considered in the emission trading business and in any improved version of the Kyoto protocol.

1.1.5 Global warming and the arid zones

A particularly crucial aspect of future climate change concerns rainfall and water availability. According to IPCC-4AR the global precipitation will slightly increase with significant regional differentiations; Fig. 1.1.6 shows the IPCC model projections for the A1B scenario. All in all, for the year 2100 models typically predict an increase in precipitation in the humid mid and high latitudes and a decrease in precipitation in the dry low latitudes (cf. Fig. 1.1.6); thereby the „aridisation trend“ is more pronounced in summer than in winter. This prediction of future climate causes particular concern among politicians and societies since it would cause – if it becomes reality – severe problems for millions of people living in a Mediterranean and subtropical climate.

On the other hand, model simulations concerning future precipitation patterns are well known to be less reliable than predictions of temperature patterns. Hence, it may again be useful to look back into the geological past: How did the semiarid and arid zones of today look like during time periods where global temperatures were higher than today? If we take once more the Upper Miocene as a rough analogue of the expected future climate then the answer is clear. As is evident from Fig 1.1.5, the vegetation of the Mediterranean and subtropical zones was much more humid in the globally warmer Upper Miocene than it is today, real deserts didn’t hardly exist. A recently published volume „Miocene Climate in Europe“ (Bruch et al. 2007a) gives further evidence that warmer climates in the Miocene were indeed

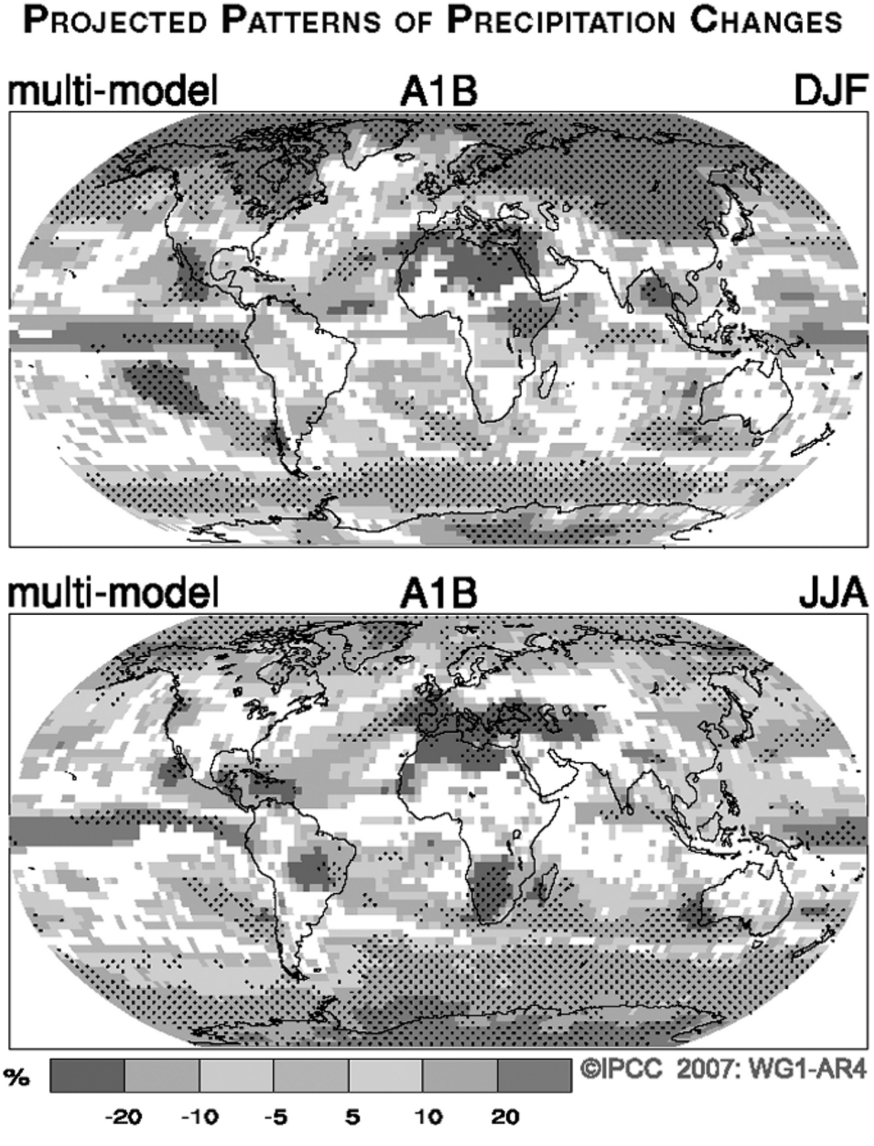


Fig. 1.1.6. Precipitation changes as predicted by the IPCC–AR4 for the A1B scenario.

linked with more humid conditions in the Mediterranean (see for instance the contributions of Bruch et al. 2007b, Martinetto et al. 2007, Jimenez-Moreno & Suc 2007). For Northern Africa it is documented that an aridisation occurred during the

Miocene in parallel to the global cooling with the spreading of savannas and open woodland only in the Pliocene (Cane & Molnar 2001).

Thus, the geological past clearly indicates that global warming is typically linked with more humid conditions also in the semiarid to arid Mediterranean and subtropical zones. Hence, one might be sceptical if the above mentioned prediction about further aridisation of these regions will indeed hold true.

1.1.6 Discussion

The earth history provides us with a plethora of information concerning the dynamics of the climate system. Whenever we are interested in the future climate it makes sense to also have a look at past climates. They allow to test and validate our climate models and – equally important – they allow empirical access to climate situations that do not or not yet exist today. In this contribution I was particularly focusing on this last aspect – past climates may teach us lessons to better understand the future climate change. I briefly considered four examples, i.e. the effect of global warming on a) seasonality and rainfall, b) on forests and climate feedbacks, c) on the Gulf Stream and European climate, and d) on the arid and semiarid zones. For these four examples the lessons from the past are most relevant for understanding and managing future climate change and are only partly consistent with model results (this is particularly true for examples c and d). Thus they may point out particular weaknesses and uncertainties of model predictions.

On the other hand it is clear that the past can never directly be used as a perfect representation of the future: earth and climate history are indeed historical processes, past situations are never repeated identically in the future. Hence, although the Neogene was considerably warmer than today and can thus be considered an interesting analogue of the future climate we have to be aware of the differences: in the Neogene the palaeogeography was different, CO_2 was probably below 400 ppm (possibly with the exception of the mid-Miocene climatic optimum; Pagani et al. 1999, Kürschner et al. 2008), and there was no human impact on landuse and vegetation. Nevertheless a critical and intelligent use of the information provided by the geological past is strongly recommended.

References

Billups, K. 2005. Snow maker for the ice ages. Nature 433, 809-810.

Bruch, A.A., Uhl, D., Mosbrugger, V. (editors), 2007a. Special Issue: Miocene Climate in Europe - Patterns and Evolution. – First synthesis of NECLIME. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 270 pp.

Bruch, A.A., Uhl, D., Mosbrugger, V., 2007b. Miocene Climate in Europe - Patterns and Evolution. – A first synthesis of NECLIME. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 1-7.

Cane, M.A., Molnar, P., 2001. Closing of the Indonesian seaway as a precursor to east Africa aridification around 3-4 million years ago. Nature 411, 157-162.

IPCC, 2007. Climate Change 2007 – The Intergovernmental Panel on Climate Change fourth Assessment Report, 2007. http://www.ipcc.ch/

Jiménez-Moreno, G., Suc, J.-P., 2007. Middle Miocene latitudinal climate gradient in Western Europe: Evidence from pollen records. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 208-225.

Kerr, R. A., 2006. False Alarm: Atlantic Conveyor Belt Hasn't Slowed Down After All. Science 314, 1064.

Kürschner, W.M., Kvaek, Z., Dilcher, D.L., 2008. The impact of Miocene atmospheric carbon dioxide fluctuations on climate and the evolution of terrestrial ecosystems. Proceedings of the National Academy of Science of the United States of America 105, 449-453.

Martinetto, E., Uhl, D., Tarabra, E., 2007. Leaf physiognomic indications for a moist warm-temperate climate in NW Italy during the Messinian (Late Miocene). Palaeogeography, Palaeoclimatology, Palaeoecology 253, 41-55.

Micheels, A., Bruch, A.A., Uhl, D., Utescher, T., Mosbrugger, V., 2007. A Late Miocene climate model simulation with ECHAM4/ML and its quantitative validation with terrestrial proxy data. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 251-270.

Mosbrugger, V., Micheels, A., 2007. Treib- und Eishausklima in der Erdgeschichte: Vegetation – der unterschätzte Klimafaktor. Biologie in unserer Zeit 37, 25-35.

Mosbrugger, V., Utescher, T., Dilcher, D., 2005. Cenozoic continental climatic evolution of Central Europe. Proceedings of the National Academy of Science of the United States of America 102, 14964-14969.

Pagani, M., Arthur, M.A., Freeman, K.H., 1999. Miocene evolution of atmospheric carbon dioxide. Paleoceanography, 14, 273-292.

Rahmstorf, S., 1997. Ice-cold in Paris.- New Scientist, 153: 26-30.

Rahmstorf, S., 2003. Thermohaline circulation: The current climate.- Nature 421, 699

Steppuhn, A., Micheels, A., Geiger, G., Mosbrugger, V., 2006. Reconstructing the Late Miocene climate and oceanic heat flux using the AGCM ECHAM4 coupled to a mixed-layer ocean model with adjusted flux correction. Palaeogeography, Palaeoclimatology, Palaeoecology 238, 399-423.

Zachos, J.C., Pagani, M., Stone, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climates 65 Ma to present. Science 292, 686-693.

1.2 Climate Change and the Water Cycle - Some Information Concerning Precipitation Trends

Christian-D. Schönwiese
J.W. Goethe University, Institute for Atmosphere and Environment,
Frankfurt/M., Germany

1.2.1 Introduction

Water in sufficient quantity and acceptable quality is of vital importance for all life on Earth. Unfortunately, these conditions are not fulfilled in many parts of the world, especially in the suptropical and partly also in tropical regions, so that approximately 1.2 billion of people (c. 20 % of the world population) have no secure access to clean drinking water (Lozán et. al., 2007). Moreover, agriculture suffers from water supply problems. Even in some industrialized regions of the mid-latitudes climate zone where humid conditions prevail, for instance Central Europe, dry spells can lead to serious problems. An example is the hot-dry summer 2003 (Schönwiese et al., 2004) leading to at least 35,000 additional deaths and economic loss of c. 13 billions of dollars in Europe (Jendritzky, 2006; MunichRe, 2004; Schär and Jendritzky, 2004). Another problem, in addition to too few water, is too much water as a consequence of heavy precipitation episodes leading to flooding. The question arises whether such problems may become more frequent in the future.

In the following the problem of global climate change is briefly addressed (chapter 1.2.2), mainly in terms of temperature rise. Then, the consequences for atmospheric circulation and, in turn, the global water cycle are outlined. The most important component of the water cycle is precipitation playing a crucial role not only with respect to both dryness and flooding but also concerning water supply of mankind. Therefore, two chapters address the observed precipitation trends on a global scale (chapter 1.2.3) and in Europe (chapter 1.2.4). As a case study, in the context of precipitation trends observed in Germany, the problem of extreme events is discussed (chapter 1.2.5). Finally, some conclusions are added (chapter 1.2.6).

1.2.2 Global climate change

Climate varies on all scales of time and space since Earth exists. However, within industrial time, roughly since 100-200 years, mankind has become an additional climate forcing factor of growing intensity although the anthropogenic influence on climate can be traced back several thousands of years due to land-use effects (development of agriculture and pasture), including deforestation. The most important recent effect, however, is the emission of infrared(IR)-active trace gases

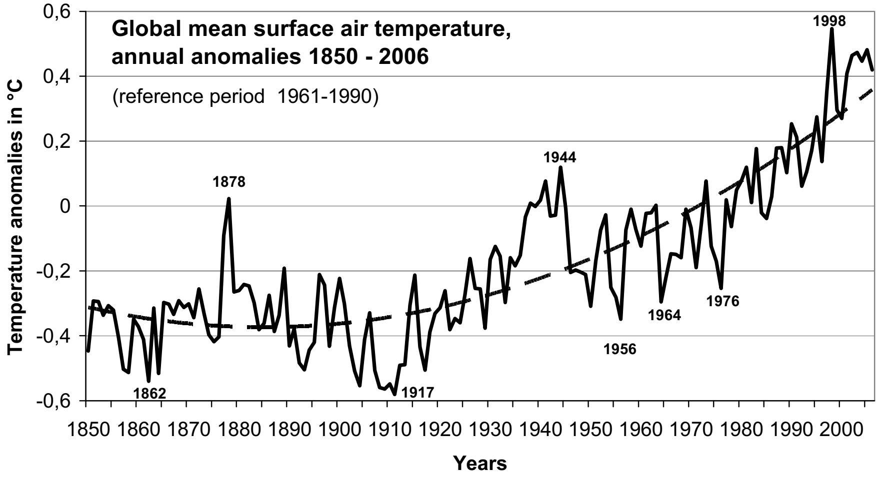


Fig. 1.2.1. Annual anomalies 1850-2006 of the global mean surface air temperature (from Jones, 2007). The dashed line indicates the polynomial trend. The linear trend 1901-2000 amounts to 0.7° C.

(greenhouse gases GHG) such as carbon dioxide (CO_2) and others due to fossil energy use (IPCC, 2007; Schönwiese, 2003). In consequence, the atmospheric CO_2 concentration has increased from pre-industrial values of approximately 270-280 ppm (nearly constant since the termination of the last ice age c. 10,500 years ago) to more than 380 ppm in 2006. In combination with the concentration increase of some other GHG (CH_4, N_2O, CFCs, tropospheric O_3 etc.) climate model simulations as well as statistical assessments attribute to this GHG forcing an increase of the global mean surface air temperature of approximately 0.7 K within the recent 100 years (IPCC, 2007); see Fig. 1.2.1. Other external forcing of the climate system like solar activity and volcanism or internal mechanisms of the climate system like El Niño and other have predominantly produced fluctuations around this long-term trend.

However, such as this trend is not uniform in time, it is also not uniform in space. This is shown for the recent 50 years in Fig. 1.2.2. We find the most pronounced temperature increase in some land areas of the northern hemisphere whereas some other relatively small regions have experienced a weak cooling. There is a marked interacting between the different temperature regimes of the Earth and atmospheric circulation and this interaction may be modified due to global climate change. Moreover, global atmospheric circulation is linked with the global water cycle; see Fig. 1.2.3. Briefly characterized, evaporation and transpiration (from vegetation; combined evapotranspiration) leads to water vapour transport into the atmosphere where in the context of uplift processes, like in case of low atmospheric pressure, clouds are formed and some of these clouds produce precip-

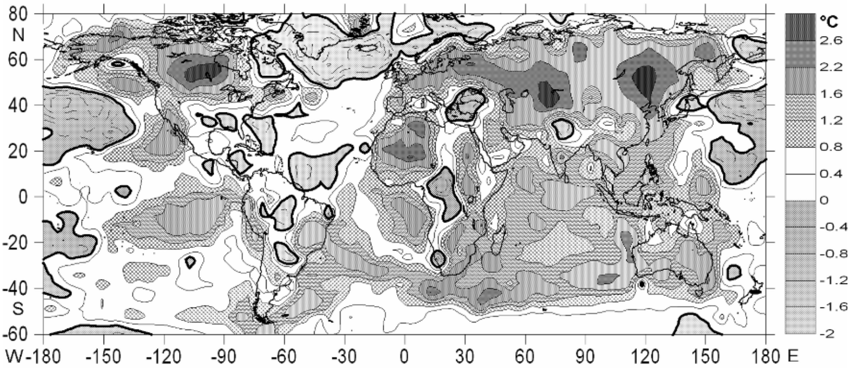


Fig. 1.2.2. Linear surface air temperature trends 1951-2000 in °C within the 80°N-60°S zone in a 5° grid resolution, contour lines at 0.4° C intervals. Data source: Jones, 2007; analysis: Schönwiese (2003, updated). The heavy lines encircle areas were a temperature decrease is observed (within these areas dashed contour lines).

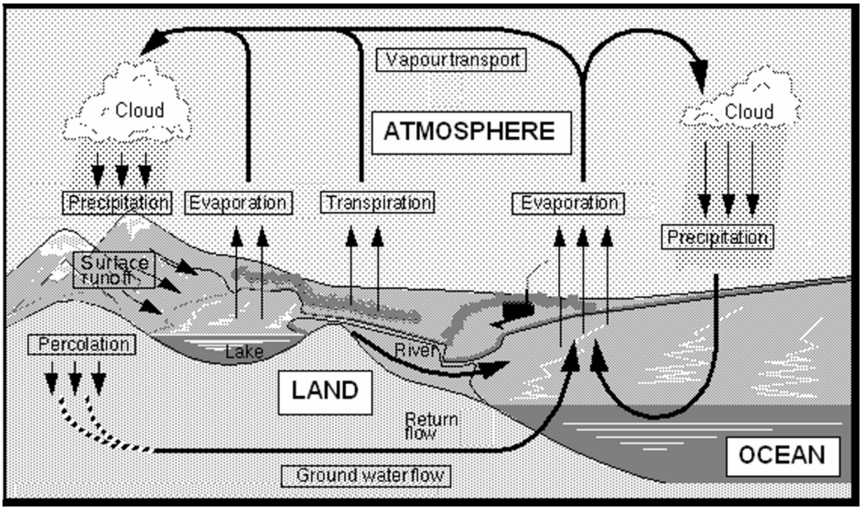


Fig. 1.2.3. Scheme of the global water cycle (from CHIAS, 2007, modified). Quantitative description see Table 1.2.1.

itation. On average, see Table 1.2.1, in case of ocean areas evaporation exceeds precipitation (arid climate) and the surplus of water vapour is transported to land areas where, again on average, precipitation exceeds evapotranspiration (humid climate). In the latter case, the surplus is transported to the ocean by river runoff and groundwater flow. Table 1.2.1 presents also the results of related climate model simulations.

Table 1.2.1. Evaporation E, precipitation P and run-off R as assessed from observational data and modelled (Max Planck Institute for Meteorology MPIM, Hamburg, coupled atmosphere-ocean circulation model ECHAM4-OPYC, reference period 1990-1999); all data from Marcinek, 2007.

Author	E (ocean)	P (ocean)	P (land)	E (land)	R (land)
Baumgartner and Reichel, 1975	425 (1176)	385 (1066)	111 (746)	71 (480)	40 (110)
Trenberth et al., 2006	413 (1143)	373 (1033)	113 (759)	73 (494)	40 (110)
Model, MPIM, cit. Marcinek, 2007	453 (1253)	411 (1138)	118 (793)	78 (527)	46 (127)

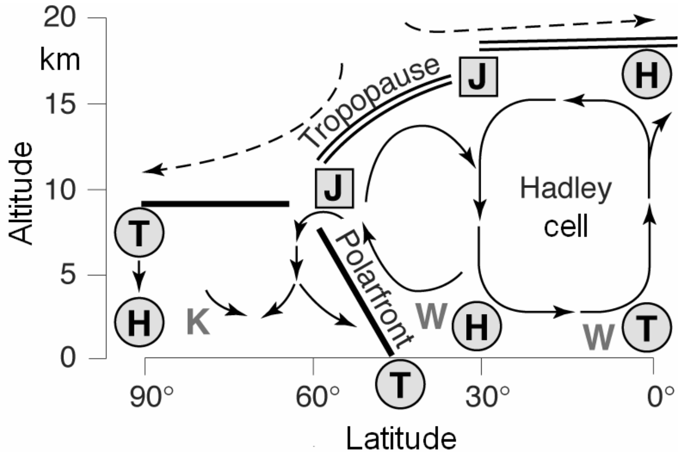


Fig. 1.2.4. Cross section of the atmospheric circulation, schematic, troposphere, one hemisphere (from Schönwiese, 2003, modified). Note that, in general, uplift (low pressure near surface, T) leads to cloud formation and precipitation whereas subsidence (high pressure near surface, H) to dryness. W means warm, K cold air masses; J = jet stream.

On a regional scale, the situation is much more complicated because as a consequence of the atmospheric circulation patterns, see Fig. 1.2.4, land areas may be humid (under the influence of relatively frequent low pressure situations, like within the tropics and mid-latitudes) or arid (high pressure situations prevailing, like in the subtropics). Now, if temperature increases, one may expect – on a global average – more evapotranspiration and more precipitation. In other words, the global water cycle may be speed up. On the other hand, there are a number of side effects. For instance, the Hadley Cell (see Fig. 1.2.4) may intensify so that the sub-

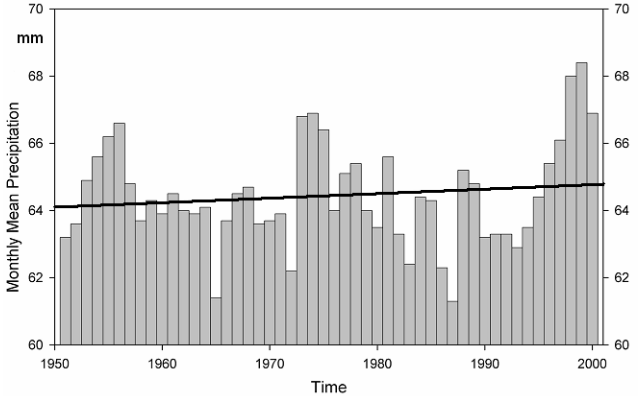


Fig. 1.2.5. Global mean (land areas) annual precipitation 1951-2000 (columns) and linear trend (heavy line). This trend shows a small statistically insignificant increase (from Beck et al., 2007).

tropical high pressure influence extends poleward. In the Mediterranean area, including the Middle East and North Africa, this may lead to less precipitation and therefore increasing aridity. Note that due to the annual cycle of the atmospheric circulation these regions are characterized by summer dryness and more or less precipitation in winter. The Hadley Cell intensification effect as mentioned above may lead to less precipitation also in winter and, in turn, growing problems with respect to water supply.

In the context of monitoring changes in the water cycle, the analysis of observed long-term precipitation trends may be helpful, both global and regional, including the regional (or sub-regional, respectively) and the seasonal patterns. So, the following chapters have their focus on global, European, and German observational precipitation trend patterns. Before this is done, it has at least to be mentioned, that precipitation implies measurement errors and poor representativeness (Schönwiese and Rapp, 1997). The measurement errors depend on the different rain gauge realizations used in different countries and are maximum in case of precipitation falling as snow under the influence of relatively strong wind. In this case, the precipitation total may be underestimated as large as roughly by >50 %. The poor representativeness means a small station-to-station correlation of precipitation measurements so that a very dense measurement network is needed not available in all countries. The shortcomings of this problem are somewhat mitigated if monthly or annual averages are considered instead of hourly or daily data.

1.2.3 Global precipitation trends

First, we may look on the global average of precipitation. However, due to huge measurement gaps over the ocean areas, such an information is available in a

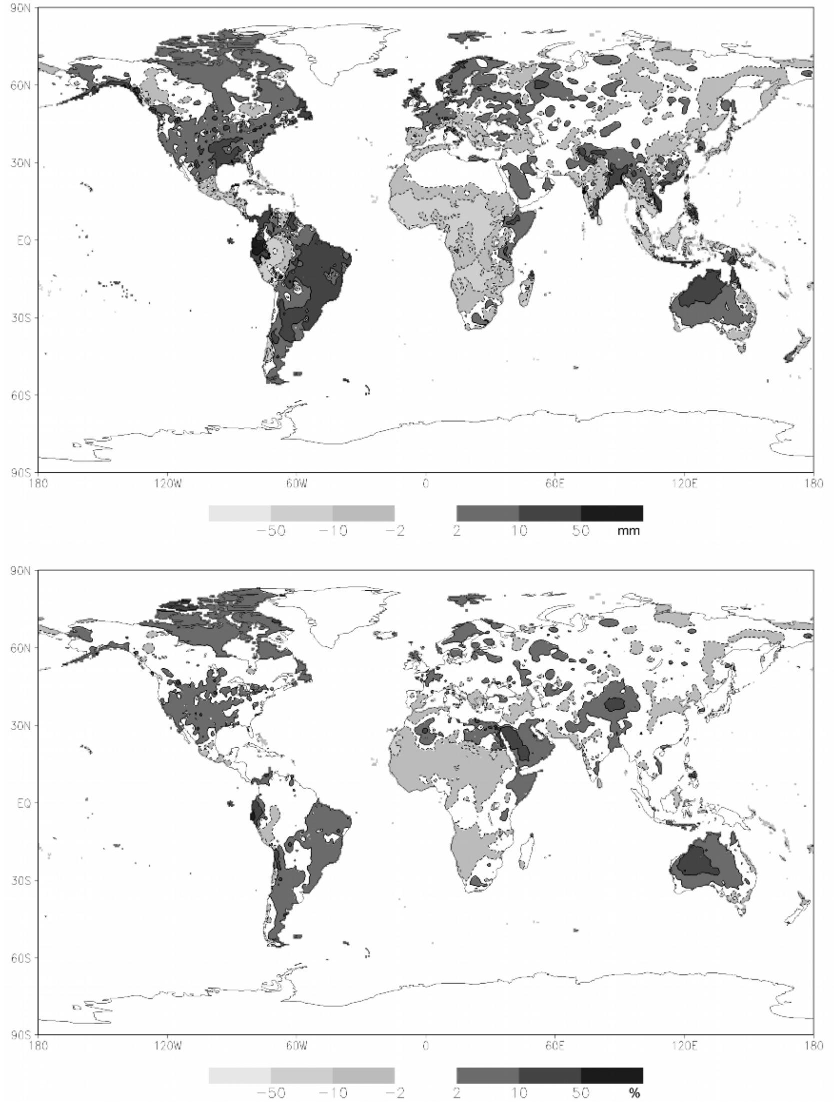


Fig. 1.2.6. Linear annual precipitation trends 1951-2000 in mm (upper plot) and percent (lower plot) per month, global patterns, 5° grid resolution (from Beck et al., 2007, modified). White areas neglected due to a small data base (Greenland, Antarctica, and a small region in northeast Africa). Dashed contour lines indicate a decrease.

sound form only for land areas. Sponsored by the German Climate Research Programme (DEKLIM) and in cooperation with the Global Precipitation Climate Center (GPCC) operating under the leadership of the German Weather Service (DWD), a Frankfurt research group (Beck, Grieser, Rudolf, Schönwiese, Staeger, and Trömel, 2007) has produced a comprehensive and intensively corrected global precipitation data set 1951-2000 based on 9,343 stations. This data base is used to assess the year-to-year change of global (land areas) and annual means of precipitation; see Fig. 1.2.5. We detect a small increase which, however, is not statistically significant because of the superimposed fluctuations which in part are correlated with El Niño years. In a similar analysis which covers the 1901-2005 period (using a considerably smaller data base) presented by the IPCC (2007) again fluctuations dominate although the increase 1901-1950 is somewhat more pronounced than afterwards. Keeping in mind, that a related analysis of oceanic data is missing, there is, based on such precipitation trend analyses, no clear indication of an global water cycle intensification, at least not within the recent decades.

However, we observe a very remarkable rearrangement of precipitation where both increasing and decreasing trends appear (more or less balanced on a global average), see Fig. 1.2.6. The most outstanding increasing trends appear *inter alia* in major parts of northern, eastern, and southern North America, extended regions in South America (especially in the east, but also Ecuador, Columbia, and Surinam), most of northwest and northern Europe, within some sub-regions scattered over Asia, some small regions in eastern and southern Africa and major parts of Australia. In the remaining regions, *inter alia* eastern Canada, northwest Brasilia and Peru, the Mediterranean and southeast Europe, nearly all of Africa, major parts of Siberia, China, India, and Indonesia, mostly a precipitation decrease is detected. Greenland, Antarctica, and a small sub-region in northeast Africa are not considered due to a too small data base (white areas in Fig. 1.2.6, such as those areas where the trends are smaller than 2 mm or 2 %, respectively.

These results of a global precipitation trend analysis are based on gridded data at a 5 degree resolution and therefore regionally very restricted. Moreover, such trend patterns are not stable in time, due to the superimposed fluctuations (see analogous situation in case of temperature, Fig. 1.2.1) and not uniform in different seasons.

1.2.4 European precipitation trends

In an earlier publication (Schönwiese and Rapp, 1997) we have presented a collection of European precipitation trend charts for the year, different seasons and months, based on data covering 1891-1990. In recent time, a majority of these charts was updated (1901-2000), where the trend analyses 1951-2000 are based on 521 stations. For comparison (see chapter 1.2.3), again this half-century period is selected and only a few examples are discussed.

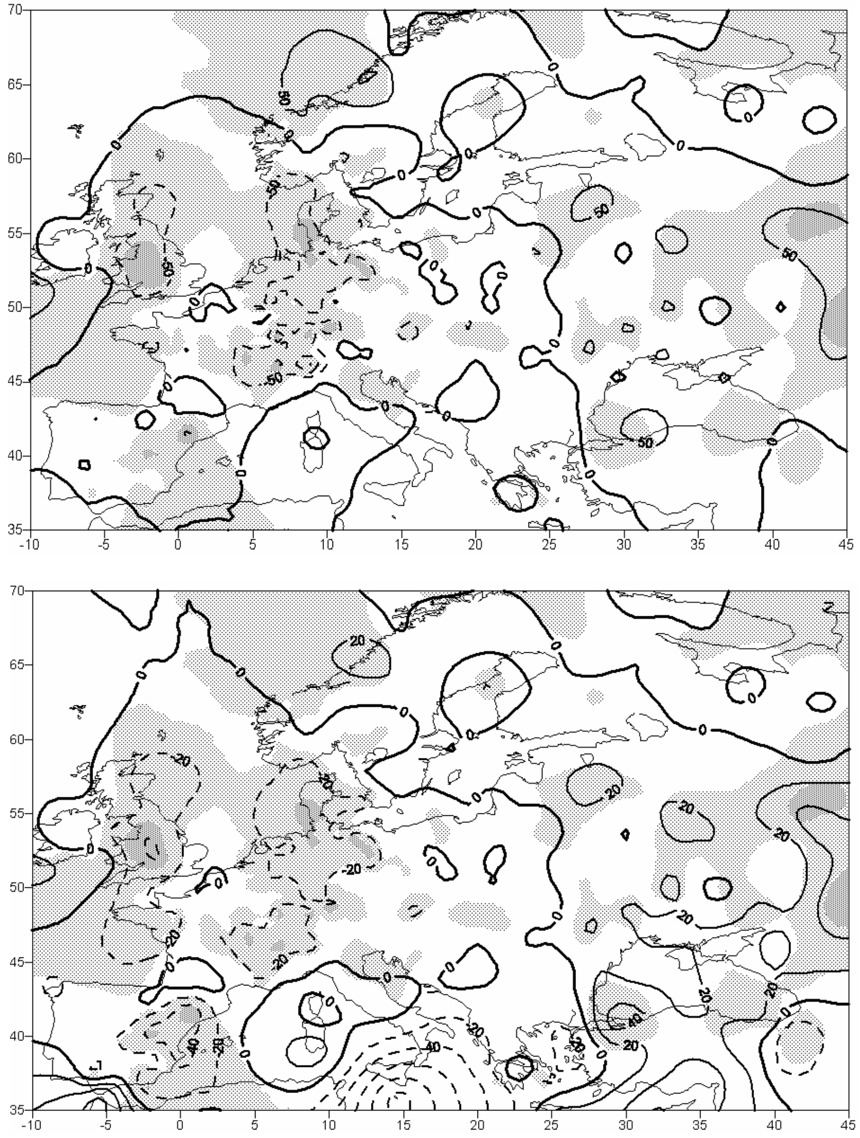


Fig. 1.2.7. Linear precipitation trends 1951-2000, European pattern, in absolute (mm, upper plot) and percent (lower plot) values, summer (June, July, and August) data (from Beck et al., 2007, based on Schönwiese and Janoschitz, 2007).

These examples refer to the summer (average of June, July, and August) and winter (average of December, pervious year, January, and February) within the coordinates 35° - 70° N, 10° W - 45° E, see Figs. 1.2.7 and 1.2.8. The trends are

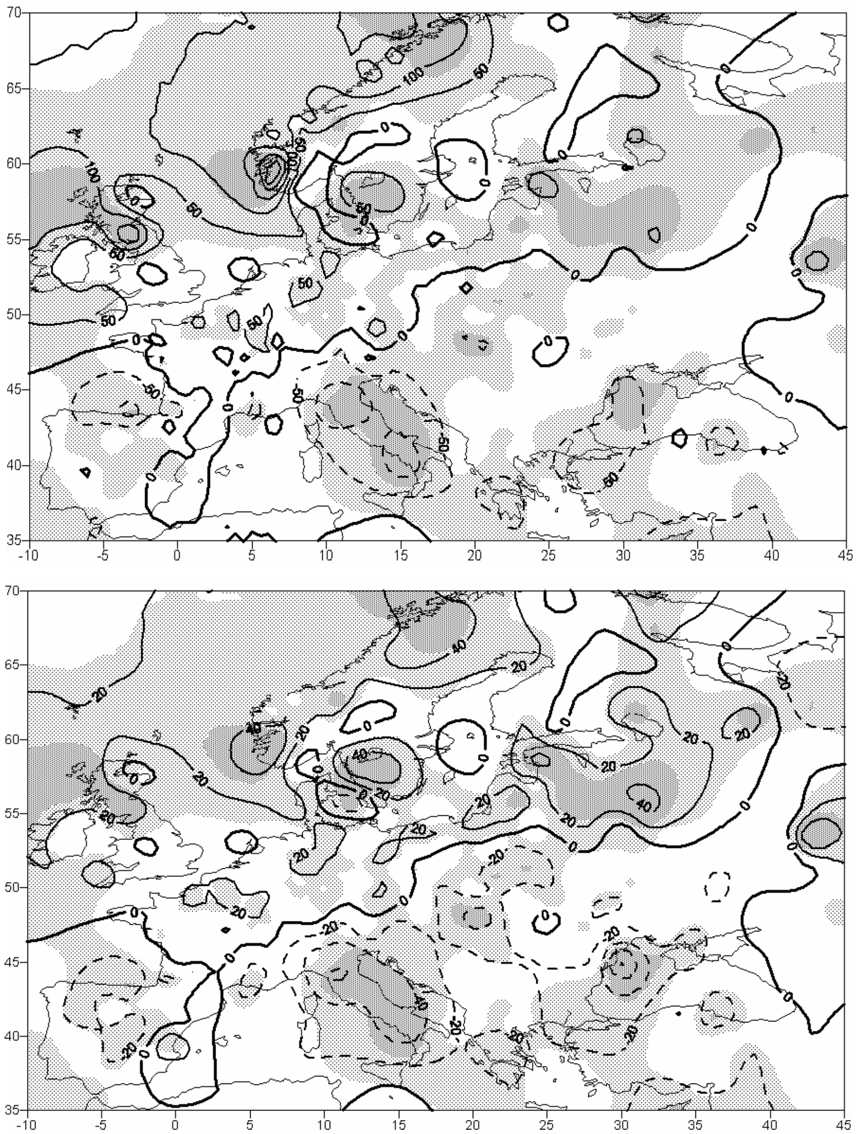


Fig. 1.2.8. Linear precipitation trends 1951-2000, European pattern, in absolute (mm, upper plot) and percent (lower plot) values, winter (December of previous year, January, and February (from Beck et al., 2007, based on Schönwiese and Janoschitz, 2007).

shown in absolute (mm) and relative (percent) values and shading indicates confidence (see Figure caption). In summer time which is of minor interest for the Mediterranean area (dry conditions) most of Europe except Eastern parts and NW Scandinavia show a decrease with maximum values >50 mm (corresponding to >20 %) in England, Germany and Switzerland. Some isolated increase areas in Northern and especially in Eastern Europe should be interpreted with care because some of this „island-like" structures may be due to measurement shortcomings or imply representative problems, respectively. Note that the very high percent values south of Italy are based on very low absolute trends and therefore are not confident.

In winter time we see a bipartition which seems to be realistic: Roughly north of a line Brest (NW France), Munich (S Germany), Kiev, Moscow (all Russia) increasing trends prevail where maximum values of >100 mm (>49 %) appear (especially Scotland and parts of Scandinavia). South of this line precipitation has decreased where the maximum values (>50 mm corresponding to >40 %) are found in Italy and some western parts of the Black Sea area. Keeping in mind that winter precipitation is very important for the Mediterranean and North Africa region concerning ground water formation and water supply, this climate trend may lead to serious socio-economic problems. In spring and autumn (trend charts not shown) the line defined above moves somewhat southward but within the Mediterranean area again a precipitation decrease prevails (for more details see Beck et al., 2007).

1.2.5 Extreme events: a case study for Germany

As can be derived from the previous chapter (in particular Figs. 1.2.7 and 1.2.8) in Germany a pronounced summer precipitation decrease is observed whereas in the other seasons, especially in winter, increasing trends dominate, concentrated on western and southern parts (for more details see Schönwiese and Janoschitz, 2005). However, long-term trends are just one aspect of climate variability among others. Neglecting the problem of fluctuations in this paper, we may briefly address the question whether climate trends are linked with a change in the frequency and magnitude of extreme events. This is an important question because in case of precipitation extreme events may lead to flooding or dryness, respectively. In order to enable an innovative approach to empirical-statistical climate extreme analysis, Trömel (2005; see also Trömel and Schönwiese, 2005), based on earlier work of Grieser et al. (2002), has evaluated a generalized method of time series decomposition into significant components and the assessment of the change of these components in time. In case of extremes the key point is an adoption of an appropriate probability density function (PDF, in empirical form frequency distribution) to the observed data and the assessment of the PDF parameters change in time.

An example may illustrate this procedure. To come to marked results, the period 1901-2000 is considered and the data refer to the German station Eppenrod (in the west, near rivers Lahn/Rhine), January totals of precipitation. Fig. 1.2.9 specifies the PDF change where the 1901 and 2000 „snapshots" are plotted. Simultaneously to an increase of the average from approximately 55 mm to 70 mm, the PDF has „broadened" which means an increase of variance. The effect on extremes is as fol-

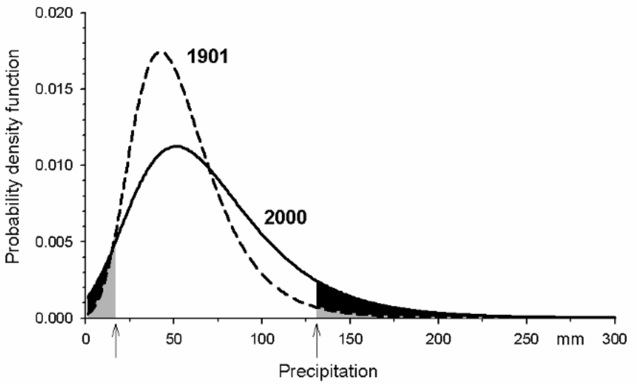


Fig. 1.2.9. Probability density function (PDF) change 1901-2000 of the January precipitation at station Eppenrod, Germany (50.4° N, 8.0° E), where the arrows indicate the (lower) 5th and the 95th (upper 5th) percentiles which amount to 17 mm or 131 mm, respectively, at this station. The related extreme value occurrence probabilities (indicated by grey or black shading, respectively) have increased for both extreme low and extreme high precipitation (for more explanation see text; from Schönwiese, Trömel, and Janoschitz, 2007).

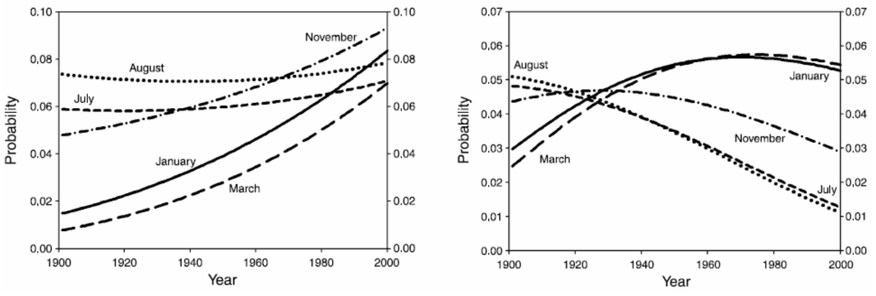


Fig. 1.2.10. Change 1901-2000 of the probability of occurring extremes (a, left) above the 95th percentile and (b, right) below the 5th percentile of precipitation in selected months at station Eppenrod, Germany (from Trömel and Schönwiese, 2007).

lows. If one defines the lower 5 % of the total data set (5th percentile) to be extreme dry and the upper 5 % (95th percentile) to be extreme moist, the shaded areas in Fig. 1.2.9 (illustrating the integral of the PDF below or above these percentile boundaries, respectively) represent the related occurrence probabilities. In this case we see that both probabilities have increased: occurrence of extreme dryness from

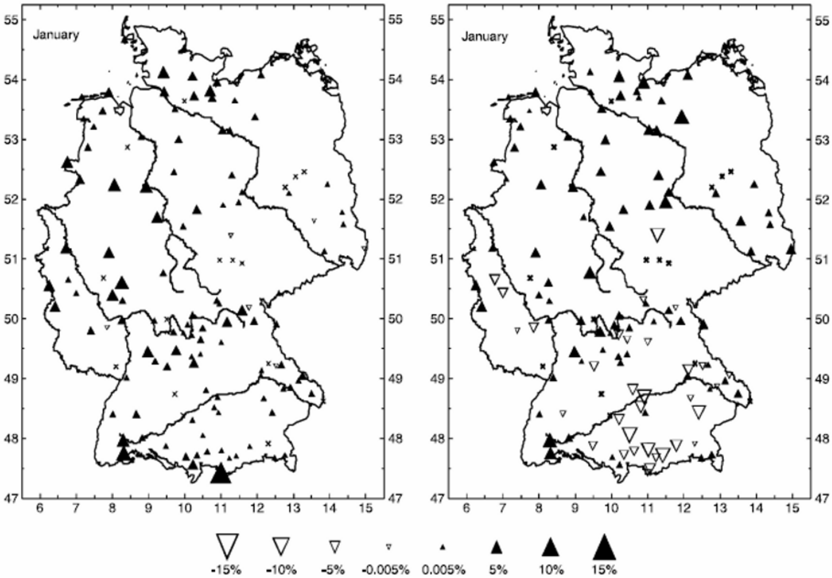


Fig. 1.2.11. Changes 1901-2000 of the probability of extreme January precipitation occurring above the 95th, left, or below the 5th percentile, right, at 132 stations in Germany. Upward black triangles indicate an increase and white downward triangles an decrease of this probability. The caption denotes the related magnitude (from Trömel and Schönwiese, 2007).

3.0 % (grey shaded area) to 5.3 % (grey plus black shaded area) and occurrence of extreme moistness from 1,5 to 8.4 % (again grey or grey plus black shaded areas, respectively).

Fig. 1.2.10 shows that this probability change of occurring extremes is a systematic process, however different in different months. From Fig. 1.2.10a where the development of the probability of occurring extremes exceeding the 95th percentile is indicated for a selection of months, it can concluded that this probability increases systematically in November, January, and March whereas it remains nearly constant in the summer months July and August. In contrast, the probability of occurring extremes falling under the 5th percentile (Fig. 1.2.10b) decreases gradually in November, July, and August but increases in January and March where, however, this increase seems to come to an end roughly around 1970 (results for all months and more stations see Trömel, 2005; see also Trömel and Schönwiese, 2007).

Just for one example, namely January precipitation, the distribution in space of such probability changes of occurring extremes is presented, see Fig. 1.2.11. It arises that the probability increase of occurring extremes above the 95th percentile is a wide-spread effect in Germany, however with relatively small magnitude at some stations, especially in the east. In case of extremes falling below the 5th percentile the probabilities have different signs, mostly positive at the majority of northern stations but mostly negative in the south (especially Bavaria). By the way, if both probabilities of extremes occurring below the 5th percentile and above the 95th percentile decrease (or one of these probabilities remaining nearly constant), this means a decrease of variability and, in turn, a less extreme climate. This points to the fact that the behaviour of extremes is complicated. As far as Germany is concerned and with a focus on winter months, however, the precipitation behaviour indicates a more extreme climate (see again Fig. 1.2.11).

1.2.6 Conclusions

Global climate change is reality. The same holds for anthropogenic forcing as an additional climate factor although some quantitative uncertainties remain (IPCC, 2007; Schönwiese, 2003). Again it is a fact, that this change has its impact on the global water cycle.

However, there are complicated regional and seasonal peculiarities. So, whereas there is no confident prove that the global water cycle may have accelerated in land areas due to global warming in industrial time, we see a complicated precipitation trend pattern with striking regional and seasonal peculiarities. On a global scale, most of the subtropical zones like Central America and the Mediterranean area suffer from a precipitation decease, in addition – *inter alia* – most of Africa, India and Indonesia (reference period 1951-2000). Simultaneously, in other regions a precipitation increase is recorded, again *inter alia* in major parts of America and Australia such as in the northwest of Europe.

As far as Europe is concerned, detailed precipitation trend analyses have been performed and the results are available for different seasons or months, respectively, and for different observation periods. Again with reference to 1951-2000, the most outstanding winter effects are an increase in northern parts (maximum trends in Scandinavia and Scotland) and a decrease in the Mediterranean area (maximum trends in Italy and the western part of the Black Sea area). In summer, increasing dryness appears also in England and Central Europe. A case study concerning the probability change of occurring precipitation extremes in Germany shows the most interesting effect in winter with simultaneously more low and much more high precipitation rates (reference period 1901-2000). This means a more extreme climate with respect to precipitation. However, even in such a small country like Germany there are a lot of (sub-)regional and seasonal (monthly) peculiarities.

The recent IPCC Report (2007) expects that much of the ob served climate trends observed so far may continue at least for some decades, broadly independent from mitigation measures due to the inertia effects of the climate system. As late as roughly in the second half of this century, mitigation measures, predominately reductions of GHG emissions, may slow down anthropogenic climate change

(IPCC, 2007). In the mean time there is no chance than to adopt on unavoidable climate change. For the Mediterranean and North Africa the main challenge is to meet the problems of water stress (aridity) with all its ecological and socio-economic consequences.

References

Baumgartner, A., Reichel, E., 1975: Die Weltwasserbilanz. Oldenbourg, München.

Beck, C., Grieser, J., Rudolf, B., Schönwiese, C.-D., Staeger, T., Trömel, S., 2007: Entwicklung einer Beobachtungsdatengrundlage für DEKLIM und statistische Analyse der Klimavariabilität. Bericht Nr. 6, Inst. Atmosph. Umwelt, Univ. Frankfurt/M.

CHIAS (Chicago Academy of Sciences / Notebaerd Nature Museum, USA), 2007: http://www.chias.org/www/edu/mitc/wkshp/ocean/water2.gif

Grieser, J., Trömel, S., Schönwiese, C.-D., 2002: Statistical time series decomposition into significant components and application to European temperature. Theor. Appl. Climatol., 71, 171-183.

IPCC (Intergovernmental Panel on Climate Change, UN), 2007: Climate Change 2007. The Physical Science Basis. Summary for Policymakers. IPCC Secretariat, c/o WMO, Geneva; http://www.ipcc.ch/SPM040507.pdf

Jendritzky, G., 2006: pers. communication.

Jones, P.D., 2007: Global temperature record. Climatic Research Unit, University of East Anglia, UK. http://www.cru.uea.ac.uk/cru/info/warming/

Lozán, J.L., Grassl, H., Hupfer, P., Menzel, L., Schönwiese, C.-D. (eds.), 2007: Global Change: Enough Water for all? Wiss. Ausw./GEO, Hamburg.

Marcinek, J., 2007: Hydrological cycle and water balance. In Lozán, J.L. et al. (eds.): Glowbal Change: Enough Water for all? Wiss. Ausw./Geo, Hamburg, pp. 33-37.

Munich Re Group, 2004: Topics geo 2003. München.

Schär, C., Jendritzky, G., 2004: Hot news from summer 2003. Nature, 432, 559-560.

Schönwiese, C.-D., 2003: Klimatologie. Ulmer (UTB), 2. Aufl., Stuttgart.

Schönwiese, C.-D., Janoschitz, R., 2005: Klima-Trendatlas Deutschland 1901-2000. Bericht Nr. 4, Inst. Atmosph. Umwelt, Univ. Frankfurt/M.

Schönwiese, C.-D., Janoschitz, R., 2007: Klima-Trendatlas Europa 1901-2000. Bericht Inst. Atmosph. Umwelt, Univ. Frankfurt/M, in preparation.

Schönwiese, C.-D., Rapp., J., 1997: Climate Trend Atlas of Europe Based on Ob servations 1891-1990. Kluwer, Dordrecht.

Schönwiese, C.-D., Staeger, T., Trömel, S., 2004: The hot summer 2004 in Germany. Some preliminary results of a statistical time series analysis. Meteorol. Z., 13, 323-327.

Schönwiese, C.-D., Trömel, S., Janoschitz, R., 2007: Variability of European precipitation within industrial time. In Lozán, J.L. et al. (eds.): Global Change: Enough Water for all? Wiss. Ausw./GEO, Hamburg, pp. 185-190.

Trenberth, K.E., et al., 2006: Estimates of the global water budget and its annual cycle using observational and model data. J. Hydrometeor., submitted (cit. Marcinek, J., 2007).

Trömel, S., 2005: Statistische Modellierung von Klimazeitreihen. Bericht Nr. 2, Inst. Atmosph. Umwelt, Univ. Frankfurt/M.

Trömel, S., Schönwiese, C.-D., 2005: A generalized method of time series decomposition into significant components including probability assessments of extreme events and application to observational German precipitation data. Meteorol. Z., 14, 417-427.

Trömel, S., Schönwiese, C.-D., 2007: Probability change of extreme precipitation observed from 1901 to 2000 in Germany. Theor. Appl. Climatol., 87, 29-39.

1.3 Moroccan Climate in the Present and Future: Combined View from Observational Data and Regional Climate Scenarios

K. Born(1), M. Christoph(1), A. H. Fink(1), P. Knippertz(2), H. Paeth(3) and P. Speth(1)

(1) Institute for Geophysics and Meteorology, University Cologne, Germany.

(2) Institute for Physics of the Atmosphere, Johannes Gutenberg University, Mainz, Germany.

(3) Institute for Geography, University Würzburg, Germany.

1.3.1 Introduction

Morocco is located between the arid regions of the western Sahara and the moderate Mediterranean and Atlantic regions. Landscape types reach from flat areas in the north-western part to high-mountain areas in the Atlas and Rif. Therefore, we can find a large variety of climates ranging from moderate humid and subhumid climates at the northern slope of the High Atlas over mountain climates to semi-arid and arid climates south of the Atlas. In this tension field, agricultural production and local economy depend very much on water availability, and thus, mainly on rainfall variability. In the past, periods of successive dry years have repeatedly shown the vulnerability to water scarcity, which results in threatened livelihoods of farmers and nomad families living from pasturing. This leads to a stream of migrants heading towards the large cities at the Moroccan coast and even to Europe. In order to counteract the peril of water scarcity, regional planning greatly benefits from information on future climate variability. Of course, the assessment of future climate scenarios in this very heterogeneous region is still a challenge for the climate research community. In this study, the actual state of climate research in IMPETUS West-Africa with respect to rainfall and temperature variability and of research on future climate scenarios is illustrated.

We start with an overview of available information from observational data and a few remarks on their quality. In the second part, results of regional climate modelling (RCM) are discussed with respect to future climate variability especially in regions south of the Atlas Mountains, where the water stress is clearly the limiting factor of agricultural production.

1.3.2 Moroccan Climate: A Short Survey of Observational Data

An analysis of climate and climate variability always starts with the acquisition of observational information in the region of interest. In Morocco, the density and quality of observations is better than in most other parts of Northern Africa, but

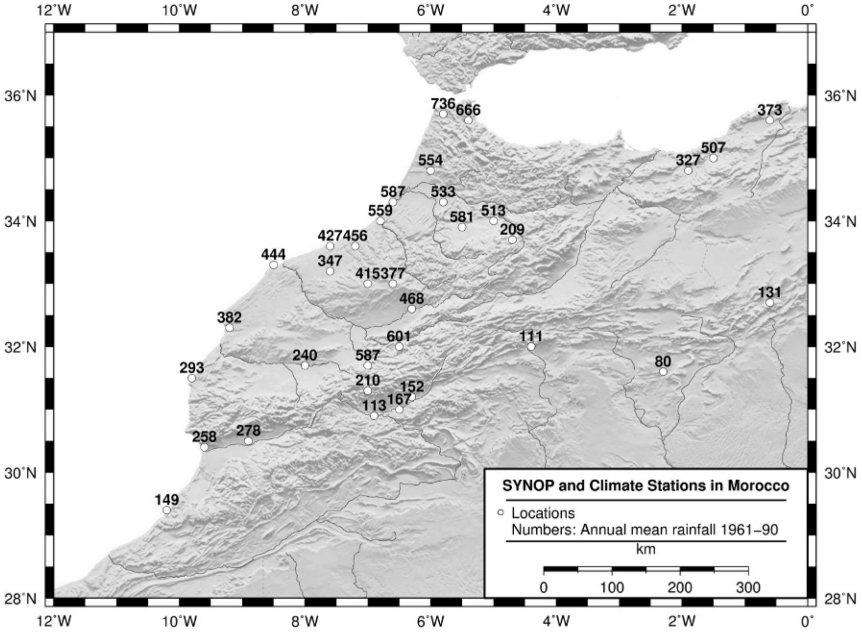


Fig. 1.3.1. SYNOP and climate stations in Morocco and the western part of Algeria. Circles represent the locations of the stations, numbers the observed 1961-1990 mean annual rainfall sum in mm.

still relatively sparse when we think of the spatial heterogeneity of climates. The first and most important source of information stems from SYNOP weather stations, which contribute to the WMO network and deliver data of a relatively high quality standard for several decades now. Unfortunately, most stations in Morocco and the western parts of Algeria are located north of the Atlas Mountains, which leaves a lack of information exactly in the southern region, where the impact of a climate shift is expected to be very strong (Fig. 1.3.1). The SYNOP data can be extended by information from individual climate stations operated by regional water management facilities and also by IMPETUS West-Africa, but the quality standard and temporal completeness of these data is not as high as for SYNOPs. Therefore, these data are mainly used to control the quality of derived climate products and do not contribute to the description of regional climates in Morocco.

In order to generate spatially distributed information on near-surface climates, the observations have to be interpolated with adequate statistical techniques. Two projects have produced world-wide data sets of climate-related meteorological parameters from a large number of available observations, which have a spatial resolution of at least 0.5° longitude and latitude. These are climate data from the Cli-

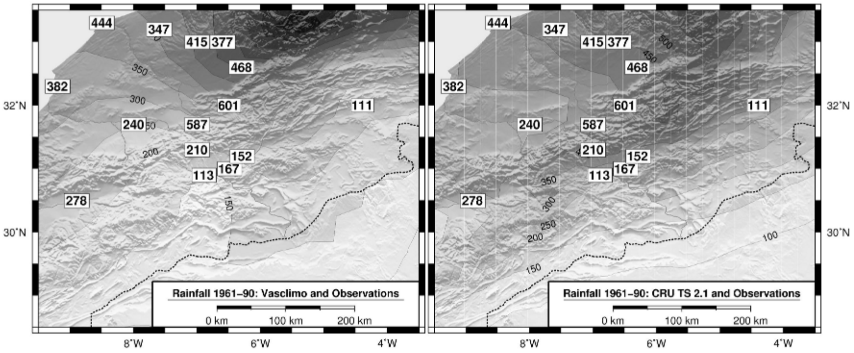


Fig. 1.3.2. Annual mean rainfall in mm (isolines with grey shading) for the period 1961-1990, as presented by the VASCLIMO data (left panel) and the CRU TS 2.1 data (right panel). The numbers in white rectangles show mean annual rainfall sums in the same period, but calculated directly from observations at SYNOP tations.

mate Research Unit of the University of East Anglia, hereafter called CRU, in the version TS 2.1 for the period 1901-2002 (Mitchell and Jones, 2005), and the VASCLIMO data (Beck et. al., 2005), which contain only precipitation data for the period 1951-2000. Both data sets contain monthly averages. The VASCLIMO data were subject to a more rigorous quality control and can therefore be used to improve the CRU data, where only information from the period 1951-2000 is requested. At the moment, these two data sets represent the most reliable long-term rainfall information despite the problems with data coverage described above.

We begin with looking at the mean annual rainfall for the so-called climate normal period 1961-1990 (Fig. 1.3.2). In order to focus on the effect of orography and missing data, the annual mean rainfall is shown for a region centred on the High Atlas, which contains the area with more observations in the north and the area with hardly any observations in the south-east. Observations at stations were plotted as coloured circles in the map and allow a comparison with the interpolated products. In general, the CRU and VASCLIMO coincide very well with the observations, but in regions with less dense stations we can find larger differences. Interestingly, none of the data really represent the high precipitation in the Mountain region. The CRU data seems to accentuate the orographic effect on annual precipitation a little stronger, but overestimates the rainfall south of the Atlas. In the following, we have to keep this uncertainty in mind when looking deeper into the characteristics of climate-related parameters.

Climate variability affects vegetation in both natural and agricultural environments. Therefore, our second view focuses on the well known Köppen climate classification, which is based on thresholds relevant for special vegetation types. We want to demonstrate the climate shift in the late 20th century by comparison of

Table 1.3.1. Definition of classes of the reduced Köppen climate classification. T is the mean monthly temperature in 2 m hight above ground, Prec is the annual precipitation sum. Max / Min T indicate the warmest and coldest month in the mean annual cycle.

Name	Climate	Criterion 1	Criterion 2
E	Ice	Max T < 10° C	
D	Snow	Max T > 10° C and Min T < -3° C	
Cs	Moderate	-3° C < Min T < 18° C	summer dry
Cf			Wet
Cw			winter dry
Af	Tropical	Min T > 18° C	Wet
Am			Monsoon climate (dry period compensated by seasonal rain)
Aw/s			winter/summer dry
BSk	Steppe	{Mean T} < {Prec} < 2 {Mean T}	cold (Mean T < 18° C)
BSh			warm (Mean T > 18° C)
BWk	Desert	cold with Mean T < 18° C	
BWh		warm with Mean T > 18° C	

climate classes obtained from a reduced version of Köppens classification scheme, which has already proven its practicability in other applications (Guetter and Kutzbach, 1990, Fraedrich et al. 2001). Fraedrich et al. (2001) have shown that the – in a statistical sense – optimal length of time spans for detecting changes in the Köppen classification is 15 years. Therefore, classification is applied to the 15-year periods 1951-65 and 1986-2000. Fig. 1.3.3 shows the classification results for the entire Mediterranean basin. In northern Africa we can clearly see a shift towards dryer and warmer climates; at the borders to Steppe and Desert a number of pixels shift from moderate and summer dry (*Cs*) to Steppe climates. The Köppen classification is quite rough and only represents a very limited number of climate classes. Especially in the *Cs* region, a finer distinction is desirable.

The classification can be improved by merging orographic information and climate parameters statistically. As an example, we computed an aridity index by integrating the area between the mean annual march of temperature and rainfall in the Walter-Lieth diagram. The orographic information was included by a multiple linear regression of surface height and exposition (slope and direction) with rainfall and temperature. Then we divided the aridity index into eight classes and obtained the classification shown in Fig. 1.3.4. The Walter-Lieth climate diagrams accord-

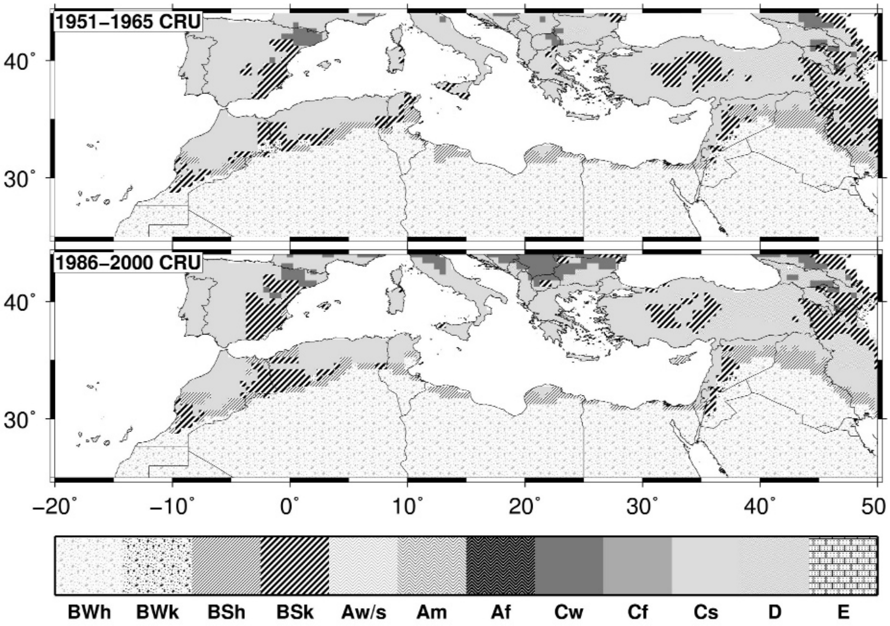


Fig. 1.3.3. Climate classification after a reduced Köppen scheme applied to the CRU TS2.1 data. The maps compare the climate classes for 1951-1965 to 1986-2000 and reveal a trend towards dryer and warmer climates in the second half of the 20th century.

ing to the climate zones are also depicted. Here, the mountain climates and the northwest-southeast aridity gradient emerges clearly – also in regions where the Köppen classification showed only the *Cs* climate. It has to be pointed out, however, that this purely statistical proceeding does not contain any information of regional and local scale weather systems of the mountain areas, which we expect to influence the near-surface climates. Ignoring these effects probably explains the overestimation of zone 4 south of the Atlas mountain ridge.

The third view focuses on the temporal climate variability. For this purpose, we look at the original observational data of SYNOP stations and combine them into regional indices. Since station-to-station differences in rainfall can be very large, we have first divided the monthly rainfall sums into 5 classes by separating the probability distribution – estimated simply by histograms – into quintiles, as recommended by the WMO No. 100 (1983). This way, each rainfall sum can be assigned to a number between 0 (no rainfall) and 5. These numbers are then averaged over regions with similar temporal behaviour of the rainfall (Fig. 1.3.5a). The regions were chosen with respect to typical rainfall bearing systems (Knippertz et al., 2003): The Atlantic region (ATL) is mainly affected by synoptic systems of the

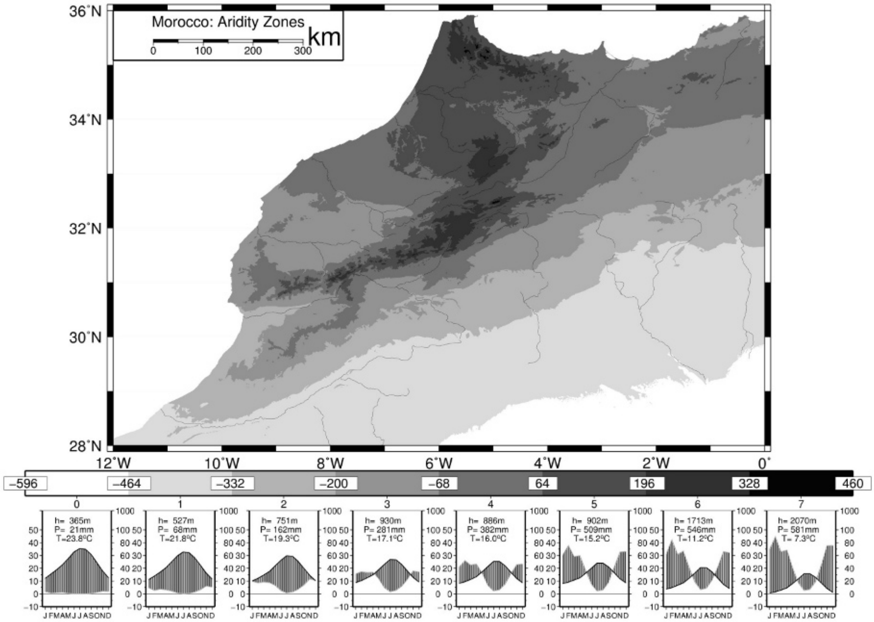


Fig. 1.3.4. Climate zones based on an aridity index computed as the aggregated difference of twice the temperature in ° C and the rainfall for the averaged seasonal cycle. The Walter-Lieth diagrams (bottom) are representative for the zones. They show the annual cycle of temperature (black lines, right axis) and monthly rainfall sums (grey line, right axis). The numbers printed each diagram contains the average surface height, annual rainfall and annual mean temperature of each zone. The numbers in the grey scale bar are aridity indices for the zones. The data are collected from the 1961-1990 climate normal period.

midlatitudes, has a seasonal rainfall maximum in the winter months (DJF) and is connected largely with the North Atlantic Oscillation (NAO). The Mediterranean region (MED) is also affected by Mediterranean pressure systems. Both regions are subhumid. The region south of the Atlas (SOA) is less affected by North Atlantic weather variability and gains rainfall relatively often from tropical-extratropical interactions. We have to notice, that the ATL region is represented by a larger number of stations – typical 25 – whereas the MED and SOA regions only contain about 5 stations.

In Fig. 1.3.5b, time series of rainfall indices for the winter months (Nov-Apr) are compared to CRU time series. The series are plotted as standardized anomalies to the 1961-1990 period. We can see, that for the ATL region winter rainfall variations (blue bars in the plot of the CRU data) are quite good in phase with the observations, but for the MED and SOA regions we can see larger differences. In this

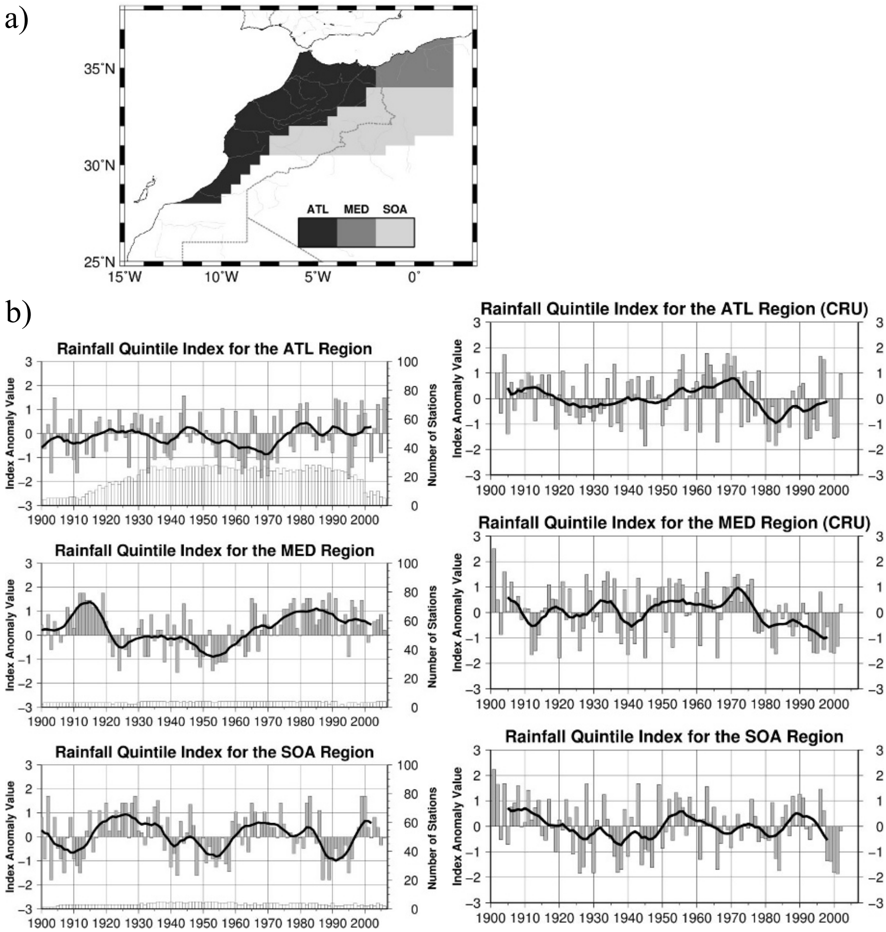


Fig. 1.3.5. *(a)* The Atlantic (ATL), Mediterranean (MED) and South-of-the-Atlas (SOA) regions, for which stations data were aggregated.
(b) Rainfall indices based on quintiles for station data (left panels) and CRU TS 2.1, for the ATL, MED and SOA region, respectively. The left series are aggregated for the rainfall season (Nov-Apr) and correspond to the blue bars in the right panel. In addition, the left graphics show filtered values (red line) and numbers of available stations.

case, we tend to value the direct observations higher than the interpolated CRU product, because the latter contains also information from far away stations due to the employed statistical interpolation technique. The time series show periods of wet and dry years, which do not seem to be entirely random, but clustered in periods of 2-4 years.

Concluding Remarks

Utilizing observational data we took three different views on observed Moroccan rainfall climate. We have to admit that the quality and density of available observations causes a large range of uncertainty especially in the region south of the Atlas Mountains which is subject to large risks due to climate shifts. We can analyze the temporal variability of rainfall on long time scales and are able to identify periods of drought and of wet years. The Köppen climate classification clearly reveals the climate shift towards warmer and dryer climates in the 20th century. Now, we have to walk a step ahead and ask for possible future developments.

1.3.3 Assessment of Future Climate in Morocco: Results from Regional Climate Modelling

Introduction

A continuation of the observed trend, which we have shown in the previous chapter, implies changes in the temporal behaviour and strength of rainfall and, therefore, is expected to affect water availability and possibilities of a sufficient water distribution. Of course, this is of interest for long-term planning of regional and local facilities connected with water distribution.

In this chapter, results of recent regional climate modelling are presented with respect to the impact of climate change on vegetation and water availability in the three observational regions above defined: the Atlantic (ATL), Mediterranean (MED) and more desert-like climates south of the Atlas (SOA). First, to evaluate the RCM scenarios, the impact on near-surface conditions is shown by means of the Köppen climate classification, then characteristics of modelled rainfall index time series are shown.

A Short Note on Climate Scenarios and Climate Models

In order to assess the impact of future climate changes on the global scale, special computational models of the climate system have been developed by climate researchers in the past decades. They are based on physical principles and laws, mostly of the Earth's atmosphere but partly also to other climate subsystems like the pedosphere and the cryosphere. For atmospheric processes, Global Circulation Models (GCMs) have been applied to study the changes of climate parameters within the next century, mainly due to increasing greenhouse gas (GHG) contents in the atmosphere. This has been documented in several publications of the Intergovernmental Panel of Climate Change. They also reflect the proceeding of climate research over the last 15 or 20 years. One of the urgent issues of the 3rd assessment report of the Intergovernmental Panel on Climate Change (IPCC, 1997 and IPCC,

2001) was the *regionalisation* or *downscaling* of GCM results, since it is well known that local conditions may be very different from what we observe on the large scale.

From GCM results of 21st century climate scenarios, a continuation of the observed warming trend is expected for the subtropical regions. However, the prediction of rainfall is not as simple, since it is steered by teleconnections and local conditions as well. For the Atlas region, teleconnections can be seen e. g. with the Northern Atlantic Oscillation (NAO), tropical-extratropical interactions (TEI, Knippertz et al., 2003) and even with the El Niño/Southern Oscillation (ENSO). Local conditions are the land-sea distribution, the mountains and the state of the vegetation canopy.

Beneath the expert model, which uses the expertise of several climatologists to „interpret“ GCM data on local regions, three more objective techniques have evolved to perform the downscaling of global scale climate data. (1) *statistical downscaling*, using statistical transfer functions between local observations and larger scale patterns obtained from reanalysis or GCM data (like we did for Fig. 1.3.4); (2) *dynamical downscaling*, using embedded finer scale regional climate models; and the mixture of both, known as (3) *statistical-dynamical downscaling*. Each of these methods has its own faults and advantages, which have to be identified and discussed when regional climate changes are estimated. For Morocco, the Atlas Mountains form a border between the desert climates of the Sahara and the moderate maritime climates. The *dynamical downscaling* performed by an application of a dynamic Regional Climate Model (RCM) embedded in atmospheric fields of GCM simulations, is expected to produce the most reliable results, as the model is able to simulate smaller scale circulations caused by the mountains.

Models and Data

The RCM has been undertaken with the Mesoscale Atmospheric Model REMO of the *Max-Planck Institute for Meteorology* (MPIfM) Hamburg. REMO is an atmospheric model based on the hydrostatic approximated set of hydrodynamic equations. The package of physical parameterizations is similar to the one of the ECHAM5 GCM in order to produce consistent results when REMO is nested into ECHAM5. The model area for this RCM approach contains North Africa and the Mediterranean (15°S-45°N, 30°W-60°E). Further details of model physics are described in Jacob et al. (2001), the application of REMO for RCM in the Mediterranean and Africa has been presented in Paeth (2004), Paeth et al. (2005), and Paeth and Hense (2005). These studies focus on the evaluation of RCM data (Paeth, 2004 and Paeth et al., 2005) and the assessment of extreme events in the Mediterranean (Paeth and Hense, 2005). They are mainly based on the period 1979-2003 and forced by atmospheric data of the ECMWF (re-)analysis data. Because the RCM results were promising, REMO has been applied in ensemble mode for the period 2001-2050 in order to study the possible future development of climate in Northern Africa. For these model studies, the atmospheric forcing has been taken from coupled atmosphere and ocean modelling using the so-called Ocean-Atmosphere General Circulation Model (OAGCM) ECHAM5/MPI-OM (Roeckner et al., 2003). The scenarios of ECHAM5/MPI-OM participate in the 4th IPCC report (IPCC, 2007). The climate forcing in REMO consists of the anthropogenic enhanced GHG effect and sea surface temperature (SST) changes, mainly inferred from the GCM, as well as land cover changes (LCC), which were assessed on the basis of FAO (Food and Agriculture Organization of the United Nations) studies. LCC is limited to Sub-Saharan Africa and contains the impacts of deforestation, desertification and the transition of natural vegetation into arable lands. It has to be kept in mind that the SST variability simulated by the OAGCM is not in phase with observed SST anomalies on shorter time scales. As a consequence, present day climate simulated with the OAGCM is not expected to coincide with observations of single years. Only the statistical characteristics of OAGCM simulations and longer-term conditions on typical climatic scales should resemble as much as possible.

State-of-the-art climate simulations perform for each climate scenario a couple of realizations, starting from different initial conditions, in order to give some information of system-immanent variability, which produces an uncertainty range of the climate simulations. The ensemble of REMO model simulations contains three control runs of the present day climate (1960-2000), three model runs of SRES scenario A1b (2001-2050) and three model runs of SRES scenario B1 (2001-2050). For the characteristics of the forcing in the SRES scenarios, see Fig. 1.3.6. In order to separate the LCC-caused part of the climate change signal, another three model runs of SRES scenario A1b for 2001-2050 with fixed (but seasonally varying) vegetation have been undertaken. Further details and results are presented in Paeth et al. (2007).

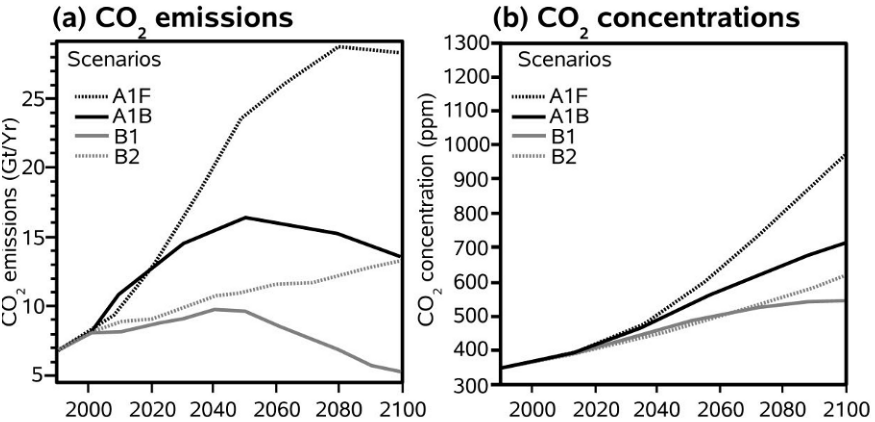


Fig. 1.3.6. CO_2 emissions (left) and atmospheric concentrations (right) in SRES scenarios. Figure taken from IPCC (2001).

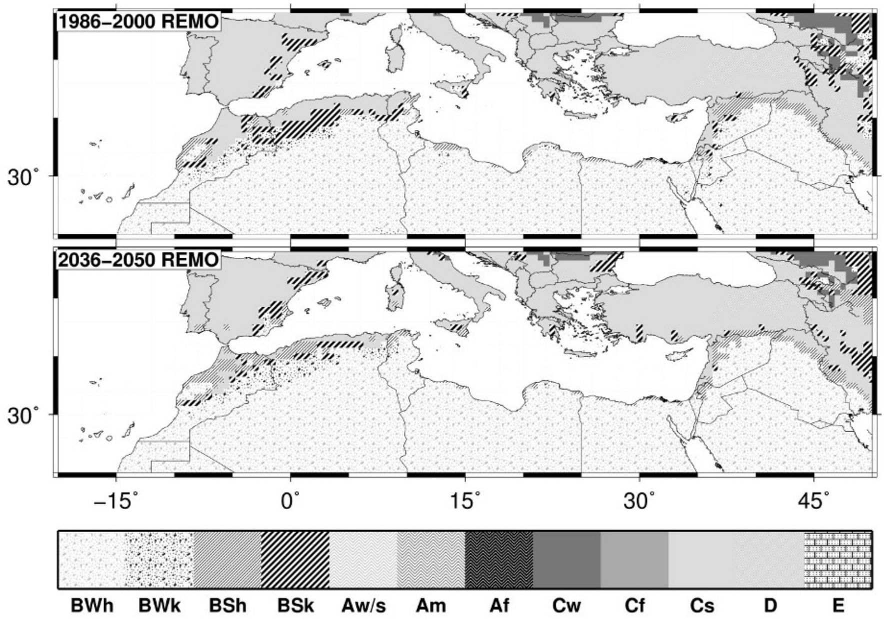
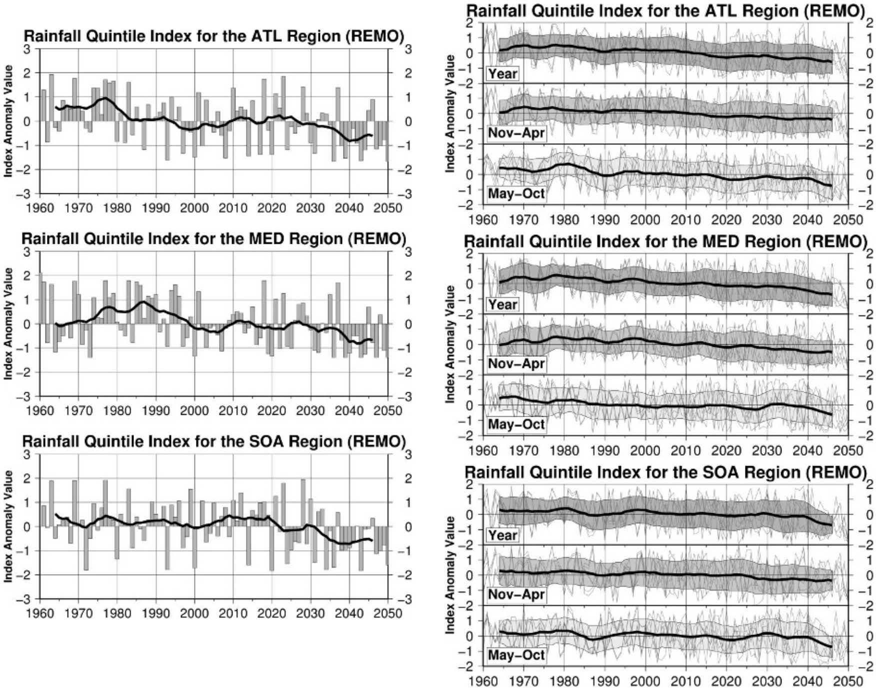


Fig. 1.3.7. Climate classification after Köppen for simulated climate scenarios from REMO.

Changing Climate in Terms of Koeppen-Geiger Climate Classification

The application of the reduced Köppen classification to RCM data (Fig. 1.3.3) allows for a qualitative evaluation of the model bias as well as for an analysis of major climate changes. For the REMO scenarios, the periods 1986-2000 and 2036-2050 are shown in Fig. 1.3.7. Comparison with Fig. 1.3.3 reveals a slight model bias: In general, REMO simulates a dryer and warmer climate than CRU 2.1 data. For the future climate in 2036-2050, RCM shows a significant transition towards Steppe for the ATL and MED regions and towards desert in the SOA region. The changes – also in other parts of northern Africa, which are not shown here – are qualitatively similar to the observed changes in the 20th century, albeit a little stronger.

In summary, the REMO model reveals a continuing and strengthening climate change towards dryer and warmer conditions all over Morocco. The warming is in accordance as well with 20th century observations as with global temperature changes simulated by GCM climate scenarios.



Rainfall Quintile Index for the ATL Region (REMO)

Rainfall Quintile Index for the MED Region (REMO)

Rainfall Quintile Index for the SOA Region (REMO)

Fig. 1.3.8. Rainfall indices for the regions of interest in winter (NOV-APR) and summer (MAY-OCT). Left panel: Index series for the three regions for one realization of scenario SRES A1b, right panel: combined REMO scenarios A1b and B1, temporally filtered (5yr filter width) and with uncertainty ranges (1 standard deviation, shaded regions) as a measure for system-immanent variability.

Rainfall in Future Climate Assessment

Rainfall is the most important climate related component for the biosphere in general and for agriculture and vegetation in specific. Therefore, the estimation of future rainfall variability is essential and extremely valuable for any economic planning. But rainfall is also one of the most uncertain weather components. Even rainfall observations at stations, which are located relatively near to each other, may differ strongly. The value of rainfall observations as well as predictions might be enhanced by examining spatial and temporal averages. Therefore, the choice of the regions ATL, MED and SOA in Fig. 1.3.5a with similar statistic characteristics of rainfall for Morocco gives a somewhat more reliable view on rainfall variability in the climate scenarios and allows a comparison with CRU data (Fig. 1.3.5b). In Fig. 1.3.8, time series of the quintile-based rainfall index for the three regions are shown for one realization of the SRES-scenario A1b and – as a summarizing view

Table 1.3.2. Trend matrix for rainfall indices in standard deviation units / 91 years for the period 1960-2050. The bold values are trends, for which the error probability for rejection of the no-trend-hypothesis is smaller than 10%. Additionally, trend uncertainties as mean deviations from the ensemble mean trend are given.

Rainfall Index Trend	ATL	MED	SOA
Winter	-0.73±0.30	**-0.86±0.36**	-0.71±0.37
Summer	-0.73±0.42	-0.46±0.38	-0.63±0.41
Year	**-0.91±0.29**	**-0.91±0.25**	-0.83±0.26

– for all ensemble members, including the range of uncertainty calculated by the standard deviation of anomalies from the temporal filtered average of the ensemble mean.

From a first view, it can be seen that a small, but statistically insignificant decrease in rainfall occurs. The decrease in annual rainfall sums reaches amounts of 25% from present day values, but the signal is hidden to a large part in interannual to decadal variability. In observations, the rainfall decrease was more prevalent for the winter season, whereas the model data show the decrease in winter and summer equally. An interesting detail is the decadal variability of the time series, which seems to be underestimated in the model data.

The trend matrix for seasonal time series (Table 1.3.2) in the three regions reveals a slightly different behaviour in the regions. In the ATL region, rainfall is simulated to decrease by nearly one standard deviation of the index series within the years 2001-2050 of the combined scenario data A1B and B1. In the MED region, the decrease is more confined to the summer months, and in the SOA region, it is again similar in winter and summer. One has to keep in mind, that averaging over a number describing distinct classes is not a linear process, thus, the trend for annual sums is not just the average of the trends in the winter and summer months.

Nevertheless, the rainfall index shows a moderate linear trend towards less rainfall in all three regions, as we already expected from the analyses of the climate classification. The linear trends do – in general – not emerge from system-immanent (sometimes called „natural") variability of the RCM. This is revealed by the error probability of the rejection of the null-trend hypothesis, which is in all cases larger than 5 %. Thus, the signal-noise ratio is small, mainly because rainfall variability is very high in subtropical and partial semi-arid regions. The mutual range of the trend, calculated simply as averaged anomalies of the trends of single ensemble members, indicates that none of the scenario members shows a trend in the opposite direction, which increases the reliability of the findings a little bit. From the index series, we can draw conclusions regarding the relevance of changes in regional rainfall, although stations may have locally different rainfall sums. However, since the summer and winter indices use different rainfall distributions, they cannot be used to discuss changes in seasonality.

Temperature in the Future Climate Assessment

Temperature predictions for the future climate are somewhat less influenced by large spatial and temporal heterogeneity than rainfall (as long as we declare the height effect in the mountains as known and easily to describe). All simulations show a continuation of the observed warming trend and are statistically significant to a very high level. One impact of rising temperatures is the shift towards warmer climate classes as discussed in the foregoing chapters. One of the strongest impacts could be the rise of the snowline in the Atlas Mountains. The amount of water stored in snow is important for runoff characteristics of single events as well as for seasonal values, since snowmelt can contribute to the available water for agriculture and households in the beginning of the dry season. Thus, temperature trends have been calculated for the winter and summer season, respectively. It reveals a stronger warming trend in the summer months than in winter, which means a more „continental“ behaviour with a strong spread between summer and winter conditions. On the other hand, the expected rise of the snowline, estimated roughly from the simulated warming and standard atmosphere conditions is not as strong as suggested by the annual values, since we assume that snowfall mainly occurs in winter months, where the warming is less pronounced than in summer. Nevertheless, the warming is responsible for a shift from Steppe towards desert climates in the Köppen climate classification (Fig. 1.3.7).

The time series of 2m-temperatures for the combined simulated A1b and B1 scenarios (Fig. 1.3.9) shows, similar to the negative rainfall trend, a continuation of the warming already observed in the 20^{th} century. The trend matrix is shown in Table 1.3.3. Different from rainfall, linear temperature trends are nearly all highly significant and reach an error probability of rejecting the null-trend hypothesis of less than 1%.

Table 1.3.3. Trend matrix for temperature in K/91 years from REMO A1b and B1 scenarios, for the period 1960-2050. For all values, the error probability for the rejection of the no-trend-hypothesis is less than 1%. Again, the range of uncertainty is given as the averaged deviation from the ensemble mean trend.

Temperature trend	ATL	MED	SOA
Winter	1.37 ± 0.28	1.33 ± 0.22	1.27 ± 0.18
Summer	1.75 ± 0.49	2.04 ± 0.55	2.02 ± 0.52
Year	1.56 ± 0.29	1.69 ± 0.31	1.64 ± 0.29

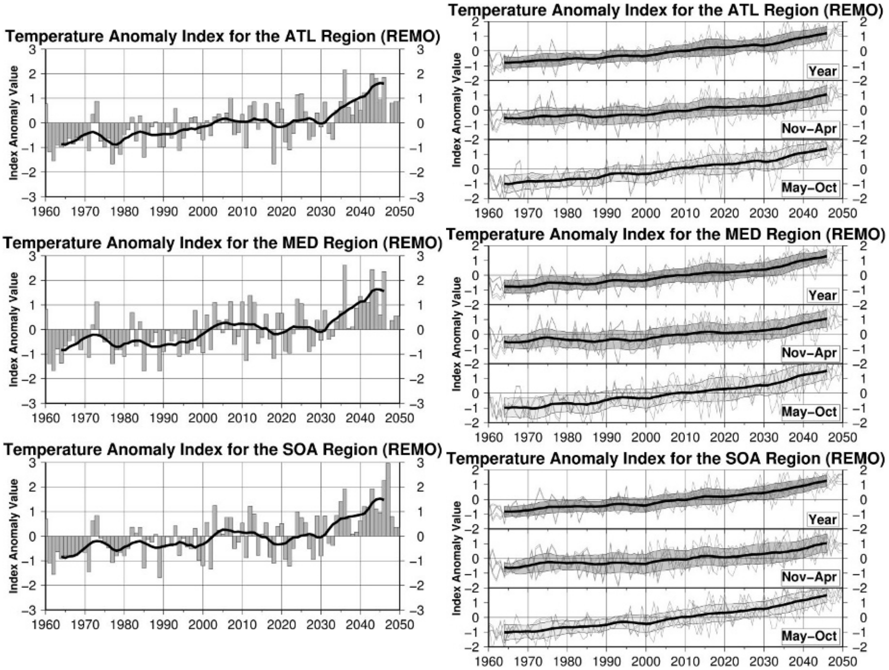


Fig. 1.3.9. Time series of spatial averages of near surface temperature (2m height) in K, as obtained from one ensemble member of the REMO climate scenarios SRES A1b (left) and as filtered time series(11-year filter width) with added uncertainty ranges for all REMO climate scenarios A1b and B1 (right).

The trend matrix clearly shows a distinct behaviour in summer and winter: the warming seems to be stronger in summer time. Regarding a supposed snowline rise, a more detailed analysis is necessary, because temporal correlation between rainfall and temperatures has to be taken into account.

1.3.4 Conclusions

Moroccan climate has been described by examination of observational values, both directly from stations as from the interpolated products of CRU TS2.1 and VASCLIMO. It turned out that the data are very sparse in regions, where the future climate shift is expected to have the largest impact on humans and vegetation. Nevertheless, the 20th century data revealed a warming and drying trend in terms of the vegetation relevant Köppen climate classification.

In order to allow for an outlook into future climate conditions, rainfall and temperature variability in present day and for future climate scenarios were estimated by an RCM approach. The analysis of the results points to a continuation of the trend observed in the 20th century. The RCM scenarios show reliable results, although a model bias towards dryer climates can be seen. The existence of this model bias is – due to the high complexity of the simulated processes – not very surprising. It has to be taken into account when interpreting the results and might be used in future research to identify sections, where the description of the climate system could be improved.

The results of our study have to be slightly restricted. Since there exists no other set of RCM scenarios covering Northern Africa with such a high resolution, our results will have to be carefully tested with other regional climate models in future climate research.

The RCM results show a trustworthy and acceptable range of uncertainty. Although differences in long-term variability between observations and model data can be seen, the uncertainty due to system-immanent (natural) variability seems to be quite realistic. Thus, the effect of global scale greenhouse gas forcing and land cover changes in Africa (which were not discussed separately in this study, but were both part of the climate change forcing in the RCM approach) on regional Moroccan climate can be assessed from RCM scenarios. The most prominent change is a shift of all climates towards warmer and dryer conditions and, therefore, a further increase in the existing water stress is expected, especially south of the Atlas Mountains.

Acknowledgements

This work was supported by the Federal German Ministry of Education and Research (BMBF) under grant No. 01 LW 06001A and by the Ministry of Innovation, Science, Research and Technology (MIWFT) of the federal state of Northrhine-Westfalia under grant No. 313-21200200.

The observational data were collected and maintained under the participation of Tim Brücher and Kristina Piecha from the Institute for Geophysics and Meteorology of the University Cologne. Robin Girmes and Kai-Oliver Heuer, who were involved in the IMPETUS project, have supplied model data management. Ralf Podzun and Daniela Jacob, Max-Panck-Institute for Meteorology in Hamburg, have realized the RCM model runs at the *Deutsches Klimarechenzentrum*.

References

Fraedrich, K., F.-W. Gerstengarbe and P. C. Werner, 2001: Climate shift during the last century. Clim. Change 50, 405-417.

Beck, C., J. Grieser and B. Rudolf (2005): A New Monthly Precipitation Climatology for the Global Land Areas for the Period 1951 to 2000. Published in Climate Status Report 2004, pp. 181 - 190, German Weather Service, Offenbach, Germany

Guetter, P. J. and Kutzbach, J. E., 1990: A modified Koeppen classification applied to model simulations of glacial and interglacial climates, Clim. Change 16, 193-215.

IPCC, 1997: The Regional Impacts of Climate Change: An Assessment of Vulnerability. A Special Report of IPCC Working group II. Eds: Watson, R. T., M. C. Zinyowera, R. H. Moss. Cambridge University Press, UK, 517pp.

IPCC, 2001:Climate Change 2001: Impacts, Adaptation & Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Eds: James J. McCarthy, Osvaldo F. Canziani, Neil A. Leary, David J. Dokken and Kasey S. White, Cambridge University Press, UK. 1000pp.

IPCC, 2007: IPCC Fourth Assessment Report (AR4) Working Group I Report „The Physical Science Basis“, available online http://ipcc-wg1.ucar.edu/wg1/wg1-report.html (Sep 16, 2007), about to appear in Nov. 2007.

Jacob, D., Van den Hurk, B.J.J.M., Andrae, U., Elgered, G., Fortelius, C., Graham, L.P., Jackson, S.D., Karstens, U., Koepken, C., Lindau, R., Podzun, R., Rockel, B., Rubel, F., Sass, B.H., Smith, R. and Yang, X., 2001, A comprehensive model intercomparison study investigating the water budget during the PIDCAP period. Meteorol. Atmos. Phys. 77: 19-44.

Knippertz, P.; Christoph, M.; Speth, P., 2003: Long-term precipitation variability in Morocco and the link to the large-scale circulation in recent and future climates. Meteorology and Atmospheric Physics, 83, 67–88.

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel, 2006: World map of the Köppen-

Geiger climate classification updated. Meteorol. Z., 15, 259-263.

Mitchell, T. D., and P. D. Jones, 2005: An improved method of constructing a database of monthly climate observations and associated high resolution grids. Int. J. Climatol. 25, 693-712.

Paeth, H., 2004, Key factors in African climate change evaluated by a regional climate model. Erdkunde 58, 290-315.

Paeth, H., Born, K., Podzun, R. and Jacob, D., 2005, Regional dynamic downscaling over West Africa: Model evaluation and comparison of wet and dry years. Meteorol. Z. 14, 349-367.

Paeth, H. & Hense, A., 2005, Mean versus extreme climate in the Mediterranean region and its sensitivity to future global warming conditions. Meteorol. Z. 14, 329-347.

Paeth, H., K. Born, R. Girmes, R. Podzun and D. Jacob, 2007: Regional Climate change in tropical and northern Africa due to greenhouse forcing and land use changes. Submitted to J. Climate.

Roeckner, E. et al. The atmospheric general circulation model ECHAM 5. PART I: Model description. MPI-Report 349, 127pp (2003).

World Meteorological Organization, 1983: Guide to climatological practices. Secretariat of the World Meteorological Organization, Geneva, Switzerland. WMO No. 100, Second Edition 1983, 198 pp.

1.4 Impact of Climate Change on Water Availability in the Near East

Peter Suppan[1], Harald Kunstmann[1], Andreas Heckl[1], Alon Rimmer[2]

[1] Institute for Meteorology and Climate Research (IMK-IFU), Forschungszentrum Karlsruhe, Kreuzeckbahnstraße 19, 82467 Garmisch-Partenkirchen, Germany. peter.suppan@imk.fzk.de

[2] Kinneret Limnological Laboratory, Israel Oceanographic & Limnological Research Ltd, PO Box 447, Migdal 14950, Israel

Abstract

The impact of climate change on water availability in the Middle East and the Upper Jordan catchment (UJC) is investigated by dynamic downscaling of ECHAM4 time slices and subsequent hydrological modelling. Two time slices (1961-90 and 2070-99) of the global climate scenario B2 of ECHAM4 were dynamically downscaled with the meteorological model MM5 in two nesting steps of 54 km and 18 km resolution. The meteorological fields were used to drive a physically based hydrological model, computing in detail the surface and subsurface water flow and water balance of the UJC.

Results of the joint regional climate-hydrology simulations indicate mean annual temperature increases up to 4.5° C and 25 % decreases in mean annual precipitation in the mountainous part of the UJC. Total runoff at the outlet of the catchment is predicted to decrease by 23 %, and is accompanied by significant decreasing groundwater recharge.

Key words Climate change, dynamic downscaling, Middle East, hydrological modelling, water availability

1.4.1 Introduction

Sufficient freshwater availability is a central prerequisite for agricultural and industrial development in the water scarce environment of the Eastern Mediterranean and Middle East (EM/ME). Political peace in the region is strongly linked to the satisfactory compliance of increasing water demands. Sustainable management of water resources requires scientific sound decisions on future freshwater availability, in particular under global climate change and increasing greenhouse gas emissions. Referring to the IPCC report (IPCC, 2007) it is expected that until the end of this century, the temperature will likely increase between 1.1 and 6.4° C compared to the current situation (1980-1999). These estimates are assessed from a hierarchy of models and lower and higher SRES emission scenarios. It is also stated that the amount of precipitation is very likely to increase in high latitudes and is likely to decrease in most subtropical land regions. Due to the uncertainty and the wide range of changes in temperature and precipitation it is very important to investigate on the regional scale. Behind this background, the impact of climate change on water availability in EM/ME and in particular the Jordan River catchment is investigated within the framework of the GLOWA-Jordan river project (http://www.glowa-jordan-river.de).

1.4.2 Regional climate modelling for the Eastern Mediterranean / Middle East and the Jordan River Region

The Jordan catchment is located within a narrow transition zone of only a couple of hundred kilometres, with a Mediterranean climate in the west and an arid climate (Negev desert) in the east/southeast. Due to the narrow zone the region has a high variability on precipitation (Fig. 1.4.1) and is therefore very sensitive to changes of

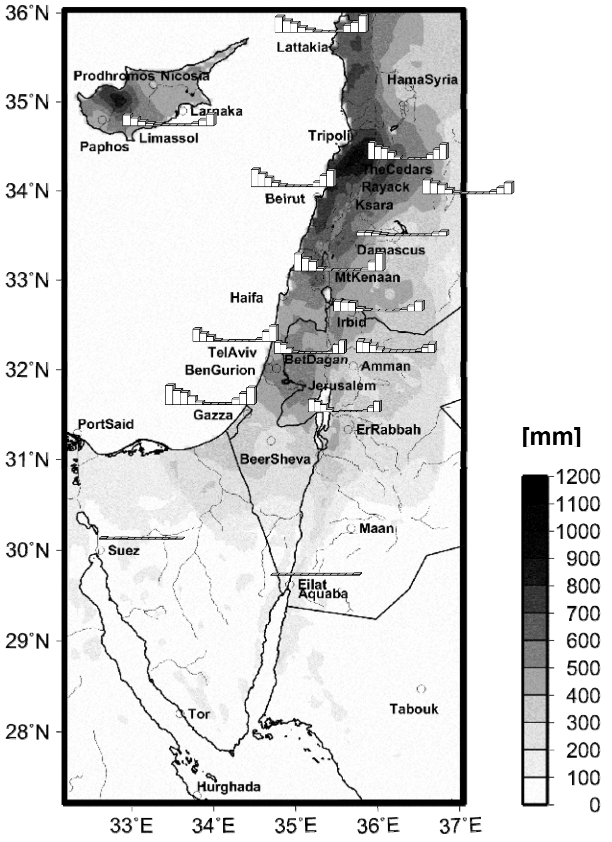


Fig. 1.4.1. Observed long term annual mean precipitation in the Eastern Mediterranean and Middle East.

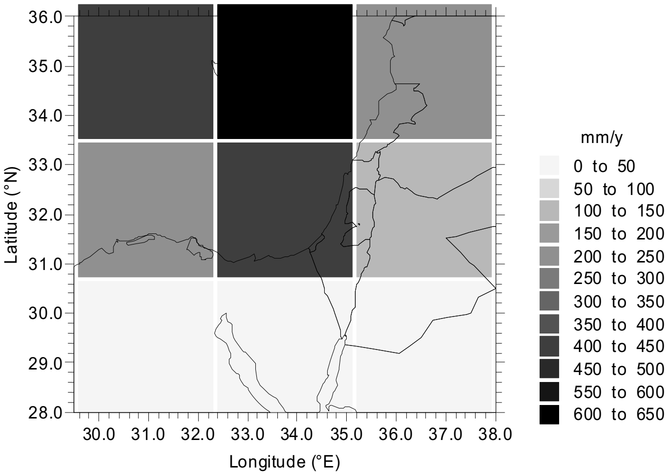


Fig. 1.4.2. Yearly mean precipitation simulated with the global climate model ECHAM4 based on the control run for a 30 years period (1991-2020).

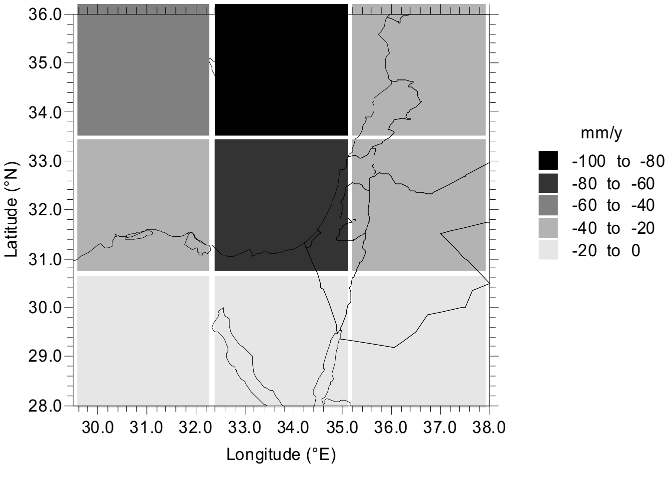


Fig. 1.4.3. Yearly mean precipitation difference (2071/2100 – 1991/2020) simulated with the global climate model ECHAM4 based on scenario A2.

the global climate. Global climate models with a resolution of 2.8° (roughly 300 km) are far too coarse for impact analysis on precipitation and water availability. As an example in Fig. 1.4.2 the yearly mean precipitation of the global climate control run of ECHAM4 for a 30 years period (1991-2020) is shown. Due to the coarse resolution of the model results, the climatology of the EM/ME region is reflected by only one grid cell and the impact on the regional scale due to orographical induced phenomena will not appear. The difference of the projected future climatology on precipitation is shown in Fig. 1.4.3 where the precipitation change from the period 2071 -2100 to the period of 1991-2020 was calculated. In order to achieve more detailed information a dynamical downscaling with a regional mesoscale model has to be introduced. For this, the non-hydrostatic model MM5 (Grell et al., 1994) is applied to model atmospheric processes in the region. To investigate the impact of global warming on the water availability in the EM/ME and in particular the UJC, the global climate model ECHAM4 (by starting this project, the global scenario simulations of ECHAM5 have not been finished and therefore have not been available for downscaling) was dynamically downscaled from 2.8° (roughly 300 km) in three nesting steps of 54 km, 18 km and 6 km resolution (Fig. 1.4.4) using 2 time slices from the control run (1961-1990) and from the emissions scenario B2 (2070-2099).

The MM5 model configuration is as follows: model top is set at 100 hPa. Terrain following coordinates and 26 vertical layers are used. Convective, subgrid-scale precipitation was parameterized according to Grell et al. (1994). Microphysics was calculated according to Reisner et al. (1998) which differentiates between water vapour, snow, ice, cloud water, rain water and graupel. The turbulent fluxes in the planetary boundary layer were parameterized according to Hong and Pan (1996). Feedback between soil moisture, temperature, vegetation, soil properties

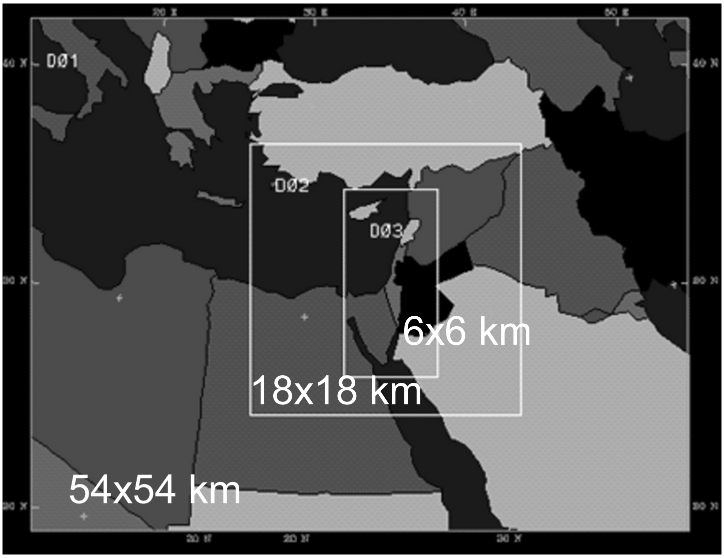


Fig. 1.4.4. ECHAM4 global climate scenarios were dynamically downscaled with MM5 using three nests of 54 km, 18 km and 6 km resolution.

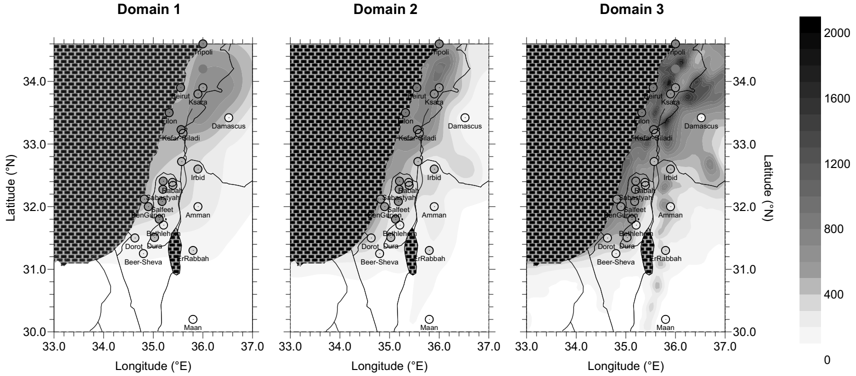


Fig. 1.4.5. Yearly mean precipitation [mm] on different scales (54 km; 18 km; 6 km) of regional dynamical downscaling simulations (mean values 1961-1975).

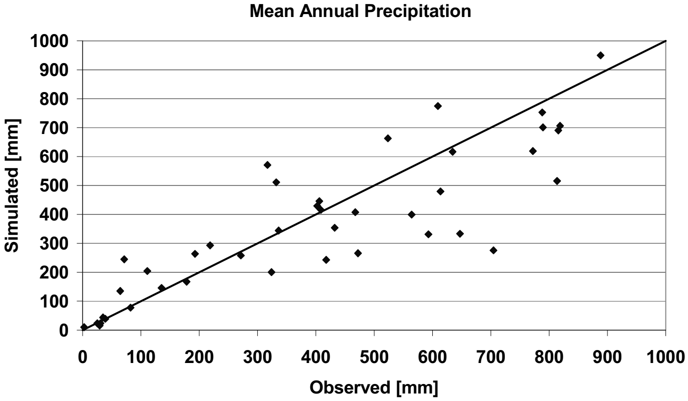


Fig. 1.4.6. Comparison of modeled (1961-90) and long-term observed (1961-90) mean annual precipitation [mm] for 41 meteorological stations in domain 2.

and atmosphere were accounted for by applying *MM5* fully 2-way coupled with the *Oregon State University-Land Surface Model* (OSU-LSM) (Chen and Dudhia, 2001).

The need for downscaling global climate model information to the regional scale is demonstrated in Fig. 1.4.5, in which the mean values for a 15 years period (1961 - 1975) for all 3 nesting steps are presented (until now only 15 years for all 3 scales are available). Already the first step of the downscaling from approximately 300 km to 54 km shows much more details. With the next step to 18 km the mountain ridges and the Jordan valley become visible by different amounts of precipitation. The final step to 6 km allows a detailed description of the precipitation in the mountainous regions in the north of the domain. Anyway, a much better and detailed description is not automatically in line with a higher accuracy. Therefore a comparison of measurements with the simulation results of the 18 km resolution was performed. Based on simulations of a 30 years time slice (1961-1990) of the global climate model ECHAM4 and of long term observations (>20 years for between 1961-1990) for 41 meteorological stations (located in domain 2 of Fig. 1.4.4) the graph in Fig. 1.4.6 indicates that the simulations reproduce observed climate satisfactorily albeit slight under- and overestimations are existing.

In a second step the B2 scenario for the time slice 2070-2099 of the global model ECHAM4 was processed. In Fig. 1.4.7 the predicted changes in mean annual temperature and mean annual precipitation based on the results of the 18 km resolution (domain2) is shown. It is seen that the temperature is increasing up to 4° C and the mean annual precipitation is decreasing by as much as 30 % in specific regions.

The temporal distributions of precipitation change in 4 different subregions (A-D) are shown in Fig. 1.4.8. For all four subregions, a significant decrease in winter precipitation and a slight increase in precipitation during spring time are predicted.

In order to investigate the impact of anticipated climate change on the terrestrial water availability, the regional climate modelling results were used to drive a distributed, physically based hydrological model of the UJC. The approach follows closely Kunstmann et al. (2004) who applied this methodology of 1-way coupled regional climate-hydrology simulations to Alpine catchments.

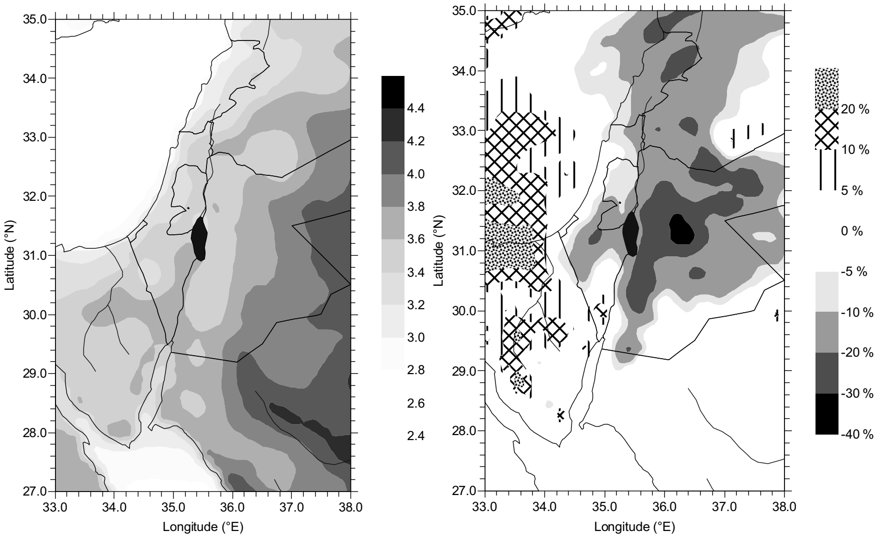


Fig. 1.4.7. Predicted changes in mean annual temperature [° C, left] and precipitation [%, right] (2070-99 vs. 1961-90).

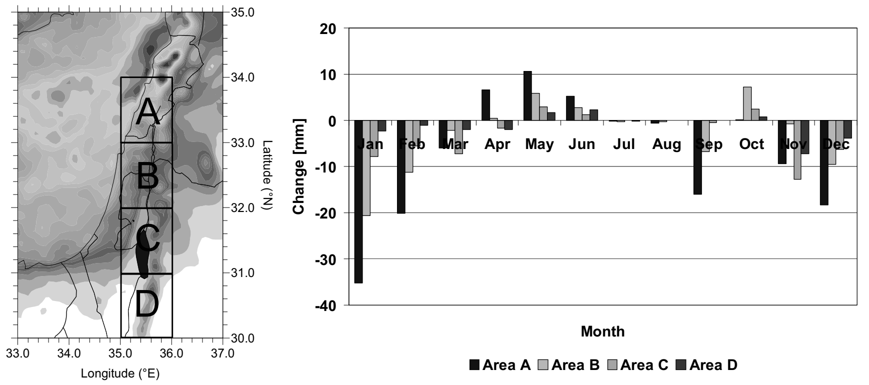


Fig. 1.4.8. Predicted change in precipitation for the 4 subregions (2070-99 vs.1961-90).

1.4.3 Distributed hydrological modelling of the Upper Jordan catchment

The distributed hydrological model *WaSiM* (Schulla and Jasper, 2000) was applied in 90 x 90 m horizontal resolution to perform the hydrological simulations of the UJC.

The river courses were derived from a digital elevation model with 90 m resolution (based on SRTM satellite mission digital elevation data). River discharge information of six gauges (Ayun, Snir, Dan, Banyas, Saar, and the Jordan at Yoseph's bridge) are available for this study. The unsaturated zone was discretised to a maximum depth of 100 m. Gridded soil data was compiled from Israeli national data sets (resolution 1:500,000; provided by the Kinneret Limnological Laboratory) and from FAO data (resolution 1:1,500,000) for the Syrian and Lebanese part of the UJC. Gridded land use information was again obtained from Israeli national data sets (25 m resolution) and derived from MODIS satellite information (1 km resolution) for Syrian and Lebanon part of the UJC. It was distinguished between 6 different soil textures and 8 different land use types within the catchment. Outflow of groundwater across the eastern (surface water-) boundary located along the Hermon Mountain and at the north-eastern edge of the Snir subcatchment, were quantified following Gur et al. (2003). Dan-, El-Wazani, Hazbani and Banyas springs are represented by constant groundwater heads.

Because the hydrological model is not able to account for the karstic environment and corresponding preferential flow paths, which are typical for the Hermon Mountain region (e.g. Rimmer and Salingar, 2006), water flow is instead approximated assuming porous conditions. The model setup therefore represents a substitutional porous media whose parameters must be interpreted as effective lumped parameters approximating the karstic environment on subcatchment scale.

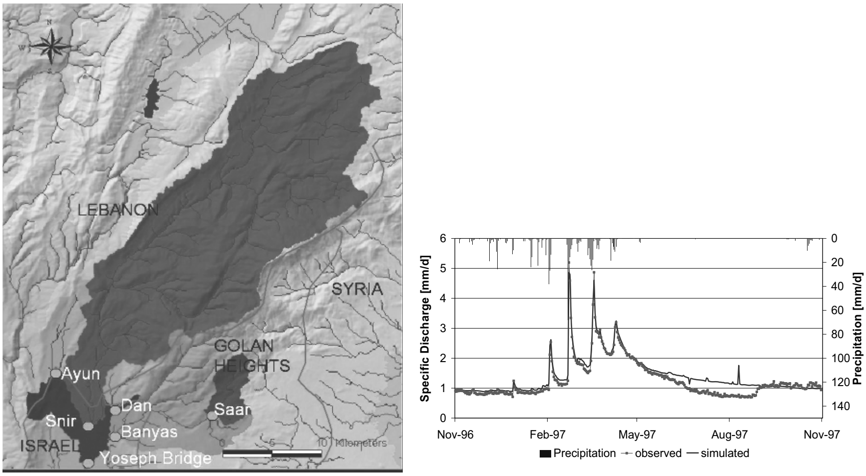


Fig. 1.4.9. Location of subcatchments and respective gauges of Upper Jordan catchment (left) and comparison between simulated and observed discharge at gauge Yoseph Bridge for the hydrologic year 1997.

Hydrological modelling of the UJC is also hampered by the limited availability of daily meteorological station data. While in the Israeli part of the catchment, only 2 precipitation stations and no climatological stations were available, no daily station data were accessible in the Syrian and Lebanese part of the catchment. Instead data from 6 Israeli precipitation stations and 2 climatological stations located outside of the catchment were applied. In Syria, Lebanon and Jordan, data from 9 precipitation stations and 6 climatological stations located outside the catchment (up to a maximum distance of 80 km to the catchment) were used. Gridded daily meteorological fields were obtained by a combination of inverse distance weighting and height dependent regression of station values. Because the amount of precipitation on the elevated regions of Mt. Hermon (>1200 m ASL) was never measured systematically, estimations of snow and rainfall in this study were based on stations located at much lower elevations.

The subcatchments and a comparison between modelled and observed discharge for the gauge Yoseph Bridge are shown in Fig. 1.4.9. Overestimation of simulated discharge of the Jordan at Yoseph Bridge during summer months is due to the fact that upstream water consumption and technically bypassed freshwater was not accounted for in the current hydrological model data. Considering these constraints it is concluded that the hydrological model is able to simulate the streamflow in the UJC satisfactorily. Current and envisaged future research focuses on additional validation of model performance using groundwater observations and environmental tracer information.

1.4.4 Results of joint climate-hydrology simulations

Meteorological fields of precipitation, wind speed, relative humidity, temperature and shortwave radiation are passed from the MM5 results to the hydrological model. In case of temperature and precipitation, a combination of height dependent regression and inverse distance weighting is applied to interpolate meteorological fields from the meteorological model resolution to the resolution of the hydrological model.

Fig. 1.4.10 shows the simulated annual mean temperature for the two time slices (left) and the predicted change in temperature (right). Temperature increase is in the order of 4.5° C in the eastern part of the catchment (i.e. the mountainous region of Mount Hermon), and around 3° C in the south-western part of the catchment, i.e. the Hula valley.

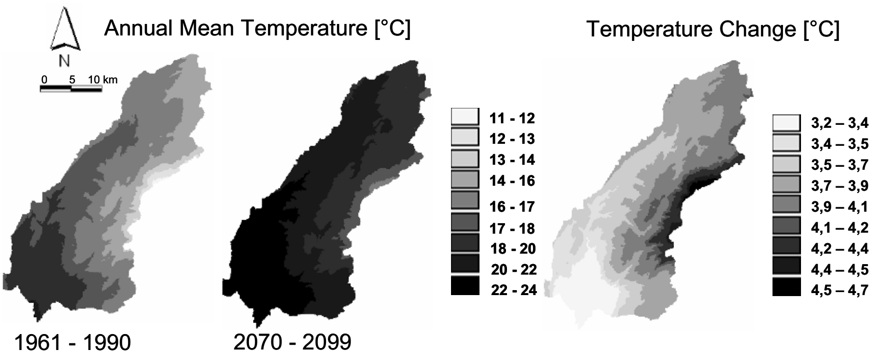


Fig. 1.4.10. Simulated mean annual temperature for the two time slices (left) and absolute change in [° C] for the UJC.

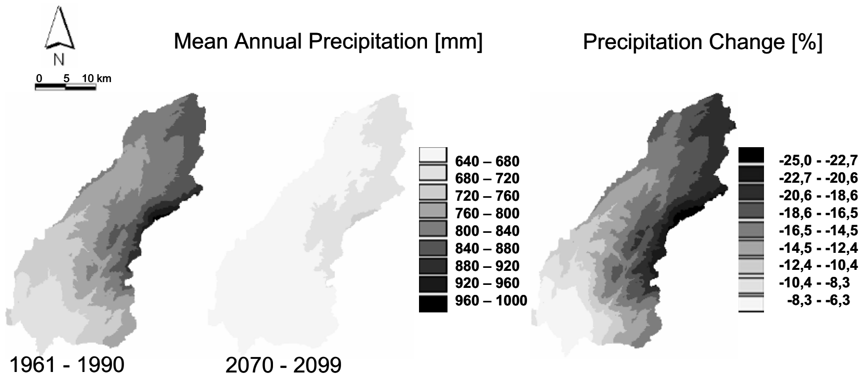


Fig. 1.4.11. Simulated mean annual precipitation for the two time slices (left) and relative change in [%] for the UJC.

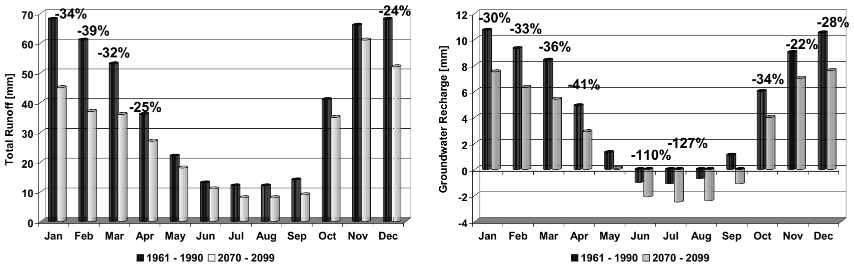


Fig. 1.4.12. Simulated temporal distribution of total runoff (left) and groundwater recharge (right) in the UJC (future 2070-99 vs. past 1961-90).

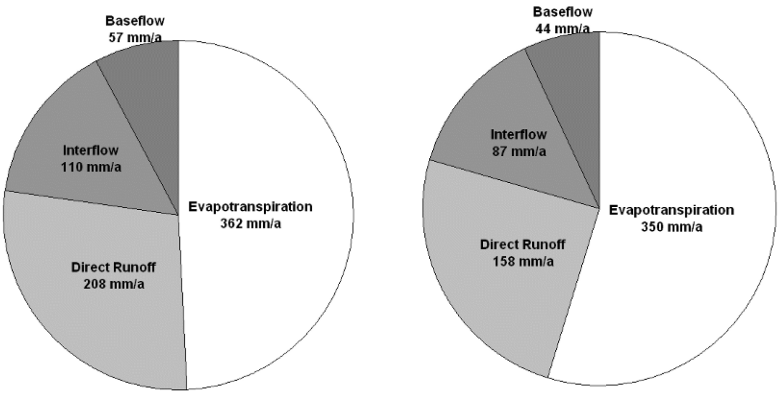


Fig. 1.4.13. Simulated changes in water balance variables: 1961-90 (with a mean annual precipitation of 788 mm/a; right) vs. 2070-99 (670 mm/a, right). Residuals in water balance (51 mm, left, respectively 31 mm, right) are due to modeled outflow of groundwater across the surface water boundary.

Fig. 1.4.11 shows likewise the simulated mean annual precipitation and the predicted changes. Precipitation decrease is around 10 % in the lower regions and reaches around 25 % in the mountainous regions.

Fig. 1.4.12 (left) shows that the simulated change in total runoff at the outlet of the catchment (Yoseph bridge) is expected to decrease by as much as 40 % in winter months. Fig. 1.4.12 (right) shows the predicted change in groundwater recharge. Changes in groundwater recharge are slightly amplified compared to changes in total runoff. Again, significant reductions are expected. Fig. 1.4.13 shows the change in the overall water balance. Mean annual sum of total runoff and evapotranspiration is decreased from 737 mm (1961-90) to 639 mm (2070-99), i.e. by around 100 mm (corresponding to 13 %). Due to higher air temperatures, the relative fraction of evapotranspiration to total water availability increases from 49 % to 54 %. Total runoff is decreased by 23 % (from 375 mm/year to 289 mm/year).

1.4.5 Summary and Conclusions

Based on the climate version of MM5 regional climate simulations have been performed in order to dynamically downscale global climate information on a very coarse resolution to a finer regional scale with 18 km and first results of 6 km resolution. Based on the SRES emission scenario B2 of ECHAM4 the results were applied to drive a distributed hydrological model allowing to simulate, the expected changes in the terrestrial water balance for the Upper Jordan Catchment. It could be demonstrated to which extend the regional topography influences the distribution of precipitation. Furthermore it could also be shown that the model is able to reproduce the high variability of the Mediterranean climate in the West and of the arid climate in the East and the South. Only such high resolution information on the precipitation distribution and the temperature change can be used in order to perform scientific sound results on hydrological issues. The predicted increasing mean annual temperature of up to 4.5° C and decreasing mean annual precipitation of about 25 % within the UJC leads to a expected decrease of the total runoff of about 23 %, and is accompanied by significant decreasing groundwater recharge. The results show a significant decrease of water availability in the region which will have tremendous consequences for water management.

Future work will focus on applying the joint climate-hydrology modeling system to further emission scenarios and different global models (like e.g. HadCM3) as well as a further downscaling of different scenarios to 6 km resolution to investigate uncertainty bounds for the derived trends and expected changes.

References

Anderson, E. (1973): National Weather River Forecast System – Snow Accumulation and Ablation Model, NOAA, Tech. Mem., *NWS-Hydro-17*, U.S. Department of Commerce, USA

Braun, L.N. (1985): Simulation of snowmelt-runoff in lowland and lower alpine regions of Switzerland, *Zürcher Gegraphische Schriften*, ETH Zürich, 21, 166 pp

Brutsaert, W. (1982): Evaporation into the Atmosphere, *Kluwer Academic Publishers*, Dordrecht

Chen, F., Dudhia, J. (2001): Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model implementation and sensitivity, *Mon. Wea. Rev.*, 129, 569-585

Grell, G., Dudhia, J., Stauffer, D. (1994): A Description of the Fifth-Generation Penn State/ NCAR Mesoscale Model (MM5), *NCAR Technical Note*, NCAR/TN-398+STR, pp. 117.

Green, W.H., Ampt, G.A. (1911): Studies on Soil Physics: I. The flow of air and water trough soils, *Journal of Agricultural Sciences*, 4, 1-24

Gur, D., Bar-Matthews, M., Sass, E. (2003): Hydrochemistry of the main Jordan River sources: Dan, Banias, Kezinim springs, north Hula Valley, Israel, Isr. J. Earth Sci, 52, pp. 155-178

Hon, S., Pan, H., (1996): Nonlocal Boundary Layer Vertical Diffusion in a Medium-Range Forecast Model, *Mon. Wea. Rev.*, 124

IPCC, (2007): Climate change 2007: Mitigation. Contribution of Working group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kunstmann, H., Schneider, K., Forkel, R., Knoche, R. (2004): Impact Analysis of Climate Change for an Alpine Catchment Using High Resolution Dynamic Downscaling of ECHAM4 Time Slices, *Hydrology and Earth System Sciences, 8(6), 1030-1044*

Monteith, J.L. (1975): Vegetation and the Atmosphere, Vol. 1: Principles, *Academic Press*, London

Peschke, G. (1987): Soil Moisture and Runoff Components from a Physically Founded Approach, *Acta hydrophysica*, 31 (3/4), 191-205

Phillip, J.R. (1969): The theory of infiltration. In: Chow, V.T. (Ed.), Advances in Hydrosciences, *Academic Press*, New York, 216-296

Reisner, J., Rasmussen, J., Bruntjes, R. (1998): Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model, *Quart. J. Roy. Meteor. Soc.*, 124B

Richards, L.A. (1931): Capillary Conduction of liquids through porous medium, *Physics 1*, 318-333

Rimmer, A., Salingar, Y. (2006): Modelling precipitation-streamflow processes in karst basin: The case of the Jordan River sources, Israel, Journal of Hydrology, 331, 524-542

Schulla J., Jasper, K. (2000): Model Description WASIM-ETH (Water Balance Simulation Model ETH), ETH-Zurich, Zurich.

Van Genuchten, M.T. (1976): A Closed Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils, *American Journal of Soil Sciences*, Vol. 44(5), 892-898

1.5 Climatic Changes in Lebanon, Predicting Uncertain Precipitation Events — Do Climatic Cycles Exist?

Abdul-Rahman M. Arkadan

Lebanese University, Faculty of Sciences. *Tel. +9613100795, Fax +9611854053.*
ararkadan@gmail.com, ararkadan@hotmail.com

Abstract

Climatic changes are the most discussed topic in recent years as they have a great influence on the surface hydrology. Understanding the hydrological properties of a study area requires an investigation of the main source of replenishment to the aquifer. In Lebanon such replenishment is being provided by precipitation. Developing water resources information in Lebanon is being challenged by the absence of adequate and accurate required hydrological data.

With precipitation being the main drive of water balance variation over space and time, changes in the type and amount of precipitation can have a very important implication on the hydrology and water resources.

The wet season in Lebanon occurs between the months of November and April with variable wet periods during September-October and May where precipitation is governed by the early or late arrival of vapor saturated clouds.

Precipitation in Lebanon is controlled by its orographical feature where the moist air that passes over the Mediterranean reaches the coast from the west is being uplifted and moves towards the mountains. Precipitation increases on the windward slopes and decreases on the leeward slopes with the band of high annual precipitation exist parallel to the mountain range along their seaward slope and coastal area.

The annual average rainfall along the coastal zone during the observed period 1965-1999, ranges between 540 and 1110 mm, whereas the annual average precipitation (rain and snow) over the mountain area ranges between 937 and 1854 mm for the same period.

A study area located north of the country and extends from the coast to the upper westerly slopes of the Mount Lebanon Mountain Range has been chosen as a case study zone. The area is bounded by a two river basins, Jaouz and Ibrahim. It was chosen as a case study since it faces the westerly and north westerly winds that brings precipitation to Lebanon during the rainy season. The study did not include the Bekaa Region located east of Mount Lebanon Mountain Range.

Analysis of precipitation data is important in predicting the occurrence of uncertain events with time and to determine if there is a meteorological cycle in which periods of heavy precipitation or drought events are part of a climatic cycle. Because of the extreme variability of precipitation events it is necessary to use sev-

eral methods to estimate the processes and the force behind it if present. Methods such as moving average, probability of exceedence, coherent rainfall and statistics concepts are used to aid in defining theses events.

Results showed that a possible cyclicity occurs at a return period of 14 years but of low coherence. This could be related to the amount of data which covers a period of 35 years, which might not be enough to determine whether a climatic cyclicity controls the prevailed climatic conditions over Lebanon.

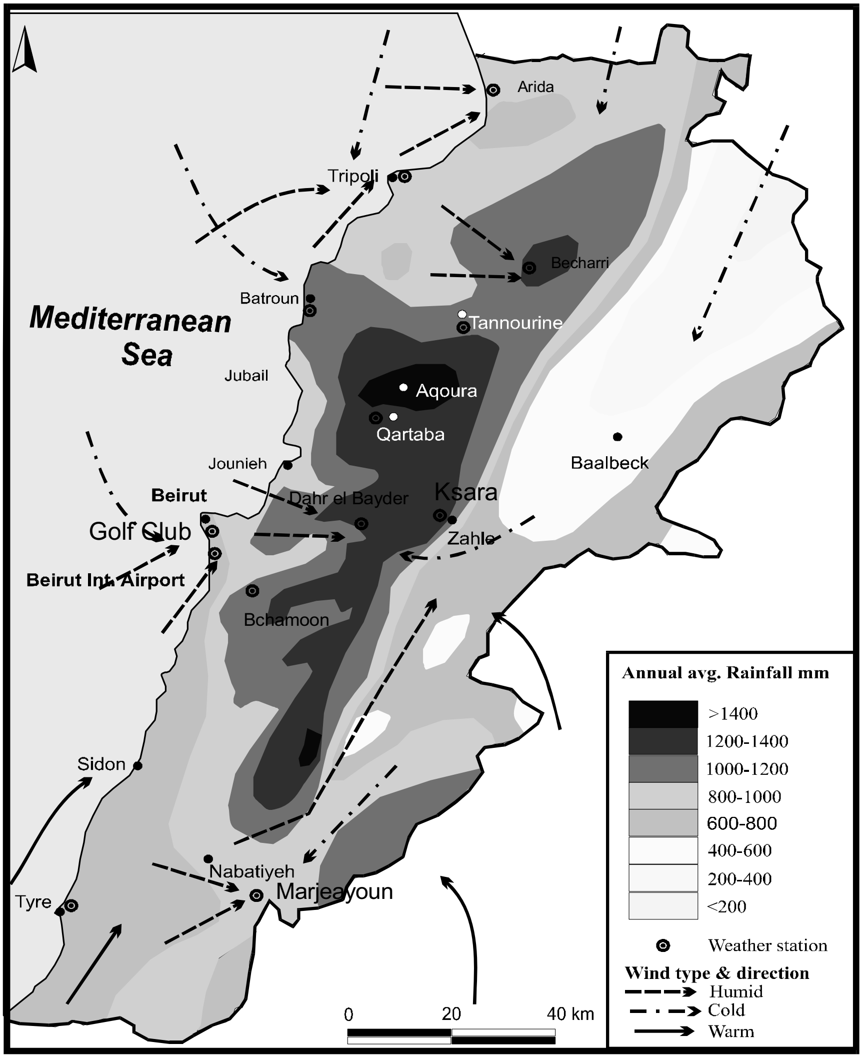


Fig. 1.5.1. Pluviometric Map of Lebanon.

1.5.1 Introduction

With its location at the transition zone between the moderate region, to the north, and the semi-arid hot continental region to the south, Lebanon enjoys a moderate climatic conditions with a cold, wet winter with snow falling on the high mountains and long hot and dry summers with soaring temperatures separated by moderate spring and autumn seasons. Annual precipitation ranges from 540 to 1110 mm on the coast and between 937 and 1845 mm of mixed precipitation (rain and snow) on the mountains, to 200 mm in the NE of the Bekaa region where arid climatic conditions occurs (CAL, 2001).

The annual precipitation rate is directly affected by the regional climatic condition that prevails around and over the Lebanese territory.

Changes in the climatic condition on the planet earth has been observed and recorded worldwide in the form of dramatic shift in the climate of regions and the disasters that accompanied it. The average calculated rate of precipitation over Lebanon is 873 mm for the period 1890 to 1963 (Mudalal, 1989). Khawlie (2000a) has estimated the average precipitation over Lebanon to be on average 150 mm less than the national average.

Fig. 1.5.1 shows the geographical distribution of annual rain fall, direction and type of winds blowing over Lebanon.

Analysis of precipitation data is important in predicting the occurrence of uncertain events with time and to determine if there is a meteorological cycle in which periods of heavy precipitation or drought events are part of a climatic cycle. Because of the extreme variability of precipitation events it is necessary to use several methods to estimate the processes and the force behind it if present. Methods such as moving average, probability of exceedence, coherent rainfall and statistics concepts are used to aid in defining these events.

1.5.2 Precipitation

Orographically controlled rainfall is dominant in Lebanon. As moist air, passing over the Mediterranean, reaches the coast is being uplifted and moves towards the mountains. By reaching the mountain slopes the moist air becomes cooler resulting in an increase in condensation, which results in the formation of extensive saturated clouds, which cause rain or snow to fall. As the clouds reach the mountain precipitation increases on the windward slopes and decreases on the leeward slopes with the band of high annual precipitation exist parallel to the mountain range along their seaward slope and along the coastal area. Such high precipitation is nearly stationary as it occurs in areas where dew point is present and associated with low pressure systems and of medium to high intensity (Singh, 2001).

Precipitation varies spatially and temporally throughout Lebanon. Within its small area differences in geography and land use can lead to the formation of local microclimatic conditions around cities and hills prior to their location along the movement of a weather front.

Annual average rainfall in the coastal zone during the period from 1965 to 1999; ranges between 540 and 1110 mm with a mean annual amount of 777 mm. The mean annual amount falls within the annual observed recorded amount (700 and 900 mm) recorded by Mudallal (1989) and the American University of Beirut (AUB) weather station along the coastal zone. The mountain zone in the study area receive annual precipitation totals between 937 and 1854 mm with an annual average of 1258 mm which is within the annual observed amount recorded (1200 and 1400 mm) by the LMD and Nicolas Chahin Observatory in Becharri area which is located north of the study area. Periods of high and low annual precipitation rates occur rarely, and events of high precipitation periods are related usually to severe cold fronts arriving from a west-northwest direction and are saturated with vapour as they pass over the Mediterranean Sea.

The wet season in Lebanon, occurs between the month of November and April with variable wet periods during the September-October and May where rainfall is related to early or late arrivals of vapour saturated clouds. The dry season comprises the months of June, July and August, with total absence of rain and rare occasions of cloudy days.

Fig. 1.5.2 and 1.5.3 illustrate the mean monthly rainfall distribution during the wet and dry season respectively. Rainfall contribution during the wet season accounts for 93% of the total annual precipitation.

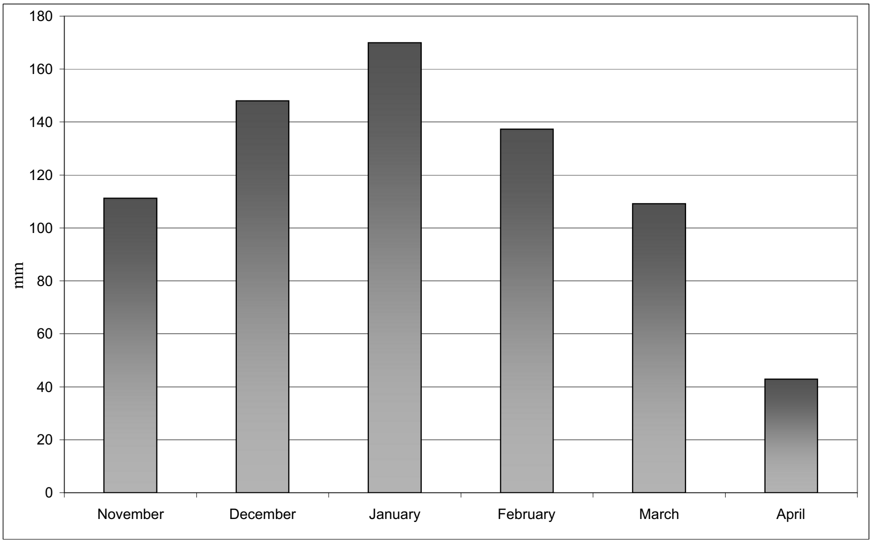


Fig. 1.5.2. Mean monthly rainfall distribution during the wet season along the coastal zone of Lebanon.

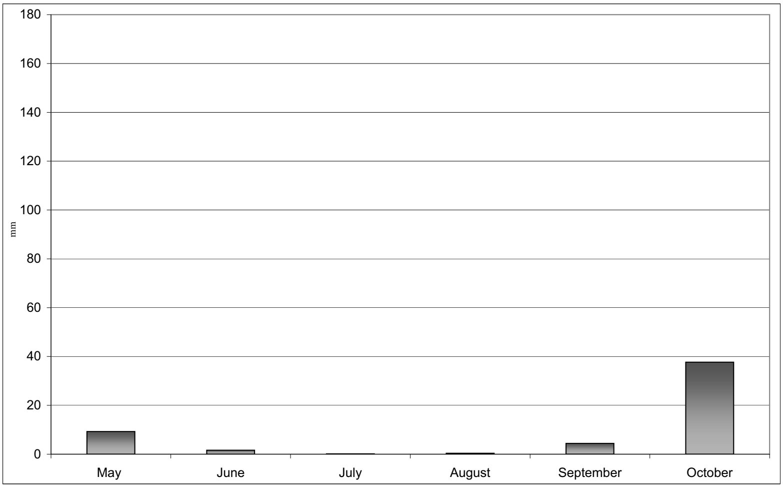


Fig. 1.5.3. Mean monthly rainfall distribution during the dry season along the coastal zone of Lebanon.

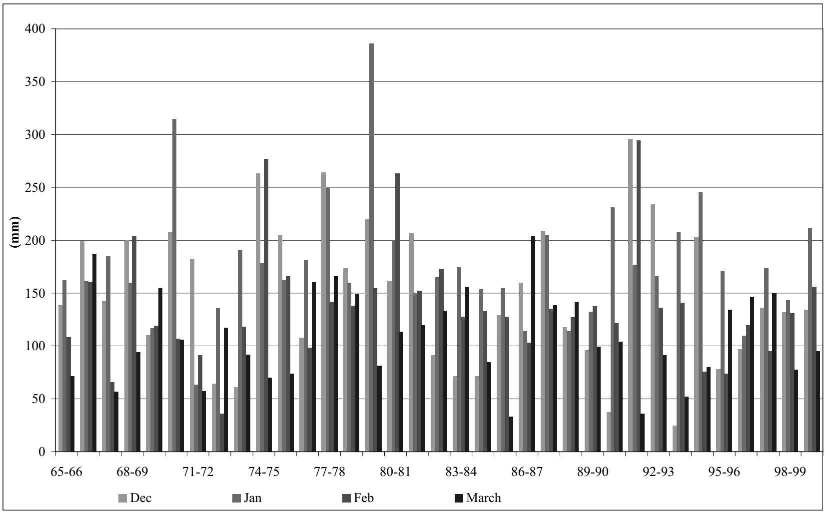


Fig. 1.5.4. Variation of precipitation intensity during main wet season months along the coastal area.

Monthly mean rainfall during the wet season varies from year to year. Spells of high rainfall rates are not persistent to a certain month during the hydro-meteorological year where intense periods tend to deviate in time from month to month during the wet period of the hydro-meteorological year (Fig. 1.5.4). Exceptions can

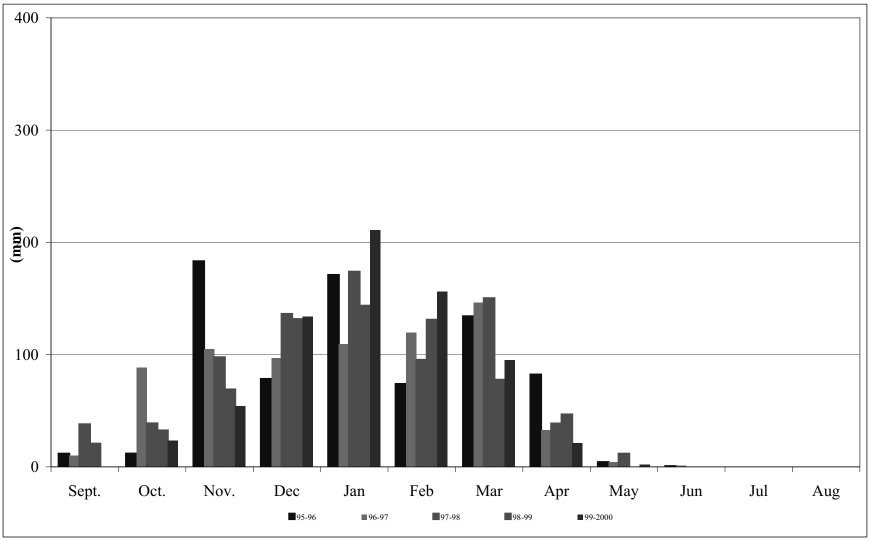


Fig. 1.5.5. Mean monthly precipitations over the coastal area of Lebanon (1995-2000).

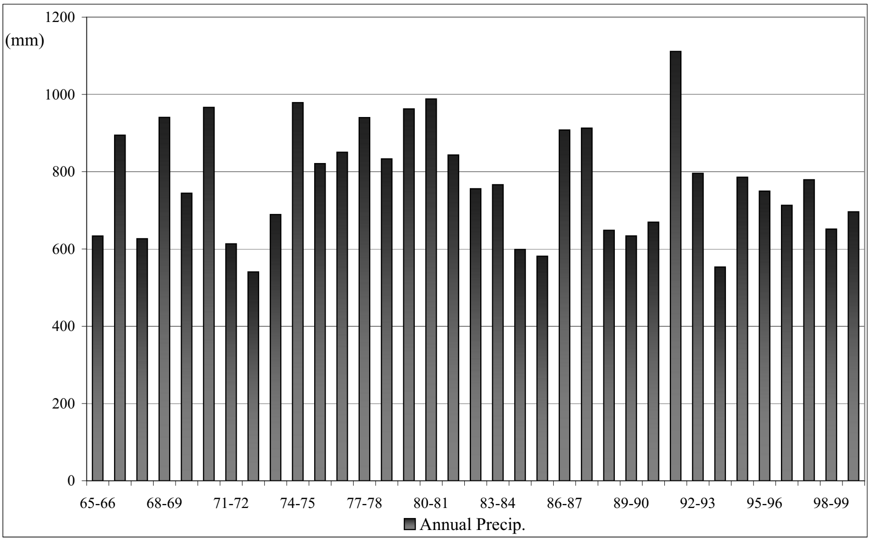


Fig. 1.5.6. Mean annual precipitations along the coastal zone of Lebanon (1965-2000) (CAL, 2001).

be seen in years of very high and very low rainfall. This is attributed to the arrival of the cold fronts from the northwest and whether they pass over the area affected by the speed of wind and its direction (Fig. 1.5.6).

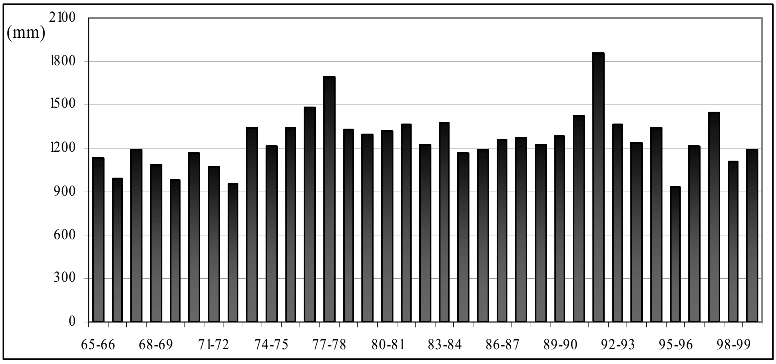


Fig. 1.5.7. Mean annual precipitations in the mountain zone of Lebanon (1965-2000) (CAL, 2001).

The variation in the amount of monthly rainfall in the wet season during a period of six consecutive years for the coastal region is illustrated in Fig. 1.5.5. The graph shows that the rate of precipitation is not distributed uniformly and persistent within the wet season of the year neither from year to year.

Annual precipitation in the mountain zone varies between 937 and 1854 mm during the period from 1965 to 2000 (Fig. 1.5.7), with a mean annual precipitation of 1259 mm.

1.5.3 Statistical Analysis of Precipitation Data

Analysis of precipitation data is important in predicting the occurrence of uncertain events with time and if there is a meteorological cycle in which heavy precipitation is part of a climatic cycle. Because of the extreme variability of precipitation events it is necessary to use several methods to estimate the processes and the forces behind them if present. Several methods such as moving average, probability of exceedence, coherent rainfall and statistics concepts are used to aid in defining these events.

Moving Average Approach

The moving average method results smooth the large fluctuation of daily rates, reducing short-term irregularities and depict the main trend of variation. Polynomial fittings of different degree can better smooth the precipitation variation and thus removes any short term irregularities that could lead to misleading interpretation. The moving average approach is based on the setting the data available using a macro language so the data for the period analyses is set in one column starting

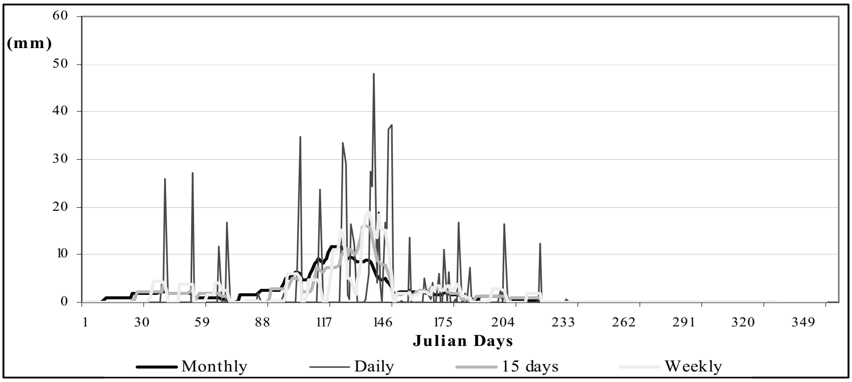


Fig. 1.5.8. Daily, weekly, 15 days and monthly moving average of precipitation in coastal zone (1999-2000).

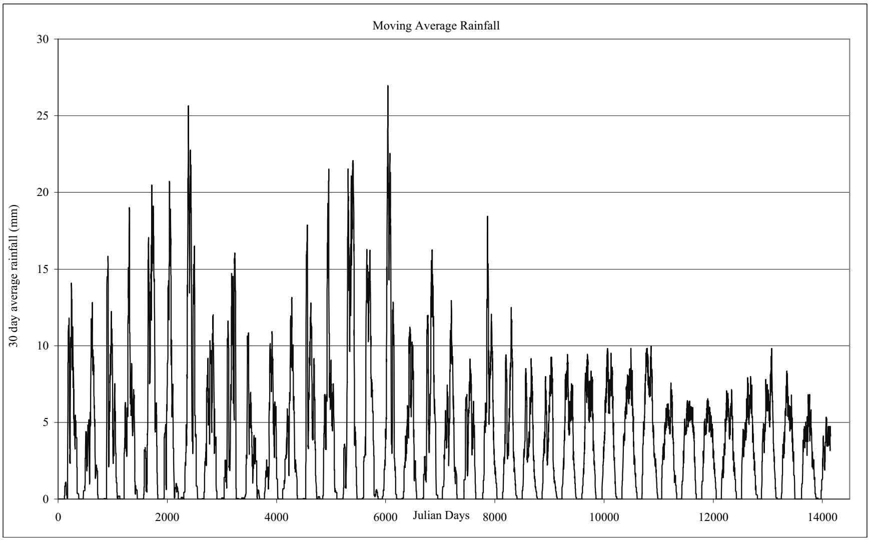


Fig. 1.5.9. Monthly moving average for precipitation over the coastal zone (1965-2000).

from the first day till the end of the data analyzed. The moving average method takes the average based on the period desired for averaging. The averaging can be on a weekly, monthly, quarter yearly or larger interval, based on what is needed to be observed and the amount of data available. Using the moving average method on precipitation data reduces the irregularities in the rate of precipitation recorded and spreads the values based on the timing period required to observe the average. Applying such method on annual precipitation along the coastal area as illustrated in Fig. 1.5.8 shows the trend of the graph based on daily, weekly, half monthly and monthly moving average. The application of such method on annual data shows peak periods where the majority of precipitation occurs. Applying the method on a longer period, like 25 years, can show the trend of precipitation and its intensity (Fig. 1.5.9).

The use of moving average graphs for longer periods to analyze precipitation data will show the trend and intensity of precipitation for the development of future projects to exploit groundwater resources where the volume of such resources is a direct interpretation to the rate of precipitation falling over Lebanon (Fig. 1.5.10, 1.5.11, 1.5.12)

Mean annual graphs for both, the coastal and the mountain area, not only show the variation in the intensity of rainfall from year to year with a limited unclear observation in rainfall decrease rate. Such observation can be clearly visible when calculating the mean annual moving average based on 5 year calculation. The moving average graph for the coastal area (Fig. 1.5.10) shows that the over all volume of precipitation based on the moving average calculation have dropped from 914.5 mm for 1976-1977 to 718 mm for the period 1995-96 moving average periods and also during the 1972-1974 period also. Such decrease is seen also in the amount of snowfall (Fig. 1.5.12). The amount of falling snow based on the 5 year moving average shows a sharp decline from 499 cm in 1965-66 to 380 cm in 1995-96 and 1973-1974. Such decline is reflected through the flow rate of the river not only annually but for a longer periods as the reservoirs needs extra volume of water to compensate the lose from the decrease in the amount of precipitation over the years. The charts illustrate the mean annual and moving average values for the

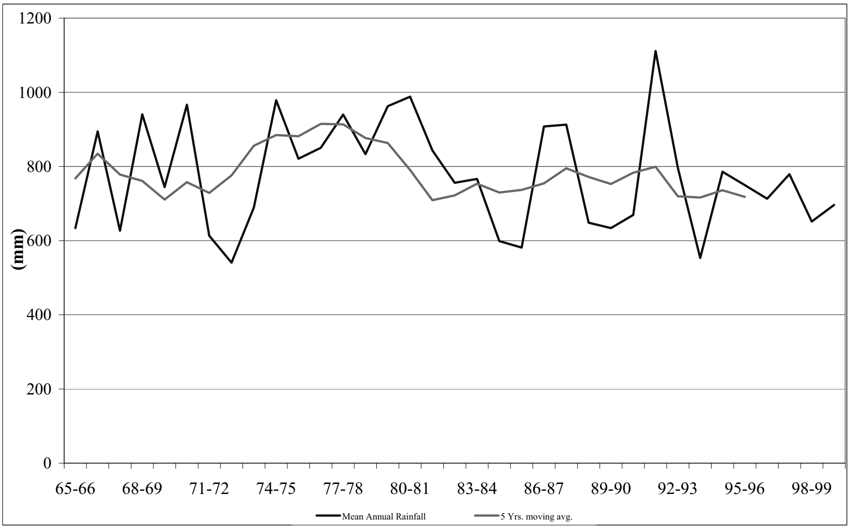


Fig. 1.5.10. Mean annual precipitation and 5 years moving average over the coastal zone (1965-2000).

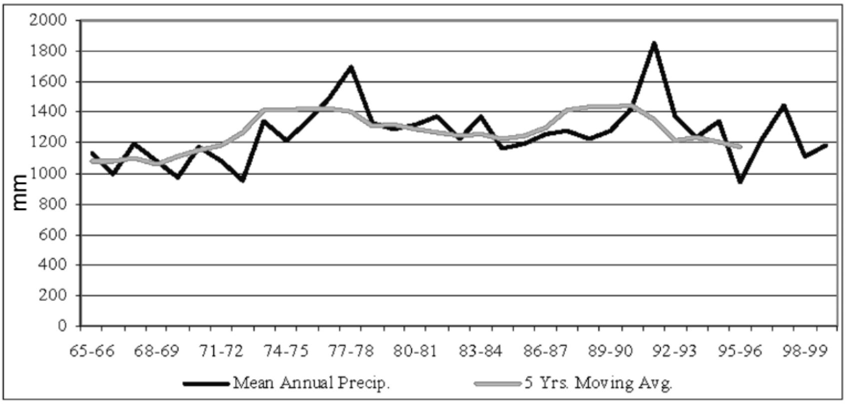


Fig. 1.5.11. Mean annual precipitation and 5 years moving average over the mountain area (1965-2000).

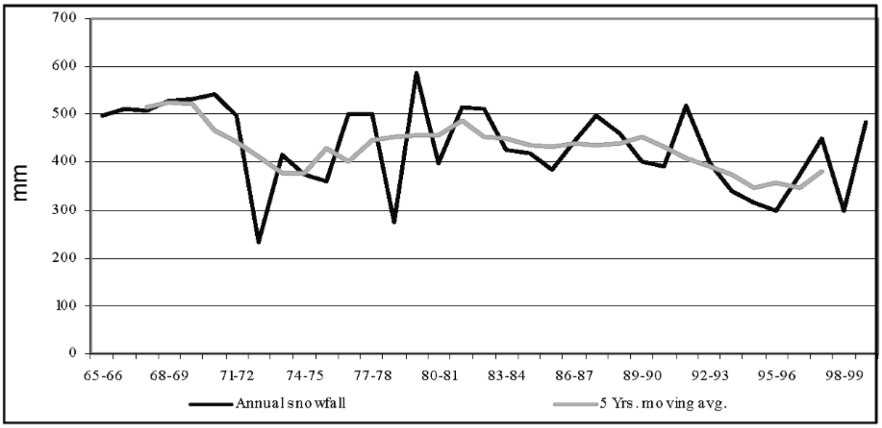


Fig. 1.5.12. Mean annual and 5 years moving average of snow fall in the mountain area (1965-2000).

period from 1965 till 1999. Mean annual rates shows great variation with years of high rates. Observing the trend of precipitation using the moving method showed a general decline in the rate of precipitation and in the amount of accumulated snow with a clearly visible decline in the 1971-1973.

Exceedence Probability Approach

Probability of exceedence is empirically defined as the number of times a specific event occurs from the total number of events measured. The occurrence of precipitation events is speculated to occur in patterns. One way to describe these patterns is to develop a frequency distribution for their values. Developing an empirical distribution of events can be done by using the plotting method. This can be done be arranging the data by magnitude using the sorting tool (smallest to largest or vice versa), and calculate an empirical cumulative probability where the probability of a value being greater than is called the exceedence probability. One of the most used model is the Weibull model which is usually used, on data of more than 25 years, as it does not tend to over- or underestimate the true probability at extreme points (Wanielista, *et al.*, 1997).

The method uses daily precipitation measurements to estimate the probability of occurrence of high precipitation events during the rainy season. It can also be used to estimate the probability of occurrence of years of high annual precipitation records and the return period which measures the average intervals in years between events equal to or exceeding a certain magnitude.

- The probability of exceedence of rainfall for each rain season is based on taking the daily precipitation measurements during the winter season and sorting them in descending order in one column and estimating the probability of exceedence for the occurrence of extreme events during a rainy season by using the following formula:

$$\mathrm{Pr} = (n - m)/(x)$$

where
n is the rainy season period (days);
m is the rank, where 1 is the rank of the lowest precipitation;
x is 1 day less than the rainy season period.

Applying the formula on a rainy season data from two different hydro-meteorological years of high and low annual precipitation resulted in plots illustrated in Fig. 1.5.13 and 1.5.14.

Fig. 1.5.13, which illustrates the probability of exceedence in a relatively high annual precipitation rate (1977-78), 1639 mm, showed that the occurrence of extremely high daily precipitation rate 89.6 mm is very low, where as most daily rainfall intensity occurs between 10 and 30 mm/ day.

Years of less annual precipitation (1995-96) 937 mm, shows a low percentage of high daily precipitation rate, 26 mm, with the majority of precipitation rate falling during such year is between 3 and 7.5 mm/day.

The same procedure can be implemented on the annual rainfall data to estimate the exceedence and return period for years of high precipitation rate.

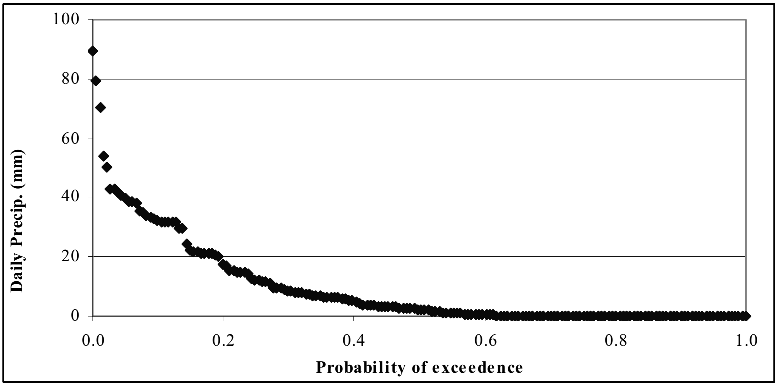


Fig. 1.5.13. Probability of exceedence of rainfall during a rainy season of a relatively high precipitation rate over the mountain area (1977-1978).

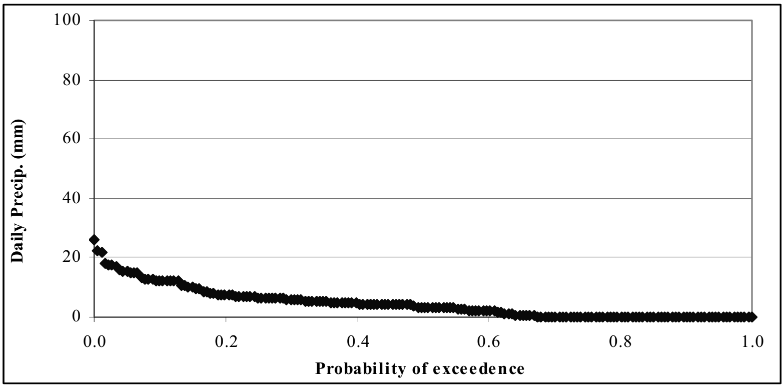


Fig. 1.5.14. Probability of exceedence of rainfall during a rainy season of relatively low precipitation rate (1995-1996).

- The usage of the Weibull method in calculating the exceedence probability and return period for extreme annual rainfall events requires the usage of more equations and data being sorted in an ascending order:

$$\mathrm{Pr} = {}^{m}\!\big/\!{}_{(n+1)}$$

where
Pr is the probability
m is the rank, where rank 1 is given to the lowest value

n is the number of data points (number of years)

$$E\,\mathrm{Pr} = 1 - \mathrm{Pr}$$

where
$E\mathrm{Pr}$ is the exceedence probability
Pr is the probability

$$Tr = 1/\mathrm{Pr}$$

where
Tr is the return period or recurrence interval (years)

Applying the Weibull method for calculating the empirical distribution function generates the following plot (Fig. 1.5.15).

Fig. 1.5.15 show that during a period of 35 years only one year of extremely high precipitation occurred. Years of mean annual precipitation between 1100 and 1350 mm have a high probability of occurrence, with some years of less value.

Annual Precipitation Correlation Method

Determining the consistency, spatial and temporal changes in precipitation rate is a difficult task especially when dealing with variable data. Understanding the variation in precipitation rate requires the use of several methods to determine if climatic cyclicities control the trend of precipitation (Thompson, 1999).

Coastal and mountain precipitation data show a variation in terms of occurrence, where periods of rain events along the coastal zone do not necessarily predict, that rain is occurring over the mountain and vice versa. Such a scenario is affected by the trend and direction of winds which are main drivers for moving of the clouds.

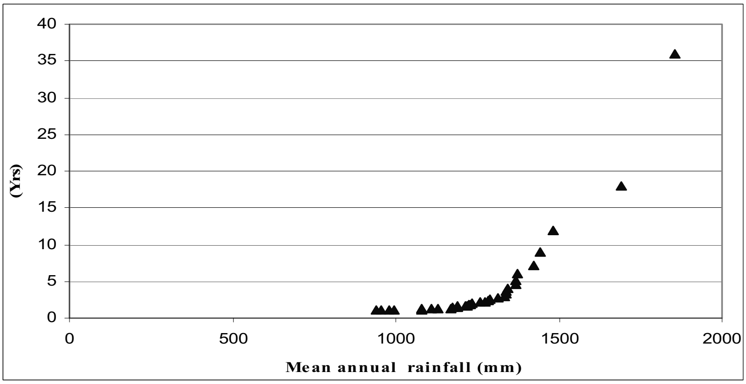


Fig. 1.5.15. Probability of occurrence of mean annual precipitation (yrs).

Table 1.5.1. Statistical analysis of monthly precipitation data.

i	Month	Min	Max	Median	Low Quartile	High Quartile	Mean
1	Sept	0	68.3	12.8	0	25	17.7
2	Oct	0	184.2	69.8	22.5	90.6	72.3
3	Nov	37	308.9	142.1	66.8	162.1	136.3
4	Dec	72.4	364.1	229.6	146.8	253.5	222
5	Jan	173.6	418.6	245.8	185.8	263	247
6	Feb	145.1	377.3	232.5	179.6	255.5	238.7
7	Mar	119.1	376.8	204.9	157	223.5	210.8
8	Apr	22	194.4	91.7	35.2	105.7	86.2
9	May	0	85.1	17.2	9.2	35.7	26.5
10	Jun	0	17.1	0	0	0	1.5
11	Jul	0	0	0	0	0	0
12	Aug	0	2	0	0	0	0.14

Weather stations may not record extreme rainfall events as they may not intercept and record these events. This is seen in lack of coherency despite the short distance between the two zones. Such variation is analyzed in two ways to determine if any coherence is present and whether it follows a certain climatic cyclicities.

Statistical analysis of mean monthly data covering the period from 1965 to 2000 has been conducted using mean monthly precipitation values and Excel spread sheet tools to obtain the minimum, maximum, median, low quartile and high quartile values (Table 1.5.1).

The statistical analysis chart obtained from Table 1.5.1 show that maximum rate of precipitation occurs during the month of January. The rate then decreases slowly during the months of February and March and decrease rapidly to cease by the month of June (Fig. 1.5.16).

Variations in annual precipitation were analysed to determine if any coherence in the rate of annual precipitation is present and whether climatic cyclicities do occur. Determining coherence has been conducted on the mean annual precipitation data for the study area using the following equation:

$$\sum_{i}^{N} \left(P_{i+j} - P_i\right)^2$$

where

N	the number of years
i	the rank of the year
j	the lag in years
P	the mean annual precipitation

Applying the equation on the available data, a graph is obtained (Fig. 1.5.17). The graph shows little coherence in the annual precipitation rate. The graph shows possible cyclicity occurs at a return period of 14 years but the coherence is generally low. The data which covers a period of 35 years may not be enough to see if there is a climatic cyclicity controlling the climatic conditions.

1.5.4 Conclusion

With the changes in climatic conditions towards a short intense rainy period and long dry events, it was essential to observe such climatic conditions from the point of view of precipitation rate and type. Since Lebanon receives it rain from the westerly and northwesterly sides on which the saturated clouds arrives from passing over the Mediterranean Sea and bringing cold winds from the North passing over Europe, it was decided to choose an area that faces these fronts as they are the primary areas that receives the cold fronts. Other areas of Lebanon have not been included due to the limitations of the study as it takes a specific geographical area a case study one. The climatic cycles are observed and monitored to determine and predict extreme events. By analyzing the results using different analysis methods

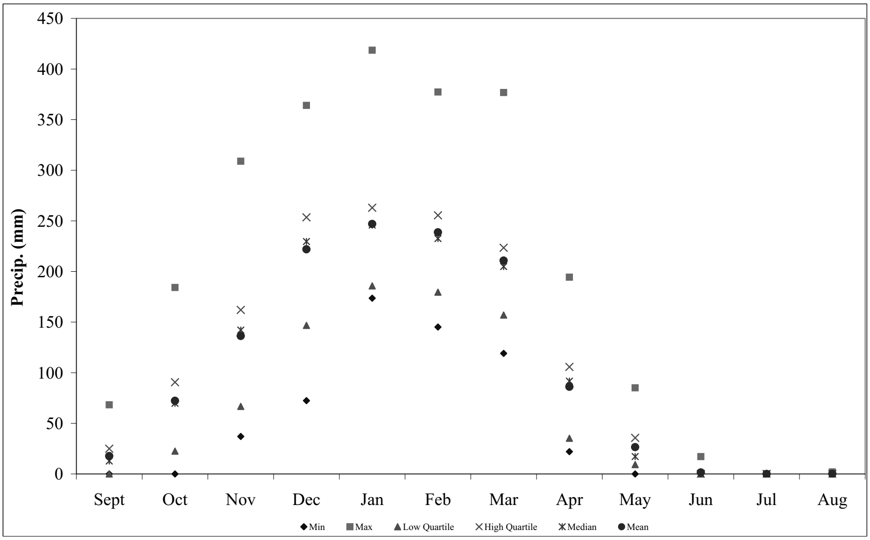


Fig. 1.5.16. Statistical analysis plotting graph of monthly precipitation data.

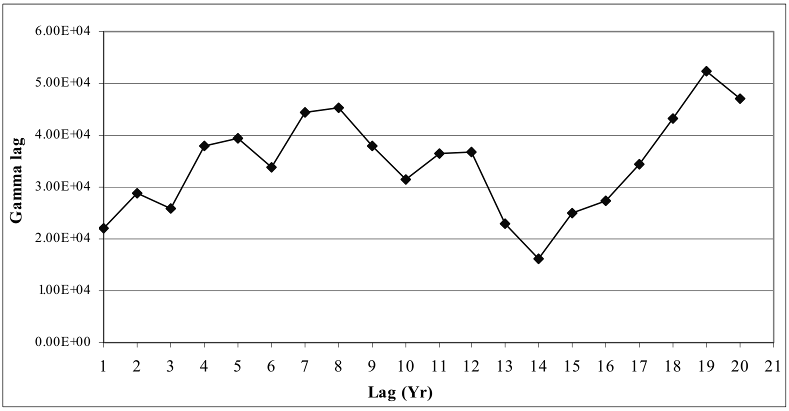


Fig. 1.5.17. Semi-variogram for mean annual rainfall.

on recorded precipitation data for the coastal and mountain zones of of the study area, showed that a possible climatic cycle occurs at a return period of 14 years but of low coherence. This could be related to the amount of data which covers a period of 35 years, which might not be enough to determine whether a climatic cycle controls the prevailed climatic conditions over Lebanon. The use of several analytical methods such as moving average, probability of exceedence and correlation method could highlights on the changes in climatic conditions in the region. Such changes need further investigation and correlation between several obtained results from the surrounding countries to obtain a clear view on the climatic changes and the best way to tackle such changes and reduce their negative impact on them.

References

CAL. 2001. Atlas Climatique Du Liban, Tome **II**, Service Meteorologique, Ministere des Travaux publics et Transports. Beirut

Khawlie, M. 2000a. Assessing water resources of Lebanon in view of climate change. Workshop on: Soil and Groundwater Vulnerability to contamination. ACSAD-BGR, Beirut, 7-10/2/2000.

Mudalal, S. 1989. Water resources in Lebanon. Dar Al Fikr Al-Arabi, Beirut. (in Arabic)

Singh, P., & Singh, V. 2001. *Snow and Glacier Hydrology*, Dordrecht, Kluwer Academic Publishers.

Thompson, R. 1999. A time-series analysis of the changing seasonality of precipitation in the British Isles and neighbouring areas. *Journal of Hydrology*, **224**: 169-183.

Wanielista, M., Kersten, R. & Eaglin, R. 1997. *Hydrology: Water quantity and quality control.* John Wiley & Sons, Inc.

2 Impact of Climate Change on Water Resources

Changes in global climate will have significant impact on local, regional and global hydrologic regimes, which may in turn impact ecological, economic and social systems. The vulnerability of natural systems to rapid changes in climate patterns is regarded as one of the most challenging issues in recent years. Water resources are a main component of natural systems that might be affected by climate change. Some of these effects will include changes to water supply and quality for domestic, irrigation, commercial and industrial uses, or in application of water in more technical fields like hydropower, navigation, and wastewater treatment. Furthermore, watersheds, where water resources are already stressed under current conditions, are most likely to be highly vulnerable to changes in mean climatic conditions and extreme events.

The detrimental effect of climate changes on water resources depends on the kind and intensity of the climate change. With regard to the two major climatic factors temperature and precipitation, there are independently from the intensity variation four options, two with parallel increase or decrease of the main factors and two with opposed development of the two factors. Increases in temperature and reduced rainfall for instance cause reduced stream flows in major catchments, reduced recharge of groundwater, reduced inflows to water storages, or exacerbated droughts. Water resources are believed to be particularly vulnerable to increased temperature and alternations in precipitation patterns. Global warming is suspected to trigger adverse environmental consequences, including desertification. Precipitation is the main driver of variability in the water balance over space and time. Changes in precipitation have very important implications for hydrology and water resources. Hydrological variability over time in a catchment is influenced by variations in precipitation over daily, seasonal, annual, and decadal time scales. Flood frequency is affected by changes in the year-to-year variability in precipitation and by changes in short-term rainfall properties. The impact of climate must be included in all evaluations of water availability. Surface and groundwater quantity is driven by the balance between atmospheric input from precipitation, and losses due to evapotranspiration. Therefore, knowledge of climate patterns provides important insight into water availability issues.

With the contribution to Chapter 2 effects of climatic changes on water resources are described particularly for the Middle East and for Morocco. Hötzl refers to Quaternary climatic changes and the resulting discharge conditions in the

Arabian Peninsula due to the N-S shifting of climatic zones. In the geologic sense climatic changes are nothing out of the ordinary. Issar continues with the paleo-climate and paleo-environment record of Holocene and the historical time. Historical records from different Mediterranean countries shows that global warming in the past caused desertification in this region. El-Fadel and Maroun outline the impact of climate change on water resources in Middle Eastern countries, and discusses potential adaptive measures in this respect, with emphasis on virtual water trade. The impacts of a possible climate change in connection with the recent warming phase on water resources in Jordan are investigated by using a physically based model, while Shaban reports from Lebanon on short term hydrologic drought as a superposition of climatic and anthropogenic effects. These contributions from the Middle East are supplemented by two reports from Morocco. Schulz et al. describe decadal precipitation change and predicted the decrease of annual precipitation sums, but with increased precipitation intensities leading to a higher number of floods. Klose et al. propose management options for a sustainable groundwater application.

2.1 Water Resources Management in the Middle East under Aspects of Climatic Changes

Heinz Hötzl

Universität Karlsruhe,76128 Karlsruhe, Germany

Abstract

Climate change is a big environmental challenge facing the world today. The Middle East region is especially vulnerable to climate change because of its already dry conditions and the limited water availability. With increased heat and increased evaporation, the problem may become even worse under global warming and there may be severe problems for people in regions that are particularly vulnerable to change. In terms of economic impact, changes in temperature and precipitation patterns may result in damage to agriculture, tourism and other strategic economic sectors. In the geologic sense climatic changes are nothing out of the ordinary. During the last two million years several more wet and even dryer phases occurred in the Middle East, causing variations between semiarid and hyper-arid climate, however not changing the dominating aridic morphodynamic. For the assessment, forecasting and respond to the impacts of climate changes on the water systems integrated water resources management is proposed.

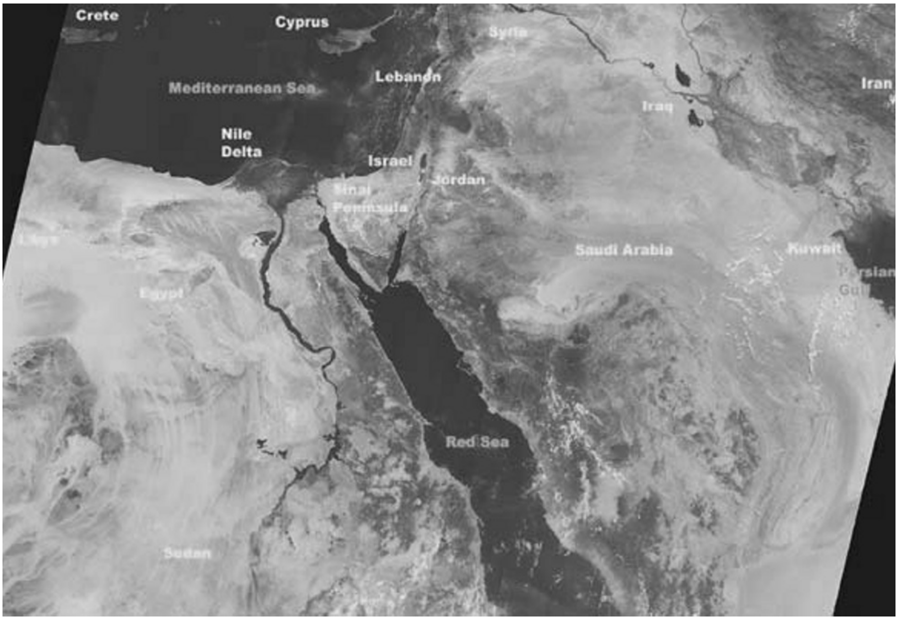
2.1.1 Climatic conditions and water availability

The Middle East is a region dominated by arid and semi-arid lands, with significant areas of extreme aridity. In the northern part of the region, a steppe climate prevails, with cold winters and hot summers. A narrow zone contiguous to the Mediterranean Sea is classified as a Mediterranean zone, with wet and moderately warm winters and dry summers, whereas the central and southern part with the core of the Arabian peninsula is extremely dry with very hot summers and moderate temperatures in winter. Water is a very limited resource. Droughts, desertification, and water shortages are permanent features of life in most of the countries in the region. Their native plants and animals are adapted to coping with sequences of extreme climatic conditions.

Across the Middle East, summer temperatures are usually around 30° C, but often soar above 40° C. In the Saudi desert, however, temperatures over 45° C are common. During the summer, winds blow unabated toward the hot interior of the Arabian Peninsula, whereas in winter the winds in the south blow off the land. In northern regions, continental winds brings some rain out to the coasts and the mountain ridges behind.

Rainfall is low in most part of the region, but it is highly variable seasonally and interannually. Except from the southern part of the Arabian Peninsula with summer rains, precipitation occurs In the Middle East during winter. The summer dry period lasts for 6-10 months (UNEP, 1997). Average yearly rainfall ranges from 0 mm to 200 mm, only in the north-western parts along the Mediterranean Sea, down from Turkey till Lebanon and the northern parts of Palestine and Jordan the values exceed 500 mm and more. There was no discernible trend in annual precipitation during the last century (1901-99) for the region as a whole, nor in most parts of the region-except in the south-western part of the Arabian Peninsula, where there was an significant increase, however, in relation to a very low base rainfall (<200 mm/ yr).

In common with other countries in this water scarce region of the northern aridic belt the Middle East has chronic problems of water resources. The region is facing a tremendous imbalance between the available water resources and the demand,



Near and Middle East

Satellite: Terra Sensor: MISR Data Start Date: 08-16-2000 Data End Date: 08-30-2000
http://visibleearth.nasa.gov/Sensors/Terra/MISR_8.html

Fig. 2.1.1. Satellite Image of the Middle East desert area with the Red Sea and Egypt (NASA 1998).

where water shortage has become of permanent nature (Brimberg et al. 1994, Arlozoroff 1966, Exact 1998). Due to its scarcity water is a precious resource that is of vital importance to the socio-economic development of the Middle East.

2.1.2 Present water management

Water availability is a major concern in most countries of the region (Middle East Water Commission, 1995; UNEP, 1997). Some countries (e.g., Syria, Iraq, Lebanon) have reliable sources of surface water; the majority, however, depend either on groundwater or on desalinisation for their water supply, both of which enable them to use water in amounts far exceeding the estimated renewable fresh water in the country (World Bank, 1995).

The sources of fresh water consist on one hand of the surface run-off. Whereby the main flux is contributed by the big river systems of Tigris and Euphrates, which are originating from the mountainous area of Turkey, and the Jordan River with its main tributary the Yarmouk River, arising from Lebanon and Syria. The second main source is the groundwater from the different aquifers. They are connected mainly to the mighty Palaeozoic and Mesozoic sandstone formations („Nubian sandstone“) mainly in Jordan and Saudi Arabia, to Jurassic, Cretaceous or Tertiary limestones distributed almost over the whole Near East, as well as to Quaternary

Fig. 2.1.2. Irrigation Project in Wadi Disi, southern Jordan, using fossil groundwater for agricultural production (Foto: H. Hötzl).

deposits of sand and gravels in the river lowlands and extended alluvial plains. In addition to these water sources seasonal storm waters in the wadis, un-renewable fossil groundwater, desalinated brackish and saline water resources as well as effluents from treatment plants are used to supply the demands of the people.

The main consumer in general is the agriculture, where in the region 60 to 75 % of the total water consumption in the different countries is used for irrigation. Domestic water supply with 25 to 35 % is increasing, while industry shares with 4 to 8 % a still small rate. In many countries of this region less than two third of the present total demand can be supplied by natural renewable resources (Govern. Jordan 1998, 2003, JMWI 1997, Taha 2006). Current deficits are covered by non-sustainable overexploitation of aquifers and by non-renewable resources causing decline of groundwater table and degradation of water quality (Taha 2006). Efforts are being made in some countries to use wastewater (McCornick et al. 2002, Murakami 1995) and to use water more efficiently, especially for agriculture. The Middle East Water Commission (1995) suggests that, for some countries, a reduction of 30% in water use for agriculture would alleviate some water crises.

Water is considered as a national resource of utmost importance. It is vital to ensure the population's well-being and to preserve the rural-agricultural sector (IMFA 2003, Murakami 1995, Allan 1996). Therefore the policies of the governments of the countries emphasize the sustainable use of the scarce natural water resources aiming to improve the living conditions of the population. However, increasing standards of living and expanding populations are requesting additional water. Main force was put in the past on the need to tape the full potential of surface and groundwater to a feasible extent. Special attention was given to explore the groundwater resources and so fare there is sufficient run-off in the rivers and wadis to construct dams for reservoirs to store seasonal water, but also to extend agricultural irrigation for food production (JMWI 1997, World Bank 2001, Wolf 1996).

Water quality is an issue of equal importance to water scarcity, and water quality degradation is a considerable issue in water management (Brimberg et al. 1994, Farber et al. 2003, World Bank 2004, Exact 1998). Rapid development of aquifers is threatening some water supplies through salinization and pollution. Due to unbalanced exploitation and return flow from irrigation, an increase in the salinity of the groundwater has occurred in many wells. Dryland salinization also cause impacts on water quality, in other countries (e.g., Oman and United Arab Emirates), seawater has intruded into freshwater aquifers (UNEP1997). In order to avoid further pollution advanced technology and practices has to be applied to protect water resources. Vulnerability assessments of the aquifers, designation of groundwater protection zones with restricting land use activities above groundwater resources and water conservation maps, have to be realized to safeguard the underlying resources. The state organisations have started regular monitoring of water resources, including: water recharge, water table levels, abstraction, salinity (chlorides) and pollution (nitrates) data, which are regularly reported.

The larger part of the population in the region is living in highly urbanized areas, for which it is easier and more efficient to organize water supply, treatment, and delivery systems than it is for rural areas. Moreover, demand can be more easily managed to promote water-use efficiency in urban areas. In most countries in the region, a large proportion of the population has running water in their homes and the quality of drinking water is increasing with centralized treatment. Although municipal and industrial water use will grow, per capita domestic use is likely to decrease. However, future urban water demands are likely to compete with the irrigated agricultural sector (Wolf 1995, Brimberg et al. 1994, Husseini 2004); 15 of the countries in the region use more than 75 % of their water for irrigation. Within the new water strategy priority in water resources allocation is given to domestic water supplies. The governments or state water authorities have adopted a comprehensive water strategy in order to mitigate the water situation. This is supported by an targeted policy and numerous supplemented measures to accelerate the implementation of water regulations.

2.1.3 Climatic changes in the past

Assessment of the present water scarcity of the Middle East leads to the question how long this problem exists, how it is related to climate and land use, how it was addressed by ancient societies, and what can be learned from this. The Middle East went through severe climate changes during the geologic history. Well documented are the changes in the recent past of the last two million years of the Pleistocene and Holocene periods, though the general aridic character of the whole region didn't changed. Even during historical times climatic changes had major effect on the welfare and thus the history of the region. Additionally, knowledge of the environmental history allows for better predictions of future developments and helps to clarify the interrelationship of climate, water systems and land use.

In order to find really humid conditions in the Middle East region, one has to go back to the Mid- and Late Pliocene period, about 1.5 to 3.5 million years B.P. (Hötzl & Zötl 1978, 1984). In contrast to the relatively short interruptions of arid climate during the Quaternary, the change of the climate in the Pliocene was intensive and long-lasting causing a complete alteration of the morphodynamic and therewith of the landscape. It differs from the recent by high precipitations, intensive chemical weathering, soil formation and enormous fluviatile erosion. On the Arabian Peninsula there were through going river systems from the Hijaz and Asir highlands in the west to the Persian/Arabian Gulf in the east. The flow rate were so strong that pebbles with diameters of 10 cm could be transported from the mountain over a distance of 1200 km to the former Pliocene shoreline at the Gulf, where they formed huge alluvial and delta fans. This deltaic gravel fans, like the Dibdibah fan in north-eastern Saudi Arabia and Kuwait, were declared long ago to be remnants of an intense humid period. However, according to the former interpretation had been taken as results of Pleistocene pluvials.

Fig. 2.1.3. Late Pliocene terrace sediments north of El Aynunah, northern Red Sea coastal plain, Saudi Arabia. The boulder size gives an impression of the strong runoff conditions during this wet period (Foto: H. Hötzl).

In contrast to this former assumption detailed studies (Al-Sayari & Zötl 1978, Jado & Zötl 1984, Issar 2003) could proof that never during the Quaternary such strong precipitations prevailed that the dominating aridic morphodynamic was altered. The Late Pliocene /Early Pleistocen landscape with its deep erosion channels and its ample gravel fans influenced by the enormous surface runoffs, was overprinted almost only by eolian processes. Deflation and dune accumulation which created the present sand dunes, dominated in the areas of the old fluviatile plains. Certainly, it would be a mistake to conclude that up to the Würm period no more humid phases occurred, just because the big rivers systems that existed in the Pliocene have never been regenerated again. A number of different conditions such as enormous eolian accumulations as well as the relatively small increase of precipitation during humid phase made a considerably stronger surface runoff impossible. Indications for more frequent climatic changes towards higher humidity are the sediments of the wadi fillings indicating several changes from eolian sequences with fluviatile sediments frequent smaller precipitation phases.

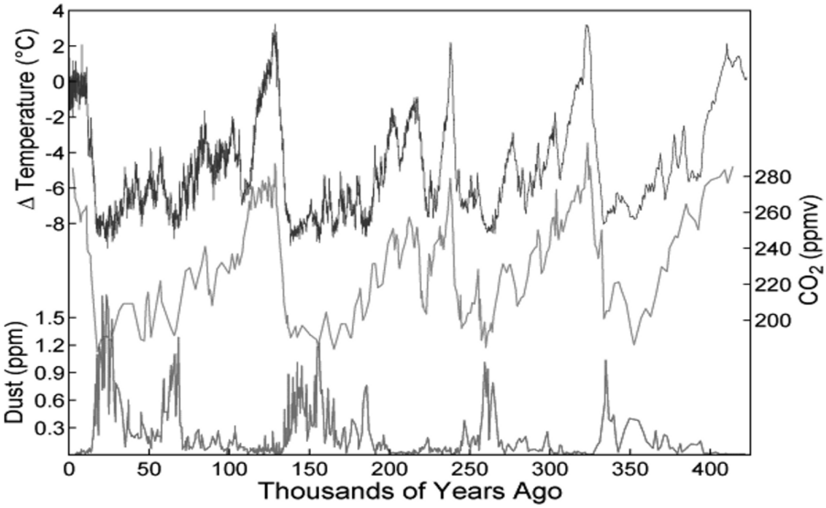


Fig. 2.1.4. Results from Vostok Ice Core, Antarctica: temperature (upper graph), graph of CO_2 (middle graph) and dust concentration (lower graph) as reported by Petit et al., 1999. Higher dust levels are believed to be caused by cold, dry periods.

For a long time there was the tendency to conclude for the subtropical regions pluvials and interpluvials parallel to the European glacial and interglacial eras. The intensive research conducted all over the world during the last 40 years concerning the Quaternary climate, however, confirmed clearly that a simple parallelisation is not possible, in contrary in the core zones of the deserts of the northern hemisphere even extreme hyper arid conditions were prevailing. However in the marginal zones characteristic changes are observed, so that during the cold periods the polar-front could advance further to the south bringing more and heavier seasonal rains to North Africa and the northern countries of the Middle East, while during the warm periods the monsoon-front could extending further to the north covering the southern Sahara and the Arabian Peninsula with seasonal rains.

Due to the dating techniques with carbon-14 we have more precise formation for the last cold period on the Arabian Peninsula (equivalent to the Würm glacial period in Europe). Duricrusts and soil formations dating back to 25,000 – 30,000 years before B.P. have been found in the southern part (Felber et al. 1978, Hötzl et al. 1984). They are in accordance with indications of increased precipitations in the south of the Sahara and in Sudan, whereas thereafter from 25,000 to 12,000 years B.P. arid conditions prevailed again in Arabia. Distinctive sand dune formations in the area of the Arabian Gulf desiccated at that time (Kassler 1973) confirm such a hypothesis. Further to the north in Lebanon, Syria and Northern Iraq wet condi-

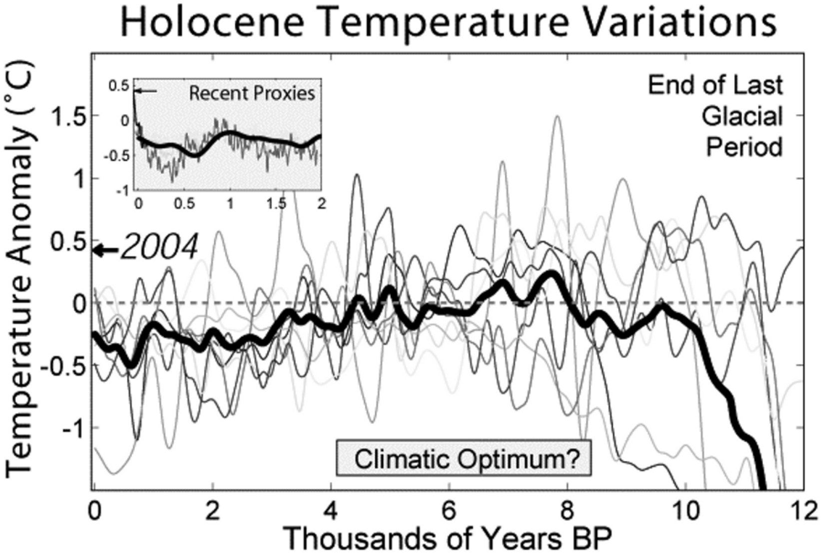


Fig. 2.1.5. Holocene Temperature variations: The colour curves are from sediment cores, ice cores, pollen distribution, the thick black line presents the average. Graph prepared by R.A. Rohde (2005) from published data.

tions prevailed during 25,000 to 18,000 years B.P. It may also be possible that there was another more humid phase at the end of the Pleistocene, as reported for the central and southern Sahara by a few authors.

Some of today's fossil groundwater reserves, especially these in deeper aquifers, e.g. from Umm er Radhuma limestones in Saudi Arabia, Qatar and Bahrain or from the Palaeozoic sandstone aquifers in north-western part of Saudi Arabia and southern Jordan, had their origin in more humid phases, when greater quantities of water infiltrated into the subsurface. Carbon–14 ages of 20,000 - <35,000 give rise to the assumption of increased precipitation during the whole cold period. However, infiltration of precipitation during the younger Holocene humid phases caused mixing so that water ages gives only mean residence time of the mixed waters and are not significant for dating the humid phases.

For the early and middle Holocene there are several indications of a higher amount of precipitation and certain surface runoff in the wadis of central and southern Arabia. Accumulation terraces as well as lacustrine sedimentation in backwaters of smaller wadis and in the dune areas are witness of a stronger surface runoff and thus heavier seasonal precipitation. They confirm a semiarid climate vegetation and animals of steppe character. Absolute time determination have been made in many cases from shells collected in limnic sediments, from peat and charcoal remnants assigning the samples to the early and middle Holocene. Another

Fig. 2.1.6. Sinter formation from a past wet period forming originally a discharge channel from a spring at the end of a basalt flow, Upper Wadi Birk, Saudi Arabia. The carbon-14 determination gave an age of about 5,500 B.P. (Foto: Hötzl).

indirect argument speaking in favour of this theory are the findings of Neolithic tools between the south-western part of Ar Rub Al Khali and Qatar, a rather inhospitable area today (McClure 1976, Hötzl et al. 1984). Sinter formations dating back to the Atlantic phase corresponding with the „Neolithic pluvial“, which is connected to a northward shifting of the monsoon zone causing also the „Climate Optimum“ with 3 - 4° C higher temperature in Europe compared with the average values of today.

The described sinter formation as well as their range between lat 21°N and lat 27°N give evidence of humid warm phases prevailing nearly over the entire Arabian Peninsula, while further to the north there was hot but rather dry conditions comparable with the „climate optimum“- phase of southern and central Europe. There are reports describing two to four humid phases the regional correlation of which have not yet been examined thoroughly enough. In conclusions drawn from the sediments of the Persian/Arabian Gulf by Diester-Haas (1973) there occurred an older humid phase between 9,000 and 8,000 years B.P. and a younger one between 7,000 and 4,500 years B.P.

Fig. 2.1.7. Fossil beach rock from a closed morphologic depression from the central part of northern Saudi Arabia. Carbon-14 age determination proved the occurrence of a lake during the wet Neolithic time (about 5,000 to 6,000 B.P.) (Foto: Hötzl).

Apart from this last larger climatic change on the northern hemisphere, local short-term and unusual climatic differences occurred in historical times or even in recent years. Examples are the slightly more wet periods during the Roman time and later in the early medieval time bringing some more rain to North Africa and the Mediterranean counties of the Middle East.

2.1.4 Impacts of climate changes on water resources

Projections of changes in runoff and water supply under climate change scenarios vary. From the past one can realize that the current climate in the Middle East is not the worst, that with regard to the availability of water there could be much dryer hyper arid conditions, which can be connected with higher or even colder average temperatures. On the other hand more wet conditions immediately improve the situation for all kind of lives. There are all kind of transitions from minor to significant increase of precipitation.

Global warming is now generally agreed to be inevitable according to the latest IPCC assessment. The climate is predicted to become hotter and drier in the Middle East, though there many differing assessments as to how much temperatures will rise and at what speed. Higher temperatures and reduced precipitation will increase the occurrence of droughts. It is found that a decrease in rainfall coupled with an increase in extreme climatic events due to climate change is likely to significantly decrease water availability in the region, with negative effects on food production and economies. Especially in rainfed areas agriculture yields are expected to fluctuate more widely, ultimately falling to a significantly lower long-term average. The same will happen with irrigated land, if the water availability in favour of domestic use have to be reduced. Poor and vulnerable populations, which exist in significant numbers throughout the region, will likely face the greatest risk.

In urban areas on one hand it is to be expected that just by the further increasing population the water demand remain under supplemental stress. On the other hand the rising temperature is further estimated to have an additional multiplying effect on water consumption due to heat effects and decreasing water quality and worsening of urban air conditions. These will cause increased pressure on surface and groundwater resources, which are currently being extracted in most areas beyond

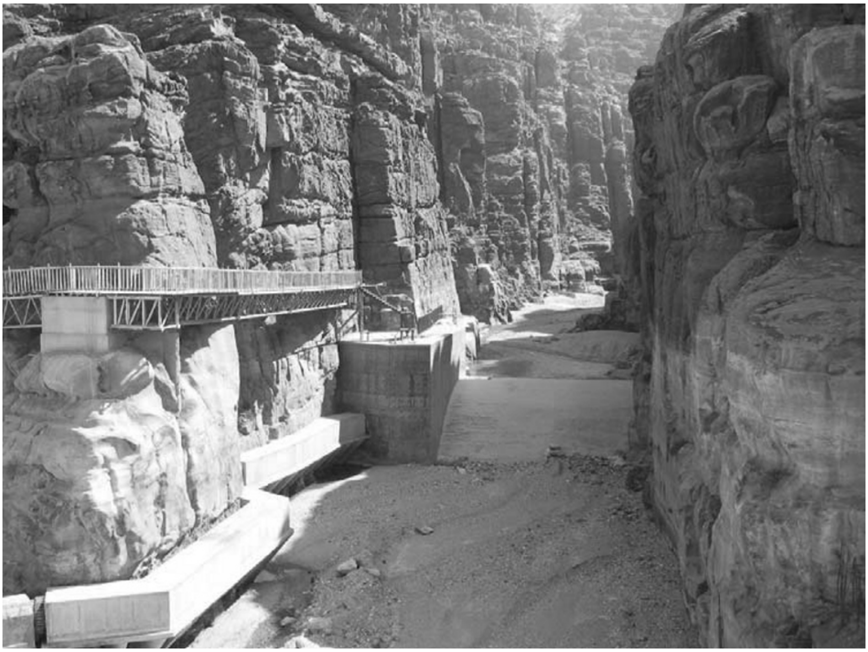


Fig. 2.1.8. Water capture with weir, intake building and deviation channel at the mouth of Wadi Mujib at the Jordan Dead Sea coast. The capture and deviation of surface water for domestic and agriculture water supply is one of the main reason for the current depletion of the Dead Sea water level (Foto: Hötzl).

sustainable recharge conditions. The competing demand and tensions between different consumer groups can lead to a water related social or economical conflict situation within one country. In case of joint utilization of water resources and water agreements between nations this could disturb the political relationships between countries. The Middle East is already an area of tension. Political stress, contracting water supplies, could aggravate animosities in the region. Water is a scarce resource-and will continue to be so in the future.

Global models predict sea levels rising from about 0.1 to 0.9 meters by the year 2100. In the Middle East there are several countries with low-lying coastal areas, like Iraq, Kuwait, Bahrain Qatar, Saudi Arabia and UAE. In Alexandria, Egypt, e.g. a 0.5 m sea level rise would leave more than 2 million people displaced with an damage of more than $ 30 billion on property and infrastructure. Water shortages and rising sea levels could lead to mass migration.

While the rising level of the open sea of the Mediterranean as well as in the Arabian Gulf due to the melting ice in the polar region will become a hazardous risk for the direct riparian, the reverse effect will cause the problem at the Dead Sea as a closed terminal lake. The expected reduction of precipitation in the Middle East in connection with the global warming will provoke a further depletion of the Dead Sea level (Salameh & Naser 1999). During the last four decades, water resources in the Dead Sea watershed have been intensively developed to meet the growing demands. Increasing amounts of water were diverted from surface and groundwater sources in the watershed to meet domestic, agricultural, and industrial needs. Today, only a fraction of the flow from the water-rich areas reach the Dead Sea. The inflow can not balance the strong loss by evaporation. This ecological and hydrological mismatch will be boosted by the expected climatic changes.

Much of the progress so far achieved by countries in the region to tackle challenges of high unemployment and integration with the global economy can be jeopardized by climate change. Income and employment may be lost as a result of more frequent droughts in rural areas, and to floods and sea surges in urban and coastal areas. Changes in temperature and precipitation patterns may result in damage to strategic economic sectors such as tourism or others with growth potential such as high-value-added agriculture. The combination of such impacts is likely to slow down the reform process.

2.1.5 Solutions requesting integrated water resources management

The Middle East, like other regions, needs to urgently examine the way in which potential climate change may affect its future water supply and this in turn means examining the inter-relationship between climate variations, water supply, land use, economic planning and demographic change. Such questions cannot be dealt with on the basis of national interest only, but demand cross-border and interdisciplinary cooperation.

Models that project changes in global vegetation in response to a for instance CO_2 driven climate suggest little change in desert communities. Although precipitation is projected by some models to increase slightly, this increase will have little impact because most of the region will remain arid. In semi-arid areas, increased precipitation eventually may lead to improved soil conditions, including larger accumulations of organic matter, enhanced moisture availability, and changed runoff patterns. The impact of climate change will be much more drastic in the semi-arid areas of the region if the forecasted reduction of precipitation will occur. Agriculture, natural grasslands, livestock, and water resources in marginal areas are highly vulnerable to such climatic change.

Solutions for the problems, which climate change may cause in relation to water, can best be achieved by integrated management plans, focusing not only on technical matters but on the interrelationship of water systems with land use, climate and the environment. Significant decisions have to be taken which require well based interdisciplinary investigations, the results of which must be made available to decision makers in time for them to act effectively.

As a comprehensive approach „integrated water resources management (IWRM)“, which was recommended by United Nations at the Dublin Conference 1992 for countries with water scarcity, can be the right tool to assess the problems of climatic change and to give the answer how to react on such impacts. This approach comprises the „coordinated development and management of water and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems“. It includes the

- integrated treatment of all water resources, namely surface- and groundwater, brackish and saline water, grey and waste water;
- integrated consideration of ecologic, economic and social issues;
- integrated transboundary water strategies and policies.

IWRM should be applied at catchment level as the smallest complete hydrological unit for analysis and management. Adoption of the best appropriate affordable technologies and best management practices have to be selected. Water and environmental management must be integrated. IWRM has to combine interests, priorities and disciplines as a multi-stakeholder planning and management process for natural water resources within the catchment ecosystem. Attention should be drawn to social dimensions. These requires attention to the use of social impact assessments, workplace indicators and other tools to ensure that the social dimension of a sustainable water policy is implemented.

These implies, firstly, sufficient information on geological, hydrological, economic, social and environmental characteristics of a catchment to allow assessment of the climate impact as well as to develop the necessary strategies and policy choices to be made. The influences of climate changes, like varying precipitation rates, have to be predicted with regard to the direct responses of the catchment system including anthropogenic factors like effluent discharges, diffuse pollution, artificial recharge, changes in agricultural or other land use practices. These will involve extensive use of numerical models integrated within a decision support system. The recognition of water as an economic good is central to achieving equitable allocation and sustainable usage in terms of balancing social, ecological and economic considerations.

The role of governments in Integrated Resources Management should be one of leadership, aimed at facilitating and coordinating the development and assisting with the provision of technical advice and financial support. Dependent on the further disposition and the local conditions appropriate reuse techniques shall be determined as well as solutions for aquifer storage developed. The implementation of these new solutions requires the establishment of a broad infrastructure (e.g. pipelines, boreholes, waterworks, pumping stations, distribution systems, irrigation systems, wastewater systems) for the regional water management. Where specific areas of responsibility fall outside the mandate of a single government, transboundary strategies and policies are requested.

References

Allan, J. A. (ed.) (1996): Water, peace and the Middle East : negotiating resources in the Jordan Basin. London; New York : Tauris Academic Studies; St. Martin's [distributor], 1996. xix, 250 p. (Library of Modern Middle East Studies, 9).

Al-Sayari, S. S.; Zötl, J. G. (Eds.): Quaternary Period in Saudi Arabia, 1, 334 p., (Springer Verlag), Wien 1978.

Brimberg, Jack; Mehrez, Abraham; Oron, Gideon (1994). Economic development of groundwater in arid zones with application to the Negev Desert, Israel. -Management Science, 40(3), 353-363.

Diester-Haas, L. 1973. Holocene climate in the Persian gulf as deduced from grainsize. Marine Geology,14,207-223, Amsterdam

Exact. (1998) Overview of Middle East Water Resources: Water resources of Palestinian, Jordanian and Israeli interest. Jordanian Ministry of Water and Irrigation, Palestinian Water Authority and Israeli Hydrological Service. Compiled by the U.S. Geological Survey for the Executive Action Team, Middle East Water Data Banks Project.

Farber, E., Vengosh, A. Gavrielli, I. , Marie A., Bullen,T.D., Mayer, B., Holtzman, R., Segal, M. and Shavit, U. (2003): The origin and mechanisms of salinization of the Lower Jordan River.

Felber, H.; Hötzl, H.; Moser, H.; Rauert, W.; Zötl, J. G.: Karstification and geomorphogeny of As Sulb Plateau. - In Al-Sayari S. S., Zötl, J. G. (Eds.): Quaternary Period in Saudi Arabia, 1, S. 166-172 (Springer Verlag), Wien 1978.

Government of Jordan (1998). The Hashemit Kingdom of Jordan, Jordan's water shortage. http://www.kinghussein.gov.jo

Hötzl, H.; Jado, A. R.; Moser, H.; Rauert; W., Zötl, J. G.: The Youngest Pleistocene. - In: Jado, A. R.; Zötl, J. G. (Eds.): Quaternary Period in Saudi Arabia, vol. 2, S. 314-324, (Springer) Wien 1984.

Hötzl, H.; Job, C.; Moser, H.; Rauert, W.; Stichler, W.; Zötl, J. G.: Isotope methods as a tool for quaternary studies in Saudi Arabia. - In: Arid-zone hydrology: investigations with isotope techniques. International Atomic Energy Agency. AG-158/16, S. 215-235, Vienna 1980.

Hötzl, H.; Zötl, J. G.: Climatic changes during the Quaternary period. - In Al-Sayari, S. S.; Zötl J. G. (Eds.): Quaternary Period in Saudi Arabia, 1, S. 301-311, (Springer Verlag), Wien 1978.

Hötzl, H.; Zötl, J. G.: Middle and Early Pleistocene. - In Jado, A. R., Zötl, J. G. (Eds.): Quaternary Period in Saudi Arabia, vol. 2, S. 332-335, (Springer) Wien 1984.

Husseini, Hiba (2004):The Palestinian Water Authority developments and challenges involving the legal framework and capacityof the PWA .- The International Israeli- Palestinian Water Conference, Antalia, Turkey,October 10-14, 2004

IMFA – Israel Ministry of Foreign Affairs (2003): MFA Newsletter, MFA Library,Sept. 2003. Focus on Israel-Development of Limited Water Resources.

Issar, A.S. (2003), Climate Changes during the Holocene and their Impact on Hydrological Systems. Cambridge University Press, Cambridge.

Issar A.S. and Zohar, M. (2004), Climate Change, Environment and Civilization in the Middle East. Springer-Verlag, Heidelberg.

Jado, A. R.; Zötl, J. G. (Eds.): Quaternary Period in Saudi Arabia, vol. 2, 360 p. (Springer) Wien 1984.

JMWI (Jordan Ministry of Water and Irrigation). (1997) Water Resources Strategy. Ministry of Water and Irrigation (MWI), The Hashemite Kingdom of Jordan, Amman, Jordan, 7 pp.

Kassler, P. 1973. The structural and geomorphological evolutiond of the Persian Gulf.- Purser, B. H., The Persian gulf, 11-32, (Springer) Berlin

Lisiecki, L. E., and M. E. Raymo (2005), A Pliocene-Pleistocene stack of 57 globally $\delta?^{18}O$ distributed benthic records, *Paleoceanography*, 20, PA1003, doi:10.1029/2004PA001071.

McClure, H.A. 1976. Radiocarbon Chronology of Late Quaternary Lakes in the Arabian desert. – Nature, 263,755-756, London

McCornick, P.G., Taha, S. and El Nasser, H. (2002) Planning for Reclaimed Water in the Amman-Zarqa Basin and Jordan Valley. American Society of Civil Engineering – Environmental and Water Resources Institute, Conference and Symposium on Droughts and Floods, Roanoke, Virginia,10 p.

Middle East Water Commission 1995. Observations regarding water sharing and management : an intensive analysis of the Jordan River Basin with reference to long-distance transfers. International journal of water resources development. Vol. 11(4) December 1995 : 351-375.

Murakami; Masahiro (1995): Managing Water for Peace in the Middle East: 319 p Alternative Strategies. United Nations University Press; Tokyo – New York – Paris

Petit J.R., Jouzel J., Raynaud D., Barkov N.I., Barnola J.M., Basile I., Bender M., Chappellaz J., Davis J., Delaygue G., Delmotte M., Kotlyakov V.M., Legrand M., Lipenkov V., Lorius C., Pépin L., Ritz C., Saltzman E., Stievenard M. (1999). Climate and Atmospheric History of the Past 420,000 years from the Vostok Ice Core, Antarctica, *Nature*, 399: 429-436.

Rohde R.A. 2005. Global warming art project.
http://www.globalwarmingart.com/wiki/Image:Holocene_Temperature_Variations.png

Salameh, E. and Naser, H. (1999) Does the actual drop in Dead Sea level reflect the development of water resources within its drainage basin. *Hydrochim. Hydrobiol. Acta* **27**, 5-11.

Taha, Suzan (2006): Jordan country paper. Conference of the Water directors of the Euro-Mediterranean & South Eastern European Countries. Athens, Greece 6-7 Nov. 2006.

UNEP. 1997. United Nations Environment Programme. *World Atlas of Desertification, 2nd edition*. Edited by N. Middleton and D. Thomas. London: UNEP. 182pp.

Wolf, Aaron 1995. Hydropolitics along the Jordan River : scarce water and its impact on the Arab-Israeli conflict.Tokyo; New York : United Nations University Press, 1995. viii, 272 p.

Wolf, Aaron 1996. Middle East water conflicts and directions for conflict resolution. Washington, D.C : International Food Policy Research Institute, [1996]. vi, 28 p.

World Bank, Rural Development, Water and Environment Group &Infrastructure Development Group, Middle East and North Africa Region (2001): The Hashemite Kingdom of Jordan Water Sector Review Update, Main Report, Report No. 21946-JO, February 1-5, 2001.

World Bank (2004): Seawater and brackish water desalinisation in the Middle East. – Final Report, Annex 3, Jordan.

2.2 Virtual Water Trade as an Adaptation Demand Management of Climate Change Impact on Water Resources in the Middle East

Mutasem El-Fadel, PhD [1] and Rania Maroun, MS [2]

[1] Professor, School of Civil Engineering and the Environment, University of Southampton, UK
Director, Water Resources Center, American University of Beirut, Beirut Lebanon

[2] Research Associate, Water Resources Center, American University of Beirut, Beirut Lebanon

Abstract

Evidence of global greenhouse gas (GHG) emissions have grown since pre-industrial times, with an increase of 70 % between 1970 and 2004 and with current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades. The increase in anthropogenic GHG concentrations is *very likely* causing the warming of the climate system since the mid-20th century, as evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. The climate system and the water cycle are closely linked, so that any change in one of these systems induces a change in the other. Yet, the implications of climate variability and climate change have not been fully considered in current water policy and decision-making frameworks. This is particularly true in developing countries, where the financial, human and ecological impacts are potentially greatest, and where water resources may be already highly stressed, but the capacity to cope and adapt is weakest. This chapter outlines the impact of climate change on water resources in Middle Eastern countries, and discusses potential adaptive measures in this respect, with emphasis on virtual water trade, as a non-conventional demand management option for water resources.

Keywords

Climate Change, Water Demand Management, Virtual Water Trade, Middle East

2.2.1 Introduction

It is generally accepted that increased global temperatures will inevitably lead to changes in the hydrologic cycle. This is attributed to increased atmospheric water vapor and enhanced poleward water vapor transport (IPCC-TGCIA 1999). However, vast regions may still experience reduced precipitation. The increase in temperature leading to higher evaporation and the expected increase in precipitation event intensity would further reduce available water in regions where precipitation is diminished or unchanged. Fortunately, water resources management systems are very adaptive by nature (or through institutional intervention) and the usual variations in climatic and socio-economic conditions have provided water managers with experiences that help them cope with potential changes in climate patterns (Strzepek 1998). However, a relatively high rate of climate change, a rate at which it becomes difficult to adapt within a reasonable timeframe, and its cumulative effect might pose serious problems.

Water Resources in the Middle East

The Middle East[1] is characterized with severe and precarious water scarcity (Berkoff 1994, ESCWA 1996, ESCWA 1999, Postel 1993). Rapid population growth, development, urbanization, and expansion in irrigated agriculture in this region as well as political interferences have led to mounting pressures on scarce resources to satisfy water demands (Beaumont 2002, Haddadin 2002). Irrigation already accounts for around 80 percent of withdrawals region wide but demand is expanding most rapidly in urban areas. By 2025, the share of population living in urban areas is expected to increase from 60 to nearly 75 percent (Beaumont 2002, Berkoff 1994). The dwindling availability of water to meet development needs has become a significant regional issue since the 1970s, especially as a number of countries are facing serious water deficit (Haddadin 2002, Seckler *et al.* 1999, Hamdy *et al.* 1995). Iraq is the only other country in the Middle East that appears to have sufficient water resources at present. However, Iraq is at the disadvantage of procuring more than two-thirds of its water resources as river flows from Turkey (Berkoff 1994). The latter are continuously decreasing due to increased upstream usage and construction of dams.

---

1. The borders of the „Middle East“ are not well established. The boundaries of this region change with changing issues. A different approach in defining the area is used in politics, geography, history, environment, economics, etc. For the scope of this chapter, the countries that have significantly interconnected water resources and that do not yet rely heavily on desalination techniques are considered. That is: Lebanon, Syria, Iraq, Israel, Jordan, and the Palestinian Authority (West Bank and Gaza Strip). Turkey is the source of a significant amount of water flowing into Iraq and Syria; however, this country is not addressed in this study due to climatic and hydrologic differences with countries under consideration.

Because of population growth, it is expected that by 2025 the average annual renewable water resources for the Middle East would have fallen to 667 m^3 per capita compared to a world average of 4,780 m^3 per capita (Berkoff 1994). Projections indicate significant water shortages in the future for most countries in the region even without accounting for potential increased capacity in desalination or wastewater reuse. Note that agricultural demand accounts for nearly 84 percent of the water demand in the region. Deteriorating water quality presents an additional threat to water availability in the region due to a combination of low river flows, absent/inadequate wastewater treatment, agricultural runoff, uncontrolled industrial effluent, and over-exploitation of coastal aquifers leading to seawater intrusion. Declining quality directly affects the utility of the water resources, whereby treatment costs become substantial if rivers and potable aquifers are to be sustained in usable forms. Hence, if Middle Eastern countries continue to tap into groundwater aquifers at a non-sustainable rate and do not develop alternative non-conventional water resources (such as the use of surplus winter runoff, seawater or brackish water desalination, wastewater reclamation, etc.), adverse impacts on water availability and quality will result even without climate change effects.

Climate Change Impacts on Water Resources in the Middle East

It is often assumed that since the Middle East region has very scarce water resources, the impact of climate change would be negligible (IPCC-WGII 1996). However, as noted before, water resources in the region are under a heavy and increasing stress. Any alteration in climatic patterns that would increase temperatures and reduce rainfall would greatly exacerbate existing difficulties. For the Middle East, General Circulation Model (GCM) simulations indicate higher future temperatures that will increase evapo-transpiration and changes in climate patterns that might reduce rainfall in the region as a whole (IPCC-DCC 1999, IPCC-WGI 1996). El-Fadel and Bou-Zeid (2003) compared climate change projections in the Middle East, calculated by four different GCMs (ECHAM4, HadCM2, CGCM1, GFDL) for the same set of assumptions (IS92a[2] scenario). Both greenhouse gases and sulfur aerosols were accounted for in the GCMs and the projections available are for the 2020s climate conditions in comparison to the period 1961-1990. The results show minor changes in mean precipitation for the region, while temperatures are projected to increase in all seasons. Mean summer temperatures, already high in the region, are expected to rise 0.8 to 2.1° C. Areas bordering the Mediterranean (Lebanon, Israel, Palestinian Authority, coastal Syria) would be the least affected. However, groundwater aquifers in these areas will be under the hazard of increased seawater intrusion due to higher sea levels. The discrepancies between

---

[2] IS92a is the IPCC Scenario that predicts GHG emissions under average development and growth projections assuming no emission mitigation policies are implemented. IS92a predicts an increase of equivalent CO_2 concentrations close to 1 %/year.

predictions of different models reach a maximum 1.3° C for Syria during the summer. However, the trend is clearly towards increasing mean temperatures. This will increase irrigation water demand due to higher evaporation. Extreme temperatures are predicted to increase more than mean temperature values. Increased temperature and evapo-transpiration coupled with constant precipitation are highly associated with desertification. Mean winter temperatures will also increase; however, the rise is lower than for the summer season. Higher winter temperatures will enhance evapo-transpiration and reduce potential groundwater recharge. If the increased runoff due to sharper precipitation patterns is also considered, the net effect will be a reduction in groundwater recharge and hence in the baseline renewable water resources.

These results are a compilation of simulations from several GCMs and represent intermediate GHG emission scenarios (IS92a). GHG emissions have followed IS92a prediction until now and this is expected to last. However, even if emissions uncertainties are disregarded, the GCMs might still have considerable errors correlated with uncertainties in climate modeling under known atmospheric GHG concentrations. Hence, the results are best guesses of likely climate change in the region.

It is noteworthy that while most models predicted an increase in temperature, few reported an opposite trend. One particular study that coupled a nested regional model for the Middle East and southern Europe to a GCM predicted a decrease in temperature for the region ranging from 0 to 1 ° C due to doubling CO_2 levels (Jones *et al.* 1997). This was attributed to sulfur aerosols cooling effect.

The impacts of climate change on the biophysical environment are likely to result in socio-economic effects, particularly in developing countries like the Middle East. In fact, the economic impact of climate change is estimated at 2 to 9 percent of annual national GDP for developing countries (IPCC-WGII 1997) in contrast to a 1 to 1.5 percent reduction in GDP for developed countries. The greater vulnerability of poorer regions (lower GDP) to climate change is related to their high reliance on weather-related activities, particularly agriculture, and the low adaptation and damage restoration capacity (Tol 1996). In the context of the Middle East, variations in water resources systems might have significant adverse effects including reduction of Gross Domestic Product, population redistribution, work force shift to alternative economic sectors, etc. Table 2.2.1 presents a qualitative assessment of expected welfare implications of climate change impacts on Middle East water resources, accounting for both the importance of the impact and the significance of the impacted sector. Accordingly, the most critical welfare impacts on the regional scale are expected to be: increased agricultural water demand, water resources distribution equity decline, water quality damage, and GDP reduction. Serious health implications and increased propagation of diseases could also result from more extreme weather events and higher temperatures. The indirect impact of climate change on hydraulic structures should not be underestimated in view of potential increases in precipitation intensities and modifications in river flow patterns.

Table 2.2.1. Socio-economic implications of climate change impacts on water resources in selected Middle Eastern countries (El-Fadel and Bou-Zeid, 2003).

Impact	Iraq	Israel	Jordan	Lebanon	Palestinian Authority	Syria
Increased industrial and domestic water demand	++	+	+	++	+	++
Increased agricultural water demand	+++	++	+	+++	+++	+++
Water resources distribution equity decline	+++	++	+++	++	+++	+++
Flood damage	+++	+	+	++	+	+
Water quality damage	+++	+++	+++	+++	+++	+++
Hydropower loss	+	+	+	++	+	+
Ecosystems damage and species loss	++	++	+	+++	++	++
GDP reduction (percent)	3-6	1-2	1-2	2-5	2-5	4-7

+++ : high; ++ : moderate; + : insignificant

Adaptation Measures

Unmet water demands in most countries in the Middle East region, the mismanagement of water resources, and the rapid population and economic growth, pose water shortage issues that are generally greater than those forecasted to result from climate change. In fact, the baseline scenario predicts a drop in per capita water resources of about 50 percent for the Middle East region by 2025 (El Fadel and Bou-Zeid 2003). The efficient management of water resources is crucial if the water imbalance in the Middle East is to be reversed. New management and planning policies that combine practical technology with political and social support are needed to overcome current problems and constraints and to avoid water shortages in the future. The effective management of water resources requires a holistic approach linking social and economic development with protection of natural ecosystems including land and water linkages across catchment areas or groundwater aquifer (Hamdy and Lacirignola 1997). Accordingly, the social and economic components of water must be balanced and weighed equitably in order to enhance development that is sustainable and that benefits all. This is best achieved via the adoption of the Integrated Water Resources Management (IWRM) approach, which combines various facets of water-related issues, including water supply, water quality management, irrigation and farm drainage, energy generation, fisheries enhancement, recreation and general aesthetics, as well as flood control. IWRM also addresses issues of access and equity, resource protection, efficient use, governance and land use (Jonker 2002, Hamdy and Lacirignola 1997). IWRM should be based on a „proactive“, „anticipatory“ approach, respecting the „precautionary principle“, and should include the application of preventative actions (Kabat *et al.*

2002). Such an approach and associated policies would provide resilience to deal with the additional, but largely unknown adverse impacts of climate change. Therefore, adaptation measures to climate change can be qualified as no-regret options, which would be beneficial regardless of the intensity of climate change impacts. These measures will improve the adaptability of water resources systems to natural variability in climate patterns (Conway and Hulme 1996). Traditional typical adaptation measures and non-conventional sources that can be exploited in the future include conservation, use of surplus winter runoff, wastewater reclamation, seawater/brackish water desalination, rainfall enhancement by seeding clouds with silver iodide crystals, and use of *submarine springs*.

A recently emerging strategy concept developed as a prospective long-term solution for preserving global water resources is known as „virtual water“. An emerging concept for the management of water resources at the national and international levels that needs to be given more attention in the Middle East region is virtual water trade, which is the main focus in the rest of this chapter.

2.2.2 Virtual Water Trade

Virtual water is defined as the volume of water needed to produce a commodity or service. For instance, it takes approximately 2,000 tons of water to produce one ton of rice, 1,000 tons of water to grow one ton of wheat, and approximately 1,200 tons of water to produce one ton of maize (Turton *et al.* 2000; Allan 1997). Lately, research activity on the trade in „virtual water“, or the water required to produce the traded goods, has increased significantly as an attractive option for achieving water security at the national and global levels. Through virtual water trade, water-scarce countries can import water-intensive products from water-rich countries instead of producing them domestically and exerting pressure on their resources. On the other hand, water-rich countries can profit from their abundance in water resources by producing water-intensive products for export. Many countries currently compensate for their poor water endowment by food imports and vast quantities of virtual water are embedded in the international political economy, with almost every state being subjected to trade in virtual water (Meissner 2002, Allan 1997). Hoekstra and Hung (2002) estimated the global volume of crop-related virtual water trade between nations at 695 Gm^3/yr in average over the period 1995-1999. This value constitutes 13 percent of the water used for crop production in the world. In the Middle East, the amount of water that enters the region as virtual water in the form of subsidized grain purchases is equivalent to the annual flow down the Nile (Allan 1997).

In this context, the concept of „virtual water“ lends itself as a potential solution to water scarcity in semi-arid and arid regions, like the Middle East Region, which can achieve both water and food security by purchasing water intensive agricultural commodities from water-rich states that produce a natural surplus of these products. Because trade of real water between water-rich and water-poor regions is generally impossible due to the large distances and associated costs, it is increasingly recognized that virtual water trade might be the means by which water-deficit economies balance their water budgets (Turton 2001). Concurrently, food trade can contribute to national food security by 1) augmenting domestic supply, 2) reducing supply variability but not necessarily price instability, 3) fostering economic growth, 4) making more efficient use of world resources (water and soil in particular), and 5) permitting global production to take place in those regions most suited to it (Konandreas 1996, cited in Turton *et al.* 2000). Virtual water trade can be classified as a demand-side management strategy to supplement water resources where they are scarce and are projected to become scarcer due to climate change. Yet, the implementation of a viable virtual water strategy is more complex, being influenced by a multitude of factors at both the national and international scale (Meissner 2002).

While virtual water appears appealing to water-short nations to achieve food and water security, the adoption of a national virtual water strategy should be consistent with national objectives other than food security including, providing national security, promoting economic growth, and improving the quality of life. In this context, besides water, resources required for agricultural production such as land, labor and capital, need to be considered when evaluating a nation's production and trade opportunities. In countries where one or more of these resources is limiting, focus on virtual water alone will not be sufficient to determine optimal policies for maximizing the social net benefits from limited water resources. For instance, in a country where labor is relatively abundant, policies that promote increased export of labor-intensive crops will improve rural income and enhance food security. Hence, a country should encourage the production of labor-intensive crops while promoting water conserving irrigation practices. Another factor that needs to be evaluated is the opportunity cost of water used in producing crops, which is its value in other uses such as the production of alternative crops, or its use in municipal, industrial, or recreational activities. Accounting for opportunity costs is essential for estimating the benefits from importing or exporting virtual water. It also allows an efficient allocation of scarce water resources at the national level. For instance, countries in which water is particularly scarce may gain from trade by importing water-intensive crops, while using their limited water supply for activities that generate greater incremental values (Wichelns 2001).

Turton *et al.* (2000) identified four key hydropolitical variables that determine the potential for a nation to be involved in virtual water trade including, water need, economic strength, and agricultural and industrial sectoral water efficiencies (SWE). According to Turton, of all the possible combination of variables, economic strength is the most important. For a country to be able to purchase virtual water, it should have an economy capable of generating sufficient foreign currency reserves. Only countries with a healthy balance of payment situation are in a position to trade in virtual water as needed to balance their water budgets. This can come from the existence of a viable industrial sector that is globally competitive (Turton 2001). As for the SWE, or the ratio of water consumed within a given eco-

Table 2.2.2. Hydropolitical variables and the potential of nations in virtual trade (Turton *et al.* 2000).

IF				THEN
Water need	Economic strength	Agricultural SWE	Industrial SWE	
High	Weak and undeveloped	Low Focus on subsistence agriculture	Low	No potential for a VW strategy
Low Medium	Weak and undeveloped	Low with potential for improvement The presence of arable land The presence of a favorable water resource base	High	Potential VW export
Low	Strong & diversified	High	High	Potential VW export
High	Strong & diversified	Low	High	Potential VW import
High	Strong & diversified	Medium	Medium	Potential VW import
Medium	Strong & diversified	Low	High	Potential VW import

nomic sector in relation to contribution of the same economic sector to overall Gross Domestic Product (GDP), it reflects the degree of efficiency of water use to a political economy. Typically, agriculture uses the largest portion of water in a given political economy, and only contributes a small component to the GDP of a country. Industry, on the other hand, uses less water and contributes a significantly larger fraction of the overall GDP. Thus, in general terms, the agricultural SWE is low whereas the industrial SWE tends to be high. Hence, in water scarce countries, it is advisable that water be diverted away from agricultural use into the industrial and urban domestic sectors, whereby 70 times more economic value can be achieved for a given volume of water (Turton 2001). Table 2.2.2 illustrates various combinations of the hydropolitical variables determining the potential role of countries in a virtual trade strategy.

Other factors that ensure a viable virtual water strategy include:

- A sound national trade policy that is in harmony with regional trade policies, facilitating exchange of goods (Turton *et al.* 2000)
- Cooperation between states
- The establishment of an international organization to control global food trade and ensure that the global distribution of food will not be used as a political weapon (Bouwer 2000)

Table 2.2.3. Average annual gross virtual water flows in relation to crops for the Middle East region and between world regions in the period 1995–1999 (Gm^3/yr) (Hoekstra and Hung, 2005).

Exporter	Import into the Middle East	Export from the Middle East	Total global gross import	Total global gross export
Central Africa	0.01	0.16	2.9	0.6
Central America	0.09	0.03	33.5	37.9
Central and South Asia	4.33	2.31	196.4	29.8
Eastern Europe	2.07	0.51	12.0	13.0
Middle East	5.13	5.13	41.1	10.8
North Africa	0.75	2.64	50.6	6.2
North America	12.75	0.47	17.5	223.7
Oceania	1.89	0.16	1.7	29.7
Former Soviet Union	5.85	0.24	9.1	18.0
Southern Africa	0.07	0.01	8.0	4.1
South America	4.05	0.10	21.4	69.4
South-east Asia	5.15	0.54	40.6	67.7
Western Europe	4.04	3.67	104.7	28.6
Total gross import	41.1	10.8	539.5	539.5

Virtual Water Trade in the Middle East

Many countries around the world have been inadvertently implementing a virtual water strategy for many years because the volume of water available for local food production has not been sufficient to meet increasing demands (Wichelns 2001). According to Allan (1997), the water scarce Middle East region has been for over a decade relying on the global freshwater surplus to balance its deficit and achieve water security for its economies via virtual water trade. Table 2.2.3 depicts flow of virtual water in relation to crop trade between the Middle East region and in comparison with world regions. Clearly North America is by far the biggest virtual water exporter in the world, while Central and South Asia constitutes the biggest virtual water importer. Central and South Asia is the largest region in terms of population, so food demand is higher than in the other regions, which explains the high virtual water import into this region. As for the Middle East region, it is a net importer of virtual water (30.3 Gm^3/yr). It imports virtual water in agricultural crops primarily from North America (12.1 Gm^3/yr), while its export activity is mainly inter-regional (5.13 Gm^3/yr). Table 2.2.4 depicts the magnitude of virtual

Table 2.2.4. Net virtual annual water import, water footprints, water scarcity, water self-sufficiency and water dependency in the Middle East.

Country	Net virtual annual water import (M^3/capita)		Water footprint (10^6 m^3) [a]	Water scarcity (%) [a]	Water self-sufficiency (%)[a]	Water dependency (%)[a]
	Hoekstra & Hung 2002	Kumar & Singh 2005				
Iraq	51.11	-	52,310	47.9	99.9	0.1
Israel	666.98	915.09	4,298	103.5	53.0	47.0
Jordan	912.91	956.71	8,536	53.4	10.6	89.4
Lebanon	202.89	446.11	1,905	21.0	61.8	38.2
Syria	-608.81 [b]	-263.64 [b]	2,493	20.3	100.0	0.0
PA	649.70 [c]		-	-	-	-

a For the year 1995 (Hoekstra and Hung 2002)

[b] Negative values refer to net exports, positive values to net imports

[c] Adapted from (Nassar 2004)

Water footprint = The sum of domestic water use and net virtual water import of a country

Water scarcity = The ratio of the total water use in the country (m^3yr^{-1}) and the national water availability (m^3yr^{-1})

Water dependency = The ratio of the net virtual water import into a country to the total national water appropriation

water trade in the countries under study[3] and shows that all of them are net importers of virtual water, with the exception of Syria, which is a net exporter of virtual water (264 - 609 M^3/capita). Yet, in most of these countries, including Iraq, Lebanon, and Palestinian Authority, virtual water has been imported independent of a clear and holistic national water management strategy. While external water resources were being sought unintentionally, existing water resources were being exploited inefficiently and unsustainably, particularly in the agricultural sector. Only Jordan and Israel have made conscious policy choices to reduce or abandon exports or local production of water intensive crops and replace them by imports or higher return crops to allow optimization of water use (Hoekstra and Hung 2005). Tables 2.2.5 and 2.2.6 examine the potential role of considered Middle Eastern countries based on the hydro-political variables identified above (see Table 2.2.2). Accordingly, Israel, Jordan and the Palestinian Authority are potential virtual water

---

3. Note that variation in the virtual water trade values between references are primarily due to differences in the methods and the data sources considered

Table 2.2.5. SWE in the Middle East.

Country	Percent sector contribution to GDP [a]			Percent water consumption by sector [c]			SWE	
	Year	Agriculture (%)	Industry (%)	Year	Agriculture (%)	Industry (%)	Agriculture	Industry
Iraq	2000 [a]	5.4	84.4	1990	92	5	0.06	16.88
Israel	2006 [b]	2.6	30.8	1997	54	7	0.05	4.40
Jordan	2000 [a]	2.3	25.5	1993	75	3	0.03	8.50
Lebanon	2000 [a]	7.3	23.7	1996	68	6	0.11	3.95
PA	2005 [b]	8	18.2	1999	63	-	0.13	-
Syria	2000 [a]	23.8	37.9	1995	90	2	0.26	18.95

[a] World Bank 2007; [b] CIA 2007; [c] WRI/Earth Trends 2007

importers, while Iraq, Syria and Lebanon are potential exporters. As such, Lebanon appears to be the only country that is not assuming the potential role in virtual trade ascribed to it in Table 2.2.6.

Except for Israel and Jordan, who are already working on managing their scarce water resources efficiently, countries in the Middle East can seriously benefit from the concept of virtual water trade by first managing their water sector locally through proper policy setting. The next step would be to enhance economic growth and development by adopting policies that enable or promote international trade patterns that reflect water scarcity. However, such a step requires careful consideration of various fundamental issues and national objectives, including issues of national and food security, economic growth, and quality of life.

Table 2.2.6. Potential of virtual water trade in the Middle East.

Country	Water needs	Economy	Agricultural SWE	Industrial SWE	Virtual Water Trade Role
Iraq	Low	Weak	0.06	16.88	Potential exporter
Israel	High	Strong	0.05	4.40	Potential importer
Jordan	High	Weak	0.03	8.50	Potential importer
Lebanon	Medium	Weak	0.11	3.95	Potential exporter
Syria	Medium	Weak	0.26	18.95	Potential exporter
PA	High	Weak	0.13	-	Potential importer

In this context, governments may opt for further promotion of virtual water imports to alleviate their water problems, and thus significantly altering cropping patterns. Accordingly, the government would have to focus on establishing viable and strong industrial and services sectors to fund the purchases of virtual water from the international market (Yang and Zhender 2002). This could be enhanced by channeling the water from the agricultural sector to other sectors that have higher value of water use and that already suffer from water shortage. Diversifying the economy to industry and service sectors, particularly tourist sector for the region's geographical proximity to Europe and the Gulf and its rich history and cultural heritage, should be taken as holistic measures in dealing with water scarcity. Of course, this should inevitably take into consideration the dominating role played by socio-economic development at large, such as required off-farm job opportunities as rampant unemployment is a problem in these Middle Eastern countries.

On the other hand, the agricultural sector in the countries under study is of great socio-economic importance despite the fact that it is the lowest contributor to GDP. It is a major source of livelihood for many households and in many cases supplements family income. In addition, irrigated agriculture contributes to poverty alleviation in poor, rural areas within these countries. Hence, there are several steps that need to be undertaken to ensure that no additional stress is exerted on the already scarce resources and to maximize the environmental and economic benefits of the flow of virtual water into and out of these countries. <u>First</u>, an effective engagement is required towards agricultural policy reform that focuses on formulating a demand-oriented water management approach in the irrigated agriculture sector through institutional reinforcement, water pricing reform and agricultural sector adjustment based on a virtual water trade analysis. Accordingly, the adoption of relevant policies are needed regarding prices and resource allocation to influence how land, water, and other inputs are used by farmers and firms in production. Exporting higher-value cash crops and importing lower-value cereal crops should be encouraged by motivating farmers to consider the true delivery and opportunity costs of water through well-defined water rights and signals of water-scarcity value. In addition, water should be dealt with as an economic commodity rather than a public good, all while addressing social implications, and a pricing structure should be established to allow full cost recovery of operation and maintenance costs as well as part of the initial investment. Water tariffs should take into consideration socio-economic conditions, water availability, irrigation method, cropping intensity, etc and should be easy to administer. In irrigation schemes where farmers have access to both surface and groundwater, water tariffs should be set lower than or equal to the private cost of pumping groundwater to avoid farmer over-exploitation of this resource. Institutional strengthening and administrative reforms of water management agencies through reduced government involvement and bureaucratic control should be pursued. The establishment of water user associations (WUA) may help in organizing water charges collection and ensuring the proper maintenance of irrigation schemes. <u>Second</u>, agricultural policies that encourage the production of competitive crops such as high value added crops (fresh fruits and vegetables) as well as organically grown produce tailored mainly for the export market should be developed. Third, macroeconomic policies should be set to influence farm-level decisions regarding crop choices in ways that are consistent with true opportunity costs. For Example, government policies in Lebanon raise the currency's exchange rate above its true market value. An over-valued exchange rate makes exports more expensive to potential buyers, while imports which constitute a sizable portion of domestic consumption become more affordable. It discourages farmers from growing crops for sale in export markets while encouraging them to produce a non-tradable crop that requires a large amount of imported fertilizer.

Recognizing that the modification of the macro-economic policy to promote exports is complex, the government would need to consider adopting a more flexible exchange rate regime vis-à-vis the US dollar in addition to the phasing out of subsidies. In addition to raising import prices, this step will have serious socio-economic drawbacks that need to be considered. In addition, national policies and programs regarding farm-level access to financial credit and training services should be tailored to influence farmers' choices in crop production (Wichelns 2004). When farmers cannot obtain affordable credit for purchasing seeds, fertilizers, and pesticides, they will choose to produce crops that require relatively small amounts of those inputs, all else equal. Public policies that enhance the farm-level availability of credit can encourage farmers to produce tradable crops that require substantial expenditures on inputs, to generate the quality required for sale in export markets. In the absence of affordable production loans, farmers will tend to choose non-tradable crops that require fewer purchased inputs (Wichelns 2003). Finally, the above mentioned steps need to be supported by serious efforts to gather relevant country-specific data, particularly, crop requirements in terms of irrigation, land, labor, and capital and the opportunity cost of agricultural water use.

2.2.3 Closing Remarks

Global climate change is expected to further exacerbate existing water shortages in the Middle East region in the near future. Although precipitation is not expected to decrease, temperature increases of 0.6-2.1 ° C would impact the water balance and reduce available resources. Adaptation measures are necessary in view of increased water demand and potential decrease in available water. Most adaptation measures are no-regret options that attempt to develop non-conventional sources of water that can be exploited in the future. The concept of virtual water trade can provide a network to absorb climatic shocks. Virtual water trade presents itself as an alternative source of water to governments confronted with water scarcity, such as in the Middle East region, having an added advantage of being environmentally sound, relieving stress on the indigenous scarce water resources. Furthermore, nations involved in virtual water trade are interdependent on each other with respect to their food trade and food security. Hence, virtual water can be viewed as a diplomatic and economic tool for attenuating conflict potential between nations and creating new enduring modes of international communication (Turton *et al.*, 2000). The strength of the virtual water concept is that it embraces the whole water management in a country or basin and allows a deeper understanding of water use through for example diet description or broader optimization of water allocation between different water uses by incorporating access to external water resources through virtual water trade. This makes the concept a practical policy tool that can be extended to detailed analysis of water resources management, environmental policies, irrigation policy and international trade issues. Until now many of these policy issues have been solved empirically by common sense food policies and strategies in many semi-arid Middle Eastern countries.

On the other hand, for countries to take part in the network of virtual water exchange they need to have access to markets and to be part of a system were a minimum of economic and political stability is guaranteed. At present, access to global markets is not fair, or is perceived to be so, and the playing field is far from being leveled. Furthermore, economically sound water pricing and the globalization process are poorly developed in many regions of the world, whereby many products are put on the world market at a price that does not reflect properly the cost of the water contained in the product. This leads to situations in which water-poor regions subsidize the export of water. Finally, the reliance on trade can hold some risks, including the hazards of deteriorating terms of exchange on world markets, uncertainty of supplies, world market price instability and increasing environmental stress if appropriate policies are not in place (Konandreas, 1996). This could be alleviated by combining food imports with domestic production and storage strategies to respond more easily to unexpected changes rather than relying solely on imports. Yet, developing countries, like most of the MENA countries, have a tougher task, since they lack an adequate legal and institutional framework for setting the much needed strategies for the management of their water resources and their economy at the local level.

References

Allan, T. (1997). „Virtual water“: a long-term solution for water short Middle Eastern economies, Water Issues Group, University of London, http://www2.soas.ac.uk/Geography/WaterIssues/ OccasionalPapers/AcrobatFiles/Occ03.pdf

Beaumont, P. (2002). Water policies for the Middle East in the 21st Century: The new economic realities, *Water Resources Development*, 18(2), 315-334.

Berkoff, J. (1994). „A strategy for managing water in the Middle East and North Africa“. The International Bank for Reconstruction and Development, The World Bank, Washington D.C., USA.

Bouwer, H. (2000). Integrated water management: emerging issues and challenges, *Agricultural Water Management*, 45, 217-228.

Central Intelligence Agency (CIA) (2007). The World Factbook. Online. Available: https://www.cia.gov/library/publications/the-world-factbook/index.html

Conway, D. and Hulme, M. (1996). „The impacts of climate variability and future climate change in the Nile basin on water resources in Egypt.“ *Water Resources Development,* 12 (3), 277-296.

Economic and Social Commission for Western Asia (ESCWA) (1996). „Water legislation in selected ESCWA countries.“ *Report E/ESCWA/ENR/1996/WG.1/WP.3*, Beirut, Lebanon.

Economic and Social Commission for Western Asia (ESCWA) (1999). „Updating the assessment of water resources in ESCWA member states.“ *Report E/ESCWA/ENR/1999/WG.1/WP.3*, Beirut, Lebanon.

El-Fadel M. and Bou-Zeid E. (2003). Climate change and water resources in the Middle East: Vulnerability, socio-economic Impacts, and Adaptation. In *Climate Change and the Mediterranean: Socio-economic Perspectives of Impacts, Vulnerability and Adaptation* (Giupponi C. and Shechter M., ed.). Edward Elgar Publishing Limited. FEEM Series on Economics and the Environment, 53-74.

Haddadin, M.J. (2002). Water issues in the Middlele East challenges and opportunities, *Water Policy*, 4, 205-222.

Hamdy, A., Abu Zeid, M. and Lacirignola, C. (1995). Water resource management in the Mediterranean Basin, *Water Resources Development*, 11 (4), 79-88.

Hamdy, A. and Lacirignola, C. (1997). Environment and water resources: Major challenges. *In: International Conference on Water Management, Salinity and Pollution Control Towards Sustainable Irrigation in the Mediterranean Region*, Italy, September 1997.

Hoekstra, A.Y. and Hung, P.Q. (2002). „Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade“, Value of Water Research Report Series No.11, IHE, Delft, the Netherlands.

Hoekstra, A.Y. and Hung, P.Q. (2005). Globalisation of water resources: international virtual water flows in relation to crop trade, *Global Environmental Change*, 15, 45-56.

Intergovernmental Panel for Climate Change, Data Distribution Center (IPCC-DCC) (1999). <http://ipcc-dcc.cru.uea.ac.uk>. (Feb. 24, 2000)

Intergovernmental Panel for Climate Change, Working Group I (IPCC-WGI) (1996). *Climate change 1995: The science of climate change*, Cambridge University Press, Cambridge, UK.

Intergovernmental Panel for Climate Change, Working Group II (IPCC-WGII) (1996). *Climate change 1995: Impacts, adaptation and mitigation of climate change, scientific-technical analyses*, Cambridge University Press, Cambridge, UK.

Intergovernmental Panel for Climate Change, Working Group II (IPCC-WGII) (1997). *The regional impacts of climate change, summary for policymakers.* R.T. Watson, M.C. Zinyowera, R.H. Moss, and D.J. Dokken, eds., Geneva, Switzerland

Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment (IPCC-TGCIA) (1999). „Guidelines on the use of scenario data for climate impact and adaptation assessment“. Version 1, T.R. Carter, M. Hulme, and M. Lal, eds., Geneva, Switzerland.

Jones, R.G., Murphy, J.M., Noguer, M., and Keen, A.B. (1997). „Simulation of climate change over Europe using a nested regional-climate model. II: comparison of driving and regional model responses to a doubling of carbon dioxide.“ *Quarterly Journal of the Royal Meteorological Society*, 123 (538), 265-.

Jonker, L. (2002). Integrated water resources management: Theory, practice, cases, *Physics and Chemistry of the Earth*, 27, 719-720.

Kabat P., Schulze R.E., Hellmuth M.E., Veraart J.A. (eds.) (2002). Coping with impacts of climate variability and climate change in water management: a scoping paper. DWC-Report no. DWCSSO-01(2002), International Secretariat of the Dialogue on Water and Climate, Wageningen.

Konandreas, P. (1996). Food security after the Uruguay Round, in *Recipe for disaster? Food security after GATT.* Catholic Institute for International Relations: London.

Kumar, M.D. and Singh, O.P., 2005. Virtual water in global food and water policy making: is there a need for rethinking? *Water Resources Management*, 19, 759-789.

Meissner, R. (2002). Regional food security: Using the concept of virtual water. *African Security Review,* 11 (3), http://www.iss.co.za/PUBS/ASR/11No3/Meissner.html.

Nassar Y. H. (2004). Virtual water trade as a policy instrument for achieving water security in Palestine. Israel-Palestine Center for Research and Information. *Israeli-Palestinian-International Academic Conference on Water for Life*, October 2004, Antalya, Turkey.

Postel, S. (1993). *Water scarcity spreading, vital signs 1993,* H. Kane, and E. Ayres, eds., World-Watch Institute, Norton & Co., New York.

Seckler, D., Barker, R. and Amarasinghe, U. (1999). Water scarcity in the twenty-first century, *Water Resources Development*, 15 (1), 29-42.

Strzepek, K.M. (1998). *Handbook on methods for climate change impact assessment and adaptation strategies, chapter 6: water resources*. J.F. Feenstra, I. Burton, J.B. Smith, and R.S.J. Tol, eds., United Nations Environment Programme and Dutch Institute for Environmental Studies.

Tol R.S.J. (1996). „The damage costs of climate change towards a dynamic representation.“ *Ecological Economics,* 19, 67-90.

Turton, A.R., Moodley, S., Goldblatt, M. and Meissner, R. (2000). An analysis of the role of virtual water in Southern Africa in meeting water scarcity: an applied research and capacity building project. Group for Environmental Monitoring (GEM) and IUCN (NETCAB), Johannesburg.

Turton, A.R. (2001). *A strategic decision-makers guide to virtual water.* African Water Issues Research Unit (AWIRU), Centre For International Political Studies (CIPS), Pretoria: Pretoria University.

Water Resources Institute (WRI)/ Earth Trends (2007). Water Resources and Freshwater Ecosystems: Country Profiles. Online. Available: http://earthtrends.wri.org/country_profiles/index.php?theme=2

Wichelns, D. (2001). The role of „virtual water“ in efforts to achieve food security and other national goals, with an example from Egypt, *Agricultural Water Management*, 49, 131-151.

Wichelns, D. (2003). The role of public policies in motivating virtual water trade, with an example from Egypt. *Proceedings of the International Expert Meeting on Virtual Water Trade, UNESCO-IHE Institute for Water Education, Delft, The Netherlands,* December 12-13, 2002.

Wilchens, D. (2004). The policy relevance of virtual water can be enhanced by considering comparative advantages, *Agricultural Water Management*, 66, 49-63.

World Bank (2007). Key Development Data and Statistics: Country Profiles. Online. Available at: http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20535285~menuPK:1192694~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html

Yang, H. and Zehnder, A.J.B. (2002). Water scarcity and food import: A case study for Southern Mediterranean countries, *World Development*, 30(8), 1413-1430.

2.3 The Impacts of Climate Change on Water Resources in Jordan

Ibrahim M. Oroud
Mu’tah University, Kerak, Jordan

Abstract

The impacts of a possible climate change on water resources in Jordan are investigated using a physically based model. Six years of historical daily precipitation and meteorological data for seven stations located in high precipitation zones across the country were combined to provide approximate assessment to the current water resources. Results show that the average annual water yield (W_Y) in the country ranges from ~200 mm/year in a very small enclave to about 5 mm/year in semi desert areas. The average simulated annual W_Y in the central and northern mountains of Jordan (area ~3100 km^2) is around 200-250 million m^3. This figure is congruent with long-term water balance estimates published by the Ministry of Water and Irrigation, Jordan. Estimates of W_Y based on monthly averages deduced from the six-year raw data were compared to daily results to establish if coarser time steps (e.g., a month) can be used as surrogates to establish the impacts of climate change on W_Y. The two data sets produce, on average, similar results, with the daily data producing slightly larger W_Y values.

Climate change scenarios were explicitly perturbed using monthly time steps by reducing precipitation and concurrently increasing air temperature. A temperature increase of 1° C reduces annual W_Y by about 10 % and 17 % in wet and dry areas, respectively. Likewise, a drop of 5 % in precipitation causes around 10 % and 23 % reductions in W_Y in wet and dry areas, respectively. The combined effect of a 2° C increase along with a 10 % drop in precipitation causes ~45 % to 60 % reduction in the annual W_Y. The consequences of a warmer and/or drier climatic conditions in the future will have devastating effects on water resources and agricultural potential in the Eastern Mediterranean.

2.3.1 Introduction

Currently, Jordan ranks the seventh poorest country in the world in its water resources. The average annual renewable water resources in the country are estimated at about 800 million cubic meters (Mm^3) (Ministry of Water and Irrigation, Jordan, 2005). This figure experiences substantial interannual fluctuations due to natural rainfall variability plaguing the Eastern Mediterranean. Anthropogenic factors along with natural forcings have been working hand in hand in exacerbating the water status. The massive population growth, the increased demands for agricultural products, and the establishment of more industrial compounds have put further strains on the very limited water resources in the country. Natural population growth during the past 50 years was about 3.6 % with a doubling period of less than 20 years. The population of Jordan, however, swelled by about 11 times during the past half century (Oroud and Al-Rousan, 2004) which gives a virtual population growth of 4.8 %. More recently, the invasion of Iraq caused mass movement of Iraqis towards Jordan.

The population growth has been paralleled by a similar increase in irrigated agriculture. The area of irrigated land in the Jordan Valley increased from ~15 thousand hectares in the early 1960's to ~37 thousand hectares in 2003. Likewise, irrigated agriculture in the Badia (desert region) increased from virtually nil in the early 1970's to ~17 thousand hectares in 2003 (Ministry of Water and Irrigation, 2005) and is still increasing. The substantial increase in the irrigated agricultural land caused further demands on freshwater. The availability of irrigation water will shrink in the near future, however, because of growing demands on this resource from domestic, industrial, and tourism sectors. For instance, the freshwater needs for the various sectors grew from 1100 Mm^3 in 1990 to 1750 Mm^3 in 2004 (Ministry of Water and Irrigation, 2005). The future water status in the country would indeed look quite bleak should population growth continue unabated and a climate change towards warmer and/or drier conditions prevail in the near future.

Long-term climatological observations provide strong evidence that near surface air temperature in the eastern Mediterranean has been increasing steadily during the past 50 years (IPCC, 2007; Oroud, 2001a; Zhang et al., 2005). Additionally, simulations based on General Circulation Models (GCM) predict that the climate of the Eastern Mediterranean will become warmer and drier in the near future due to the accumulation of greenhouse gases in the atmosphere. There is almost a consensus among most GCM that a global warming will affect the Eastern Mediterranean adversely (IPCC, 2007). Model results suggest that the temperature will rise and precipitation will decline. Model results suggest that air temperature near the ground surface will increase by 1°–3° C following an equivalent doubling of greenhouse gases in the atmosphere. The projections for precipitation amount, its temporal distribution and variability are not as certain. Due to the northward displacement of the polar front during the winter months, however, it is expected that the Eastern Mediterranean will experience less cyclogenic activities, and as such less winter storms (cyclones). This means that precipitation in this region will decline following the proposed climate change. Jordan receives ~75 % of its precipitation in the winter months, December through March due mainly to cyclogenic activities. The other 25 % is received during transitional periods (Spring and Fall) in the form of cyclones and also as thunderstorms activities caused primarily by Red Sea troughs.

It is evident that anthropogenic activities and natural causes work hand in hand to adversely impact Jordan's limited water resources in the very near future. Consequently, serious measures must be taken to alleviate this situation. As such, two questions of operational importance need to be addressed:

1) what would be the near future water needs in the country for the various sectors (domestic, agricultural and industrial)?, and

2) what would be the water status (availability) for the near future following a climate change? Answering these two questions properly is essential for a better assessment of the overall situation of the water status and its allocation for the various sectors.

The objective of the present paper is to address the water status in the mountainous areas of Jordan following a climate change. Seven stations representing to a large extent the rainiest areas in the country are chosen to carry out the investigation. The focus of this paper is on warmer and drier climatic conditions scenarios. No attempt is made to examine the freshwater situation should the climate become more benign (e.g., wetter, cooler temperatures or both). This paper, which is part of the GLOWA Jordan River project, is geared as a risk assessment measure of water resources in Jordan following a climate change in the Eastern Mediterranean.

2.3.2 Future Water Needs

The future water status in Jordan is determined by anthropogenic and natural factors. Fig. 2.3.1 shows the projected population of Jordan up to 2040 using three population growth scenarios (3.4 %, 2.8 %, 1.5 %) and assuming that "quasi-steady state!!" conditions will prevail (i.e., no sudden influxes of refugees, epidemics of infectious diseases, non-conventional wars, etc.)[1]. The first number represents a figure similar to that which prevailed over the past 50 years or so; The second one represents the current population growth, and the third one represents an "optimistic," but unlikely, population growth rate implemented by the government. According to these scenarios, by 2040, the population of Jordan would be between 11 and 22 million people (Oroud and Al- Rousan, 2004). A more likely figure for the population of Jordan by 2040 would probably be around 13-15 million people.

Official figures provided by the Ministry of Water and Irrigation (2005) indicated that current domestic freshwater supply is 200 [2]liter per person/day, which gives a total annual freshwater need of 400 Mm^3. Nowadays, with only 5.6 million inhabitants (excluding fresh refugees), most of the people in Jordan receive a specified amount of water during the summer months, and domestic water is supplied

---

1. The first assumption is bluntly violated. The invasion and subsequent occupation of Iraq caused massive flux of Iraqis seeking refuge in Jordan. Following this occupation, the population of Jordan swelled by more than 15 %-20 %, and the future demographic dynamics may experience worse dilemmas in the very near future.
2. The official figure is 200 litre/person per day. A more realistic figure is close to 100 (or even smaller) litre/(person. day) only. A country with a value < 1000 liter/ (person. a day) is considered water- poor. It should be indicated, however, that the efficiency of water use for domestic purposes in Jordan as a whole is around 50 % only (Ministry of Water and Irrigation, 2005).

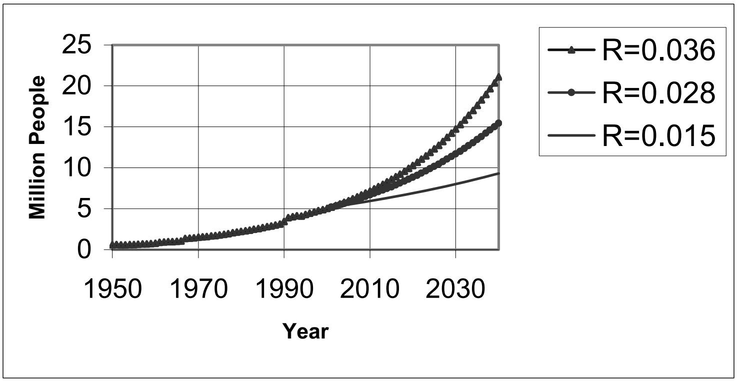


Fig. 2.3.1. Population growth in Jordan during the past 50 years along with the projected number up to 2040.

one day (24 hours) per week. The renewable water resources are not enough to meet the water demands in the country, and as such Jordan has been using intensively renewable and non-renewable fossil freshwater during the past decades. This has caused a steady drop in the level of underground aquifers. The future water needs will progressively get worse as time passes. Projections based on current population growth estimate that the water needs for the various sectors of the country would be close to 2100 Mm^3 by 2015 (Ministry of Water and Irrigation, 2005). By 2025 the domestic water needs alone will be around 700-800 Mm^3. This figure is very close to the total renewable water resources of the entire country even without a climate change.

The agricultural water needs was about 1100 Mm^3 in 2000. By 2015 irrigation water needs is expected to rise to 1200-1400 Mm^3 (Ministry of Water and Irrigation, 2005). The amount of water allocated for irrigation must drop, however, in the near future because of demands by other sectors, particularly domestic. The industrial water needs is expected to be close to 200 Mm^3. Although treated sewage/grey *„water“* is expected to be intensively utilized in the irrigation of certain restricted crops, it is very unlikely that tangential, yet costly, uncertain, and potentially hazardous measures such as this will make any difference. Thus, it is clear that the future water status in the country looks quite bleak even without a climate change. Should the climate of the Eastern Mediterranean become warmer and/or drier, the country will face a tragic freshwater dilemma in the very near future.

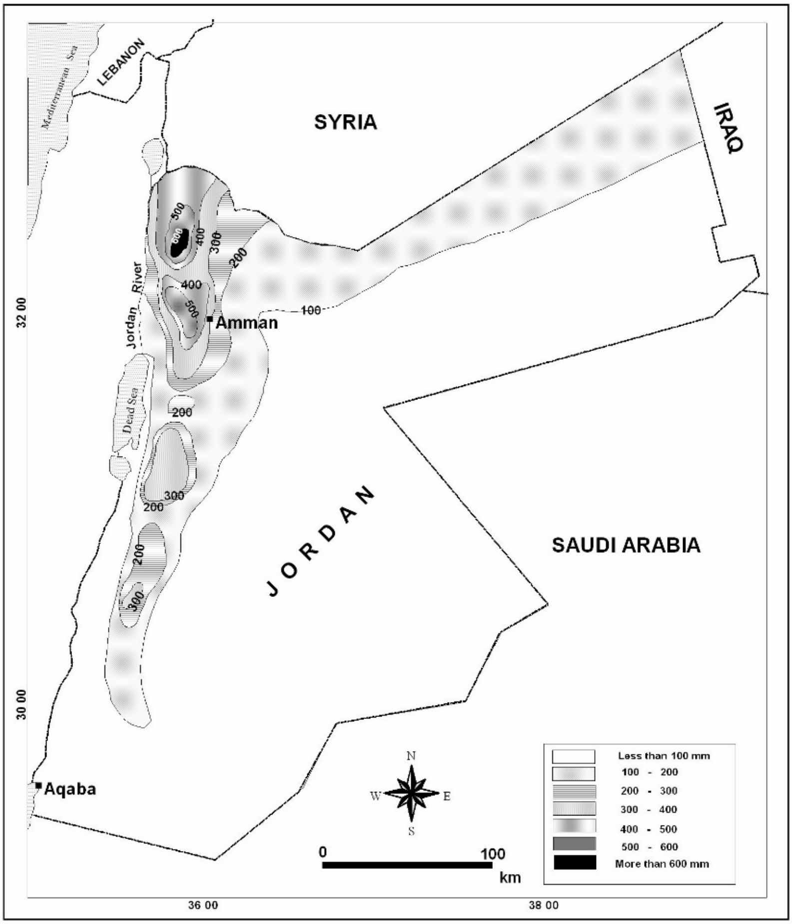


Fig. 2.3.2.a. Average annual rainfall distribution in Jordan.

2.3.3 Study Area and Data Sets

Precipitation in Jordan ranges from less than 5 mm/year in the south eastern corner near the Saudi borders to about 600 mm in limited areas in the northern mountains (Fig. 2.3.2.a). The annual volume of precipitation falling on the country has strong interannual variability, with values during the period 1937-1997 ranging from 17.8 x10^9 m^3 in exceptionally wet years to less than 4.5 x10^9 m^3 in drought-stricken years. The future water status in Jordan is primarily determined by the water balance in the mountainous areas as most of the useful precipitation in the country occurs there. On the one hand, rain-fed agriculture (green water) is cultivated there, and on the other a large amount of surface runoff and subsurface

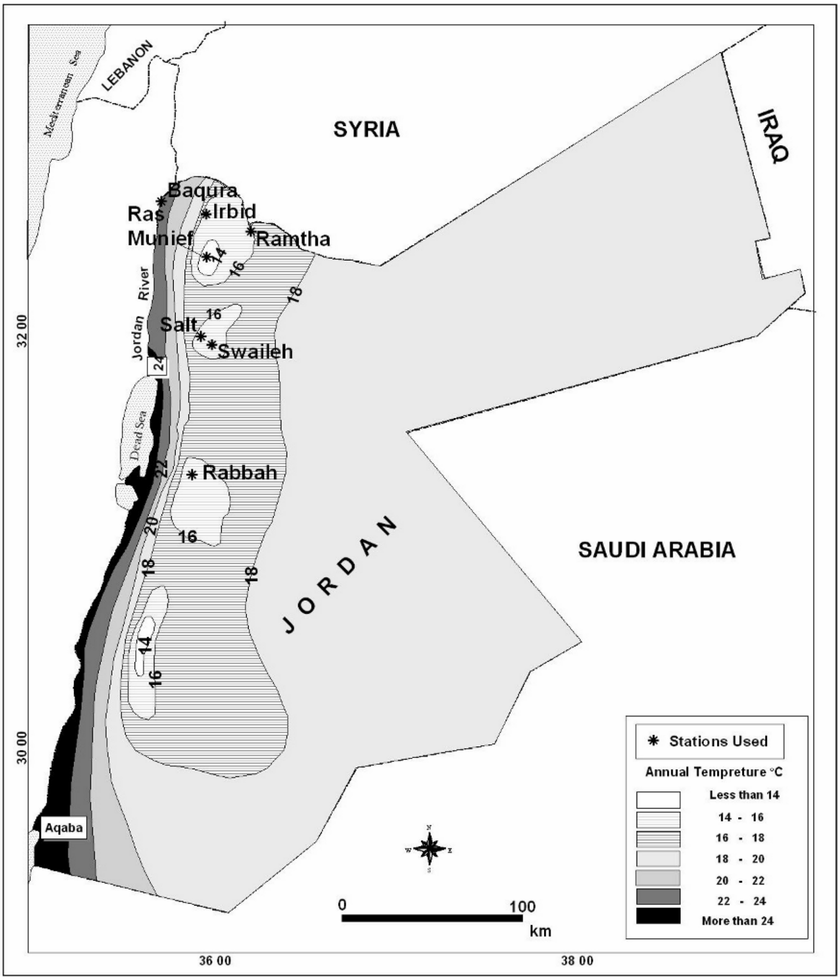


Fig. 2.3.2.b. Average annual air temperature along with the location of stations used in the analysis.

recharge (blue water) originate in these mountains. Furthermore, the eastern Jordan valley relies heavily on precipitation falling on these mountains, with many water dams established on creeks and small wadies flowing towards the Jordan rift.

Six years of daily meteorological data for seven stations obtained from the Department of Meteorology, Jordan were used to establish the current and future water resources in the country (Fig. 2.3.2.b). During the six-year period, the annual precipitation sums ranged from as low as a little more than 100 mm/year in the drier stations to about 770 mm/year during wet years in the humid enclave. This enabled us to capture a relatively wide range of climate variations and how they impact the annual water yield.

2.3.4 Method of Investigation

The Basic Equation

The water balance of an unmanaged catchement may be evaluated using the following equation (e.g., Alley, 1984; Carter et al., 2006; Fowler, 2002; Zhang et al., 2001)

$$\frac{w^{n+1} - w^{n}}{\Delta t} = P - AE - I - Ro \qquad \textbf{(2.3.1.)}$$

Where w^{n+1} and w^n are soil water content at current and previous time steps, t, P, AE, I, and Ro are the time step, precipitation, evapotranspiration, infiltration to the deeper layers, and surface runoff, respectively. For a relatively long period of time (several years), the change in storage (the first term on the left) approaches zero, and I emerges as surface flow, at least in wet environments. For a relatively long period of time (several years), a balance is established between P on one hand and AE and Ro on the other. This fact has been exploited by many investigators to study the hydroclimatology of catchments to evaluate AE and its linkage to the dryness index (e.g., Budyko, 1974; Morton, 1982; Zhang et al., 2001) and precipitation elasticity following a climate change (e.g., Subramanian and Vogel, 2001; Sankarasubramanian et al., 2001). Actual evaporation is driven by meteorological and soil properties forcings,

$$AE = f(P_E, S) \qquad \textbf{(2.3.2.)}$$

Where P_E is potential/reference evaporation and S is hydraulic properties of the soil. Potential evaporation, which is a climatological indicator of the drying power of air, is evaluated using the Penman- Monteith equation adopted by the FAO (Allen et al., 1998). Calculations of the meteorological components (e.g., solar, net radiation, saturation vapor pressure, etc..) are presented elsewhere (e.g., Oroud, 1997; Oroud, 1999, 2001b; Oroud and Nassarallah, 1998).

The Soil Component

The specification of the surface components (e.g., soil texture and depth, vegetation cover and type, slope, geology, geomorphology) is crucial for a proper assessment of the water balance and its ultimate partitioning into blue and green water fluxes (e.g., Alley, 1984; Mwakalila et al., 2002; Mwakalila, 2003; Farmer et al., 2003). For similar precipitation amounts, catchments covered with grass have larger blue water yield than their counterparts covered with trees (e.g., Bradford et al., 2001). The specification of the soil depth profile plays a crucial role in determining water yield in semiarid regions (Farmer et al., 2003). The study area consists of either bare surfaces or covered with annual grass, with a small enclave covered with shrubs and trees. Grass grows during the end of February, and as such most precipitation occurs when the land is virtually grass-free.

The surface layer is broken down into two layers, a shallow upper layer (S_1) with a water holding capacity of 25 mm and a deeper layer (S_2) with a water holding capacity of 125 mm. The choice of these figures influences the water balance components (e.g., surface flow, subsurface recharge, actual evaporation), particularly for monthly time steps because of the inherent assumption that runoff/ recharge „does not" occur until these layers reach the assumed field capacity. If the water holding capacity is smaller than the figures quoted above, then actual evaporation is expected to be less because the soil reaches saturation with less precipitation and as such surplus water is allowed to occur (e.g., surface flow and subsurface recharge). Although figures quoted above are not expected to hold for entire catchments due to variability in slope, vegetation cover and type (trees, shrubs, grass), land use, soil depth and structure, they, however, provide a realistic approximation giving the large spatial geographic extent of the study area.

Two time steps are used in this paper, a daily one and a monthly one. In the daily time step, with the exception of one station, water is allowed to spell over (runoff/ underground recharge) if the field capacity of both layers was reached or when daily precipitation exceeds 20 mm. For Ras Munief station, water surplus occurred when precipitation exceeded 25 mm because land cover there is composed of bushes and scattered trees. The above assumption is deduced from author's experience. It was frequently noted that runoff over natural lands in the mountainous areas of Jordan occurs, in general, when daily precipitation exceeds 20-25 mm. For monthly time steps, blue water is allowed to occur only when the field capacity of both layer is reached. This assumption is probably valid for average conditions.

In this formulation, water is supplied to the soil layers when precipitation exceeds evaporation. The upper soil layer must reach saturation before any recharge goes to the lower layer,

$$R_{upper} = P - P_E\text{: P} > P_E \tag{2.3.3.}$$

$$R_{deep} = P - P_E\text{: P} > P_E \text{ and } \mathrm{S}_1\text{: saturated} \tag{2.3.4.}$$

Where $R_{upper,}$ and R_{deep} are water recharge to upper and deeper layers, respectively, P is precipitation. When both layers ($S_{1,}$ S_2) are saturated and precipitation exceeds evaporation, then blue water occurs,

$$R_{off} = P - P_E\text{: P} > P_E\text{; } \mathrm{S}_{1,2}\text{: saturated} \tag{2.3.5.}$$

Actual evaporation (A_E) is identical to reference evaporation when precipitation exceeds or equal to reference evaporation.

$$AE = P_E\text{: P} \geq P_E \qquad \textbf{(2.3.6.)}$$

When precipitation is less than reference evaporation, then water loss by evaporation (actual evaporation) represents the sum of precipitation and water extracted from the two soil layers,

$$A_E = P + \delta S_1 + \delta S_2\text{: P} < P_E \qquad \textbf{(2.3.7.)}$$

$$S_1 > P_E > P\text{: S}_1 = \delta S_1 - P_E \qquad \textbf{(2.3.8.)}$$

$$S_1 < P_E > P\text{: } \delta S_1 = S_1 \qquad \textbf{(2.3.9.)}$$

More specifically, evaporation from the upper layer is readily available for evaporation, and as long as moisture in this layer exceeds the water deficit, then evaporation proceeds at its potential to satisfy this deficit. If water demand exceeds the capacity of the first layer, then moisture extraction function follows a linear pattern proportional to moisture in the two layers,

$$\delta_{S_2} = P_E - (P + \delta_{S_1})\frac{S_2}{F_C(S_1,\mathrm{S}_2)} \qquad \textbf{(2.3.10.)}$$

Where δS_2 is the change in water in the deeper layer, S_2 is water amount in the deeper soil layer, and $Fc(S_1,S_2)$ is the total water holding capacity of the two soil layers. The above equation is widely documented.

2.3.5 Results

Current Water Yield

The previous conceptual model was used to calculate the annual water yield based on daily simulation for the seven stations during the six-year period. Fig. 2.3.3.a shows the linkage between annual W_Y and annual precipitation based on daily sums of W_Y,

$$\mathrm{W_Y} = \sum_{i=1}^{n} W_{yi} \qquad \textbf{(2.3.11.)}$$

Where n is the number of days in the year (the Eastern Mediterranean receives precipitation during the cold months of the year, usually October through April). There is a curvilinear relationship between precipitation and W_Y, with the latter ranging from virtually zero when precipitation is ~200 mm/year to approximately 300 mm/year when annual precipitation ~800 mm. This relationship is well docu-

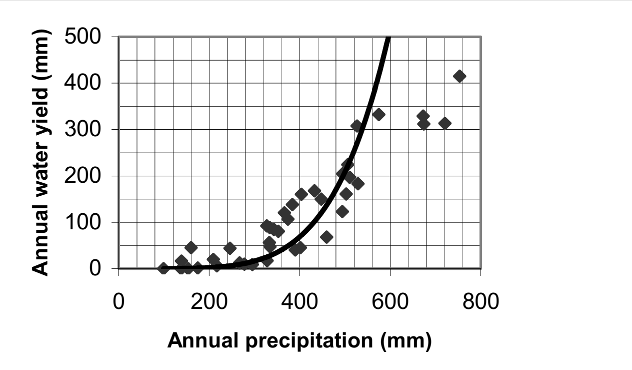


Fig. 2.3.3.a. Relationship between annual precipitation and annual water yield in the seven stations based on six years of daily calculations.

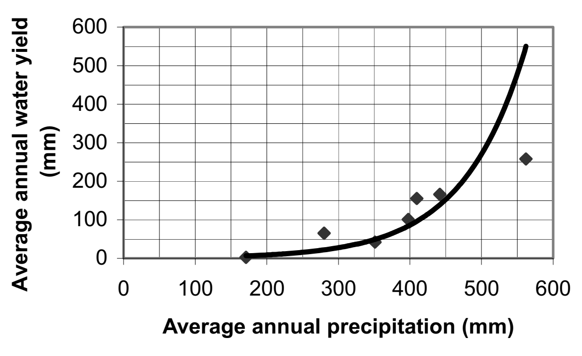


Fig. 2.3.3.b. Same as 2.3.3.a but for the average of the six-year period.

mented in the literature (e.g., Budyko, 1974; Bradford et al., 2001; Zhang et al., 2001). Fig. 2.3.3 shows the six-year average for each station, and a relation similar o that in Fig. 2.3.3.a is established, with less scatter, of course. When water yield is plotted against the index of dryness $\phi = (\sum PE)/(\sum Pi)$ (not shown here), the fit becomes more pronounced. Although the number of cases is limited, the linkage is quite clear and resembles documented data in the literature (e.g., Zhang et al., 2001; 2004).

The total average annual W_{YT} in the mountainous areas, which represent the major water resources in the country, may be approximated.

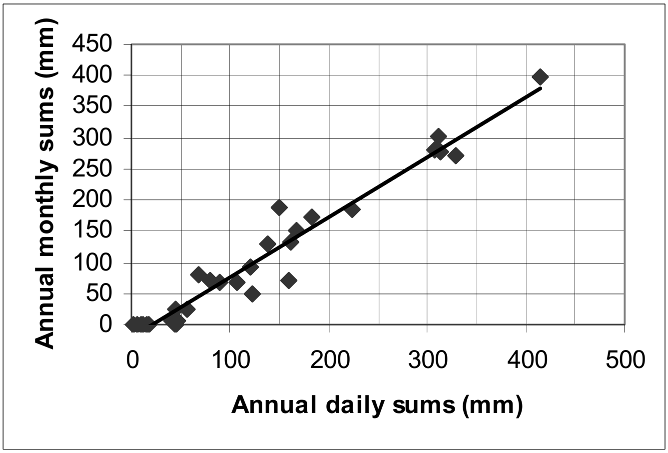


Fig. 2.3.4. Monthly versus daily estimates of annual water yield in five stations during the six-year period.

$$W_{YT} = \sum_{i}^{n} W_{Yi} A_i \qquad \textbf{(2.3.12.)}$$

Where W_{Yi} is average annual water yield in area i, and A_i is $_i$th area with a given precipitation. The incremental sums give an approximate annual average of ~ 200-250 x 10^6 m^3 of blue water per year. This figure is congruent with long-term water balance estimates provided by the Ministry of Water and Irrigation, Jordan (2005). This lends support to the applicability of the present model in generating authentic outputs.

Water yield based on daily and monthly calculations are also compared (Fig. 2.3.4). The two estimates are close to each other, with daily calculation providing more realistic estimates at the lower precipitation values/drier regions. For instance, daily calculations show that W_Y could occur at relatively small annual precipitation sums. For daily time steps, runoff or underground recharge is expected to occur following a large rain storm, whereas for monthly time scales no runoff/recharge occurs unless the soil bucket is completely „filled". Daily calculations give slightly higher W_Y. Giving the many uncertainties involved in climate change projections, monthly time steps would probably be quite sufficient for W_Y projections following a climate change (e.g., Matondo et al., 2004; Nash and Gleick, 1991).

Table 2.3.1. Climate change scenarios used in the analysis.

Temperature Change (δT: ° C)	Precipitation Percentage		
0	100	95	90
+ 1.0	100	95	90
+ 2.0	100	95	90

2.3.6 Projected Water Yield

Water yield is simulated for the six-year period with explicit perturbations to both temperature and precipitation. Table 2.3.1 shows the climate change scenarios. These scenarios provide a „pessimistic“ look at the future water status in Jordan, and no attempt is made, however, to simulate benign climatic changes (e.g., more precipitation following a plausible climate change). The simulations were carried out for monthly averages of six years of historical data for four stations.

The effect of climate change on W_Y is affected by the specific climate zone. For instance, a temperature increase of 1° C reduces annual W_Y from a minimum of 9 % as is the case for central Jordan to 17 % in a drier location in southern Jordan. A 5 % drop in annual precipitatio.n reduces annual W_Y from a minimum of 10 % in the most humid area of the country to a maximum of 23 % in the drier realms in the south. Fig. 2.3.5.a - 2.3.5.d) show the response of average annual W_Y in four mountainous locations calculated over a historical period of six years following different climate change scenarios. With a 2° C temperature increase along with a 10 % reduction in precipitation, annual water yield decreases by about 40 % - 60 % in these mountains. The sensitivity to climate change is more pronounced in drier regions (see e.g., Wigley and Jones, 1984; Farmer et al., 2003). Assuming that other things are constant (e.g., little effect on water use efficiency due to increased CO_2, little changes to precipitation intensity, etc..) this means that the country will lose at least 50 % of its renewable water resources following a climate change. It should be indicated further that a large portion of the country is arid and semiarid, which means that W_Y there will more likely vanish following warmer, drier conditions. It is clear that a climate change will aggravate the fresh water status in the country severely.

Following a climate change the atmosphere will likely become more energetic due to increased atmospheric moisture a, it is more likely that precipitation intensity would be stronger. Such changes will affect the partitioning of precipitation into runoff/recharge and green water fluxes. Although the figures presented above are approximate reproduction of what to expect given the many uncertainties and complexities of a climate change, they, however, provide the best available indicator of the future freshwater status in the country. Such a projection should be used as an approximate tool to guide the decision-making process and planning for future scenarios.

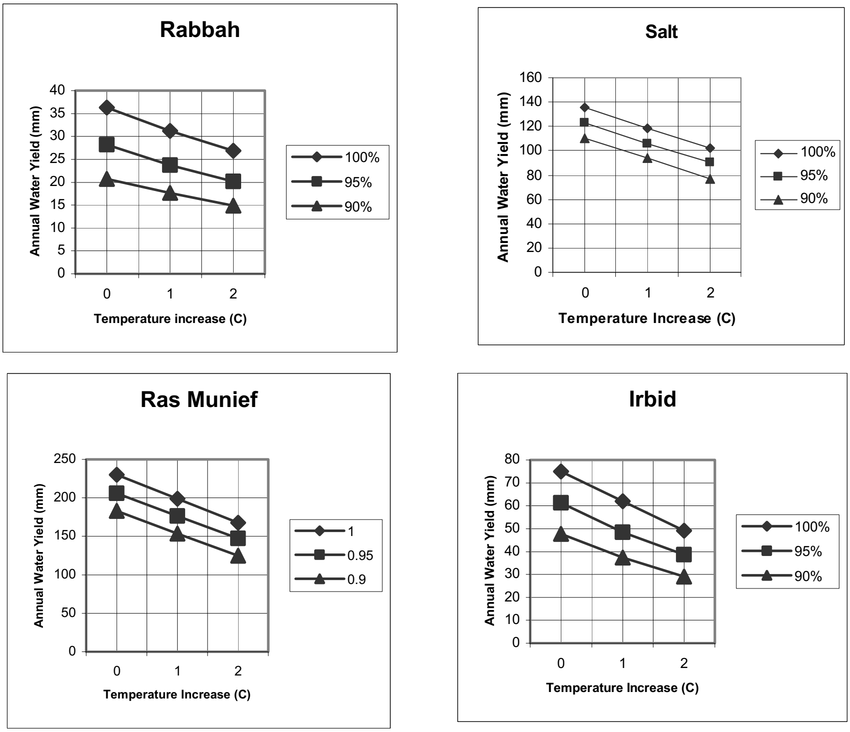


Fig. 2.3.5.a. - 2.3.5.d.
Annual water yield response to climate change scenarios in four stations calculated based on six years of historical data (**a.** Rabbah, **b.** Salt, **c.** Ras Munief, **d.** Irbid.)

2.3.7 Discussion and Conclusion

The Eastern Mediterranean already suffers substantial freshwater shortage in all sectors. Anthropogenic and natural forcings are geared to worsen the water status in the near future. There has been a substantial population growth during the past half a century, and this trend is expected to continue albeit at a lower rate. A climate change towards drier and/or warmer conditions, as predicted by GCM, will aggravate the freshwater situation further. The consequences of such changes will lead to economic, political, social and environmental turmoil. Results obtained in this paper, although qualitative, indicate that W_Y in the mountainous areas of Jordan will substantially decrease following a climate change. With a 2° C and 10 % reduction of precipitation, water yield will decline by about 40 % - 60 %.

Although the picture painted in this paper is pessimistic, there are a few options that can be taken to mitigate the adverse consequences of a drier and/or warmer climate changes in the future. One such measure would be for the government to implement measures to improve water use efficiency in the agricultural and domestic sectors, and to seek new water options (e.g., connection of the Dead Sea with the Red Sea; water harvesting at small and large scales). The rapid population growth along with the increased demands by the industrial and tourist sectors will force the decision makers to reallocate freshwater from agricultural use to domestic supply. In addition to its impacts on water resources, a climate change will have debilitating consequences on the agricultural sector, both irrigated and rain-fed, the grazing potential, and the natural habitat (see also Harding, 2005). It may be concluded that a climate change in the Eastern Mediterranean will have environmental, political, economic and social ramifications, and thus more cooperation at regional and international levels is needed to mitigate the adverse impacts of climate changes in this area.

Acknowledgement

This paper was carried out as part of the Glowa Jordan River Project (phase II) which is funded by the Federal Ministry of Education and Research, Germany.

References

Allen, R.G., et al., 1998, ***Crop evapotranspiration guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56***, Food and Agriculture Organization of the U.N., Rome.

Alley, W. M., 1984, On the treatment of evapotranspiration, soil moisture accounting, and aquifer recharge in monthly water balance models, ***Water Resou. Res., 20***, 1137-1149.

Bradford, A., Zhang, L., and Hairsine, P., 2001, Implementation of a mean annual water balance model within a GIS framework and application to the Murray-drainage basin, ***Tech. Report, 01/8***, Cooperative Research Center for Catchment Hydrology, Australia.

Budyko, M. I., 1974, ***Climate and Life***, 508 pp., Academic, San Diego, Calif.

Carter, J. M. & Driscoll, D., 2006, Estimating recharge using relations between precipitation and yield in a mountainous area with large variability in precipitation. ***J. Hydrol. 316***, 71-83.

Farmer, D., Sivapalan, M., and Jothityangkoon, C., 2003, Climate, soil and vegetation controls upon the variability of water balance in temperate and semiarid landscapes: Downward approach to water balance analysis, ***Water Resour. Res., 39,(2), 1035,*** doi: 10.1029/2001wr000328,2003.

Fowler, A., 2002, Assessment of the validity of using mean potential evaporation in the computation of the long-term soil water balance, ***J. Hydrol., 256***, 248-263.

Harding, L.E., 2005, Climate change and biodiversity: A global perspective, Presented at: ***Implications of Climate Change in BC's Southern Interior Forests***, April, 26-27, Revelstoke, B.C., Canada.

IPCC, 2007, Climate Change 2007: The Physical Science Basis, Geneva.

Matondo, J.I., Graciana, P., Msibi, K.M., 2004, Evaluation of the impact of climate change on hydrology and water resources in Swaziland, ***Phys. Chemist. Earth, 29***, 1181-1191.

Ministry of Water and Irrigation, 2005, ***Water and Agriculture in Jordan*** (in Arabic), Amman.

Mwakalila, S., 2003, Estimation of stream flows of ungauged catchments for river basin management, ***Phys. Chemist. Earth, 28***, 935-942.

Mwakalila, S., Feyen, J., and Wyseure, G., 2002, The influence of physical catchment properties on baseflow in semiarid environment, ***J. Arid Env., 52***, 245-258.

Oroud, I.M., 1997, ***Principles of Physical Climatology*** (in Arabic), Amman, Jordan, 208 pp.

Oroud, I.M.,1999 Temperature and evaporation dynamics of saline solutions. ***J. Hydrol, 226***, 1-10.

Oroud, I.M., 2001a, ***Climate Change in the Balance*** (in Arabic), Amman, 256 pp.

Oroud, I.M., 2001b, A new formulation of evaporation temperature dynamics of saline solutions, ***Water Resour. Res. 37***, 2513-2520.

Oroud, I.M., and Nassarralah, H., 1998, Incoming longwave radiation enhancement by cloud cover, ***Phys. Geogr., 19***,256- 270

Oroud, I.M. & Al-Rousan N., 2004, Urban encroachment on rain-fed agricultural lands in Jordan during the second half of the 20th century. ***The Arab World Geographer, 7,*** 165-180.

Sankarasubramanian, A., Vogel, R. & Limbrunner, J. (2001) Climate elasticity of stream flow in the United States, ***Water Resour. Res. 37***, 1771-1781.

Wigley, T.M., and Jones, P.D., (985) Influence of precipitation changes and direct CO2 effect on streamflow, ***Nature, 314***, 149-152.

Zhang, L.; Dawes, W.R., Chiew, & Walker, G.R., 2001, The response of mean annual Et to vegetation changes at catchment scale. ***Water Resour. Res. 37***, 701-708.

Zhang, L., Hickel, K., Dawes, W.R., Chiew, F.H.S., Western, A.W., and Briggs, P.R., 2004, A rational function approach for estimating mean annual evapotranspiration, ***Water Resour. Res., 40, W02502***, doi:1029/2003WR002710.

Zhang, X., Aguilar, E., Sensoy, S., Melkonwan, H., Tagiyeva, U., Ahmad, N., Kutaladze, N., Rahimzadeh, F., Taghipour, A., Hantosh, T.H., Albert, P., Semawi, M., Ali, M.K., Al-Shabibi, M.H.S., Al-Oulan, Z., Zatari, T., Khelet, I.A., Hamoud, S., Sagir, R., Demircan, M., Eken, M., Adiguzel, M., Alexander, L., Peterson, T.C. & Wallis, T., 2005, Trends in Middle East climate extremes indices from 1950 to 2003. ***J. Geophys. Res. 110***.

2.4 Impact of Climate Change on Water Resources of Lebanon: Indications of Hydrological Droughts

Amin Shaban
National Council for Scientific Research, Remote Sensing Center,
Riad El-Solh St., P.O. Box 11-8281, Beirut, Lebanon

Abstract

As a global meteorological process, change in climate conditions has become a serious topic that many researchers work on. However, data availability is still the major problem to analyze this process. Lebanon, as a Mediterranean region is influenced by climate change, which is viewed not only from fluctuation in the climatic elements, but also from its influence on the regime of water resources. These resources show an abrupt volumetric decrease in water supply, the so-called *„hydrologic drought“*. Thus accusation of water shortage has become a national issue. The study of this phenomenon is tackled through analyzing different indices of surface and subsurface water, thus comparing different records on graphical illustrations and numeric values. Results of this application in Lebanon revealed an obvious decline in the amount of available water. This decline shows a variance between different sources. However, those which are not in a direct touch with human, like precipitation and snow cover, are less influenced and a decrease of 12-16 % was resulted. These two elements directly represent the climate impact on water inputs. While, this percentage gets higher in the case of rivers and groundwater, in which their decrease ranges between 23-29 %. This adds the human interference to the climatic conditions, which is due to over exploitation form groundwater and rivers. Moreover, the number of springs and their discharge as well as the number of local reservoirs exhibits the most excessive influence, Consequently, it was reduced to 43 % and 79 % for the springs and local reservoirs; respectively. This high percentage is attributed to the dependence of human on these two sources. The obtained results in this study are quite alarming and expose a dramatic exceed in the level of hydrologic drought in Lebanon that would be worth taking decision as soon as possible to water conserve by following a wise-use of water resources.

Key words: *water resources, climate change, descending tend, Lebanon*

2.4.1 Introduction

Recently, climate change has been raised as a global issue that covers all regions of the world. It followed with different human implements to assess mitigate its impact on the whole globe, with particular concerns to sensitive areas. However, several explanations and scenarios have been made using different approaches of analysis to evaluate the status-quo of climatic trends in space and time.

The Mediterranean region, as a typical example, is witnessing the impact of change in climatic components, which is mainly reflected by the decline in its water resources. In the Mediterranean region, rapid population growth and industrialization are imposing rapidly growing demands and pressures on the water sources, thus the demand in the 20th century has increased by 60 % in the last 25 years. Also, in a short period of one generation, in a country after the other, the picture has changed from one of relative abundance to one relative sacristy (Hamdy and Lacirignola, 2005). Therefore, an obvious water shortage is essentially resulted over time and thus refereed as a „*Drought*“ phenomenon. It is a creeping phenomenon of natural hazard, drought makes it difficult to determine its onset and end.

Likewise for desertification, drought should not be viewed as merely a physical phenomenon; however, it is the result of interplay between a natural event and the demand placed on water supply by human-use systems. It has become a common feature of long-term natural hazards in many regions of the world. It is negatively reflected on significant economic, environmental, and social aspects. Thus, it is among the most complex and least understood of all natural hazards.

Normally, climatic variability expresses the initial stage of drought, thus originates two major meteorological elements:

1. Precipitation deficiency over an extended period of time including volume, intensity and timing
2. Increase in temperature, wind velocity and sunshine, and decrease in relative humidity and cloud cover

Drought should be considered relative to some long-term average condition of water productivity and balance between precipitation and evapotranspiration, in a particular area. It is also related to the timing (i.e., principal season of occurrence, delays in the start of the rainy season, occurrence of rains in relation to principal crop growth stages) and the effectiveness (i.e., rainfall intensity, number of rainfall events) of the rains. Other climatic factors such as high temperature, wind, and low relative humidity are often associated with it in many regions of the world and can significantly aggravate its severity.

Many classifications have been done to diagnose drought types. Namely, hydrological, meteorological, agricultural and socioeconomic are the most frequently used types. However, all these types are water-related and attributed, in a broad sense, to climate change as an initial process (Fig. 2.4.1). In addition, human influence has a minor role in the process of climate change. This can be viewed from the impact of negative human activities, such as industries, forestation, smoke effect, etc.

Viewing it from a *Meso* (national) scale, water resources in some countries such as Lebanon have more today than they are capable to manage through deficiencies existed. Other states such as Jordan and Palestine presently are consuming about 15 % more water than is annually renewable. Amery and Wolf (2000).

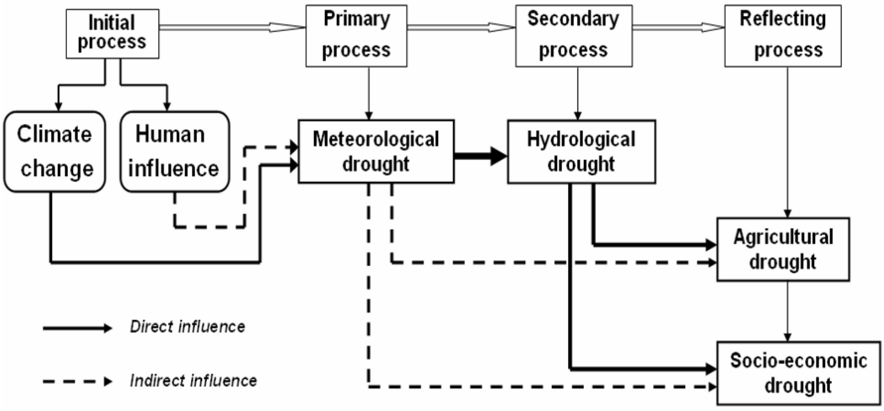


Fig. 2.4.1. The sequence of drought process and its major types.

Lebanon, as a Mediterranean country is witnessing a drought condition, which is definitely observed from the change in its climate events and trends that followed by decrease in the amount of water from different sources. This, in combination with the rapid increase in population size, results in a shortage in water availability per capita. Therefore, obtained scenarios showed that human quota of renewable fresh water in Lebanon will be declined from 1900 m^3/year to 1100 m^3/year between 1990 and 2025 (UN, 1994).

This study aims to quantify the hydrologic drought that conditioning Lebanon. As well as to evaluate its trend in space and time, certainly for the last few decades when data started available and human interference took place. For this purpose, several tools of analysis were utilized in this study. Mainly, meteorological and hydrological records as well as remotely sensed data.

2.4.2 Concept and indices of hydrologic drought

In a simple definition, hydrologic drought is a period of time below the average water content in streams, reservoirs, aquifers, lakes and soils (Yevjevich et al., 1977). This period is associated with effects of precipitation (including snowfall) shortfall on surface and subsurface water supply, rather than with direct shortfalls in precipitation. The frequency and severity of hydrological drought often defined on a watershed or hydrologic system scale. Although all droughts originate with a deficiency of precipitation, hydrologists are more concerned with how this deficiency plays out through the hydrologic system.

Accordingly, monitoring hydrologic drought mainly needs controlling indices of change in water storage among different hydrologic systems. These indices can be viewed from the volumetric decrease in both surface and subsurface water sources, which are influenced by climatic conditions and human overexploitation.

Identification of these indices helps characterizing drought condition spatially and temporally as well as its intensity, duration, and severity (Redmond, 1991). Each of the indices has different description with respect to water shortage.

Table 2.4.1 shows the major indices represent the hydrologic drought. It includes precipitation, as a major index, though precipitation often referred by many researchers only to meteorological drought; however, it is included here because it is considered as an integral component of the hydrologic cycle and has a major role in water regime.

Particular indices of hydrologic drought exist in specific regions. In other words, not all indices exist in the same region. For example, snow cover can be utilized as a drought index in some regions like Lebanon, but it would not be so where it does not exist like Egypt.

Several measures have been established to study drought indices. They mainly depend on equations to attain numerical values, thus inducing the existence of drought and its magnitude of impact. However, most of these measures involve meteorological components, notably precipitation as a fundamental parameter. The major known measures of these indices are:

- Percent of Normal: and it is computed by dividing the actual precipitation by the normal precipitation, which is typically considered to be a mean of 30-year (Manacelli et al. 2005). It is expressed by the following equation:

$$I = \frac{\langle P \rangle}{\langle P \rangle_{30}} \times 100$$

Where values of the index less than 100 means drought conditions exist.

- Deciles: in which the distribution of the time series of the calculated precipitation for a given period is divided into interval each corresponding to 10 % of the total distribution (*decile*). Gibbs and Maher (1967) proposed to group the deciles into classes of events (Table 2.4.2)
- Palmer Hydrological Drought Index (PHDI): which integrates water supply (precipitation) with water demand (evapotranspiration as computed from temperature) in a soil moisture model (Palmer, 1965),
- Standardized Precipitation Index (*SPI*):
- Surface Water Supply Index (SWSI): is developed by Shafer and Dezman (1982) to complement Palmer index for moisture conditions, which is applied mainly to homogenous region and does not occur for snow. SWSI is designed for surface water as mountains-water dependant, in which snow pack is a major component.

For better assessment of drought condition, notably the hydrologic type, all available indices must be included. In addition, the assessment must be analyzed for long term to figure out a time trend, i.e. at least several years. Whilst, applying

Table 2.4.1. Major indices of hydrologic droughts.

Index	Elements	Criteria
Precipitation	Volume	Long-term decrease
	Intensity	Intensive spills of rainfall
Rivers and Stream	Stream course	Shallow running water High chlorophyll content Low transported bed load
	Discharge	Decrease in discharge at mouth Low water velocity
	Length	Decrease in total tributaries lengths Intermittency in water flow in courses
Spring	Discharge	Decrease in discharge Quality deterioration
	Permanency	Total disappearance of some springs Discharge intermittency
Lake and reservoirs	Water level and quality	Lowering in water level Surrounded mud cracks and sediments Quality deterioration
Snow	Areal coverage	Decrease in snow areal coverage Low dissipation Lower frequency
	Thickness & density	Lowering in thickness Lowering in density
Groundwater	Pumping	Decrease in yield from wells Flow intermittency
	Water table	High depletion in water level
	Water quality	Saltwater intrusion
Soil moisture	Water content	Decrease of water content below normal level

it only for a couple of months as some worker stated (Sibai and Jinad, 2005) does not reveal a comprehensive figure, especially drought is a creeping natural hazard that takes long time to reflect its impact.

2.4.3 Data Requirements and Availability

In accordance with the indices in Table 2.4.1, the following approaches and tools are typically applied to assess and monitor hydrologic drought indices:

1. Locating rainfall gauges in several representative sites and with a uniform geographic distribution,

Table 2.4.2. Tools and data availability of hydrologic droughts indices in Lebanon.

Index	Elements	Tool	Available output	Date	Creditability
Precipitation	Volume	Gauge stations	Records & graphs	1967-2006	Reliable
	Intensity	Gauge stations & TRMM	Records & maps	1998-to date	
Rivers	Discharge	Flow-meters	Records & graphs	1965-2006	Reliable
Spring	Number of springs	Topographic maps	Desk study	1963-2005	Reliable
	Discharge	Flow-meters	Records & graphs	1965-1999	Reliable
Lake and reservoirs	Number of lakes	Topographic maps and aerial photos	Desk study	1963-2005	Partially reliable
	Areal extent	Satellite images	Non-continues measures	1973-2005	Partially reliable
Snow cover	Areal Coverage	Satellite images	Maps	1973-2007	Reliable
Groundwater	Pumping Water table Water quality	Well testing and measure records	Discharge, depth and steady state flow	No regular and continues measures	Partially reliable
	Submarine springs	Airborne survey	Radiometric images	1973 & 1997	Reliable

*TRMM: Tropical Rainfall Mapping Mission extended by NASA.

2. Mounding hydrographs and flow-meters on rivers and springs to record water discharges measures,
3. Fixing scale-levels to measure water level in lakes and ponds,
4. Using remote sensing data (NOAA, AVHRR, MODIS, etc) to monitor snow coverage. This can be also applied to monitor changes in the areal extent of lakes and wetlands,
5. Monitoring groundwater level in aquiferous rock formations, using manometers and water table measures in drilled wells,
6. Using available equipments and laboratory testing to measure soil moisture.

In order to attain reliable measures, human interference must be avoided. For example, measuring stream flow should not influenced by water pumping from stream courses, especially if this pumping changes from year to another. Therefore, measures on source sites would be more creditable, since it has a least influence by human impact.

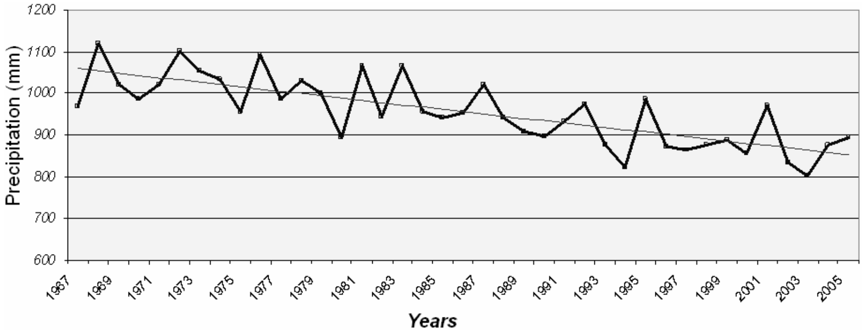


Fig. 2.4.2. The cumulative precipitation rate in Lebanon between 1967 and 2006.

In Lebanon not all favorable measures for drought indices have prefect records. Lack of sequential records and limitations of dates often exist (Table 2.4.2). While, some data are not available at all, like that for soil moisture except for limited sites and specific times.

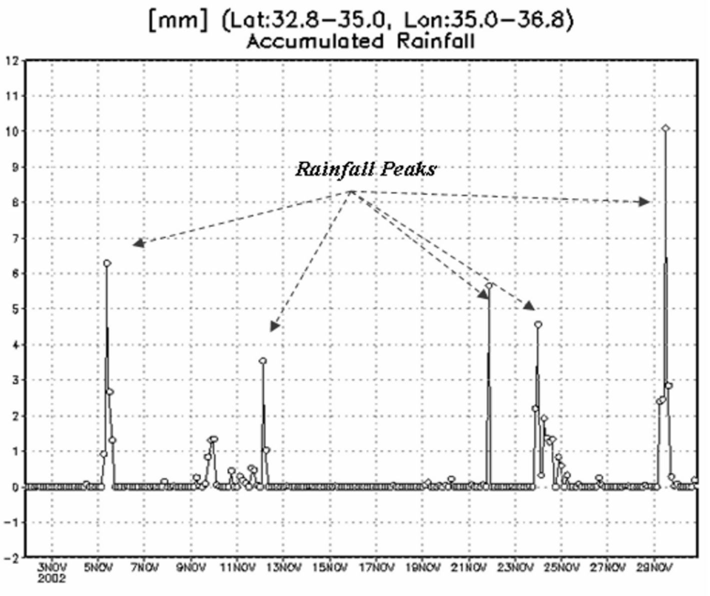
In this study, the assessment of hydrologic indices was obtained depending on graphical analysis of records on time series. This enables to show a complete and comprehensive figure of trends for different hydrological indices.The approaches of data collection (tools) are different from one index to another (Table 2.4.2). They combine between conventional methods of measures through gauging stations and new techniques of remote sensing. However, they are integrated in some instances, like that in the case of precipitation.

2.4.4 Method of Analysis

For the case of Lebanon, likewise many regions of the world, a detailed analysis of the available data was obtained to assess the majority of trends in water resources. Therefore, out of the 7 indices of hydrologic drought (Table 2.4.1), six ones could be analyzed as follows:

Precipitation

Available data on precipitation in Lebanon are found to be reliable to build a complete figure on rainfall trends over more than 40 years, i.e., since 1966, (Fig. 2.4.2). In this study, the precipitation trend was built for the whole Lebanon and not for selective sites. These data were primarily (i.e., until year 1978) from 70 gauging stations distributed over Lebanon, where 64 % of them were in the western part. However, after this date the number of gauge stations was reduced to 11, until 1997, and then increased to 24 ones.



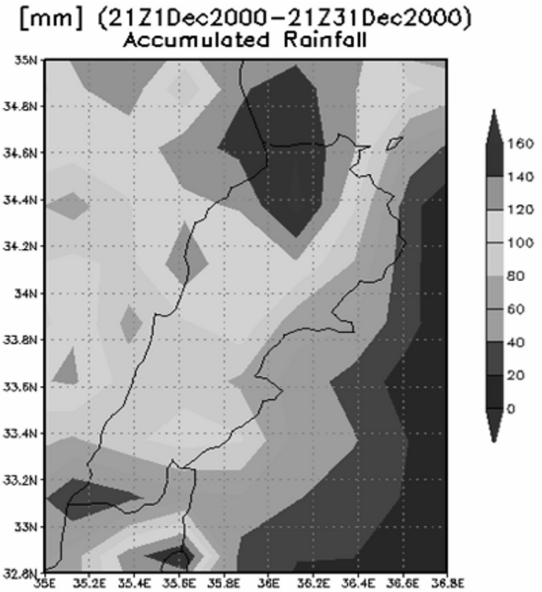


Fig. 2.4.3. Measuring precipitation rate and rainfall peaks using TRMM data in graphic and mappable forms.

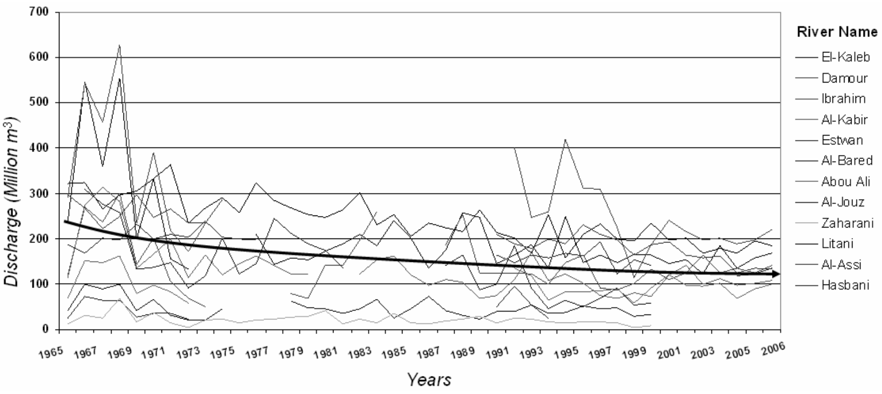


Fig. 2.4.4. Discharge from Lebanese rivers between 1965 and 2006 (LRA, 2006).

Obviously, the major trend is descending and the first decline in precipitation started around the1980s (Fig. 2.4.2). Before this time, the average precipitation rate was 1043 mm, thus it declined to 917 mm (up to 2006), which is equivalent to 12 %

For rainfall intensity, normal graphic plotting was also carried out from the available climatic data till the year 1998 when TRMM (Tropical Rainfall Mapping Mission) was extended by NASA to introduce daily climatic information as images and graphs (Fig. 2.4.3). The accuracy of the TRMM data was verified by comparison between these data and ground data from gauging stations in Lebanon. A clear correlation was observed for the timing of events, although there was some variance in the amount of precipitation recorded, presumably arising from varying geographic coverage and accuracy of measurement.

The number and rates of rainfall peaks were of utmost concern, since they influence flooding events and water losses to the sea. An obvious increase in the number and rate of rainfall peaks was reported, notably in the period after 1980s. Therefore, the average number of rainfall peaks was <15 peak/year and 24 peaks/year for the periods before and after the1980s; respectively. Moreover, the average rate of torrential water from these peaks was between 15-20 mm/day before the 1980s and 18-22 mm/day after.

Rivers

Lebanon occupies 12 permanent watercourses (rivers). Besides, there is about 60 major streams (Wadis) that occupy rain water for few months. Lately, all these watercourses have witnessed an obvious decrease in water level and some are reduced to about 50 % of their normal level.

In a simple method to assess rivers discharge, the available data on rivers flow were graphically presented for the period between 1965 and 2006 (Fig. 2.4.4). However, some measures were lacking due to the damage in hydrographs, which have not re-activated until the beginning of the 1990s.

The hydrographs mounted along the primary courses of the Lebanese rivers were fixed at different confluences and diversions. In addition, many hydrographs fixed on river mouths (outlets). In this study, the interpolated measures of rivers discharge were obtained only for hydrographs along the river mouths.

Even though, there is much turbulence in the discharge rate for each of the located rivers, yet the overall discharge rate is obviously in a descending trend for all issuing rivers (Fig. 2.4.4). It is found that the average discharge rate of the Lebanese rivers was 246 million m^3/year in the year 1965, thus reduced to about 186 million m^3/year in the year 1965, which is equal to 23 % over 40 years.

Springs

Lebanon is known by a big number of springs, which are mostly of the karstic, overflow and fault types. For example in western Lebanon (~ 5000 km^2) there are 853 major springs, in which 60 % are located at altitudes over 750 m (Shaban, 2003). They are, on average, mostly of the 4th class (6.31-28.3 *l*/sec) of known magnitude according to Meinzer classification (1923), but 3rd class is frequent and there 22 springs with 2nd and 1st magnitude (0.283- >2.83 m^3/sec) Meinzer classification.

Two approaches were followed in this study to assess water discharge from the Lebanese springs. First, depends on a comparative analysis for the number of spring over the past four decades, while the second deals with a graphic illustration of the major spring.

- For the number of spring with low discharge, they were found to be reduced since four decades. Even though, many of the existing springs on the topographic maps (plotted in 1963) are now being totally disappeared.
- For the major springs, which are fed from deep aquiferous formations, the increase in the number of well has a role in reducing the number of these springs. Whilst, those springs, which capture water from shallow water-bearing stratum, they merely affected by the decrease in the rate of rainfall. In this study, Lebanon is divided into three areas according to its geomorphologic units. These are: occidental, oriental and the Bekaa plain. In each area the number of springs was counted at the time when the topographic maps were produced in 1963 and recently in 2005 as obtained from field survey data. Table 2.4.3 shows the results of this comparison. It reveals a regression in springs yield reaching to about 50 %.

Table 2.4.3. Comparison between the number of springs in 1963 and 2005.

Geomorphologic unit /Year	Number of spring *		
	Occidental Lebanon	Bekaa plain	Oriental Lebanon
1963	853	345	237
2005	419	196	158
Decrease (%)	52	43	33

* Springs of all magnitudes according to Meinzer Classification (1923)

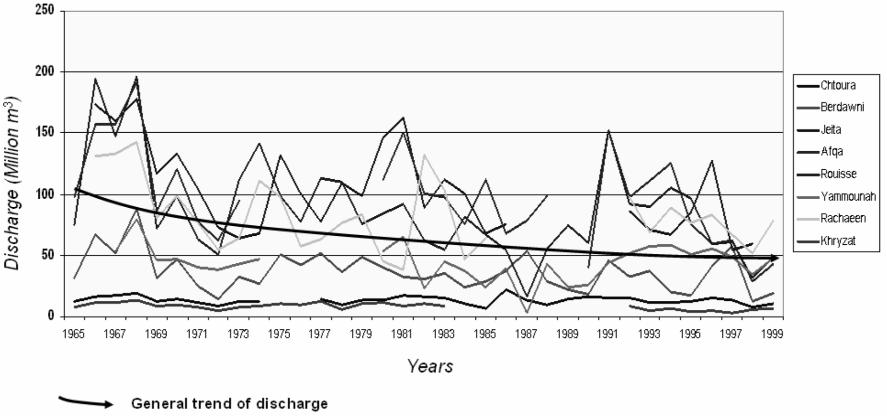


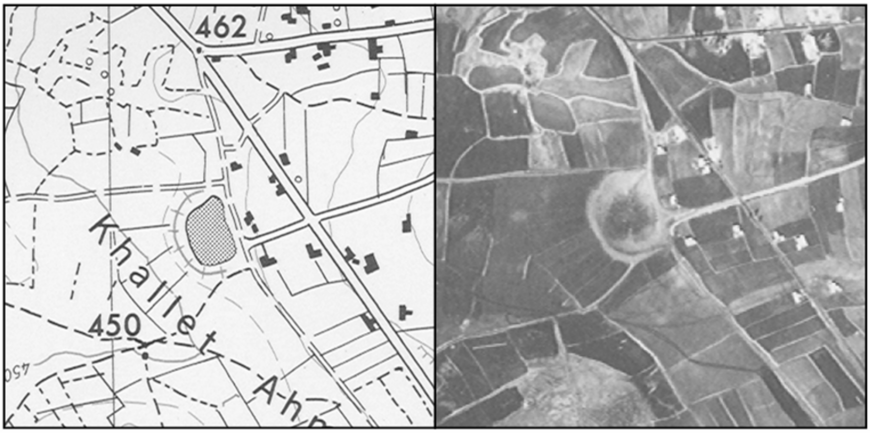
Fig. 2.4.5. Discharge from major Lebanese springs between 1965 and 1999 (LRA, 2006).

For the graphic illustration, no complete records for springs discharge are known. However, for some major ones, discharge measures were obtained in spite of the non-continues recording. Therefore, in this study, nine major issuing springs were investigated. They are typical of the spring type in Lebanon, since they represent the three major types of springs (karstic, overflow and fault springs).

Fig. 2.4.5 shows the trend in discharge from these springs, which is clearly descending and abruptly changed since three decades. The average discharge from these springs was 104 million m^3/year, and reduced to 49 million m^3/year between 1965 and 1999. This is equivalent to 53 % over 34 years.

Lakes and reservoirs

No natural lakes have been occurred in Lebanon, but all known ones are man-made ones and were selected according to their geomorphic setting, which is almost a depression-like shape, thus constructing (local reservoirs). The unique large-scale one is the Qaraoun Lake, which was made in 1962 (Shaban and Nassif, 2007). Thus, human contributed in adapting these localities for surface water storage.



Topographic map

Aerial photo

Fig. 2.4.6. Identification of local reservoirs from topographic map and aerial photo.

Recently, most of know local reservoirs (Berrkah) have been neglected since they became unable to store water due to the less amount of rainfall if compared with last decades. In addition, the only large-scale (4.5 km^2) lake of the Qaraoun has undergone a decrease in its normal area.

- For the local reservoirs, they we assessed by counting them at two different times. First was from topographic maps and aerial photos (Fig. 2.4.6), which were made in 1963, then in 2005 as obtained from high resolution satellite images and field survey.

Results show that: out of 234 known reservoirs in Lebanon during 1963, only 48 are still in use until 2005. While some other ones are remain, but no water storage has been noticed among these reservoirs. This is other than the new built reservoirs with new approaches, the so-called „hill lakes".

- The large-scale reservoirs, and more certainly the unique one in Lebanon the Qaraoun Lake, has undergone many fluctuations in its dimensions. This can be noticed from one year to another according to precipitation rate. However, a general decrease in the lake size is recorded and obviously noticed by the inhabitants. In this respect, a comparative analysis has been applied using the available satellite images to induce these changes with time.

The analyzed satellite images were not in a complete sequential time series and attributed to different dates as follows: 1973, 1984, 1985, 1987, 1989, 1992 and 1997-2005. These dates were adapted from different available satellite images (i.e., Landsat MSS, TM, ETM+, SPOT and ERS) to compose the most continues time order. These images with different resolution (5-120 m) were processed using different software types dedicated for this purpose. Namely, *Erdas Imagine ENVI-4.2* and *PCI.* Therefore, several optical and digital advantages were applied to measure the exact areal extent of the lake at different dates.

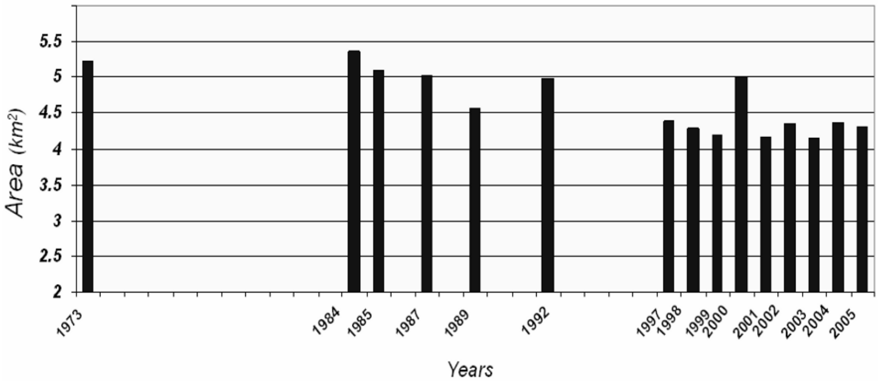


Fig. 2.4.7. Change in Qaraoun Lake area at different years, between 1973 and 2005.

The selected images for processing were of close times, which often in winter to represent the maximum storage in the lake of Qaraoun. Consequently, the width and length of the lake were calculated to measure its area for these years.

Fig. 2.4.7 shows the change in the area of the Quaroun Lake at different years of the period between 1973 and 2005. Even though, the time series is not complete; however, the general trend exhibits reduction in the area of the lake through the investigated dates.

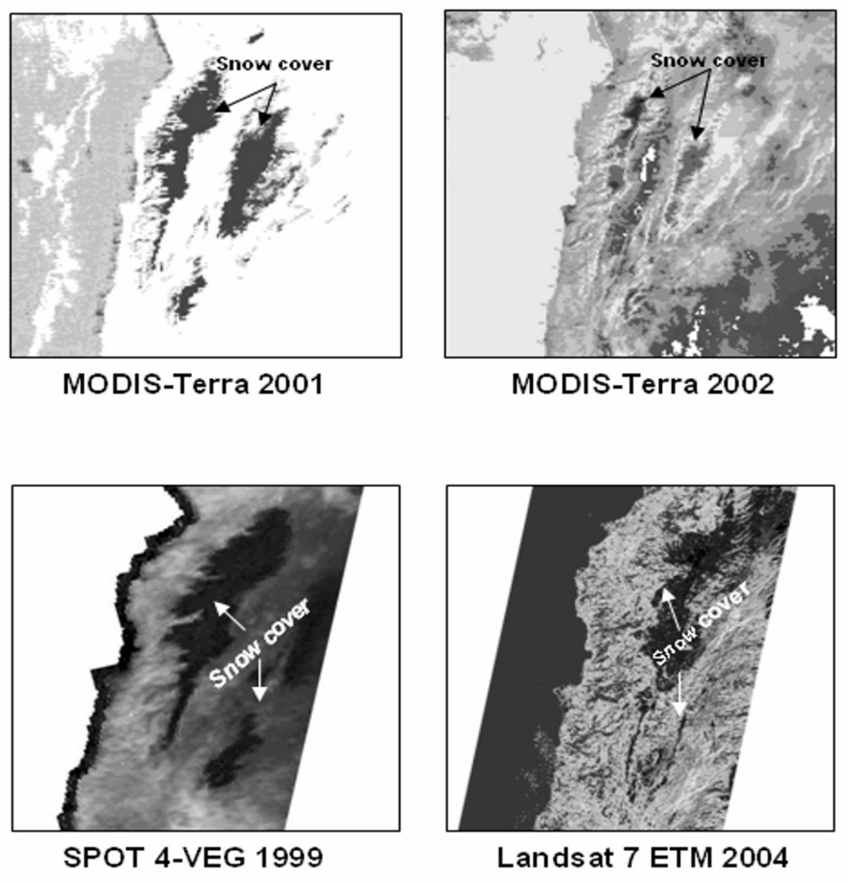
The average area was 5.14 km2 in the period before 1990 and thus decreased to 4.35 after 1990 until 2005, which is equivalent to 15 % of the normal area of the lake.

Snow cover

Lebanon, as a junction between Europe and Asia and located in the Eastern Mediterranean region, receives a considerable amount of snow that covers about 25 % of its terrain (Shaban et al., 2004). Normally, snow covers the regions above 1200 m, thus shapes the mountain chains of Lebanon.

No creditable measures on snow cover have been done in Lebanon; only local measurements for snow depth were obtained for different dates and regions. However, the development of remotely sensed techniques helped estimating the area of snow cover. Yet, this estimation depends on satellite imagery availability.

In this study, the same images used to analyze the Qaraoun Lake were utilized, plus MODIS-Terra images and SPOT 4-Veg., which have 1 km resolution (Fig. 2.4.8). The data on the area of snow cover could be obtained at different periods since 1973 and thus from 1998 until February 2007. The depth and density of snow were not estimated as they need field verification. Nevertheless, the areal extent of snow cover is indicative to the intensity of snow, thus to the amount of water derived from snowmelt (Shaban et al., 2004).The processed MODIS-Terra



MODIS-Terra 2001 MODIS-Terra 2002

SPOT 4-VEG 1999 Landsat 7 ETM 2004

Fig. 2.4.8. Different satellite images at different dates showing the change in snow cover on Lebanon.

images were on a daily basis, but in this study the maximum snow cover was considered for each year (Fig. 2.4.8). The same approaches and softwares, as for the Qaraoun Lake, were used in the case of snow cover.

Analysis of satellite images for different periods show a noticeable decrease in the area of snow cover. This accompanied with a decrease in the residence time (i.e., melting) of dense snow cover as a reflection of the increase in temperature level (Fig. 2.4.9). In this study, dissipated snow cover was not considered, because it does not represent a dense snow, and this was applied for all the analyzed satellite images.

Even though, the number of the analyzed years is not pretty much enough to induce a complete figure of snow cover change, yet they show a general and obvious changing trend. Thus, before 1990s, dense snow often covers more than 2000

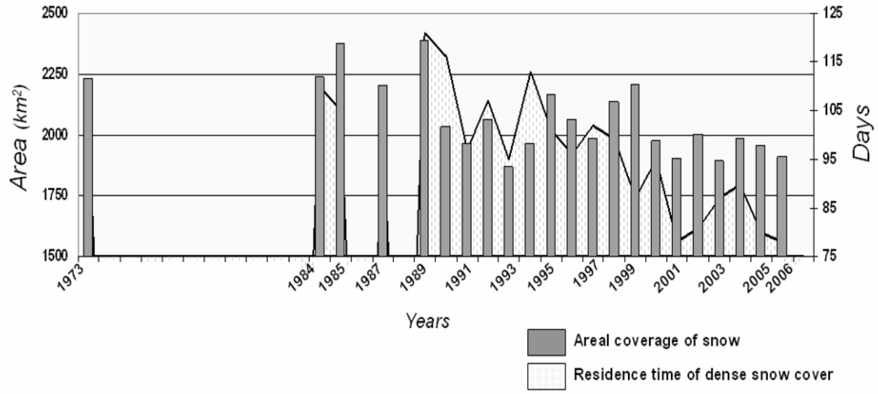


Fig. 2.4.9. Areal extents of snow cover on Lebanon and their residence time.

km^2 of the Lebanese mountains and averaging about 2280 km^2. Lately, it declined to less than 2000 km^2 with an average area of about 1925. In addition, the time that dense snow remains, before melting processes have taken place, was also decreased from 110 days to 93 days.

Groundwater

Groundwater is an important index for hydrologic drought and can give more accurate results, since it is not affected by climatic conditions after the time water percolates downward into aquiferous rock formations. Besides, the chaotic and immeasurable pumping from dug wells into potential aquifers misleads the accurate records of the pumped quantities of water.

In Lebanon, no creditable records for discharged water from dug wells have been made, but decline in water quantity from wells as well as the non-steady state in water pumping are well observed and remarked by wells owners. In addition, the coastal aquifers are witnessing obvious saltwater intrusions that exceeded the known limits (El Moujabber et al. 2005). These intrusions are found even in some coastal stretches where no groundwater exploitation by human exists, like that near Naquora area.

All these elements if mangled together; however, they obviously indicate a regression in groundwater volume with time. In this view, human influences on groundwater regime have an essential role as much as the change in climatic conditions, notably with the excessive exploitation of groundwater that created with population increase.

In this study, a comparison for water discharge from wells has been applied and based on available data from different dates and regions (Fig. 2.4.10). It tackles the major water reservoirs in Lebanon (Cenomanian Limestone aquifer and Jurassic Limestone aquifer) that exist in different regions, even where no groundwater

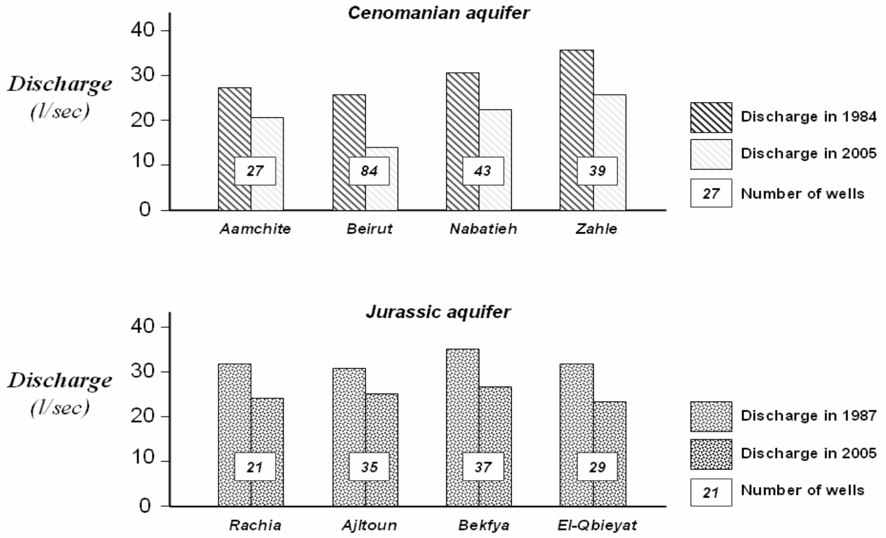


Fig. 2.4.10. Change in the discharge from wells in the major aquifers in Lebanon at different dates.

extraction by human is known, like that near Rachaya area. In the Cenomanian aquifer, 193 water wells were investigated from four different regions to induce the change in water yield between two dates (1984 and 2005). While for the Jurassic aquifer, 122 wells were studied and from another four regions in Lebanon (Fig. 2.4.10).

In both cases, a clear decrease in the pumped water was recorded, notably in the coastal regions, thus reflecting the human over exploitation. The average discharge from wells of the Cenomanian aquifer in 1984 in the four studied regions was 29.5 *l*/sec. It was decreased to 20 *l*/sec. While the in the Jurassic aquifer, the discharge was 31.75 *l*/sec and 23.5 *l*/sec, for 1987 and 2005; respectively.

Of course, the decrease in the discharge from wells in the two aquifers was accompanied with depletion in water table level. This is well recorded in all surveyed wells as well as in several other wells in different regions. Nevertheless, no précised measurable values have been plotted since there is noticeable fluctuation in the depletion in water table. Only, estimates were obtained by several authors. For example, an average drawdown in water table was reported as 20-25 m and 5-10 m in the Cenomanian and Jurassic aquifer; respectively in the area of the Litani River watershed in the last fifteen years (CNRS, 2007).

Accordingly, and as an index of hydrologic drought among the change groundwater regime, in the coastal area of Lebanon has undergone the problem of saltwater intrusion. This phenomenon has been known since three decades, but lately it has got a dramatic increase, notably in areas with high population rate, such as Jbeil, Jounieh, Beirut, Choueifat and Saida.

In this concern, different studies were done for different coastal segments, and all reported an increase in the salinity ratio as well as stretching in the saltwater boundaries to several kilometres on-land. Mainly of these studies those obtained by Lababidi et al. 1987; Hachache, 1993; Khawlie et al. 2003 and El Moujabber et al. 2005.

In addition, the decrease in the number of the groundwater discharges into the sea (i.e. submarine springs) is another index for hydrologic drought in Lebanon, and is it relates to saltwater intrusion. These springs were found to be in an descending trend since three decades. A comparative study was applied to these springs along the coastal stretch between Beirut and Anfeh (North Lebanon). It was found that in 1972 the number of the springs along this stretch was 46 and decreased to 27 in 1997. These results were obtained by FAO (1972) and NCRS, 1997 through airborne survey using thermal infrared.

Conclusion

Likewise, several regions in the world, the Mediterranean countries are witnessing the impact of climate change on different physical processes. In this regard, the most effected process is that related to water resources regime and volume. Thus, a clear decrease in the amount of water has been recognized and affected the social living.

The decrease in water can not be attributed only to climate change, but also to the human interference, either by the increase in population or the improper use of water resources, thus affects the behaviour and the quantity of water and interrupted water budget in many areas.

Even though, the lack of insufficient/or non-continues data on climate and water in Lebanon, yet the decline in water resources is obvious and well sensed. However, different approaches of analysis were applied, but all end up with the same conclusion though the variance in the resulting numbers.

In this study, the major elements of hydrologic droughts were analyzed through comparative assessment of the available data and records on time series. All these elements obviously showed a remarkable decrease in water quantity. However, this decease varies from one element to another, but all are considerable and alarming. Therefore, since the last four decades, the amount of available water in Lebanon is in a descending trend as a result from combination between climate change and human interference.

For the climate, the decrease in the amount of waters is quite similar in precipitation and snow cover, which ranges between 12 to 16 %. While, the decrease is widened in the case of rivers and groundwater and ranges between 23 and 29 %. Thus reflects the human interference as a direct pumping from rivers an over exploitation form groundwater. Besides, the most usable and dependant conventional water resources were highly affected by hydrologic droughts. Thus, the number of springs and their discharge as well as the number of local reservoirs has the most excessive influence, as they were a major source of water in before 1960s. Consequently, it was reduced to 43 % and 79 % for springs and local reservoirs; respectively.

This study, though of lack of some data, exposes a clear figure of hydrologic drought, the phenomenon the spread over vast areas in the world, notably in arid and semi-arid regions. In this regard, sudden implements must be taken to conserve water resource; however, by applying water resources management approaches on a large-scale application.

References

Amery, H. and Wolf, A. 2000. Water in the Middle East: A geography of peace. University of Texas Press.

CAL, 1982. Atlas Climatique du Liban, Tome II. Service Météorologique, Ministère des Travaux publics et Transports, 31p.

CNRS. National Council for Scientific Research. 2007. Final Technical Report on the project: Towards an ecosystem approach to the sustainable management of the Litani River-Lebanon. IDRC & CNRS & LRA and DSA.

DGAC, 2006. Direction Générale de l'Aviation Civile, rapport annuel, Beyrouth, Liban, 32p.

El Moujabber M., Darwish T., Shaban A., Atallah Th., Abi Saab M., and Janho R. 2005. Regional water balance as a tool to monitor groundwater contamination by seawater intrusion on the Lebanese Coast. International Conference on Water, land and Food Security in Arid and Semi-Arid Regions. Mediterranean Agronomic Institute of Bari. 6-11 September, Groundwater management: 1-13

FAO, 1972. Project de développement hydro-agricole du Liban. Thermometric aéoroportée par infrarouge.

Gibbs, W.J.; and J.V. Maher. 1967. Rainfall deciles as drought indicators. Bureau of Meteorology Bulletin No. 48, Commonwealth of Australia, Melbourne.

Meinzer, E., 1923. Outline of groundwater hydrology with definitions: USGS WateSupply Paper, 494p.

Hachache, A. 1993. Origin of water salinity in the coastal Sarafand aquifer (South Lebanon). ONL. Proc. National Conference on Water. Ministry of water, Beirut.

Hamdy, A. and Lacirignola, C. 2005. Coping with water scaricity in the Mediterranaen: What,why and how?. CIHEAM Publishing Bari, Italy. 739p.

Khawlie, M., Shaban, A. and Darwich, T. 2003. Saltwater intrusion in Beirut groundwater and the possibilities to reduce its impact. A conference on Saltwater management and treatment in Beirut area. ESDE, Beirut, Lebanon, 19th Dec, 2003.

Lababidi, H., Shatila, A. and Acra, A. 1987. The progressive saliniation of groundwater in Beirut. Int.Journal of Environmental Stidies. 30:203-208.

LRA (Litani River Authority). 2006. Rivers discharge. Technical information support. LRA, Beirut, Lebanon.

NCRS, 1997. TIR survey for fresh water resources on the marine environment along the coastal stretch of Lebanon. National Council for Scientific Research. National Center for Remote Sensing, Beirut, Lebanon.

Palmer, W.C. 1965. Meteorological drought. Research Paper No.45. US Weather Bureau. NOAA Library and Information Services Division. Washington, D.C. 20852.

Redmond, Kelly, 1991, Climate monitoring and indices, in Wilhite, D.A., Wood, D.A., and Kay, P.A., eds., Drought management and planning: International Drought Information Center, Department of Agricultural Meteorology, University of Nebraska-Lincoln, IDIC Technical Report Series 91-1, p. 29-33.

Shaban, A. 2003. Etude de l'hydroélogie au Liban Occidental: Utilisation de la télédétection. Ph.D. dissertation. Bordeaux 1 Université. 202p.

Shaban, A., Faour, G., Khawlie, M., and Abdallah, C., 2004. Remote sensing application to estimate the volume of water in the form of snow on Mount Lebanon. Hydrological Sciences Journal, 49(4):643-653.

Shaban, A., and N. Nassif. 2007. Pollution in Qaraoun Lake, Central Lebanon. Environmental Hydrology, 11(15)2007. 14 p.

Shafer, A. and L. Dezman. 1982. Development of Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snow pack-runoff area. Proceeding of the Western Snow Conference, pp.164-175.

Sibai, M. and I. Jinad. 2005. Drought definition, impact and management. Expert Meeting on Climate Change Induced in the Arab Region. Damascus, 28-30 March.

United Nations. 1994. World Population Prospects. The 1994 Revision. New York: The United Nations.

Yevjevich Vujica, Hall, W.A., and Salas, J.D., eds., 1977, Drought research needs, in Proceedings of the Conference on Drought Research Needs, December 12-15, 1977: Colorado State University, Fort Collins, Colorado, 276 p.

2.5 The Impact of Global Warming on the Water Resources of the Middle East: Past, Present, and Future

Arie S. Issar
Professor (Emeritus)
Ben Gurion University of the Negev, Israel
J. Blaustein Institutes for Desert Research
Israel
Issar@bgu.ac.il

Summary

The correlation of data from paleo-climate and paleo-environment time series and historical records from different Mediterranean countries shows that global warming in the past caused desertification in this region. Thus the present water shortage may intensify as the globe becomes warmer, and a catastrophic shortage of water in the Middle East due to seems imminent. Based on past records the decrease in the precipitation is estimated to be in the range of 20 % to 30 %. To avoid the catastrophes which happened in the past emphasis should be put on enlarging long-term storage capacity, especially that of groundwater resources, even if this will be to the detriment of the free flow of springs and the quality of the water. At the same time the application and further development of more efficient irrigation methods and the use of waste water should be adopted. Desalination of brackish groundwater and seawater also has to take place. Parallel to this, the planning and implementation of regional projects should begin, to transport water to arid regions from areas with a surplus.

2.5.1 Introduction

The investigations, the results of which are presented in the following chapters, started in 1981 with an invitation by the Division of Water Sciences of UNESCO to join a working group in the framework of the International Hydrolocic Program (IHP). In this framework a research started, which aimed to determine whether the data on past climate changes in the Middle East, and their impact on the availability of water resources, could be used to assess such an impact in the context of a global change. It was found that the climate changes observed in the Middle East can be correlated with the major world-wide changes. A later study focused on the influence of climate changes during this period on the environment and history of the Middle East (Issar and Zohar, 2004, 2007). This region, the root of Western Civilization, is, rich in archaeological remains and ancient documentation, allowing correlation with the time-series of environmental changes derived from proxy data, such as sea and lake levels, isotopic composition of stalagmite rings, pollen ratios in lake and sea-bottom deposits, and so forth.

The major conclusion was that rather severe climate changes had indeed influenced the proto-history and history of this region. During cold periods, the climates were humid and the desert flourished and was settled. The warm periods, on the other hand, spelled dryness, desertification, migrations and invasions of populations from the regions that were drying up, into the fertile belts along the big rivers.

Combining the results of the two investigations (Issar, 2003; Issar and Zohar, 2004, 2007), the forecast can be made that a future rise in global temperature will cause the drying up and desertification of regions with Mediterranean-type climates having a regime of winter rains (such as California, southwestern Africa and eastern Australia, among others), while regions of summer rains will suffer from heavy rain storms, causing floods and soil erosion. The combination of climatic disasters with the increase in population density in these regions will undoubtedly result in starvation, heavy loss of life and destruction of property.

2.5.2 From the Anthropogenic to the Neo-Determinist Paradigm

One of the phases through which the Negev and Jordan Deserts flourished was from the 4th century B.C. to the 6th century A.D. Beautiful cities surrounded by rich farms flourished under Nabatean and later Roman and Byzantine governments. A group comprising of two botanists and irrigation engineer, investigating the ancient irrigation and agricultural methods of these farms, concluded that the blooming of the desert was due only to the ingenuity of the ancient inhabitants, who developed methods of water harvesting (Evenari et a, 1971). They also concluded that the desertion of the cities and the surrounding farms was due to the invasion of the Fertile Crescent by the Arabs, nomads who did not care about agriculture and the maintenance of dams and terraces. Moreover the collapse of the Byzantine administration system caused the deterioration of the caravans' system, the backbone of the trade from Arabia to the Mediterranean ports. This trade, according to the Anthropogenic Paradigm, was the economic basis, which subsidized the agricultural system. The need to subsidize the agricultural sector resulted from the world view that the climate in the past was the same as that of the present and thus the agricultural system could not have survived on its own (Evenari, *op.cit.* Hillel, 1982). This Anthropogenic Paradigm was and is still the leading explanation for the rise and demise of agricultural societies in the ancient Middle East (Rubin 1990). A detailed description of the stages, through which this paradigm took control, during the first decades of the 20th centuries, replacing the Deterministic Paradigm, can be found in the books by the present author in the chapter references (Issar, 1990, 2003, Issar/Zohar 2004, 2007).

The rejection of the ruling Anthropogenic Paradigm and its replacement by a neo-deterministic paradigm started when this author's investigations showed that the invasion of the sand dunes to the coastal plain of Israel and decline of the level of the Dead Sea was synchronous with the desertion of the cities and agriculture of the Negev. The same thing happened on a much larger scale at the end of the Last Glacial Period. The warming up of the climate also coincided with an invasion of sand dunes to the Coastal Plain of Israel, which was synchronous with the regression of the Lisan Lake, the precursor of the Dead Sea. The parallel chain of events brought the author to conclude that a warming process occurred at the end of the Byzantine Period, which caused a decline in the amount of precipitation over the Middle East. The further conclusion was that nature bore the blame for the desertion of the Negev cities and their agriculture rather than human misgovernment. That, indeed, the amount of precipitation declined drastically at this period was later supported by evidence based on the research of the isotopic and chemical composition of the Soreq Cave stalagmites, near Jerusalem. The analyses found a reverse correlation between the intensity of the rain, the temperature, the oxygen 18 and the deuterium (Hydrogen 2) composition of the water dripping in the cave. This enabled calculation of the annual average precipitation for the different periods within the last 7000 years, by correlating isotopes of the dated sections of the stalagmites to the ratios in contemporaneous rainwater (Bar-Matthews et al.,1998, Ayalon et al., 1998).

Detailed investigations carried out recently in Jordan on the soil and agricultural history, in connection with the flourishing, decline and desertion of the Decapolis cities, showed that, indeed, optimal climatic conditions during Roman and Byzantine periods caused the quick growth of these cities, while the negative change of climate brought their collapse (Lucke 2007).

2.5.3 The past as a key to the future

Correlating the time series observed in the Middle East first with data in various other regions across the globe and secondly with historical events, (disregarding the Anthropogenic Paradigm) reveals that climates alternated since the early history of mankind, and thus affected the history of humanity. The influence was especially severe along the borders of the warm deserts having a Mediterranean type climate. Such is the region along the northern margins of the Sahara-Arabia desert belt. During summer it is dominated by the subtropical high pressure cells, with dry sinking air making rainfall unlikely, while during winter the polar jet stream and associated periodic storms, blowing from northwest to southeast, bring precipitation. Such regions like the Middle East, during warm climates phases were dominated to a larger extent by the subtropical high pressure cells and thus received less precipitation, causing desertification and socio-economic crises (Uitto, 1997, Issar, 1995, 2003, Dalfes/Kukla/Weiss (Eds.) 1997 Issar/Zohar 2004, 2007).

The chain reaction started with the water deficiency causing crises in agriculture, the economic backbone of the local civilizations extending along the desert borders. Once these were weakened, the nomadic desert tribes, driven by the drying up of springs, wells and their herds' pasture lands, invaded the irrigated lands. This happened whenever there was global warming; and thus desertification affected the Middle East. It occurred at ca. 4000 B.P (Before Present) with the Amorite tribes invading Mesopotamia, the Hyksos invading Egypt ca. 3800 B.P, and the Arab tribes invading the Levant at 1400 B.P , (Issar/Zohar 2004, 2007).

The causes for the climate changes during the last ten thousand years, the geological period named the Holocene, are still under debate and are outside the narrow scope of our present study, which concentrates on what may be the future impact of the present global warming, and how to cope with it (Issar, 2003). Here it is crucial to point out that the aridity of the tropical regions at ca. 4000 B.P. has been attributed to the massive melting of ice in the polar and sub-polar zones causing the influx of fresh water into the North Atlantic. This is evidenced by the isotopic data of the cores taken at the bottom of the ocean in the Bermuda high, dated and analyzed for their oxygen isotopic composition. The decrease in the ratio of heavy oxygen (18) from about 4,500 years B.P. tells us that the glaciers composed of water rich in light oxygen (16) melted and caused the ocean water to become lighter in their isotopic composition, which would indicate a global warm phase (Street-Perrot and Perrott, 1990).

Yet, as time passed, human intelligence succeeded in inventing new devices in order to cope with the limited supply of water. Thus, for instance, in the Middle East, during the Middle Bronze (between 4200 to 3500 B.P), a relatively dry period, compared to the humid Early Bronze period (between 5300 to 4200 B.P) tunneling into the feeding system of springs was invented. In Iran about 3000 years BP the system of chain of wells (qanats) was developed (Issar 2007 a).

For the Middle East, understanding the past offers a key to the future. During the past ten thousand years, cold climates brought more precipitation, while warm climates led to less precipitation, bringing droughts and famine. The regions nearer to the deserts, which flourished during the cold and humid period, dried up and were deserted by its agricultural inhabitants.

2.5.4 Scenarios of the future

Past time series (Fig. 2.5.1) may help in some way to quantify the rate of decline in precipitation due to future warming (if extreme scenarios suggested by the climatologists are not considered). A scenario of past warming and drying is that which occurred during the Arab Period. As can be seen on the correlation curve between the precipitation in the region of Jerusalem already mentioned (Bar-Matthews, et al, 1998, Ayalon, et al, 1998) with the Scandinavian glaciers (Karlen 1991) there is a minimum at ca. 1000 B.P. In this author's opinion the maximum of this phase of warm climate and dryness occurred at ca 1200 -1100 B.P. This estimate is based on the curve of the Dead Sea levels by Bookman et al. (2004), as well as the humidity curve of the region of Lake Van as expressed in the composition of the sediments of Lake Van of Eastern Turkey (Lemcke/Sturm, 1997).

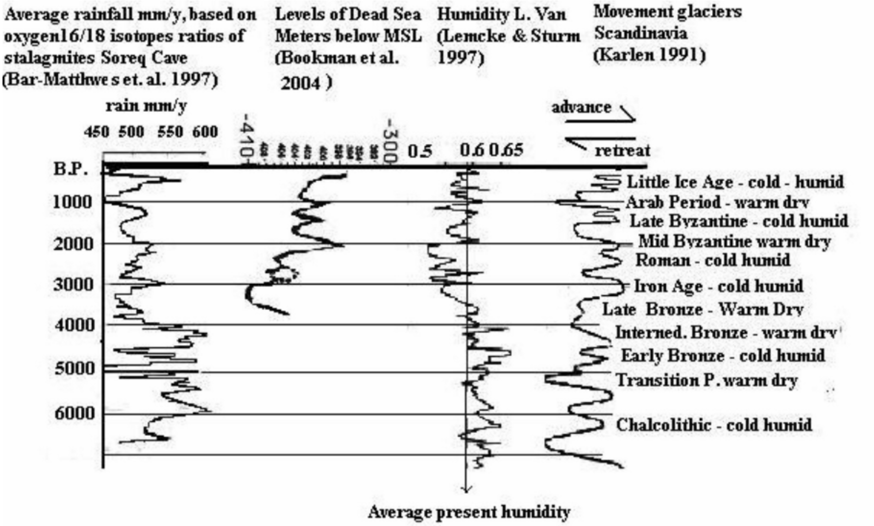


Fig. 2.5.1. Correlation of time-series of paleo-environmental data.

It should be taken into consideration that the curve of precipitation based on the isotopic composition of the Soreq Cave will not indicate years of very low precipitation like that of 1999, when the precipitation was about 50 % of the average. In such years direct evaporation and transpiration by the vegetation will evapo-transpirate the precipitated water leaving zero-quantity to infiltrate below the root zones (Lerner, et al, 1990).

In as much as the present average annual precipitation at Jerusalem is 550 mm and that at the minimum during the Arab Period it reached about 450 mm, i.e. about 20 % reduced, the decline in the average precipitation in the Middle East as the globe warms up should be in this order of magnitude. Yet, taking into further consideration that the years of severe droughts were not recorded, due to minimal or lack of infiltration to groundwater and thus percolation into the caves, the estimate of 30 % to 40 % seems more reasonable. This rate of decline does not take into consideration the catastrophic scenarios beyond the range of historical or even geological events, which some climatologists foresee (IPCC 2007).

In our day, global observations show that there is a constant increase in sea and atmospheric temperatures, parallel to the increase in atmospheric carbon dioxide content. At the same time satellite observations show that the rate of the present melting of the sea ice in the Arctic is faster than a few decades ago, parallel to the sharp rise of air temperatures in this region. This, climatologists believe, may mean that the climate is reaching a tipping point, namely that the stable climate system of the recent past has changed direction. From now on the change may be gathering momentum causing increased summer melt to outpace winter growth of arctic ice

(Renfrow 2006). The last report of the IPCC, emphasizes these conclusions. In this report it is stated that 11 of the last 12 years (1995 -2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). Moreover the linear warming trend over the last 50 years of about 0.13° C per decade is nearly twice that for the last 100 years. According to the map presented in the IPCC 2007 report (p. 18) based on the results from computerized climatic models the decline of the precipitation in the future (2090-2099) will be at least 20 %. This confirms the estimate by the present author discussed above.

Yet, not only these models but also field observations confirm the author's forecasts, such as for the Iberian Peninsula that climate warming will cause the drying up of this region. Indeed, during 2006 Spain suffered from the worst drought for 60 years, when the worst-hit area was the south-east (Tremlett 2006). Likewise Portugal is suffering from its worst drought in decades; January 2005 was the driest January in more than 100 years. The impact of the drought is clear from the images taken by NASA where the green of Portugal's forests and fields, apparent in the image captured on February 11, 2004, is missing from an image captured on February 13, 2005. The dry winter increased concern about the summer fire season in the country, which may have lost as much as 10 percent of its forests during a terrible fire season in 2003.

Another confirmation of the author's forecast regarding the Circum Mediterranean region comes from the European Commission's crop yield forecasts published in Brussels on 14 July 2006, that „Once again, a drought is keeping crop yields at low levels in southern Europe (Spain, Portugal, France, Italy and Greece). A number of the areas affected by drought in 2006 are among those most affected in 2005. This causes concern for the status of water reserves. Furthermore, an analysis of extreme drought events over the last 30 years shows increasing frequency in drought conditions in the last 15 years in some of the affected areas: i.e. south-eastern Spain, north-western France and central Italy“ (EC 2006).

In the eastern part of the Mediterranean investigations have confirmed that „drought has become a recurrent phenomenon in Turkey in the last few decades. Significant drought conditions were observed during years of late 1980s and the trend continued in the late 1990s. The country's agricultural sector and water resources have been under severe constraints from the recurrent droughts (Sonmez et al. 2005).

A report prepared for Greenpeace by Jacqueline Karas on 'Climate Change and the Mediterranean' (Karas 2000). concluded that future climate change „may add to existing problems of desertification, water scarcity and food production, while also introducing new threats to human health, ecosystems and national economies of countries. The most serious impacts are likely to be felt in North African and eastern Mediterranean countries“.

Summarizing the meteorological and hydrological observation in Israel, Prof. Pinchas Alpert from The University of Tel Aviv and Dr. Arie Ben Zvi from the Hydrological Survey, report an increase of summer temperatures of about 0.25-0.21 centigrade per decade, parallel to a decrease in winter temperatures. A series of dry years since the eighties of the last century parallel to an increase in floods was also observed. If one excludes the anomaly of high amount of precipitation during the rain season of 1991/2, which was most probably due to the Pinatubo explosion, then there is a negative trend in the average amount of annual precipitation since 1985 (Alpert/Ben Zvi 2001).

The main conclusions from these experts' reports is that the future rise in global temperatures will cause a decrease in the average annual precipitation over the Middle East, which will be expressed by a trend of increasing frequency of series of drought years. From time to time, however, years of higher precipitation may occur, causing floods, especially with the recurrence of volcanic explosions like that of the Pinatubo in 1991.

In coastal areas the influence of the rise of sea level must be considered. Such a rise will cause the interface between the sea and groundwater to rise and thus penetrate deeper into land, which on one hand may reduce the volume of subsurface water flowing to the sea, while on the other hand will limit the potential lowering of the groundwater table. The range of penetration of the interface depends on the gradient of the groundwater table which is related to permeability and recharge. The rate of the rise of the interface depends on the rate of the climatic change and the global scenario which may evolve. At present it is about 3mm/year.

It has to be taken into consideration that part of the groundwater, which at present flows out directly to the sea may appear as new springs along the channels of the river walls and beds and add to the subsurface flow. This may happen due to the rise of sea level which will cause a rise in the ground water level along the coastline, connected to the rise in the ground water seawater interface.

2.5.5 The potential of long term storage in regional aquifers

With the forecast of series of years of droughts, which may alternate with short spells of years of abundant rains, the first question is whether conditions exist in the regional hydrological system in which water can be stored in the good years to be supplied in the dry years. In the past the only artificial storage was that of surface water. The dams were built, however, to regulate the flow on the basis of a season or of a few years. When it comes to water storage for longer periods of drought, surface water dams, even gigantic in size, are of limited value. In their place as the main storage system, local and regional aquifers must be considered, once these aquifers have a high storage cooficient, (defined as the volume of water released per unit change in head of groundwater) Fortunately such regional aquifers do exist in the Middle East because during most of the Mesozoic and part of Cenozoic this region was along the margins of the Thetis Sea in which limestone and dolomite rocks were deposited. During such periods of sea regression as the Lower Cretaceous, sandstone rocks were deposited in the belt along the margins of Afro-Arabian shield. During the Quaternary gravel and sands were deposited in deltas and coastal plain regions. The combination of the geological and climatic

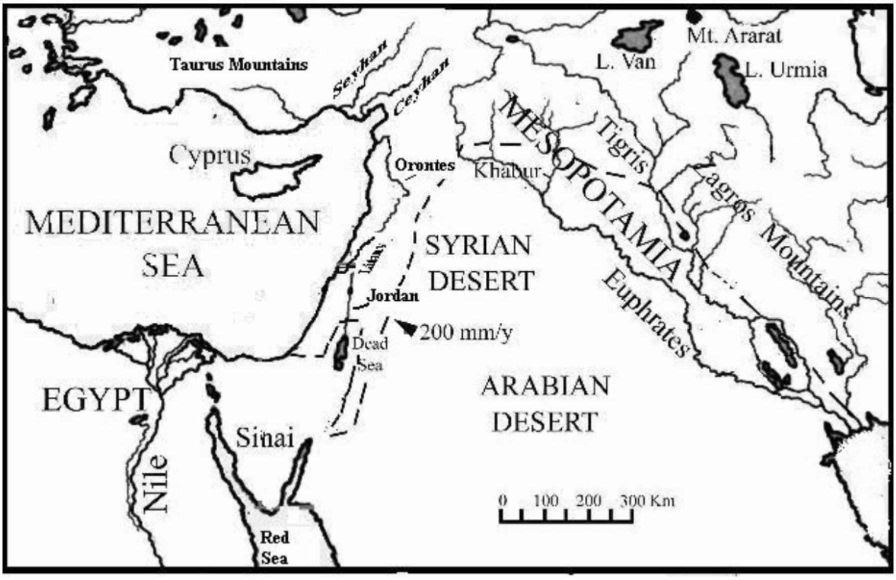


Fig. 2.5.2. Main River Basins Middle East.

characteristics of the various provinces of the Middle East determines the hydrological regime and thus the potential of storage in each region. Thus from the hydrological point of view the Middle East can be divided into the following four main systems:

The regional river basins

The Euphrates-Tigris system. This system has its main source in the mountains of southern Turkey. The Tigris also gets its water from the Zagros Mountains of Iran. In southern Iraq the Tigris and the Euphrates unite to form the Shatt al-Arab, which flows into the Persian Gulf. The average total flow of both rivers is about $85x10^9$ m^3/y (Euphrates 36 $x10^9$ m^3/y, Tigris 49 $x10^9$ m^3/y).

The Nile system. This system has two main sources of water which are the Ethiopian highlands and the equatorial region around Lake Victoria. The first source contributes more than 60 % of the water through the Sobat, Blue Nile, and Atbara Rivers. The floods of these rivers are during the summer. The remainder of the flow arrives by way of the White Nile, through the swamps of the Sudd, which act as a retarding and long storage system, which guarantees the base flow. The annual average for 95 years is estimated to be $91.2x10^9$ m^3.

Thus while the long term storage of the Euphrates and Tigris is supplied by the aquifers of the Anatolian and Zagros mountain chains, that of the Nile is due to the lakes and the marshes of subequatorial Eastern Africa. With regard to the impact of the future climate change it should be taken into consideration that the two river systems i.e. the Mesopotamian and the African belong to different climate systems. While the Mesopotamian system belongs to the Mediterranean climate belt, the Nile is fed by the tropical rains falling on east central Africa and the subtropical monsoonal system stretching north to the equator. The latter system is seasonally, as well as periodically, in an off-phase regime to that of the Mediterranean. Thus in case of a global warming up of the climate the two systems should behave in opposite ways: the Mediterranean system will become drier while that of the Nile more humid. Yet it should be taken into consideration that once a major melting of the glaciers will occur then the subtropical system of eastern Africa may also become drier due to the cooling of the ocean's surface water as happened four thousand years ago (Street-Perrott and Perrott 1990).

The Mesopotamian river system is fed, during the winter and spring by the floods generated by the rains falling on their catchment areas and during summer the base flow is fed by the limestone and dolestone aquifers, which build the central and southern Anatolian and western Iranian mountain chains.

The decline of precipitation values due to the climate change will most probably have a negative influence on the volume of floods, during years of drought as well as on the base flow, due to the its decrease which is dependent on the flow of the regional springs. Yet, even during the dry years, not to speak of infrequent humid years, extreme events of flooding may occur. The storage of the water of these floods is problematic from the engineering and thus economic point of view. It is beyond the expertise of the present author to discuss possible solutions to this problem. What can be said within the framework of the present article is that solutions will have to be within a regional plan of surface and groundwater storage, as will be discussed later on.

The Mesozoic and Cenozoic carbonate aquifers mountains systems

The frame and backbone of the countries in the Eastern Mediterranean are the folded chains of mountains composed mainly of carbonates, chalks, limestones and dolestones of Mesozoic age (Jurassic, Cretaceous and Eocene). The landscape, especially that of the Taurus and Zagros mountains, is rugged due to the relatively young age of the folding and later upheaval, which occurred at the end of the Tertiary and the beginning of the Quaternary. These mountains are in the trail of the cyclonic lows coming from the sea loaded with moisture and thus they receive much precipitation. The higher ranges are covered by snow during the winter and some even most of the year. The limestones and dolestones are very permeable and as the thickness of the carbonate aquifers may reach about 2000 meters, the storage capacity is enormous and provides the base flow of the perennial regional large springs, which emerge at their foothills.

In addition to the regional springs emerging at the foothills of the mountain ranges there also exist many relatively small perched springs, emerging in the intermountain valleys. These springs were the source of supply to the cities and city-kingdoms, which flourished in these mountain valleys throughout the history of this region. Jerusalem, Nablus and Hebron are just a few of these mountain valley cities (Issar 1976). The systems feeding these springs are local as is their storage capacity. Thus during dry periods such springs dried up, which brought about the desertion of the cities dependent of them. This happened a few times in the history of this region, as for example during the Intermediary Bronze Period about four thousand years ago and the Arab Period twelve centuries ago (Issar/Zohar 2004, 2007). On the other hand the regional springs, which emerge at the foothills of the regional mountain ranges and which depend on the relatively high values of precipitation on the mountain ranges and the tremendous storage capacity of the aquifers feeding them, did not dry up, although their capacity diminished. As such springs provide the base flow of the main rivers, especially the Euphrates Tigris and Orontes the flow in these rivers, during dry periods, diminished but did not dry up.

Southern Anatolia. As some of these mountain ranges reach the sea coast, like the Taurus chain of Southern Anatolia and the Lebanon Mountains, it should be taken into consideration that there is a direct flow of groundwater into the sea, which from the practical point of view is a wasted resource. This flow is in addition to the surface flow from the rivers like the Magawat, Seyhan and Ceyhan, whose combined outflow is about $17x10^9$ m^3/y. Since the quantity of the annual precipitation on the Taurus Mountain range is about 2 m, the area of the outcrops of the permeable carbonates is about 35.000 km^2, and the rate of recharge is about 30 % then the annual groundwater flow towards the Mediterranean should be in the order of magnitude of about $25x10^9$ m^3. From this about $17x10^9$ m^3 flows out in the rivers and about $5x10^9$ m^3 flows out directly to the sea, on top of the potential annual use of water in this region which is about $8x10^9$ m^3.

Taking into account that the warm climate change may reduce the precipitation and thus the groundwater recharge by 20 %, at least, then the flow of groundwater will reach only $20x10^9$ m^3, from which about $8x10^9$ m^3, has to be reserved for the local needs. Thus in total about $12x10^9$ m^3 will flow to the sea either as surface or subsurface flow. The volume of the flow due to the climate change is difficult to estimate, but a conservative estimate of the total volume of about $8\text{-}10x10^9$ m^3 should be considered as a potential for export. Turkey offered to export the order of magnitude of about $2.4x10^9$ m^3/y through the „Peace Pipeline“ and by sea to other Middle Eastern Countries (Mithat, 2004). In view of the prediction that due to the climate change the flow of the Euphrates and Tigris may be lower in the order of magnitude of about 20 %, and already today the division of the flow of these rivers is disputed between the riparian countries, the water of the planned Peace Pipeline should be reserved for the mitigation of this dispute, which the future shortage may bring to a conflict. Needless to add that at the same time advanced water saving methods of irrigation should be introduced.

Syria and Lebanon

Syria Mountain ranges. The limestone and dolestone aquifers of Mesozoic age extend into Syria and Lebanon where they build the anticlinorial mountain ranges, the strike of which is north-north-east and northeast. The aquifers' thickness is about 2000 m (ESCWA 2002), and they extend also below the plains to the east. Due to the direction of the mountain ranges they form a barrier to the cyclonic lows coming from the west and northwest. As along the foothills of the Taurus and Zagros, also in Syria and Lebanon, the outflow from these aquifers is in the form of springs which feed the rivers. Such are the springs that emerge along the foothills from the slopes parallel to the coast, and feed the rivers crossing the mountains (like Nahar el Kebir, north and south, or directly into the sea.[1] The springs emerge also in the valley separating the western coastal ranges from the inland ranges feeding the Orontes and the Litany rivers. To the east springs emerge from the eastern foothills of the Anti-Lebanon flowing to the plain of Damascus. To the south springs from the Anti-Lebanon feed the Jordan River.

Due to the fact that the rivers are spring-fed, they show strong seasonality with sometimes ephemeral characteristics (METAP 2001). The amount of water available for use in Syria is not well quantified, nor is the amount extracted fully monitored. Nevertheless it is clear that all available resources are used to the limit and that coping with further increases in water demands will require immediate and well-planned action (World Bank and UNDP, 1999, World Bank 2001). The same reports indicate that the total estimated volume of water use is about 15 billion cubic meters, of which 87 percent is used for irrigation, 9 percent for domestic use, and 4 percent for industry. The surface water and groundwater shares of total irrigated areas are about 40 percent and 60 percent respectively. Due to over-pumping groundwater levels have declined in some locations up to 20 meters in the last 5 years. From 1999 to 2001 a considerable decline in the level of groundwater was reported. On the basis of these and various other reports, a general summary was compiled (Salman/Mualla, 2002), which concludes that most of the basins are in deficit. This will become more extreme in regions in which large urban areas already exist while the population growth rate continues (about 3 %).

These studies and others carried out to date by the various Syrian and international agencies did not take into account the negative impact of future climate change. Considering the forecasted reduction of annual precipitation it is quite

---

[1] The existence of this direct flow was known to the ancient sailors, and the Roman historian Gaius Plinius Secundus namely „Pliny the Elder“ wrote that fresh water can be drawn from the sea off the coast of Syria at „Aradus“ (Pliny, *Naturalis Historia*, Book II, CVI, 224, as per, H. Rackham (trans.), *Pliny: Natural History*, (Loeb Classical Library, Harvard University Press, 1967), Vol. I, p. 353.) . Yet, it has to be taken into consideration that during Pliny's time, the climate was more humid. Once the climate becomes warmer and precipitation decreases, while the level of the sea rises the groundwater flow to the sea will decrease, if not disappear.

clear that the negative trends described in this report will become worse. In this case there will be a further advance of the seawater intrusion, which has started in the coastal basin located in northwestern Syria, and which is the richest basin in terms of water resources (World Bank and UNDP[2], 1998).

The flow of the perennial rivers like the Orontes and Litany will most probably diminish, in proportion with the decline of the precipitation, while the smaller rivers, the flow of which is minimal during the summer, may dry up during this season. Such are the rivers, which flow to the Plain of Damascus, namely the Barada and Al Awaj. As mentioned, the source of these perennial flow are the springs fed by groundwater, the recharge of which is by the precipitation over the Anti-Lebanon. The aquifer system, underlying the Damascus plain extend from the Anti-Lebanon foothills in the west to the volcanic formations in the south and east of the country and is composed of gravel and conglomerates inter-fingering with clays and marls. Its thickness is up to 400 metres and it is recharged from wadi and river flow, irrigation return, and leakage from the Cenomanian-Turonian aquifer. Groundwater quality ranges from 500 to more than 5000 ppm (ESCWA 2002).

Syria's eastern plains. Further east the calcareous Mesozoic aquifers are confined and contain fossil water. This conclusion is based on an investigation on the isotopic characteristics of the water in the limestone-dolestone aquifers of Cenomanian - Turonian age under the Al-Qalamoun Basin These aquifers stretch from the eastern foothills of the Anti-Lebanon Mountains in the west to the Sabkhet Al-Mouh Basin in the east near Palmyra. The isotopic composition has shown that most of the present groundwater in these aquifers is older than 20,000 years and was recharged during the last Pleistocene pluvial periods. Only 10 % of the groundwater may be younger than 10,000 yr. The total recharge rate of the Sabkhet-al-Mouh Basin range between 1 to 2×10^6 m^3/yr only. That means, that any groundwater withdrawal of this region means groundwater mining (Geyh 1996).

Lebanon

The estimated annual groundwater potential of Lebanon ranges from 0.4 to 1.0×10^9 m^3 (World Bank, 1996, METAP, 2001). As discussed above, once the climate becomes warmer this recharge will diminish by about 20 % to 40 %. This will reduce the flow of the streams fed by springs as well as the direct flow of groundwater into the streams. In this case the irrigation in the Beqaa valley will have to shift to pumping from groundwater, especially in the late summer months. The salinization of wells in the coastal plain, which has already started (World Bank 1996), will most probably advance, once the demand and thus pumping increases.

---

[2] United Nations Development Project.

Groundwater storage and supply of Israel and Palestinian Authority

Sea of Galilee catchment. The Mesozoic carbonate aquifers of the Anti-Lebanon supply the base flow of the Jordan River, which flows into the Sea of Galilee[3]. This lake is also fed by floods coming during the winter from the Galilee region and the Golan Heights. From 1980 to 1985, the mean annual contribution of the Jordan River to the lake was about 0.5×10^9 m^3. Surface runoff and waste water contributed an additional 0.2×10^9 m^3. The rest came from the direct precipitation, saline springs at the lake bottom, and partial diversion from the Yarmuk River adding to the total of 0.8×10^9 m^3, of which about 0.3×10^9 m^3/y was lost to evaporation from the lake. About 0.5×10^9 m^3 was pumped out partly into the National Carrier for urban and rural demands of central and southern parts of Israel (Nativ and Issar, 1988) The long term storage capacity of the Sea of Galilee is limited to about 0.6×10^9 m^3 due to the existence of saline springs at the bottom of the lake and to the location of the city of Tiberias and other settlements on its banks. This because a lowered lake level in dry years may cause higher salt content of the lake water due an increased inflow of the saline springs, while a heightened level in years of abundance will flood the settlements on its banks.

The Cenomanian Turonian aquifers of the anticlinorium of Galilee and Central Israel and Palestinian Territory. These ranges extend from the Valley of Esdraelon in the north to the Valley of Beer-Sheva in the south are built of permeable Cretaceous (mainly Cenomenian-Turonian) limestones and dolestones. The permeability is high and is a function of karst dissolution processes. The recharge takes place in the mountainous areas of the Galilee and the Ramalla-Jerusalem-Hebron area where permeable rocks outcrop. In the foothill regions it is not recharged as the aquifers are covered by impermeable layers of Upper Cretaceous and Tertiary chalks and marls. In these regions the water table of the Cretaceous aquifer is confined. The annual recharge into the aquifer of the central part of the country is about 0.35×10^9 m^3. In the past, the aquifer discharged to the west, north, and east through freshwater, brackish, and saline springs. The increase in water pumping from the aquifer reduced the western natural discharge to less than 0.05×10^9 m^3/y of brackish water. About 0.16×10^9 m^3/y still flow in all other directions (Nativ and Issar, 1988).

The Nubian Sandstone aquifer of Lower Cretaceous age. An additional aquifer, of importance mainly for the Negev Desert and Arava Rift Valley, is the Nubian Sandstone aquifer. It underlies the central and northern Sinai Desert and extends northward to the Negev Desert. The aquifer is composed mainly of sandstones. The water it contains is brackish to saline containing about 1 g/l chlorine and 0.5 g/l sulfate and between 6 to 9 g/l TDS, and its age is a few ten thousands of years. Thus, the water is fossil like the water under the Sahara Desert and parts of Jordan and the Arabian Peninsula. In Israel, along the Arava Rift Valley, extending from the

---

[3] The Sea of Galilee is called Lake Kineret in Hebrew. The former, English name will be used here.

Dead Sea to the Red Sea, water from the upper part of this aquifer is pumped for irrigation, mining, and chemical industry. The present annual pumping is about 0.03×10^9 m^3. Water in this aquifer is artesian to sub-artesian (confined), and is not currently recharged. Consequently, pumping of water from the aquifer is actually mining of a non-renewable resource.

A series of studies by the present author and his collaborators (Issar et al. 1973, Issar and Nativ 1988, Tzur et al 1989, Issar 1994) have shown that a few hundred million cubic meters per year may be pumped out of the Nubian sandstone aquifers underlying the Negev and Sinai, for at least the coming century. The actual quantity and duration would be a function of the management policies and various economic factors. In principal, however, such a project is technically feasible, and the water is of adequate quality. Although this water source is not replenished, it may be regarded as any other one time resource such as oil, coal, iron etc.. In other words, the evaluation of whether or not to use it should be based on long term economic considerations. The water may be used in the region of the Negev Desert to the Beer Sheva Plain as a replacement supply for the industry in this region which does not require water of drinking quality and which is supplied at present with water from the National Water Carrier and the Mountain Aquifer, which underlies the Beer Sheva Plain, but is now pumped to its full capacity This will require the transport of water over a distance of about 100 km. The economic feasibility of such an alternative compared to that of use of reclaimed sewage has still to be investigated.

The Coastal Plain Aquifer: Long-Term Storage for Israel and the Palestinian Authority. The Coastal Plain aquifer is built of permeable sandstone rocks with inter-fingering layers of semi-permeable loams to impermeable clays, dividing them into sub-aquifers units. This subdivision is especially developed in the western part of the coastal plain, where one borehole may go through a few separate sub-aquifers, each having a different water level (sometimes „sub-artesian“ i.e. confined) and different quality. Due to this separation the infiltration from the rain falling on the sandstone layers in the western part, as well as polluting solutes, affects only the upper-most sub-aquifer. Also the salinity of the ground water due to the penetration of sea water affects each sub aquifer separately, and is a function of its over pumping. Yet, the separating layers disappear a few kilometers away from the shoreline towards the east, and the sub aquifers merge together to form one system, forming a phreatic aquifer, namely that the water table of the aquifer is directly fed by the water infiltrating into the subsurface. On the whole the thickest part of the sandstone aquifer, which reaches about 200 m, is along the sea shore. Towards the east the aquifer thins out to a few tens of meters. The Coastal Plain aquifer is recharged by the rain falling on its surface, and to some extent by floods coming from the mountains. It is also fed by return flow from irrigation and leakage from the sewage systems. There is practically no recharge from the limestone aquifers lying towards the east, as there exists a thick layer of impermeable rocks between which separates the limestone aquifers and the sandstones. In the southern half of the Coastal Plain, the sandstone layers are in contact with semi-permeable chalk layers, which contain brackish water. This causes the water in the south-eastern part of this aquifer to become brackish too (4 to 8 g/l Cl) (Livshitz/Issar, 2006).

Generally, the ground water flow in the Coastal Plain aquifer is from east to west (from the recharge area on land toward the outlet which is the sea), except in areas of over-pumping, where the massive lowering of the water table has produced cones of depressions in the ground water levels. In these places the direction of flow is towards these cones. The potential (or safe) yield of the Coastal Plain aquifers of Israel and Gaza is about $0.3x10^9$ m^3/y. Already this aquifer is over-pumped, and present pumping exceeds supply in Israel by 30 % and in Gaza by 50%. Because of this over pumping, saline sea water intruded into this aquifer in a few regions, causing higher salinities. Furthermore, infiltration from irrigation and sewage systems caused salinization of the groundwater. In general the salinity of the water in this aquifer in Israel is 50 % higher today, than it was during the thirties. Average chlorine content of the water in this aquifer went up, from 100 to 155 mg/l[4]. Yet for human consumption, the most negative effect is the pollution of this aquifer by nitrates from fertilizers and sewage. Nitrates have increased from an average of 10 mg/l in the 1930's to more than 50 mg/l at present. In 9 % of the boreholes, nitrate levels exceed 90 mg/l (Mercado, 1995) In the part of the Coastal Plain underlying Gaza, the situation is even worse, and approximately 40 % of the wells show nitrate concentrations higher than 90 mg/l (Melloul and Collin, 1994)

As the Coastal Plain becomes one of the most densely populated areas in the world, further pollution cannot be avoided. Moreover, the rapid urbanization of this region causes wider and wider parts of it to be covered by impermeable concrete and asphalt, which reduces the natural recharge to this aquifer. At the same time, the interruption of the hydrologic cycle of the Coastal Plain and continued pumping for irrigation have reduced to a minimum the quantities flowing to the sea while constantly increasing the salinity in the aquifer.

2.5.6 Suggested future planning

Southern Anatolia

In view of the prediction that climate change may reduce the flow of the Euphrates by about 20 %, it is suggested that the volume of about $8\text{-}10x10^9$ m^3, which will continue flowing to the sea either as surface or subsurface flow from the rivers' systems of the Magawat, Seyhan and Ceyhan, should be considered to be caught and piped westward. This will reduce some of the pressure on the Euphrates system

---

[4] The chlorine content is used in Israel as a parameter since the water in this region was used mainly for the irrigation of citrus groves, and the chlorine content is the major constraint when it comes to citrus tolerance (Yields are affected by salinities above 250-300 Mg/l Cl., while for drinking purposes salinities above 500 Mg/l Cl, are undesirable).

Syria and Lebanon

The constraints and the negative trends discussed above, and those yet to come because of climate change, call for the re-evaluation of the role of groundwater in the national water supply of these countries. In the first place supply of groundwater will have to replace surface water supply, which will call for investment in drilling and pumping schemes. An important part of these schemes will have to be managing the flow of the springs and direct flow to the sea. This will involve the planned lowering of the groundwater table during the summer months in order to enlarge the empty underground space in the subsurface, to allow more storage. Thus during winter months this empty space will be refilled and stored for the summer irrigation months. Needless to say that this will cause the drying up of the springs, which flow today, especially in winter and spring months, thus partially wasting their water. This calls for a national plan of exploitation and distribution, an important part of which will include compulsory metering and control of pumping, as well as the introduction of modern methods of irrigation.

Israel and Palestinian Territories

Limestone and dolostone aquifers of Cenomenian Turonian age

As mentioned above these aquifers are not suitable for long term storage because of their high permeability. Yet, in order not to lose their water through springs, as happens in Syria and Lebanon, their management is by the over-pumping of water during the dry season. This empties a volume for recharge during the winter and spring. The result is that most regional springs did practically dry up.

Cooperative efforts will enable the two parties to apply the same policy in order to capture the water from the eastern subsurface drainage basin of the Mountain Aquifer, which flows to the Rift Valley to emerge as brackish or saline springs (about $0.1\text{x}10^9$ m^3/y) (Issar, 1993).

The Coastal Plain sandstone aquifer of Quaternary age

The sand and sandstone layers from which this aquifer is built have a high storativity coefficient, due to their high porosity, but at the same time, relative to the limestone aquifers, the velocity of flow in this aquifer is relatively low. Moreover, in the eastern part of the Coastal Plain a large volume of these aquifers is yet unsaturated and thus can be recharged, filled up artificially, and utilized for additional storage. The shifting of the recharge and storage areas to the east is essential to meet the future requirements for storage, which should reach about five times what it is today.

One has to take into consideration that the Coastal Plain aquifer will have to become the conjoint storage for Israel and the Palestinian Authority. Once the recharge of reclaimed sewage and storage areas will shift from western part of the region to its eastern part it will also be possible to recharge and store the floodwater coming from the Palestinian territories in the mountainous part of the country. At the same time Israel will have to plan anew its recharge areas for its reclaimed sewage as well as flood waters. Due to paleo-environmental conditions which existed during the Quaternary period, all the river beds which cross the Coastal Plain are underlain by thick layers of clay. Moreover, adequate natural sites for storage dams are very rare in the central and western parts of the Coastal Plain. These conditions dictate that the best places for storage and later gradual recharge of the floods are in the eastern parts of this region, close to the foothills.

As part of the new cooperative planning, storage in the part of the Coastal Plain underlying the Gaza Strip should follow a similar policy, namely to be dependent on long term storage in the eastern part of the aquifer, which is in Israel. In the first stage, however, recovery of the over pumped aquifer of the Gaza Strip will have to take place. This can only be done once the gap between supply and demand in the Strip will be supplied from Israel and by desalination of sea water.

Once the role of the Coastal Plain aquifer is recognized as a storage area for Israel's and Palestine's water supply, a related target of planners should be to guarantee that the Mountain (Judea Limestone) aquifer, which was mentioned above, is secured as the main supply of water of drinking quality. This will require close cooperation between Israel and the Palestinian Authority.

2.5.7 Summary and Regional Conclusions

The forecasts of a decrease in precipitation in the Eastern Mediterranean Region by a rate of 20 % to 40 % due to the global warming, require new and advanced approaches of water development and management to be applied in the framework of long term and regional plans. Future steps will have to achieve the following aims:

A. Management of the flow of regional springs from the mountains' carbonate aquifers to prevent wastage of water to sea and salt lakes.

B. In cases where capture of springs is not feasible, because of topography, as in Southern Anatolia, diversion of springs by pipe line to regions which may suffer from drought should be examined.

C. Introduction of advanced methods of cultivation and irrigation, under the motto –“More crop per drop“ should be adopted on a national and regional basis. This calls for national programs of education, especially in the rural sector.

D. Introduction of desalination projects of seawater and brackish groundwater for urban centers. The subsurface storage of desalinized water during hours and seasons of minimum demand should be examined.

E. As about 40 % of consumption in urban centers becomes sewage, the reclaiming of this water for its re-use for irrigation has to become part of the local and national plan.

F. The storage of the reclaimed sewage during the seasons of low demand may be either in the subsurface, as in the case of the Coastal Plain of the Israel, or in natural or artificial lakes.

2.5.8 Global Conclusions

According to the present author's investigations, warm periods in the past have caused droughts and famine in various parts of the world, and heavy flooding in others. Recent climatologic data reveal that the current global warming process is gaining momentum, with peaks that overshadow those from past records. The conclusion is that its impact is going to surpass that of past warm climates. Moreover, populations in the danger zones have multiplied many times over and both drought and flooding are expected to exact a heavy toll. Will the conventional policy of 'sustainable development' enable humanity to avoid or even mitigate this global disaster? It is claimed that in order to mitigate the global crisis, profound and sweeping changes in the natural environment have to be effected at the expense of existing reserves and environments. The well-being of future generations needs to be addressed by giving priority to investment in science education, research, and the planning of new environments.

References

Alpert P., Ben Zvi A., (2001) The influence of climate changes on the water resources of Israel (in Hebrew) Maim Handassat Maim (Water, Water Engineering) 51: 10 -15

Ayalon A., Bar-Matthews M, Sass E, (1998) Rainfall-recharge eelationships within a karstic terrain in the Eastern Mediterranean Semi-arid region, Israel: ^{18}O and D characteristics J Hydrol 207: 18-31

Bar-Matthews M, Ayalon A, Kaufman A (1998) Middle to late Holocene (6,500-year period) - palaeoclimate in the Eastern Mediterranean region from stableisotopic composition of speleothems from Soreq Cave, Israel. In: Issar AS. Brown, N (eds) Water, Environment and Society in Times of Climate Change, Kluwer Academic Publishers, Dordrecht, The Netherlands pp. 203-214

Bookman (Ken-Tor) R, Enzel Y, Agnon A, Stein M (2004): Late Holocene lake levels of the Dead Sea. Geol Soc Amer Bull 116::561

Dalfes Nüzhet H, Kukla, G, Weiss H. (eds.) (1997) Third Millennium BC Climate Change and Old World Collapse. NATO ASI Series, vol 149 Springer Verlag Berlin - Heidelberg – New York

ESCWA (Economic and Social Commission for Western Asia) (2002) Expert Group Meeting on Implication for Water Resources Protection and Conservation, (Beirut, ESCWA Sercreteriat)

European Commission's Crop Yield Forecasts Brussels, 14 July 2006 MEMO/06/284.: http://agrifish.jrc.it/marsstat/

Evenari M, Shannan L, Tadmor N (1971) The Negev : the Challenge of a Desert. Harvard University Press, Cambridge, Mass.

Geyh M (1996) Isotope hydrological studies in the Sabkhet-al-Mouh Basin and adjacent areas Report of Bundesanstalt für Geowissenschaften und Rohstoffe Hannover.

Hillel D (1982) Negev: Land, Water, and Life in a Desert Environment. Praeger, New York

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate Change 2007: The Physical Science Basis Summary for Policymakers, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva

Issar AS (2003) Climate Changes during the Holocene and their Impact on Hydrological Systems Cambridge University Press, Cambridge UK

Issar AS (1994) Fossil water under the deserts of the Middle East: A safeguard against strife. In: .Isaac J, Shuval H, (eds) Water and Peace in the Middle East. Proceedings of the First Israeli-Palestinian International Academic Conference on Water. Zurich, Switzerland

Issar AS (1995) Impacts of climate variations on water management and related socio-economic systems. Technical Documents in Hydrology, (IHP-UNESCO, Paris, Sc.95/Ws.260

Issar AS (1993) Recharge and salinization processes in the carbonate aquifer in Israel. Environ Geol, 21:152-159

Issar AS Nativ R (1988) Water Beneath Deserts: Keys to the Past, A Resource for the Present Episodes, 11:. 256-262

Issar AS (in press)– A tale of two cities in ancient Canaan: the groundwater storage capacity of Arad and Jericho decided their history, in Climate Change and Groundwater Geological Society Publishing House, Bath, England

Issar AS (1990) Water Shall flow from the Rock. Hydrogeology and Climate in the Lands of the Bible, (Springer-Verlag.(

Issar AS (2003) The driving force behind the cold climate spells during the Holocene, In: Kotarba A (ed.) Holocene and Late Vistulian Paleogeography and Paleohydrology. , Polska Akademia Nauk, Prace Geograficzne Nr. 189, 291-297

Issar AS Zohar M. (2004) Climate Change – Environment and Civilization in the Middle East, Springer –Berlin Heidelberg New York

Issar AS Zohar M. (2007) Climate Change - Environment and History of the Near East, Springer –Berlin Heidelberg New York

Issar AS, (2007): The evolution of groundwater exploitation methods in the Middle East through out history Integrated Water Management in Environmental History: Local and Traditional KnowledIge and Modern Practices Université Laval, Quebec

Issar A (1976) „The Evolution of the ancient water supply system in the region of Jerusalem". Israel Exploration Journal 26:130-136

Karas J (2000) Climate Change and the Mediterranean Region, Special report for Green Peace 25 May 2000,http://archive.greenpeace.org/climate/science/reports/fulldesert.html

Karlén W (1991) Glaciers fluctuations in Scandinavia In: Starkel L, Gregory KJ. Thornes JB (eds.) Fluvial Processes in the Temperate Zone During the Last 15000 Years, (John Wiley and Sons.)

Lemcke G. Sturm M (1997) δ^{18}O and Trace Element as Proxy for the Reconstruction of Climate Changes at Lake Van (Turkey): Preliminary Results In: Dalfes G. Kukla G. Weiss H (eds.) Third Millennium B.C. Climatic Change and Old World Collapse. (NATO ASI Series I: Global Environmental Change, vol. 49. Springer Verlag, Berlin

Lerner DN., Issar AS., Simmers I (1990) Groundwater Recharge: A Guide to Understanding and Estimating Natural Recharge, A,A, Balkema Publishers, The Netherlands and IAH,

Lindsay RW Zhang (2005) The thinning of Arctic sea ice, 1988-2003: Have we passed a tipping point? J Climate 18: 4879-4894

Livshitz Y Issar AS. (2006) Impact of climate changes on the hydrogeology of the chalk aquifer of the Lachish and Revivim regions, Central Israel. In Duran JJ. Andreo V Carrasco F (eds.)Karst, Cambio Climático y Aguas Subterráneas, Publicaciones del Instituto Geológico y Minero de España. Serie: Hidrogeología y Aguas Subterránes No. 18. Madrid pp 421-430

Lucke B (2007) Demise of the Decapolis Past and Present Desertification in the Context of Soil Development, Land Use and Climate, Ph.D. thesis Brandenburg University of Technology Cottbus, Germany

Maher S Wael M (2002) The Utilization of Water Resources for Agriculture in Syria: Analysis of Current Situation and Future Challenges IPTRID, AGL, FAO, Rome, Italy & the Faculty of Civil Engineering, University of Damascus, Damascus, Syria

Mercado A (1995) Policy for the Advancement of the Hydrological Research and Development in the State of Israel Ministry of Science and Art, Jerusalem,. (In Hebrew)

METAP, (Mediterranean Environmental Technical Assistance Program) (2001) Country Report on Water Quality Management And Potential Interventions – Syria, (Washington, DC METAP Secretaria(

Mithat R (2004) Water Transfer from Turkey to Water Stressed Countries in the Middle East In: The Second Israeli-Palestinian International Conference on Water for Life in the Middle East, Antalya, Turkey

Nativ R Issar AS (1988) Problems of an over-developed water system - The Israeli Case. Water Quality Bulletin, Vol.13: 126-132.

Pliny, Naturalis Historia, Book II, CVI, 224, H. Rackham (trans.), Pliny: Natural History, (Loeb Classical Library, Harvard University Press, 1967, vol. I, p 353.) .

Renfrow S (2006) Arctic sea ice on the wane, Now what? NASA, Earth System Science Data and Services.

Rubin R (1990) Was the climate more humid during the Byzantine Period? (in Hebrew) Ofakim B'geografia 31:. 209-217

Sönmez K Kömüscü AÜ Erkan A Turgu E (2005) An analysis of spatial and temporal dimension of drought vulnerability in Turkey using the Standardized Precipitation Index Bulletin Natural Hazards 35:. 243-264

Street-Perrott Al Perrott A 1990: Abrupt climate fluctuations in the tropics: The influence of Atlantic Ocean circulation . Nature 343: 607-612

Tremlett G (2006) Spain heading for worst drought since 1947 as reservoir levels fall. The Guardian June 7, 2006

Tzur Y Hokyoun P Issar A (1989) Fossil groundwater resources as a basic for arid zone development? An economic inquiry. International Journal of Water Resources Development 5:.191-201

Uitto JI., (1997) Global warming and groundwater resources in arid lands in Uitto JI. Schneider J (eds.) Freshwater Resources in Arid Lands, UNU Global Environmental Forum Tokyo - New York – Paris, United Nations University Press

World Bank (1996) Lebanon Environment Strategy Framework Paper. The Middle East and North Africa Region, Natural Resources, Water and Environment Division, Washington, D.C.

World Bank (2001) Syria – Irrigation Sector Report, World Bank, Washington DC

2.6 Decadal Precipitation Variances and Reservoir Inflow in the Semi-Arid Upper Drâa Basin (South-Eastern Morocco)

Schulz, O.°, Busche, H.° and Benbouziane, A.*
°Department of Geography, University of Bonn, Germany
*Secrétariat d'Etat auprès du Ministère de l'Aménagement du Territoire de l'Eau et de l'Environnement, Chargé de l'Eau, Rabat, Morocco
Contact: oschulz@uni-bonn.de

Abstract

Water resources in the Upper Drâa basin south of the High Atlas Mountains are of high importance for the persistence of human settlement in this region. To enlighten the hydro-climatologic situation, precipitation data from regional stations was analysed with respect to changes in annual precipitation sums and intensities. Then the inflow into the reservoir, its annual variability and its connection to precipitation events of different intensities was investigated. It was found that precipitation has a high variability that covers possible trends during the last decades. The study is concluded with an appraisal of the current and future hydrological regime of the Upper Drâa basin in the regard of water availability. Climate change is predicted to decrease annual precipitation sums but to increase precipitation intensities which leads to a higher number of floods. Since it was shown that floods provide most of the water volume for the reservoir Mansour Eddahbi, more research of the regional interdependencies is needed.

2.6.1 Introduction

Water resources in the Oued[1] Drâa basin (Upper Drâa 15000 km^2, Middle Drâa 14000 km^2), south of the High Atlas Mountains are of high importance for the persistence of human settlements in this region. For more than 780000 people (census 2004) concentrated more or less in the proximity of valleys within the provinces of Ouarzazate and Zagora the Oued Drâa and its upper tributaries deliver the base supply of water. There exists a general difference between upstream and downstream riparians of the reservoir Mansour Eddahbi near the city of Ouarzazate. While the Upper Drâa basin experiences an undisturbed hydrological regime of the semi-arid subtropics, the river Drâa downstream of the reservoir is controlled by

---

[1] Oued is the traditional and current expression in north-western Africa for rivers with episodic to perennial runoff.

lâchers[2] which are managed depending on the refill level of the reservoir (current capacity: 460 Million m^3). During the last years there can be observed a decline in agriculture in the Middle Drâa Valley that was formerly well-known for its date production.

This study enlightens the hydro-climatological situation of the Upper Drâa basin represented by decadal variability of precipitation and inflow to the reservoir. In a first step, the precipitation at different climate stations with record lengths of more than 60 years is analysed with respect to changes in annual sums. In a second step, precipitation intensities, for the same stations and additional stations with shorter record lengths, are checked for trends within the last decades. The last step includes an investigation of inflow into the reservoir, its annual variability and its connection to precipitation events of different intensities. Outcomes are discussed with regard to the current and future regional water availability.

This study is a contribution to environmental monitoring and research undertaken by the Moroccan administration going back to the 1930s and the German IMPETUS[3] project that started in 2000.

2.6.2 Study area

The watershed of the Oued Drâa is situated on the southern slope and in the foreland of the High Atlas Mountains in south-eastern Morocco (Fig. 2.6.1). It is divided into three parts, the Upper, Middle and Lower Drâa Valley. Runoff rarely reaches the Lower Drâa Valley that takes course in south-west direction towards the Atlantic Ocean while draining the southern Anti-Atlas. So, from the hydrological point of view, investigations started in the High Atlas Mountains and ended at the formerly filled and nowadays normally dry end lake of Lac Iriki, which is situated at the Algerian border, and constituting the transition zone to the northern Sahara (Hamada du Drâa). This region corresponds to the research area of the IMPETUS project which is restricted to the Upper and Middle Drâa Valley. Lately, the Upper Drâa basin is in the scope of this article's investigation.

The Upper Drâa basin (15000 km^2) ranges from the High Atlas Mountains (up to 4071 m) in the north to the elevated plain of Ouarzazate (1100 m - 1400 m) and the bordering low mountain range of the Anti-Atlas and Jebel Saghro (up to 2500 m) in the south.

Due to the geological setting three domains can be distinguished corresponding to the main topographical zones. The domain of the High Atlas Mountains is dominated by outcropping Liassic limestones and Triassic sandy siltstones intercalated by basaltic intrusions. The Mesozoic rocks were folded and thrusted during the

---

[2] Lâcher is a local expression for a period of water release from the reservoir for irrigation purposes.

[3] The IMPETUS project is part of the GLOWA initiative and pursuits an integrated approach to the efficient management of scarce water resources in West Africa; www.impetus.uni-koeln.de; www.glowa.org

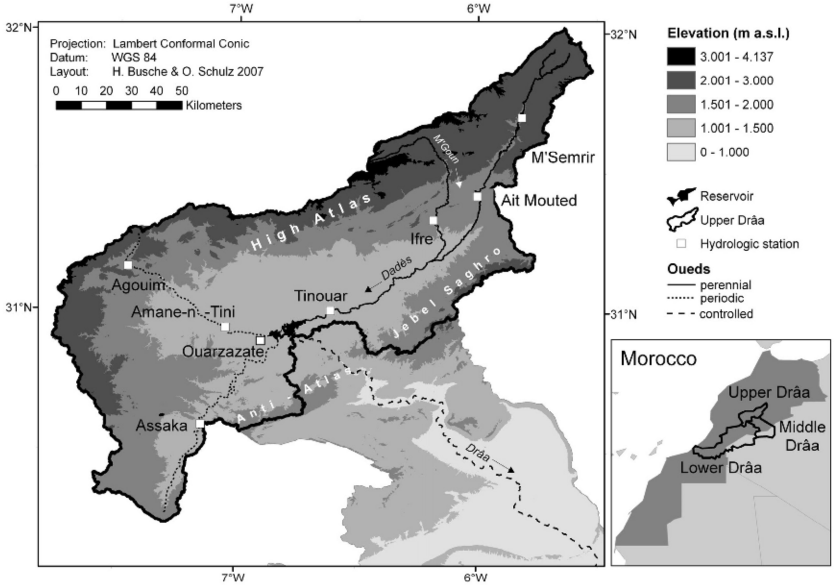


Fig. 2.6.1. Map of the study area with location of measurement stations.

Mesozoic and Neogenic orogenesis of the High Atlas. The Triassic rocks represent fractured media with largely low permeability. The partly karstic Liassic limestone can have medium to high permeability and plays the major role for direct groundwater recharge processes in the High Atlas Mountains (Cappy 2006, Cappy and Reichert 2005). Neogenic continental deposits of silt, sand and conglomerate prevail in the adjacent Basin of Ouarzazate. The Basin of Ouarzazate displays a complex multilayered aquifer system of both porous and fractured media of medium to high permeability. The northern slope of Jebel Saghro (Central Anti Atlas) is mainly built up by Precambrian rocks such as granites and rhyolites (Piqué 2001). Due to tectonic stress during the Eburnean, Pan-African and Hercynian orogenesis these rocks are fissured and have generally low permeability. Therefore river stream infiltration is the most important process of groundwater recharge within the Upper Drâa catchment (Cappy 2006, Cappy and Reichert 2005).

The climate of the Upper Drâa basin is semi-arid with remarkable differences in temperature and precipitation between the more humid High Atlas Mountains and the dry basin of Ouarzazate (Joly 1949, Hasler 1980, Schulz 2006). Situated in the subtropical zone on the leeward side of the principle climatic and weather barrier of the main mountain chain, precipitation is generated by three weather systems (Knippertz 2003, Knippertz et al. 2003a, 2003b, Speth and Diekkrüger 2006):

1. low pressure activity in mid-latitudes with storm-tracks reaching from the northwest over the High Atlas Mountain ridges during the winter months;

2. transport of moisture from the Atlantic Ocean, generated by troughs or cut-off lows located west of the Moroccan coast;
3. tropical-extratropical interaction from areas south of the Sahara with water vapour transport in higher elevations (>3 km) mainly in spring and autumn.

Annual precipitation sums in the High Atlas reach 800 mm (Joly 1949, Wiche 1953, DAF 1957) consisting of rain and snow which has a percentage of more than 50% in altitudes above 3000 m (Schulz 2006). The basin of Ouarzazate is usually dry with some rare but efficient precipitation events. Total precipitation adds up to 100-150 mm (stations Tinouar, Assaka Tafounante and Amane-n-Tini, Fig. 2.6.3).

The Upper Drâa basin experiences a semi-arid hydrological regime. Discharge is perennial only in the eastern high mountain part (Oueds M'Goun and Dadès). Downstream of the confluence of M'Goun and Dadès in the basin of Ouarzazate the Dadès flows to the reservoir Mansour Eddahbi. All other oueds are episodic and the discharge is generated only after efficient precipitation events or during snow melt (Riser 1973, Cappy 2006). The Mansour Eddahbi reservoir was opened in 1973. Through 2003 its initial capacity of 560 Mio. m^3 has decreased by 100 Mio. m^3 due to sedimentation (ABH Souss/Massa/Drâa 2003). The dam's functions are to supply the six date palm oases in the Middle Drâa Valley with controlled water portions of annually 250 Million m^3 for irrigation purposes (Pletsch 1971, Riser 1973, DRPE 1994) and to produce hydro-electrical energy.

Downstream of the dam, the Oued Drâa has cut a transverse valley through the Anti-Atlas and delivers water for irrigation of the date palm oases further south in form of lâchers. For most of the year the river bed is dry. The hydrological and hydrogeological setting and development of the Middle Drâa Valley is examined by Klose et al. (2007).

During the last decades a decline of agriculture can be observed in the Middle Drâa Valley that was formerly well-known for its date production (Fihri 2007). Today even the regional market is dominated by imported dates from Tunisia. During years of severe drought all stream water from upstream is stored in the reservoir. Only between one and three lâchers are executed in dry years to stop the decline of groundwater levels in the Middle Drâa Valley (ORMVAO 2003). Irrigation with surface water does not take place in dry years, so irrigation is only possible with groundwater which is increasingly extracted by motor pumps. The local population associates the observed decreased regional water availability with the absence of stream flow in the river bed after the construction of the reservoir (Rademacher in prep.; inhabitants of the Middle Drâa Valley, personal communication 2001-2006).

Table 2.6.1. Precipitation (P) at measuring stations, inflow (I) respectively runoff (R) into the reservoir Mansour Eddahbi (data provided by the DRPE Rabat and the Service Eau Ouarzazate).

Station	Coordinates	Elevation	Measured Variable	Time Series used
Agouim	31.01°N, 7.10°W	1647 m	P	1969-2003
Ait Mouted	31.43°N, 6.00°W	1545 m	P	1940-2003
Amane-n-Tini	30.94°N, 7.04°W	1170 m	P	1982-2003
Assaka-Tafounante	30.59°N, 7.14°W	1380 m	P	1975-2003
Ifre	31.34°N, 6.18°W	1500 m	P	1940-2003
Ouarzazate*	30.93°N, 6.90°W	1140 m	P	1940-2003
Tinouar	31.01°N, 6.61°W	1136 m	P	1974-2003
M'Semrir	31.71°N, 5.81°W	1942 m	P	1940-2003
Mansour Eddahbi reservoir	30.90°N, 6.75°W	1100 m	P R: Zaouïa-n-Ourbaz I: water balance	1973-2003 1940-1972 1973-2003

* The meteorological station Ouarzazate is operated by the National Moroccan Weather Service (Direction de la Météorologie Nationale) and accredited by the World Meteorological Organization.

2.6.1 Data and methods

In this study, the characteristics of precipitation and discharge in the upstream area of the reservoir Mansour Eddahbi (Upper Drâa basin) during the last decades are analysed. The database consists of regional measured records of precipitation and reservoir inflow provided by the regional water service (Service Eau de Ouarzazate, M. Sabbar) and by the National Water Secretariat at the Moroccan Ministry for the Management of Water and Environment (Secrétariat d'État aprés du Ministère de lAménagement du Territoire de l'Eau et de l'Environnement chargé de l'Eau, Rabat). Information about the stations is listed in Table 2.6.1, and their sites are mapped in Fig. 2.6.1. Precipitation recording at the Moroccan hydrologic stations used in this study goes back to 1930 (Ouarzazate), but other stations started later (the youngest station is Amane-n-Tini, which started in 1982). To cover the longest period possible and to be comparable with reservoir data, for the analysis of the long-term variability, only those records with more than 60 years of data were selected.

The hydrologic stations of the regional water service are of the manually operated type. They consist of discharge gauges and climate stations. A technician reads four times a day the current sums of precipitation, current air temperatures, psychrometric differences for the calculation of air humidity, just as wind direction and wind velocity. The climate stations are situated on open ground in the vicinity of the discharge gauges where water level in the river bed is measured with fixed staff gauges and with mechanical hydrographs. Discharge is calculated using frequently revised stage-discharge relationships. Before the reservoir Mansour Eddahbi was constructed, the runoff at the former discharge gauge of Zaouïa-n-Ourbaz was considered as theoretical inflow to the reservoir. This gauge was situated at the entrance of the Drâa gorge where the dam is located today. Since 1973 the daily inflow is calculated from water level changes, taking into account losses from evaporation, seepage and extractions for the water supply of Ouarzazate (DRPE 1988). Daily inflow data of the reservoir for 1998 to 2003 were analyzed including wet and dry years.

The methods used were normalizing annual sums of precipitation and inflow as well as classifying and cumulating daily precipitation data to provide a base for data interpretation. For every hydrological year the annual precipitation sum of the stations Ouarzazate, Ifre, Ait Mouted and M'Semrir was averaged to get one value for the area under investigation. This average value was normalized against the overall average of the record length (1940-2003).

Daily precipitation data of six stations distributed in the Upper Drâa basin was classified into six classes of intensity (0,1-5 mm, 5-10 mm, 10-25 mm, 25-50 mm, 50-75 mm, >75 mm) according to its effect on discharge. The classification is based on own observations for the lower classes (<25 mm) and on a study about flood risk at the reservoir's tributaries (DRPE 1988) for the upper classes. Below 5 mm usually all precipitation evaporates. Discharge is initialized by 5-10 mm. For higher daily precipitation the flood risk is weak (<25 mm), medium (25-50 mm), high (50-75 mm) or very high (<75 mm). Since the available data starts between the 1963 and 1982, no averages were calculated and the cumulative sum of all classes is plotted for each station.

Annual inflow sums into the reservoir Mansour Eddahbi was normalized (1940-2003). For the period 1998 to 2003 the daily inflow was divided in two classes of magnitude according to normal base flow and floods. Finally, the number of flood days per hydrological year was calculated.

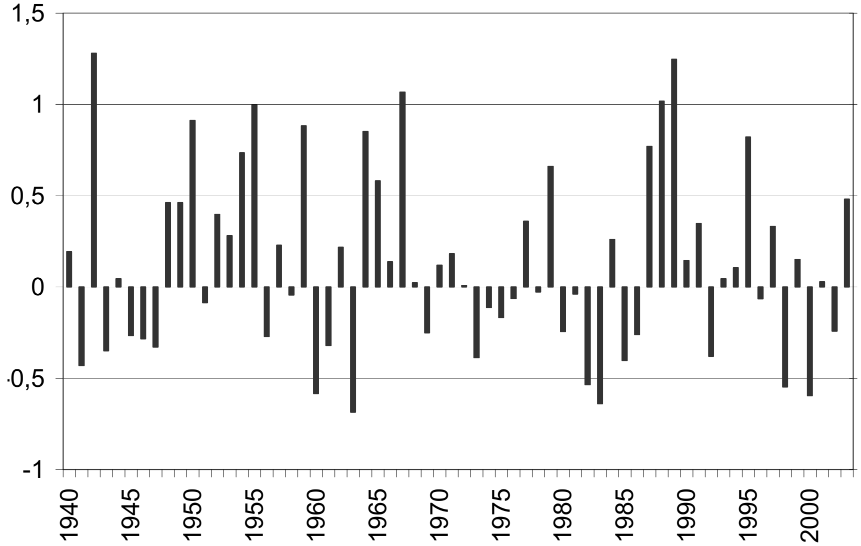


Fig. 2.6.2. Normalized average of the annual precipitation sums at the stations Ouarzazate, Ifre, Ait Mouted and M'Semrir (1940-2003).

2.6.2 Results

Decadal variability of annual precipitation sums

There is highly variable development of precipitation sums at the long time recording stations of the Upper Drâa region (Fig. 2.6.2). Although the variability at and between the stations is high (Fig. 2.6.3, Table 2.6.2), it can be seen that they coincide in the presentation of clusters of drier and more humid years with a persistence of three to seven years. More humid periods can be identified for the late 40s to the mid 50s, the mid 60s and the late 80s. Periods of drought were the early 70s, the early 80s, and the late 90s to the beginning of the new millennium. The decades between the late 40s and the late 60s were wetter than the period before and wetter than the last 30 years before today with exception of the late 80s. Besides this nonlinear characteristic, neither a clear cycle nor a clear trend can be seen so far within this highly variable evolution (standard deviation >50%). For example, Knippertz (2003) found positive precipitation index values for the south Atlas region beginning in the 1980s. Then again, the drought of the last ten years has been interrupted by single years with roughly normal precipitation amounts. These observations are important for the discussion of water availability from the reservoir.

Comparing these results for the regional data base with findings at the larger scale of the south Atlas region identified by Knippertz (2003), it can be concluded that the additional data supports the known facts of the decadal variability of pre-

Table 2.6.2. Averages of annual precipitation sums and standard deviations at measuring stations for different record lengths (data provided by the DRPE Rabat and the Service Eau Ouarzazate). For locations and description cp. Table 2.6.1.

Station	1940-2003		1975-2003	
	Annual precipitation (mm)	Standard deviation (mm; %)	Annual precipitation (mm)	Standard deviation (mm; %)
Agouim			244	134 (55%)
Ait Mouted	181	90 (50%)	161	81 (50%)
Amane-n-Tini			100 (1982-2003)	61 (61%)
Assaka-Tafounante			117	69 (59%)
Ifre	171	89 (52%)	165	95 (57%)
Ouarzazate	117	62 (53%)	113	60 (54%)
Tinouar			105	55 (52%)
M'Semrir	223	102 (46%)	221	84 (38%)

cipitation as the main climatic characteristic. Furthermore the variability at the smaller regional scale of the stations under research in this study shows the difficulty in defining one station as representative for a region.

Precipitation intensities

The precipitation intensities in the study area are calculated on the base of daily data which is available for most stations in the Upper Drâa basin since the beginning of the 1960s. The stations, included in the following analysis, are: Ifre, Ait Mouted, Amane-n-Tini, Assaka Tafounante, Tinouar and Agouim. The locations of the stations cover most of the study area. Only the extreme western part and the central northern part are not represented well since the locations were selected for discharge measurements of the reservoir's main tributaries. Daily precipitation sums at each station were classified into six classes according to the amount of precipitation. Thresholds were chosen at 5 mm, 10 mm, 25 mm, 50 mm and 75 mm (Fig. 2.6.3). A change of intensity would give reason to suspect a change of the local or regional climate system.

The time series of cumulated precipitation intensities for each year at the mentioned stations show that in most cases high annual precipitation sums originate from an increase of moderate to high precipitation rates. Therefore a single year is more characterized by the sum of few high daily precipitation events than by the accumulated precipitation of days with less than 25 mm. The result for all investigated stations is that the redistribution of precipitation to classes of intensity does

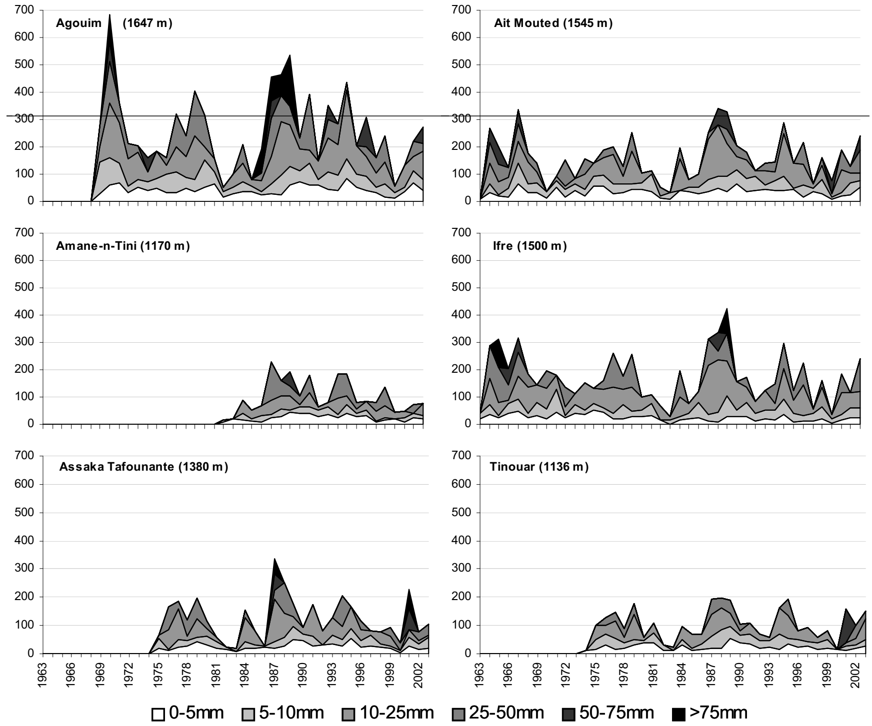


Fig. 2.6.3. Precipitation intensities and annual cumulative sums at the stations Agouim, Amane-n-Tini, Assaka Tafounante, Ait Mouted, Ifre and Tinouar.

not indicate a trend during the last forty years. At all stations the annual variability covers a slight change if there is one. This outcome repeats the facts of the analysis of annual precipitation sums.

It can be concluded from these findings that there is no regional trend in precipitation sums or intensities but a decadal variability with drier and more humid periods.

Decadal reservoir inflow variability

Water availability in the urban area of Ouarzazate and in the Middle Drâa Valley depends highly on the refill level of the reservoir Mansour Eddahbi. Since the initially planned annual volume for irrigation (250 Mio. m^3; Pletsch 1971, Riser 1973) of the six oases downstream of the reservoir was not available during the last decade of predominant drought, groundwater extraction has increased remarkably, which led to a decline of groundwater levels (Klose et al. 2007). It could be shown

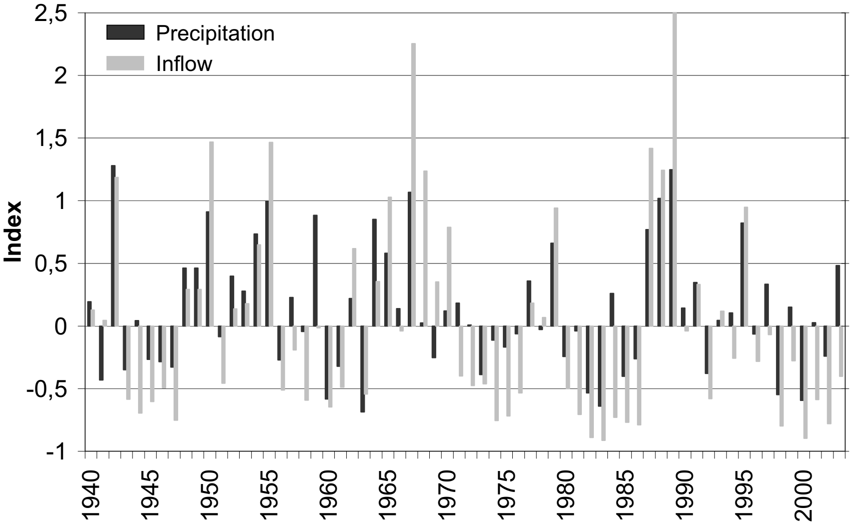


Fig. 2.6.4. Normalized inflow into the reservoir Mansour Eddahbi and normalized average of the annual precipitation sums at the stations Ouarzazate, Ifre, Ait Mouted and M'Semrir (1940-2003).

in the previous chapters that the rate and intensity of precipitation in the region does not follow a trend but has been highly variable during the last decades, thus the inflow into the reservoir followed this pattern.

In Fig. 2.6.4 the annual inflow is indexed to the average of the whole time series (1940-2003) and compared to the index of average precipitation at the stations M'Semrir, Ait Mouted, Ifre and Ouarzazate, which represent the centre and the eastern part of the Upper Drâa basin.

The annual inflow amounts (average: 409 Mio. m^3) correlate satisfying with the mean precipitation (R^2=0.67).

Results of climatological modelling for the Drâa region (Speth and Diekkrüger 2006) predict a slight decrease of overall precipitation and change to more extreme rainfall events. To estimate the consequences of this assumption we analysed the inflow into the reservoir on daily basis (1997/98 to 2002/03). This allowed taking into account the redistribution of two types of inflow, notably perennial basic inflow (low flow) and flood events. The threshold between low flow and floods was set to 10 m^3/s since the main tributaries to the reservoir add to approximately 10 m^3/s (Oueds M'Goun, Dadès and Ouarzazate). Fig. 2.6.5 is based on measurements and water balance calculations. The water balance of the reservoir in the hydrological years 1997/98 to 2002/03 characterizes the water availability: two

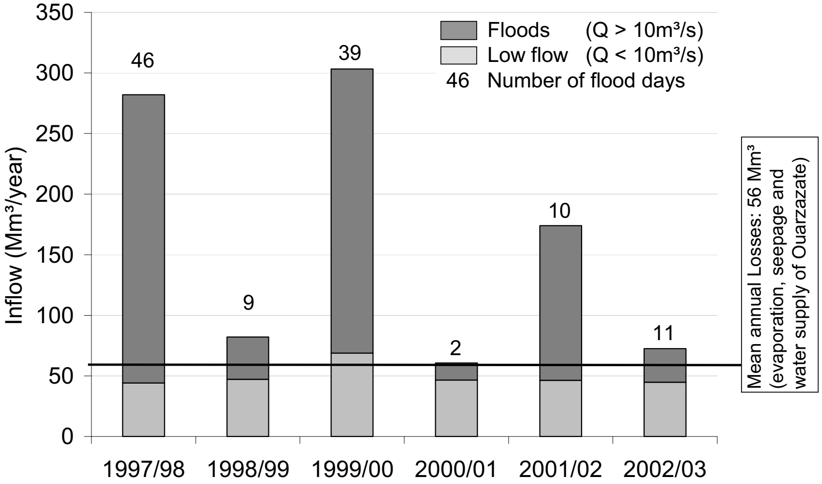


Fig. 2.6.5. Annual inflow sums into the reservoir Mansour Eddahbi and number of flood days for the hydrological years 1997/98 to 2002/03, calculated from daily data. In 1997/98 only eight months and in 2002/03 ten months were available.

years clearly below average, one year of relative and three years of severe drought. The initially planned annual water supply for the Middle Drâa Valley of 250 Million m^3 was clearly out of reach in the years of drought.

Regarding the low flow conditions, it can be summarized that only 50 Million m^3 contribute to the water balance, which is in the same magnitude than the mean annual losses through evaporation, seepage and water supply of Ouarzazate. In humid years the low flow represents 20% of the total inflow whereas in the years of drought it aids with 60 to 80%. This underlines the importance of the High Atlas Mountains with its higher precipitation, notably from snowmelt and groundwater recharge (Schulz 2006, Schulz and de Jong 2004, Cappy 2006) to overcome periods of drought.

2.6.3 Perspectives

The consequences of a climate change scenario according to the IPCC (2001) for Morocco were discussed by Benarafa (1992). An augmentation of temperatures in the magnitude of 3° C until 2050 would increase the potential evaporation about 200 mm per year, a rising of the altitudinal limits of agriculture, but also an acceleration of desertification phenomena. The implications of livestock management, arboriculture and tourism were explored by Parish and Funnell (1999). They found that there will be a need to change tenure conditions and other rules of management.

According to Maselli (1995) the variability of precipitation and the frequency of dry years have increased in the Western High Atlas during the last 30 years. The proportion of heavy rainfalls in wet years also appeared to have increased in that region. This could not be found for the Central High Atlas to the present state.

Scenarios of climate change in the south atlas region (Speth and Diekkrüger 2006) imply an increased warming of the atmosphere through rising greenhouse gas concentrations. Increasing snow lines of about 200 m in altitude (from 2000 to 2200 m a.s.l. in general, with high variations between snowfall events) are expected to enlarge the portion of liquid precipitation. The Drâa basin as part of the South Atlas region is generally influenced by low pressure activity of the mid-latitudes during the cold months and by tropical-extratropical interactions from areas south of the Sahara. According to these two main processes leading to precipitation, different scenarios were developed. In the scenario of a shifting northwards of the North Atlantic Oscillation activities reduced precipitation is expected in the High Atlas Mountains whereas the basin of Ouarzazate experiences less but more intense rainfall events. According to IPCC (2001) the North Atlantic Oscillation is a key factor in Moroccan climate vulnerability. In the scenario of an enhanced humidity advection caused by rising temperatures, an augmentation of winter precipitation is expected, with more intense events in the High Atlas (Speth and Diekkrüger 2006). The predicted increase of extreme precipitation events causing floods in the future is assumed to deliver more water to the reservoir than today. Rising temperatures continue the trend to less snow in winter which in that case falls as rain and increases the direct and interflow. The snow storage would be reduced and the time lag between snowfall and melt is shortened. Since it was shown that floods play a major role in refilling the reservoir Mansour Eddahbi, it has to be further investigated whether a slight decrease of annual precipitation sums can be compensated through less frequent but more intense rainfall events in the Upper Drâa basin. Siltation of the reservoir which is an already known problem in Morocco (Lahlou 1988) will increase under these circumstances. The current and future water availability in the Drâa region is subject to ongoing research within the cooperation of the Moroccan administration and the IMPETUS project.

Acknowledgements

We would like to thank our colleagues at the DRPE Rabat and at the Department of Geography, University of Bonn for the support of our climatological and hydrological work. The Office Régional de Mise en Valeur Agricole de Ouarzazate (ORMVAO) provided additional data and reports. The staff of the Service Eau de Ouarzazate helped during field work with discussions, transport and data. Both administrations are thanked for their support.

Responsible for the IMPETUS automatic weather stations monitoring network is the climatology group (Winiger, Loeffler) at the Department of Geography, University of Bonn.

This work was supported by the Federal German Ministry of Education and Research (BMBF) under grant No. 01 LW 06001B and by the Ministry of Innovation, Science, Research and Technology (MIWFT) of the federal state of Northrhine-Westfalia under grant No. 313-21200200.

References

ABH Souss/Massa/Drâa (Agence du Bassin Hydraulique de Souss/Massa/Drâa à Agadir) (2003): Hydrologie du Haut et Moyen Drâa. Agadir.

Benarafa, S. (1992): Le Maroc en l'an 2050. Impacts d'une eventuelle evolution climatique sur la vegetation et les ecosystems. Royaume du Maroc. Ministère des Travaux Publics, de la Formation Professionelle et de la Météorologie Nationale. Rabat.

Cappy, S. (2006): Hydrogeological characterization of the Upper Drâa catchment: Morocco. PhD thesis at the University of Bonn.

Cappy, S. and B. Reichert (2005): Water balance and hydrogeochemical investigations in a mesoscale catchment in High Atlas: The Assif-n-Ait-Ahmed catchment. In: Ait Hamza, M. and H. Popp (Eds.): Pour une nouvelle perception des functions des montagnes du Maroc. $7^{ème}$ Colloque scientifique maroco-allemand, Rabat, 23-25 September 2004.

DAF (Direction de l'Agriculture et des Forêts) (1957): Carte des precipitations. Rabat/Paris.

DRPE (Direction de la Recherche et de la Planification de l'Eau) (1988): Etude de la gestion de retenues de barrages. Partie B: Barrage de Mansour Ed Dahbi. Rabat.

DRPE (Direction de la Recherche et de la Planification de l'Eau) (1994): Etude du plan directeur de l'aménagement des eaux des basins du Guir, Ziz, Rheris, et Drâa: étude des schémas d'aménagement. Volume II, Rabat.

Fihri, Hafid Fassi (2007): Nos oasis sont mencées de disparition. L'Opinion, internet source: http://www.lopinion.ma/spip.php?article15997 (9.7.2007).

Hasler, M. (1980): Der Einfluss des Atlasgebirges auf das Klima Nordwestafrikas. Geographica Bernensia G11.

IPCC (Intergovernmental Panel on Climate Change) (2001): Climate Change 2001. Impacts, Adaptation, and Vulnerability. Contribution to the Working Group II to the third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge.

Joly, F. (1949): Géographie du Maroc.

Klose, S., Reichert, B. and A. Lahmouri (2007, this book): Developing management options for a sustainable groundwater use in the Middle Drâa Oases under the pressure of climatic changes. In: Zereini et al. (Eds): Climatic Changes and Water Resources in the Middle East and in North Africa. Frankfurt. (this citation has to be updated)

Knippertz, P. (2003): Niederschlagsvariabilität in Nordwestafrika und der Zusammenhang mit der großskaligen atmosphärischen Zirkulation und der synoptischen Aktivität. Dissertation. Mitteilungen aus dem Institut für Geophysik und Meteorologie der Universität zu Köln, Heft 152. 137 Seiten.

Knippertz, P., Fink, A., Reiner, A. und P. Speth (2003a): Three late summer/early autumn cases of tropical-extratropical interactions causing precipitation in Northwest Africa. American Meteorological Society, p. 116-135.

Knippertz, P., Christoph, M. and P. Speth (2003b): Long-term precipitation variability in Morocco and the link to the large-scale circulation in recent and future climates. Meteorology and Atmospheric Physics 83, p. 67-88.

Lahlou, A. (1988): The silting of Moroccan Dams. IAHS Publ. 174, p. 71-77.

Maselli, D. (1995): L'écosystème montagnard agro-sylvo-pastoral de Tagoundaft (Haut-Atlas occidental, Maroc): resources, processus et problèmes d'une utilisation durable. Geographica Bernensia African Studies Series A12.

ORMVAO (Office Régional de Mise en Valeur Agricole de Ouarzazate) (2003): Report sur la situation de la Vallée Moyenne du Drâa. Ouarzazate.

Parish, R. and D.C. Funnell (1999): Climate change in mountain regions: some possible consequences in the Moroccan High Atlas. Global Environmental Change 9, p. 45-58.

Piqué, A. (2001): Geology of Northwest Africa. Berlin.

Pletsch, A. (1971): Strukturwandlungen in der Oase Dra. Untersuchungen zur Wirtschafts- und Bevölkerungsentwicklung im Oasengebiet Südmarokkos. Marburger Geographische Schriften 46.

Rademacher, C. (in prep.): Arbeitsmigration und Aspekte souio-ökonomischen Wandels in einer süd-marokkanischen Oasensiedlung. PhD thesis. University of Cologne.

Riser, J. (1973): Le barrage Mansour Eddahbi et les amenagements agricoles de la vallée du Dra moyen. Revue de Géographie du Maroc, No. 23-24, p. 167-177.

Schulz, O. (2006): Analyse schneehydrologischer Prozesse und Schneekartierung im Einzugsgebiet des Oued M'Goun, Zentraler Hoher Atlas (Marokko). PhD thesis at the University of Bonn.

Schulz, O. and C. de Jong (2004): Snow melt and sublimation: field experiments and modelling in the High Atlas Mountains of Morocco. Hydrology and Earth System Sciences, 8 (6), p. 1076-1089.

Speth, P. and B. Diekkrüger (Eds.) (2006): An integrated approach to the efficient management of scarce water resources in West Africa – case studies for selected river catchments in different climatic zones. Second Final Report. Period: 01.05.2003-31.07.2006, Cologne.

Wiche, K. (1953): Klimamorphologische und talgeschichtliche Studien im M'Goungebiet. Mitteilungen der Geographischen Gesellschaft Wien Bd. 95.

2.7 Management Options for a Sustainable Groundwater Use in the Middle Drâa Oases under the Pressure of Climatic Changes

Stephan Klose*; Barbara Reichert*, Abdeddaim Lahmouri **
* Institute of Geology, University of Bonn, Nussallee 8, D-53115 Bonn, Germany
** Secréterait d'État chargé de l'Eau, Ministère d'Aménagement du Territoire de l'Eau et de l'Environnement, Rue Hassan Benchekroun, Agdal Rabat, Royaume du Maroc

2.7.1 Introduction

Since the late 1970s the occurrence of drought years increases in Northwest and West Africa presenting a major constraint to the future development of these regions. According to the IPCC conventions, a general decrease in rainfall together with a prominent surface heating can be expected for sub-Saharan Africa and north of the Sahara until 2050, resulting in further decreasing fresh water availability.

Morocco is spending huge effort on integrated water resource management. Based on the water law (no. 10-95) adopted in 1995 the National Water Plan gives a national framework for water management addressing institutional reforms, economic aspects and technical co-operations as well as specific issues such as alternative irrigation methods (URL 1; Oubalkace, 2007). Facing the grave water-related tasks the principal aims are framed at the watershed scale by water agencies for each basin (ABH, Agence de Bassin Hydraulique). Especially the southern Moroccan watersheds often referred as Sud-Atlasique are seriously affected by water scarcity (Mokhtar, 2004; Oubalkace, 2007), but a lack of data impedes a comprehensive analysis of the current situation for each basin. However, for one of the southern catchments, the Drâa, an ABH is not established so far. Current public discussions on water issues are initiated by the MATEE (Ministère de l'Aménagement du Territoire, de l'Eau et de l'Environnement) using the platform of the Débat national sur l'eau (e.g. in March 2007 in Ouarzazate).

In this context IMPETUS („An Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa") was initiated to offer management options to the already pressing water problems in West Africa, focusing on the hydrological cycle as determining process for water availability. With an interdisciplinary approach, IMPETUS identifies and quantifies its different system components and their complex interaction within two river catchments in West Africa (Wadi Drâa, Morocco and the river Ouémé, Benin). Specific water related studies such as water availability, land use change or food security are carried out in the framework of multidisciplinary tasks, following the Driving force-Pressure-State-Impact-Response (DPSIR) approach (URL 2; URL 3). In order to solve possible future problems of water availability, IMPETUS offers tangible ways of translating scientific results into science-based strategies and model-based operational tools such as Information Systems (IS) or Spatial Decision Support Systems (SDSS). Based on sound investigations on all aspects of the water budget, the different management options and adapted operational tools can be compared and evaluated for various scenarios in close co-operation with local stakeholders. The project aims at providing a reliable basis for political measures and international agreements.

As an example of an arid watershed IMPETUS focuses on the Drâa catchment, one of the ten driest catchments of the world (Ravenga, 1998). Due to its aridity, population, infrastructure and husbandry are concentrated along rivers and oases. The ephemeral flows of the rivers force people to use groundwater to meet their water demand. Thus, integrated management of groundwater is of paramount importance for the water supply in this region as reflected by the newspaper *L'Opinion* (19. June 2007): The principal national aim is ‚to establish a modeling system including hydrologic, economic and demographic data' (URL 4). However, so far the development of appropriate model concepts and choosing the best management option was severely limited by the insufficient availability of reliable groundwater data and their insufficient spatial resolution. Here, we will identify and provide management options based on groundwater availability estimations at the watershed scale of the Middle Drâa, taking into account scenarios of climatic change (Speth & Christoph, 2003; IMPETUS, 2006). With the tailored lumped parameter groundwater budget model BIL considering withdrawal of groundwater (Klose & Reichert, 2006), the projection of climatic and socio-economic scenarios is possible.

2.7.2 Basin characteristics of the Middle Drâa Valley (South Morocco)

The Middle Drâa Valley is located in the Anti Atlas region south of the Central High Atlas Mountains and northerly adjacent to the Saharan Desert. This basin is about 15 000 km in size and features arid conditions (Fig. 2.7.1).

The Central Anti Atlas range and the southward opening Drâa Valley are predominantly characterizing the basin topographically. The Anti Atlas Mountains trend mainly WSW-ENE and form the northern limit of the Middle Drâa basin. Resistant sandstones and quartzites shape ridges and cuestas, e.g. the Jbel Bani. Less resistant schists form valleys and depression zones, so called feijas (Riser, 1988). Altitude ranges from around 2500 m a.s.l. in the Central Anti Atlas to 450 m a.s.l. in the Saharan foreland at Lac Iriki, the former end lake of the Oued Drâa. In the same direction aridity increases (Schulz, 2006).

The climate of the Drâa region is dominated by a bimodal distribution of annual precipitation and high rainfall variability, where the rainy seasons are spring and autumn (Müller-Hohenstein & Popp, 1990; Hulme, 1992; Knippertz et al., 2003). A mean annual temperature of 22.4° C and a mean annual precipitation of 58 mm are observed at the meteorological station in Zagora (Schulz, 2006). The potential

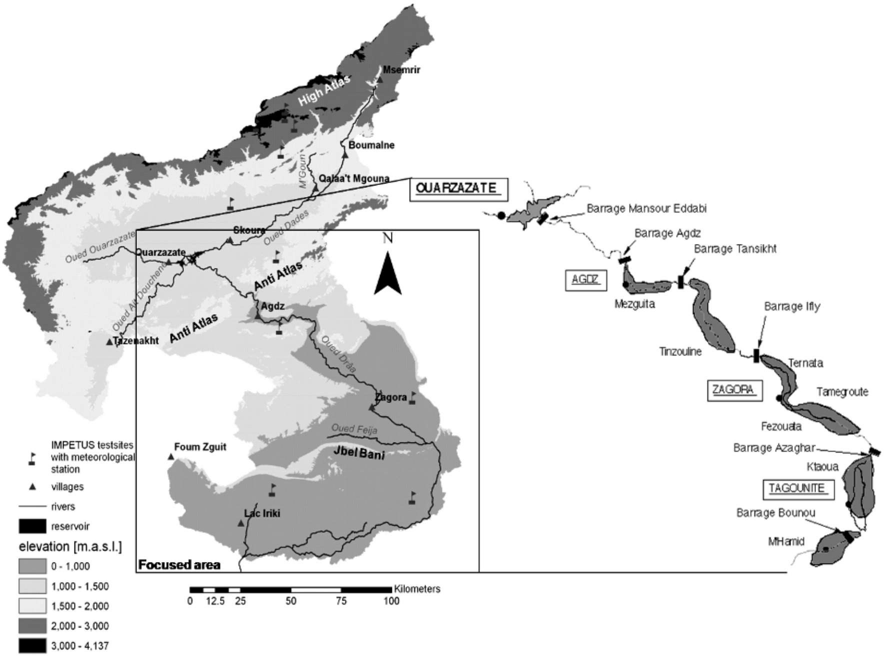


Fig. 2.7.1. Catchment area of the Upper and Middle Drâa (based on SRTM DEM (Shuttle Radar Topography Mission digital elevation model) by Anna Zeyen, IMPETUS) and the oases chain downstream the Mansour Edhabbi reservoir as area under investigation.

evaporation reaches around 3000 mm per year (DRH, 2001). The actual evapotranspiration is higher in the oases along the Oued Drâa than in the scarcely vegetated surroundings (Huebner et al., 2004), where rates of 60 to 80 % of the total annual precipitation are calculated (Weber, 2004).

Natural river discharge within the basin occurs ephemerally. The Oued Drâa drains parts of the High Atlas Mountains, the Anti Atlas Mountain range and the Saharan Foreland. The discharge system of the Middle Oued Drâa is artificially regulated by the management of the reservoir Mansour Edhabbi near Ouarzazate by the regional agricultural authority ORMVAO (Office Régional de Mise en Valeur Agricole de Ouarzazate). Outlets from this reservoir, so called Lâchers, are periodically released up to five times a year. In terms of water distribution for irrigation, the water of these Lâchers can be retained in minor „barrages“ (reservoirs) along the Oued Drâa. The water is distributed using a network of canals and applying traditional rights (ORMVAO, 1995; Ouhajou, 1996; Doukkali, 2005). Hence the water availability in the Middle Drâa Valley depends basically on the inflow from the upper Drâa catchment of the upstream located reservoir (Schulz, 2006; Cappy, 2006); the number and volume of the Lâchers are depending on its fill level. Regarding to the time period between the years 1975 to 1994, the mean annual volume of the Lâchers amounts to 173 Mm^3 (DRH, 2001), but in dry years it can decrease below 100 Mm^3. Before the construction of the reservoir Mansour Edhabbi in 1972 the Oued Drâa flew as an ephemeral river down to the Lac Iriki with a mean annual discharge of about 390 Mm^3 (Chamayou, 1966).

Paleozoic rocks and Quaternary deposits dominate the geological setting. The bedrocks consist of Precambrian series of crystalline rocks and metamorphic sediments of the West African Craton (Collins & Pisarevsky, 2005). Cambrian series of carbonatic and evaporitic rocks with intercalating tuff layers overlay the basement discontinuously. Alternating Cambrian to Ordovician sandstones and schists follow on top. The Cambrian to Silurian sandstones and quartzites are the limiting elements of the incised Drâa Valley. The alternating less resistant schist-series represent the substratum of the Drâa Valley (Destombes, 1962, 1963, 1985). After a hiatus Quaternary deposits occur in form of mostly alluvial terraces and slope debris. Tectonic imprints of the Eburnean, the Pan-African and the Hercynian orogeneses (thick skinned tectonics) are decisive for the structural setting of the Anti Atlas region (Michard, 1976; Piqué, 2001; Burkhard et al., 2006). Paleozoic rocks are compressed and slightly folded. The principal striking shows approximately E-W direction. The Graben of Zagora trending SW-NE east of Zagora cuts through the rocks. West of Zagora this Graben is trending SE-NW and changing over to the Graben of Bou Azzer, a Precambrian inlier (Hoepffner et al., 2005).

Typical desert soils are prevailing in the Middle Drâa Valley. While in the feijas (Feija de Zagora, Lac Iriki) sandy soils with high skeleton contents dominate, shallow soils rich in skeleton characterize the slopes (Cavallar, 1950). The agriculturally used oasis soils are different, as they are formed on loamy loess-like river sediments. They are nearly free of skeleton, up to 5 m thick and sandy to silty (Brancic, 1968).

The predominant vegetation in the Middle Drâa valley consists of Hamada steppe (*Hamada scoparia*) and dwarf-shrub dominated Saharan rock communities. Along the lines of periodical discharge, Acacia trees occur. *Tamarix amplexicaule* can be found at the margins of the oasis and on dunes. In general vegetation cover is very sparse and degraded by grazing (Finckh & Staudinger, 2002).

The land use is widely dominated by pastoralism, cropping is mainly restricted to the loamy sediments along the oueds. Along the Oued Drâa six oases are lined up, where date palms, wheat, barley, and alfalfa are the main crops. The oases are predominantly subdivided into small parcels of land. The agricultural activities create little income, which ranges in many cases below the subsistence level (Rademacher, in prep.).

Cultivation is based on irrigation by both surface water of the Lâchers and pumped groundwater. A change in irrigation strategies took place during the last few decades. Due to the recurrent droughts and an increased availability of motor pumps farmers access the groundwater reservoir independently by irrigation wells. Most of these wells are dug wells, but partly combinations of dug and drilled wells

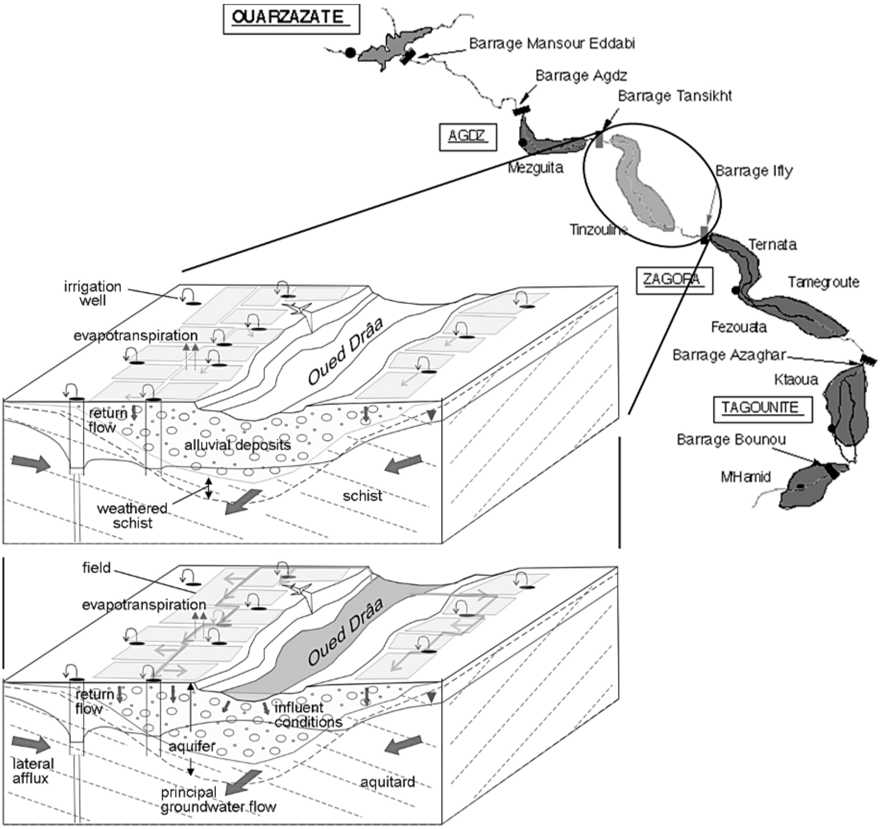


Fig. 2.7.2. Hydrogeological setting for both the times in-between (upper block diagram) and during the Lâchers (lower block diagram) (based on Chamayou, 1966; ORMVAO, 1995; DRH, 2001).

can be observed (Fig. 2.7.2). Although the actual number of wells and pumps is not exactly known, the amount of groundwater abstraction has likely increased within the last decade.

The population of urban centers in Middle Drâa Valley (Agdz and Zagora) amounted to 13,600 inhabitants in 1982 (DRPE, 1994), and increased to about 45,100 in 2005. A significant migration aspect is noticed and expected to provide a great deal of the average income (Rademacher, in prep.).

2.7.3 Hydrogeological Setting

The research area can be divided into six different sub-catchments considering similar hydrologic conditions and biogeographic zones (Fig. 2.7.1). Each sub-catchment comprises an oases underlaid by an alluvial aquifer. Natural hydraulic barriers such as outcropping quartzites, sand- and siltstones as well as tectonic lineaments form the downstream limits of the alluvial aquifers. A cuesta of outcropping Paleozoic quartzite shapes the downstream limit of the oases Tinzouline, Fezouata and Ktaoua. In place the Oued Drâa has eroded gorges through the cuestas, so called foums. A diorite dyke forms the southern limit of Mezguita. While the Zagora Graben separates the aquifers of Ternata and Fezouata, the downstream limit of the most southern oasis M'Hamid is not clearly defined.

Vertically the aquifer system mainly depends on the internal structure of the terrace sediments and their different texture. Loamy sediments on top represent a thin cover up to 5 m with a medium to high permeability. While young terraces have high to very high permeabilities, the terraces of medium and old Quaternary age exhibit slightly reduced hydraulic conductivities, due to cementation and compaction. The hydraulic conductivity of the alluvial deposits ranges between 10^{-5} and 10^{-2} m/s according to pumping tests, the lower values corresponding to the cemented facies (Tab. 2.7.1; Chamayou, 1966, Aoubouazza & El Meknassi, 1996; DRH, 2001). The alluvial aquifer is underlaid by a fringe of highly weathered Ordovician schists with moderate to high permeability. This weathered zone changes over to a fissured substratum of very low to moderate permeability.

Table 2.7.1. Properties of the aquifer system of each oasis: hydraulic conductivity K, storage coefficient S, thickness M and surface area (after Chamayou (1966) and Aoubouazza & El Meknassi (1996)).

Aquifer	K* [m/s]	S** [%]	M* [m]*	Aquifer surface* [km^2]
Mezguita	$1 \cdot 10^{-3}$	5	25	45.0
Tinzouline	$6.8 \cdot 10^{-3}$	5	25	69.0
Ternata	$3 \cdot 10^{-3}$	5	25	45.4
Fezouata	$1.5 \cdot 10^{-3}$	3	30	72.1
Ktaoua	$2.5 \cdot 10^{-4}$	5	40	50.0
M'Hamid	$2.7 \cdot 10^{-4}$	5	50	124.6

* Chamayou (1966) ** Aoubouazza & El Meknassi (1996)

Adjacent to the alluvial aquifers of the Drâa the Ordovician shales shape a fissured aquifer of very low to low permeability. The Paleozoic quartzites and sandstones as well as the Precambrian rocks act also as fissured aquifers with a low to very low hydraulic conductivity. The Cambrian limestones and dolomites are partially karstified, thus forming a moderate to highly permeable aquifer.

Groundwater underflow of the Oued Drâa is the principal flow within the basin (Chamayou, 1966; DRH, 2001). The alluvial aquifers are hydraulically connected forming an aquifer-cascade, where the underflow can pass across the barriers through a relatively small sized flow section within the alluvial deposits and fractures of a subjacent highly weathered zone. Lateral inflow into the alluvial aquifers is given by the circumjacent rocks, whereas local preferential flow originates as underflow of little Oueds and likely along faults. As an anthropogenic overprint, the recent groundwater extractions lead locally to a drawdown surrounding the pumping centers. In combination with drought conditions the withdrawal can result in an enhanced regional transient depletion of groundwater levels.

2.7.4 Hydrogeological concept

Adapted to the observed hydrogeological setting a hydrogeological concept for the aquifer systems of the six oases is developed. The structure of the individual aquifer is simplified by combining the alluvial Quaternary deposits and the weathered zone of the subjacent Ordovician schists into one shallow aquifer. Both the period during the Lâchers and the times in-between are considered (Fig. 2.7.2).

Between the Lâchers, when the Oued Drâa is dry, the underflow of the Oued Drâa is the principal groundwater flow. The alluvial aquifer is replenished indirectly by lateral inflow from the adjacent rocks. The lateral inflow is determined by diffuse or localized infiltration of precipitation, which occurs over whole subcatchment area (Fig. 2.7.4). Considering long-term conditions and a regional scale this lateral inflow can be understood as a specific flux, mostly depending on the climatic conditions. Furthermore the flood irrigation leads to recharge by return flow. But, simultaneously evapotranspiration processes have to be taken into account (Fig. 2.7.2, upper block diagram).

During the Lâchers a disconnected influent stream flow takes place. The shallow aquifer is recharged by both infiltration through the river bed and an enhanced return flow of irrigation water derived from the Lâchers. This enhanced actual recharge is clearly evidenced by measurements of hydraulic heads. If surface water is available the amount of groundwater pumping is reduced, thus the anthropogenic overprint is weakened. Therefore, in combination with the influent situation of the Oued Drâa and the lateral afflux local groundwater flow patterns can change (Fig. 2.7.2, lower block diagram).

2.7.5 Groundwater balance approach BIL

For the assessment of the groundwater availability in the basin scale of the Middle Drâa Valley the groundwater balance model BIL was specifically developed. This lumped parameter model was chosen due to limitations in the available groundwater data in space and time. At one side restrictions exist in the validity limits of geostatistical methods. At the other side the potential preferential groundwater pathways along faults are ungauged. In addition, a root mean square error of ± 18.5 m in the SRTM (Shuttle Radar Topography Mission) DEM (digital elevation model) complicates the discretization. The approximate definition of boundary conditions in combination with coarse data resolution results often in an inconsistent simulation of flow pattern within the shallow aquifer (cp. Cappy, 2006).

The model BIL estimates an annual groundwater budget for each of the six aquifers based on an EXCEL-spreadsheet. This approach displays the hydraulic connection of the aquifer cascade by a dynamic coupling of the different balance volumes. Thus, it allows the projection of scenarios and the simulation of the whole system based on the state of research and data availability (cp. Carrillo-Rivera, 2000; Flint et al., 2002). Furthermore the single items of the balance are pre-processed by different approaches, which can make a model calibration dispensable (cp. El Idrisy & De Smedt, 2006). Currently the aquifer budgets are based on data which were provided either by the Moroccan partners or own hydrogeological studies, but will be refined by more detailed data provided in the context of the ongoing IMPETUS-Project. The input data are compiled from different sources, especially because first simulations based on one single data source led to erroneous results.

Excepting evapotranspiration which is considered indirectly and as a lump-sum, all recharge and discharge components are summarized in BIL with the equation 2.7.1 (Fig. 2.7.3):

$$V_{gw} = R_p + R_l + R_i - Q_i - Q_s + F_{gw} - D_{gw} \qquad \mathbf{(2.7.1.)}$$

V_{gw} = Change in groundwater volume
R_p = Recharge by infiltration of precipitation
R_l = Recharge by infiltration of Lâchers water
R_i = Recharge by return flow of pumped groundwater for irrigation
Q_i = Amount of pumped irrigation water
Q_s = Amount of pumped groundwater for water supply
F_{gw} = Groundwater afflux from the upstream aquifer
D_{gw} = Groundwater discharge to the downstream aquifer

The diffuse recharge by infiltration of precipitation (R_p) is implemented by applying infiltration coefficients on the mean annual precipitation within the sub-catchments of each oasis (after DRE, 1976; Aoubouazza & El Meknassi, 1996; Weber, 2004). Thereby the lateral inflow is taken as a specific flux condition. Taking into

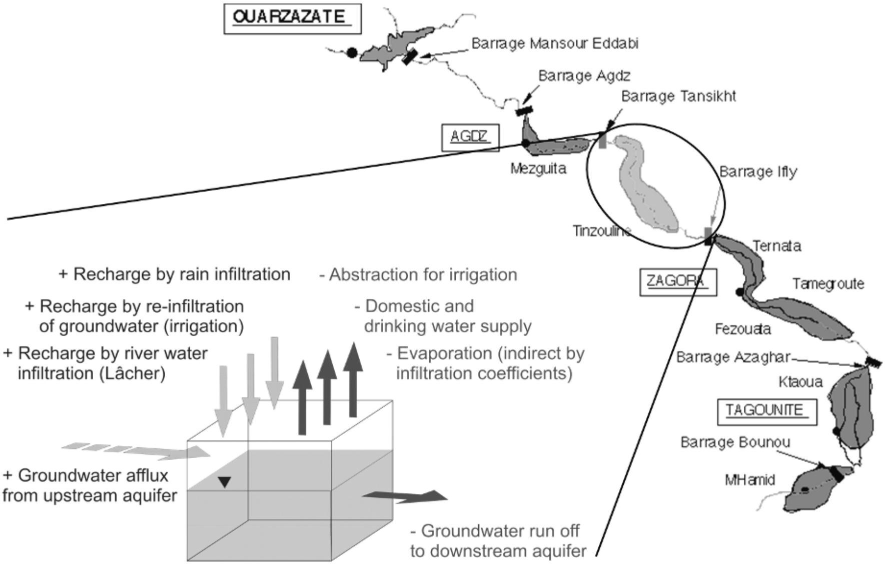


Fig. 2.7.3. Scheme of the groundwater budget estimation for one oasis.

account the river-aquifer interconnection the percolation is simplified using an infiltration coefficient (after Chamayou, 1966). As long as no detailed data are available this parameter is combined with estimations on the return flow by irrigation and gives infiltration coefficients of Lâchers water (R_l) between 20 and 30 % (IMPETUS, 2006). These coefficients are multiplied by the annual Lâchers volume for each oasis. The required data on the volumes and fractional distribution of the Lâchers were provided by the ORMVAO (unpublished). The return flow of pumped groundwater for irrigation (R_i) is approximately 20-30 %. This rate is multiplied with the assessed amount of annual groundwater extraction for irrigation (Q_i) (Fig. 2.7.4). In 1992-93 at average climatic and hydrologic conditions, annual groundwater abstraction for irrigation was estimated to 20 Mm^3 (ORMVAO, 1995; DRPE, 1994; URL 5), whereas the amount in 2005, was at least 55 Mm^3 (Heidecke & Kuhn, 2006). Groundwater withdrawal for water supply (Q_w) is considered as well for the cities Agdz and Zagora (DRPE, 1994). The connection between the different aquifers within the reservoir cascade is realized by the calculation of 1D groundwater flow (F_{gw}, D_{gw}) based on the Darcy Equation.

Scenario examples

Based on the regional climate modeling (Paeth, 2004) a scenario of climatic change is projected with BIL up to the year 2020 (Fig. 2.7.5). Until 2050, a 10 % decrease of the average annual precipitation is projected according to the REMO-modeling

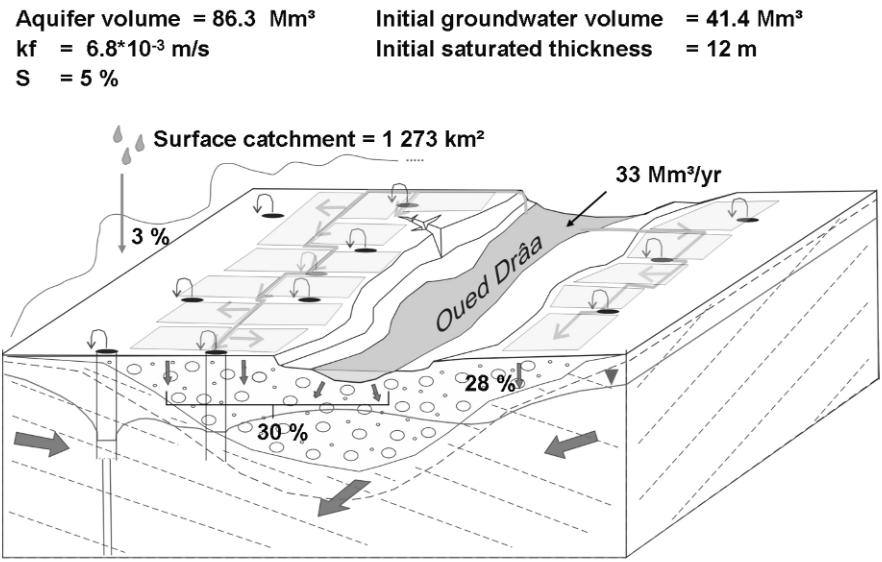


Fig. 2.7.4. Parameterization of the shallow aquifer of Tinzouline for 2005 (Data based on Chamayou, 1966; ORMVAO, 1995; Aoubouazza & El Meknassi, 1996; DRH, 2001).

(Paeth, 2004). The reduction of rainfall will mainly affect the charging level of the reservoir Mansour Edhabbi and thus, the volume of the Lâchers and the recharge condition in the Middle Drâa Valley. Additional, this reduction influences the recharge by infiltration of precipitation. In BIL the effect of reduced precipitation was taken into account by a representative reduction of the available annual volume of the Lâchers, which will cause serious problems of groundwater depletion in the near future at the oases Tinzouline and Ternata (Fig. 2.7.5). For the years 2000 to 2007 the influence of the reduced Lâchers is obvious and follows the preliminary projection of a linear trend up to 2020. This linear trend will be replaced by hydrologically proven calculations of possible future Lâcher volumes. Due to the fact that the downstream boundary conditions can not be sufficiently defined, the computed groundwater levels for M'Hamid seem too high resulting in a positive feedback to the upstream aquifer of Ktaoua. Therefore, the hydraulic gradient to M'Hamid appears to be underestimated within the hydraulic aquifer connection, which slightly buffers the drawdown of the upstream oases.

The impact of the assumed climatic change would lead to an increased depletion of groundwater levels by around 2 m up to the year 2020 according to the first comparison of the climatic change scenario and the straight forward modeling. Thereby, the major impact is caused by the reduced annual volume of the Lâchers.

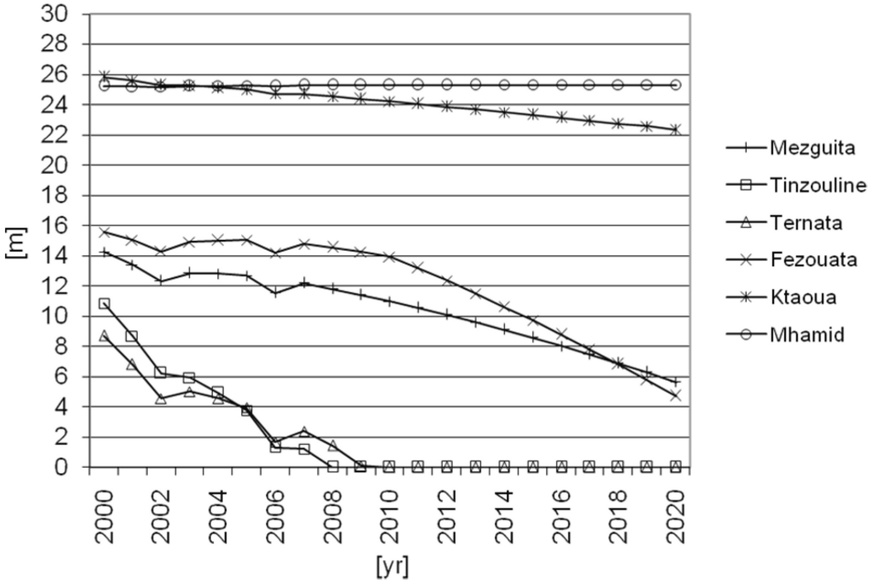


Fig. 2.7.5. Development of the saturated thickness for each oasis under the pressure of climatic change assuming reduced annual precipitation.

Consequently, the saturated thickness of the aquifer of Fezouata is estimated to 7.25 m following the straight forward modeling, according to the scenario of climatic change the saturated thickness is estimated to 5.23 m.

As to the management options, another projection considers the impact of a stream flow regeneration of the Oued Drâa by passing the water of heavy rain events directly to the oases chain without reservoir storage. This scenario is based on both the assumption of reduced evaporation losses in the reservoir as well as the higher mean annual discharge before the construction of the reservoir (before: 390 Mm^3, after: 173 Mm^3). Thus, an increased annual amount of discharge of 200 Mm^3 in the Middle Oued Drâa was adopted. At the same time the use of the surface water for irrigation was assumed, although heavy rainfall usually appears in late autumn and spring time and disregarding conventional irrigation times. Furthermore this scenario takes into account the optional range of infiltration coefficients with values between 20 and 25 %. First modelling results depicted the anticipated replenishment of the aquifers (Fig. 2.7.6), e.g. the aquifers of Ternata and Fezouata will be filled up in the year 2018 and 2020 respectively. But the oasis Tinzouline still will face groundwater scarcity.

Consequently, an additional management measure was introduced. Instead of the common distribution of the Lâchers water between the oases (cp. ORMVAO, 1995), the surface water was distributed according to meet the specific requirements of the single oases. Thus the oasis Tinzouline receives 8 % more of the

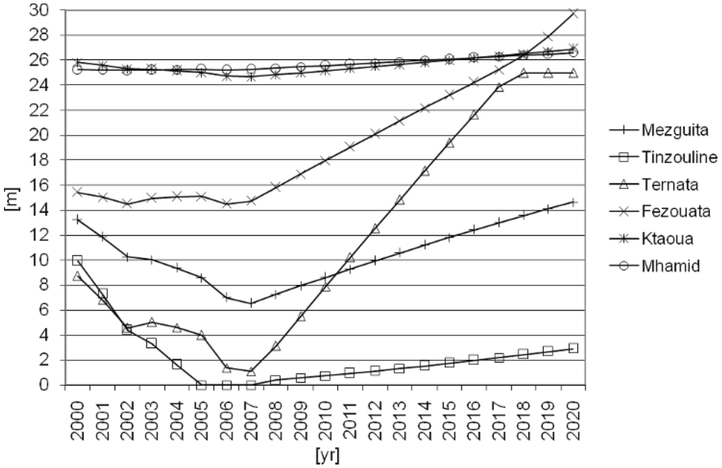


Fig. 2.7.6. Development of the saturated thickness for each oasis considering an alternative reservoir management assuming an annual Lâchers volume of 200 Mm^3 (first results).

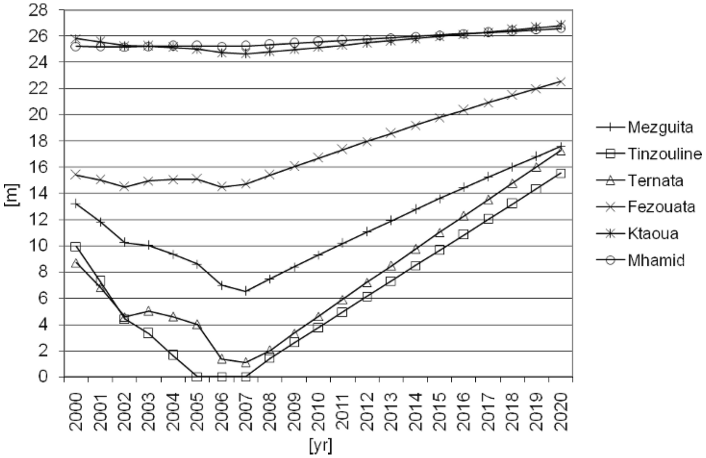


Fig. 2.7.7. Development of the saturated thickness for each oasis considering an alternative reservoir management and an adapted water distribution under the assumption of an annual Lâchers volume of 200 Mm^3.

annual Lâchers volume, while Ternata and Fezouata get 5 and 3 % respectively less. With this additional management option the observed groundwater recharge is more uniform without filling up any aquifer (Fig. 2.7.7).

Perspectives of BIL

As expected the sensitivity of the parameters in BIL differs significantly, e.g. recharge by infiltration of Lâchers water (R_l) shows a higher sensitivity than recharge by infiltration of precipitation (R_p). The amount of groundwater extraction for irrigation (Q_i) displays a high sensitivity with respect to the relatively small volume of the aquifers. Furthermore the specific infiltration coefficients are very sensitive parameters carrying a high degree of uncertainty.

In spite of existing uncertainties of the input data, the first modeling results are in good accordance with the general trends observed in hydrographs (pers. comm. M. Sabbar, Service Eau Ouarzazate and M. Bendali, ORMVAO). Thus, BIL was confirmed to be an appropriate assessment tool for the groundwater availability in the Middle Drâa Valley with the capability of scenario projection. Nevertheless, further model optimization is required and currently under way. In this context, hydro-chemical and isotopic data will be used to verify both the estimation of artificial recharge by the Lâchers (cp. Carrillo-Rivera, 2000; Külls, 2000; Scanlon et al., 2002; Glynn & Plummer, 2005; El Idrisy & De Smedt, 2006) and the natural recharge processes (cp. Sophocleous, 2002; Xu & Beekmann, 2003). Additionally the already started establishment of a groundwater monitoring network in the Drâa catchment in close collaboration with the regional water authorities, the Service Eau Ouarzazate, will support a scientific based and more sophisticated validation of the model BIL. Besides, a survey of the groundwater extraction is recommended, in order to include a more realistic ratio of pumped groundwater and the available volume of surface water in the model.

2.7.6 Groundwater management options

Useful options for a regional groundwater management can be currently obtained from the adapted model BIL. In this context Bil might be a tangible tool for other arid water sheds facing severe water problems. Our results show that only a combination of concerted actions can lead to a sustainable groundwater management. For example, plans of a potential stream flow regeneration of the Middle Oued Drâa should consider hydrogeological expertise as well as alternative surface water distribution schemes respecting the traditional rights. Moreover, integrated research on this issue is urgently required, as tackled within the multidisciplinary problem complexes of the IMPETUS framework.

A SDSS (Spatial Decision Support System) is currently developed, including different disciplines, to define the „Impact of Water Exploitation on Groundwater and Soil“ (IWEGS) in the Middle Drâa basin. Being model-based, IWEGS will support decisions on required measures, and when and where further investigations should take place, considering an annual assessment per oasis. To this end, four disciplinary models are coupled in a framework based on Java and ArcGis Engine (Laudien & Bareth, 2007) (Fig. 2.7.8).

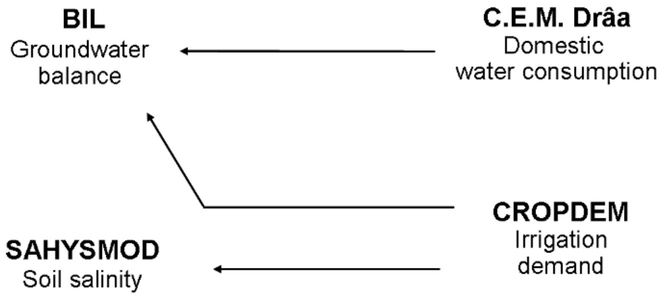


Fig. 2.7.8. Principal of the model coupling within the SDSS IWEGS.

BIL calculates the annual volume of available groundwater for each oasis. The model C.E.M. Drâa (Consommation d'Eau Ménagère Drâa) estimates the annual domestic water consumption per oasis considering the observed demographical trends. Cropdem presents a look up table based on the model CropWat (URL 6), which assess the annual water demand of the major crops for each oasis. The model SahysMod simulates an annual value of the soil salinity (electric conductivity) per oasis. By coupling the models, C.E.M. Drâa and Cropdem pass their results to BIL as negative items of the groundwater balance. Thereby, the crop water demand is set equal to the minimum irrigation amount pumped. SahysMod receives also the result of Cropdem as input (Fig. 2.7.6). All results are provided in a separate table, charts and maps. The SDSS IWEGS will support the regional evaluation in search for the best management options (IMPETUS, 2006). In the local scale where sufficient data are available, BIL will be supported by the numerical groundwater flow model MODFLOW.

Various management options will be simulated with the IWEGS in close cooperation with the Moroccan colleagues. For example, the use of alternative irrigation techniques like drip irrigation will be evaluated considering the enhanced risk of soil salinity. Based on this risk the model SahysMod is currently set up for an exemplary agricultural crop land in the Feija west of Zagora and will be applied in the Drâa oases focusing the basin scale (ILRI, 2005; IMPETUS, 2006; URL 7).

Water pricing can be another management option. In terms of assessing and simulating water pricing the integrated economic optimization model MIVAD (Modèle Integrée du Vallée du Drâa) was already tested at the basin scale in the context of IMPETUS. It incorporates the same groundwater balance approach as presented before. First results show the possibility of stabilizing the groundwater tables by charging the use of groundwater. Against the background of subsistence farming the bad economic situation in the Drâa Valley should be considered carefully, and historical, social, and political aspects have to be taken into account (Ouhajou 1996, Heidecke & Kuhn, 2006).

Acknowledgments

This work was supported by the Federal German Ministry of Education and Research (BMBF) under grant No. 01 LW 06001B and by the Ministry of Innovation, Science, Research and Technology (MIWFT) of the federal state of Northrhine-Westfalia under grant No. 313-21200200, and the Universities of Cologne and Bonn.

The IMPETUS-Project and especially the colleagues of the sub-project IMPETUS-Morocco set the frame for this study. Our Moroccan partner of the national and regional water authorities, MATEE (Ministère de l'Aménagement du Territoire, de l'Eau et de l'Environnement), ABH Souss-Massa et Drâa and Service Eau Ouarzazate, as well as the regional agricultural authorities, ORMVAO, supported this work. Roland Oosterbaan provided the model SahysMod and contributed with valuable discussions. We owe sincere thanks to the master students Sonia Breuer, Klaus Haaken and Roland Stumpf, Geological Institute, University of Bonn, for their valuable and dedicated work. Furthermore sincere thanks to Jamal Ait El Hadj (Impetus-Project, Ouarzazate), Mustafa Sabbar (Service Eau Ouarzazate), Aziz Labdi (Assistant), Rachid Essafi (MATEE), Johannes Wolfer (ACSAD-BGR), who supported us in this work

References

Aoubouazza M & El Meknassi YE (1996) Hydrologie et Hydrogéologie du bassin de la Feija de Zagora (Province Ouarzazate).- Étude sur la lutte contre la désertification dans la vallée moyen de l'Oued Drâa. Royaume du Maroc, Ministère de l'agriculture du Génie Rural, Direction du Développement et de la Gestion de l'Irrigation. Rabat.

Brancic B (1968) Sols de la Palmeraie de Fezouata. Office Régional de Mise en Valeur Agricole Ouarzazate, Ouarzazate.

Burkhard M, Cartig S, Helg U, Robert-Charrue C, Soulaimani A (2006) Tectonics of the Anti-Atlas. C.R. Geosciences 338:11-24.

Cappy S (2006) Hydrological characterization of the Upper Drâa Catchment: Morocco. PhD-Thesis, Faculty of Mathematics and Sciences, University of Bonn. http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2007/cappy_sebastien/index.htm

Carrillo-Rivera JJ (2000) Application of the groundwater-balance equation to indicate interbasin and vertical flow in two semi-arid drainage basins, Mexico. Hydrogeol J 8:503-520.

Cavallar W (1950) Esquisse Préliminaire de la Carte des Sols du Maroc. Direction de l'Agriculture, du Commerce et des Forêts du Maroc. Division de l'Agriculture et de l'Elevage, Rabat.

Chamayou J (1966) Hydrogéologie de la Vallée du Dra Moyen. Thèse de doctorat d'Université.

Collins AS & Pisarevsky SA (2005) Amalgamating eastern Gondwana: The evolution of the Circum-Indian Orogens. Earth Sciences Reviews 71:229-270.

Destombes J (1962) Stratigraphie et paléogéographie de l'Ordovicien de Anti-Atlas (Maroc): un essai de synthèse. Bulletin de la Société Géologique de France 4(3):453-460.

Destombes J (1963) Données stratigraphiques sur l'Ordovicien de l'Anti-Atlas montagne (Maroc). Revue de l'Institut Français du Pétrole 18(10):1464-1471.

Destombes J (1985) Ordivician. In: Destombes. In: Holland CH (ed.) Lower Palaeozoic of north-western and west central Africa. 1. Edition. Chichester.

Doukkali MR (2005) Water institutional reforms in Morocco. Water Policy 7:71-88.

DRH (Direction de la Région Hydraulique d'Agadir de Souss Massa et Drâa) (2001) Étude d'approvisionnement en eau potable des populations rurales de la province de Zagora, Mission 1 : Analyse de la situation actuelle du service de l'eau et collecte des données de base, Volume 2 - Etude des ressources en eau. Direction de la Recherche et de la Planification, Direction Générale de l'Hydraulique, Ministère de l'Equipement, Royaume du Maroc. Rabat.

DRE (Devision des Ressources en Eau) (1976) Étude des ressources en eau souterraine de l'Anti-Atlas Central (Région d'Ouarzazate). Programme spécial de recherche d'eau dans les zones déshéritées. Direction de l'Hydraulique, Ministère des Travaux Publics et des Communications. Royaume du Maroc. Rabat

DRPE (Direction de la Recherche et de la Planification de l'Eau) (1994) Étude du plan directeur de l'aménagement des eaux des bassins du Guir, Ziz, Rheris et Drâa. Mission 3 : Étude des schémas d'aménagement, Volume II : Unîtes Haut et Moyen Drâa, Bas Drâa, Guelmim et Tiznit-Ifni. Administration de l'Hydraulique, Ministère des Travaux Publics de la Formation Professionnelle et de la Formation des Cadres, Royaume du Maroc. Rabat.

El Idrisy H & De Smedt F (2006) Modelling groundwater flow of the Tarifa aquifer, Morocco. Hydrogeol J 14:1265-1276.

Finckh M & Staudinger M (2002) Mikro- und makroskalige Ansätze zu einer Vegetationsgliederung des Drâa-Einzugsgebietes (Südmarokko). Ber. d. Reinh.-Tüxen.-Ges. 14:81-92.

Flint AL, Flint LE, Kwicklis EM, Fabryka-Martin JT, Bodvarsson GS (2002) Estimating recharge at Yucca Mountain, Nevada, USA: comparison of methods. Hydrogeol J 10:180-204.

Glynn PD & Plummer LN (2005) Geochemistry and understanding ground-water systems. Hydrogeol J 13:263-287.

Heidecke C & Kuhn A (2006) Simulating groundwater charges for the Moroccan Drâa River basin. Agricultural and Marine Sciences 11 S.I., 47-54.

Hoepffner C, Soulaimani A, Piqué A (2005) The Moroccan Hercynides. Journal of African Earth Sciences 43:144-165.

Huebner H, Schmidt M, Sogalla M, Kerschgens M (2004) Simulating evapotranspiration in a semi-arid environment. Theoretical and Applied Climatology (published online first).

Hulme M (1992) Rainfall changes in Africa (1931-1960 to 1961-1990). International Journal of Climatology, 12:658-690.

ILRI (2005) SahysMod – Descriptions of Principles, User Manual and case studies – Version 1.7. http://www.waterlog.info/pdf/sahysmod.pdf.

IMPETUS (2006) Second Final Report –1.5.2003 – 31.7.2007. University of Cologne and Bonn. http://www.impetus.uni-koeln.de/content/download/EB2006/FinalReport2003_2006.pdf.

Klose S & Reichert B (2006) Groundwater management in the Middle Drâa-River Basin (South-Morocco). Conference presentation, ISCO 2006, Marrakech. www.tuson.ars.ag.gov/isco.

Knippertz P, Christoph M, Speth P (2003) Long-term precipitation variability in Morocco and the link to large-scale circulation in recent and futures climates. Meteorol. Atmos. Phys. 83:67-88.

Külls Ch (2000) Groundwater in North-Western Kalahari, Namibia – Estimation of recharge and quantification of the flow systems. PhD-Thesis. Julius-Maximilian University of Würzburg.

Laudien R & Bareth G (2007) Entwicklung und Programmierung räumlicher Entscheidungsunterstützungs-systeme mit Java und ArcGIS Engine. GIS - Zeitschrift für Geoinformatik, 4:16-21.

Michard A (1976) Elément de géologie marocaine – Notes et mémoires du Service géologique du Maroc, 252.

Mokhtar B (2004) Rapport national 2004 sur les ressources en eau Maroc. UN Water-Africa.

Müller-Hohenstein K & Popp H (1990) Marokko. Ein islamisches Entwicklungsland mit kolonialer Vergangenheit. Stuttgart.

ORMVAO (Office Régionale de Mise en Valeur Agricole de Ouarzazate) (1995) Étude d'amélioration de l'exploitation des systèmes d'irrigation et de drainage de l'ORMVAO- Phase 1 – Diagnostic de la situation actuelle,Vol. 1. Ouarzazate.

Ouhajou L (1996) Espace hydraulique et société au Maroc – Cas des système d'irrigation dans la vallée du Drâa. Faculté des Lettres et des Sciences Humaines. Thèse et Mémoire. Agadir.

Oulbalkace M (2007) Rapport national du Maroc – Commission Méditerranéenne du Développement Durable, Stratégie méditerranéenne pour le développement durable, Suivi des progrès dans le domaine de l'eau et promotion de politiques de gestion de la demande. Zaragoza.

Paeth H (2004) Key factors in African climate change evaluated by a regional climate model. Erdkunde 58:290-315.

Piqué A (2001) Geology of Northwest Africa. 310 p. Gebr. Borntraeger. Berlin.

Rademacher Ch (in prep.) Arbeitsmigration und Aspekte sozio-ökonomischen Wandels in einer süd-marokkanischen Oasensiedlung. Dissertation. Philosophische Fakultät, Universität zu Köln.

Ravenga C (1998) Watersheds of the world. Ecological value and vulnerability. A joint publication of the World Resources Institute and the Worldwatch Institute, Washington.

Riser J (1988) Le Jbel Sarhro et sa retombée saharienne (Sud-Est Marocain) – Étude Géomorphologique. Notes et Memoires du service Géologique No. 317. Direction de la Géologie. Ministère de l'Énergie et des Mines, Royaume du Maroc. Rabat.

Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol J 10:18-39.

Schulz O (2006) Analyse schneehydrologischer Prozesse und Schneekartierung im Einzugsgebiet des Oued M'Goun, Zentraler Hoher Atlas (Marokko). Dissertation. Mathematisch-Naturwissenschaftliche Fakultät, Universität Bonn.

Sophocleous M (2002) Interaction between groundwater and surface water: the state of science. Hydrogeol. J. 10:52-67.

Speth P & Christoph M (2003) IMPETUS West Africa, An integrated approach to the efficient Managment of scrace water resources in West Africa – case studies for selected river Ctachments in different climatic zones. In Zereini F, Jaeschke W (eds) Water in the Middle East and in North Africa, 275 – 286.

Xu Y & Beekman HE (2003) Groundwater recharge estimation in Southern Africa. UNESCO IHP Series. No. 64. Paris.

Weber B (2004) Untersuchungen zum Bodenwasserhaushalt und Modellierung der Bodenwasserflüsse entlang eines Höhen- und Ariditätsgradienten (SE Marokko). Dissertation. Mathematisch-Naturwissenschaftliche Fakultät. Universität Bonn.

URL 1: http://www.mcinet.gov.ma/mciweb/baseslegales/115.pdf

URL 2: http://www.eea.eu.int/main_html

URL 3: http://reports.eea.eu.int/92-9167-067-7/en/page001.html

URL 4: http://www.lopinion.ma/spip.php/article15997

URL 5: http://www.water.gov.ma/01presentation/17draa.htm

URL 6: http://www.fao.org/ag/AGL/AGLW/cropwat.stm

URL 7: http://www.waterlog.info/sahysmod.htm

3 Water Resources and Water Management

The fast growing world population putting the world's supply of fresh water under pressure. While the world's population tripled in the 20th century, the use of renewable water resources has grown six-fold. Already one person in five has no access to safe drinking water. The scarcity of fresh water is calling for new approaches for water planning and management. As countries are using their water resources with growing intensity, poor rainfall increasingly leads to national water crises as water tables fall and reservoirs, wetlands and rivers empty. The severity of the water crisis is best expressed by the United Nations Millennium Declaration, to achieve the goal by the year 2015 to halve the proportion of people, who are unable to reach or to afford safe drinking water.

Growing water demand and climate change present major challenges for water resources management. Impacts of climate change on water are of particular significance. This is complicated by major spatial differences in runoff and water demands so that water resources are currently fully or over-exploited in many regions. This applies in particular for the arid and semiarid Middle East and North African countries which are already naturally dry areas suffering under scarcity of water. Changes in temperature and precipitation patterns may result in additional damage to strategic economic sectors such as high-value-added agriculture, tourism or others with growth potential such as industrial developments.

In this context, the primary objectives are to support the affected regions in their efforts to improve the management, conservation, and sustainable use of water resources by promoting social and economic growth. Specific actions should involve the promotion of water governance, assistance in the development of policies and regulations for integrated water resource management. It is an integrating concept for all water sub-sectors such as water supply and sanitation, irrigation and drainage, and environment. An integrated water resources perspective ensures that social, economic, environmental and technical dimensions are taken into account in the management and development of water resources. It supports capacity building in regional, national and local institutions, and promote the exchange of information.

Within this third Chapter on „water resources and water management“ 14 contributions from most of the countries in the region are compiled giving a comprehensive overview on the actual water governance and the promotion of new technologies and concepts for introducing an integrated water management. Several contribution dealing directly with new management concepts (Droubi et al., Oulidi et al., Schmidt et al., Toussaint). Details of water resources management or technologies are presented in another group of contributions, such as groundwater exploration techniques (Messouli et al.), geophysical, hydrochemical and isotopical methods (Toll, Lange et al.) or water resources protection (Margane et al.). Other contributions are focusing on specific hydrologic processes and process understanding, like eco-hydrological processes in Lake Kinnereth (Gophen), seal formation effects in soils (Ben-Hur), the importance of groundwater during droughts (Gaaloul), seawater intrusion (Saadeh), the shrinking of the Dead Sea (Salameh & El-Naser) and at least the interaction of population dynamics and transformation in water supply systems, which are discussed in the last contribution (Hummel).

3.1 A Decision Support System (DSS) for Water Resources Management, – Design and Results from a Pilot Study in Syria

Droubi, A., Al-Sibai, M., Abdallah, A., Zahra, S. & Obeissi, M.
The Arab Center for the Studies of Arid Zones and Dry Lands – ACSAD,
www.acsad.org

Wolfer, J., Huber, M., Hennings, V. & Schelkes, K.
Federal Institute for Geosciences and Natural Resources – BGR,
www.bgr.bund.de

Abstract

Within the framework of a technical cooperation project between ACSAD and BGR a Decision Support System (DSS) for water resources management was developed and applied in two pilot areas.

The DSS consists of three major components, a project database, a groundwater flow model (MODFLOW2000) and a user-friendly water evaluation and planning software (WEAP, www.weap21.org). The modelling components MODFLOW and WEAP have been dynamically linked so that for each time-step results of one model are transferred as input data to the other. MODFLOW calculates groundwater heads, storage and flow, whereas WEAP calculates groundwater recharge, river stage, irrigation demand and the remaining water balance components. Via the WEAP interface the user can manipulate inputs and evaluate and compare results of various current as well as future scenarios in the target area, such as:

- Human activities (population growth, urbanization, domestic demands)
- Agriculture activities (land use, crop types, irrigation practices)
- Climate impacts (climate change models, regional climate cycles)
- Network characteristics (transmission link losses and limits, well field characteristics, well depths)
- Additional resources (artificial recharge, waste water reuse)

The results are visualized as graphs, maps and tables (hydraulic heads, water balances, etc.) and support the decision making process among the relevant stakeholders and decision makers.

In two pilot areas, the Zabadani basin, Syria (outlined in this paper) and the Berrechid basin, Morocco (still under calibration) the DSS has been tested and applied. These applications have been proved the strengths of the DSS-tool especially considering the impacts of climate change, changes in demand and supply, waste water reuse and artificial recharge scenarios on water availability. The DSS has been giving the local stakeholders, institutions and decision makers a valuable base for their current and future water management planning.

Thus the developed DSS and its software components have been approved to be a user-friendly, inexpensive, efficient and easily shareable tool for water resources management.

3.1.1 Introduction

The situation of Water Resources in the Middle East and North Africa (MENA) is characterised by scarcity and at the same time by increasing demands caused by rapid population growth and inefficient use of water especially by the agricultural sector. The groundwater extractions often exceed the natural recharge volumes, resulting in a decline of the groundwater table and in a deterioration of the soil and water qualities (e.g. salinization). In several countries of the MENA region groundwater flow models exist for some areas, but are often not updated and most commonly basin or administrative „basin“ water balances are calculated on very rough assumptions. A comprehensive tool for surface and groundwater management and decision support has been missing up to now in the region.

Therefore the objective of the technical cooperation project „*Management, Protection and Sustainable Use of Groundwater and Soil Resources*“ has been to develop a user-friendly, efficient, inexpensive and easily sharable instrument for water resources management (Decision Support System, DSS), to apply it in two pilot areas (Zabadani Basin, Syria and Berrechid Basin, Morocco), and to distribute it with regard to a more integrated water resources management among the MENA countries and beyond.

The DSS has been built by the combination and linkage of three components, a project database, a groundwater flow model (MODFLOW2000) and a user-friendly water evaluation and planning software (WEAP, www.weap21.org). As most MENA countries of the region rely on groundwater as the main water resource the incorporation of a spatial groundwater flow model is a must for the DSS. MODFLOW2000 was utilized to calculate the groundwater heads, storage and flow. WEAP calculates groundwater recharge, river stage, irrigation demand and the remaining water balance components. By a dynamic link, results of one model are transferred as input data to the other for each time-step. Via the WEAP interface the user can manipulate inputs and evaluate and compare results of various current as well as future scenarios in the target area, such as human and agricultural activities, climate and climate change impacts, network characteristics and the mobilisation of additional resources.

3.1.2 DSS-concept and components

The DSS itself is a software product that gives the user the capability to calculate and visualize the effects on a hydraulic system over time, if one or many of the system's parameters change. DSS-users can easily build scenarios of those changes in a Graphical User Interface (GUI) and directly view the results.

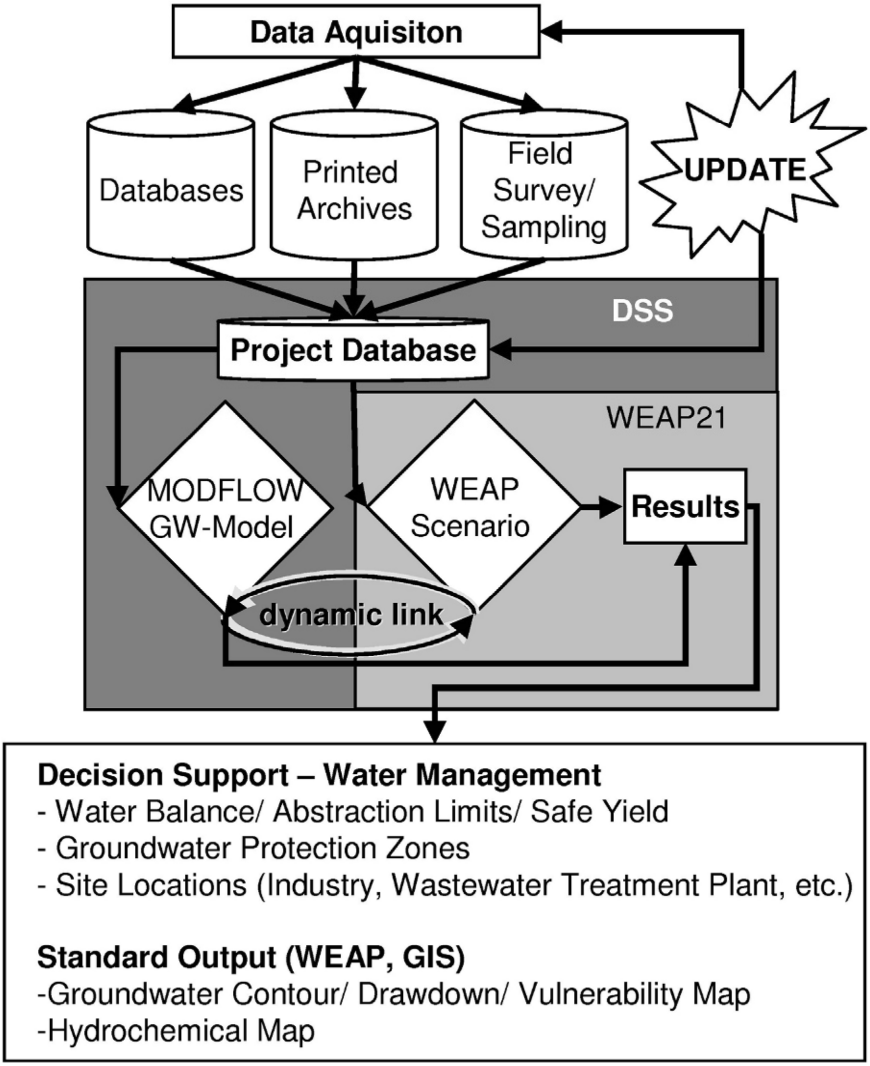


Fig. 3.1.1. DSS-concept.

It consists of three components (Fig. 3.1.1):

- Database
- Groundwater Flow Model (MODFLOW2000)
- Water Evaluation and Planning System (WEAP21)

Table 3.1.1. Main input parameters into the modelling components MODFLOW and WEAP for a reference year scenario (for more details see below or the references).

Modflow	Weap
3D geometry of the model area as a 3D grid mesh (relief, layers, top and bottom surfaces)	Schematic model linking catchments, groundwater and demand site nodes and rivers
Permeabilites of respective cells and layers (optional anisotropy in 3D)	Delimination and area assignment of (sub-)catchments and landuse classes
Starting head	Climate data (precipitation and depending on the algorithm utilized additional parameters)
Water stresses (abstractions/ recharge)	Landuse data (crop coefficient and depending on the algorithm utilized additional parameters)
Boundary conditions at the margins of the model	Irrigation scheme
Drain attributes (bottom elevation, conductance, if springs shall be modelled)	Water use rates, consumption fractions, return flows, transmission losses
River attributes (bottom elevation, conductance if groundwater – river interaction shall be modelled)	Optional additional features like waste water treatment plants, artificial recharge sites, reservoirs, river diversions, etc.

A database is used to store all relevant data (climate, landuse, abstraction rates, etc.); as each institution and region applies its own database system, queries and links or downloads can be applied to input respective data sets into the modelling components.

The modelling components are a combination of two existing software products that are dynamically linked to and affecting each other. Table 3.1.1 gives an overview of the main input parameters of the two modelling components, which will be explained in more detail in the following sections. MODFLOW calculates groundwater heads, storage and flow, whereas WEAP calculates groundwater recharge, river stage, irrigation demand and the remaining water balance components. WEAP holds the Graphical User Interface for the DSS and acts as a „remote control“ for MODFLOW, which is running in the background. As its name implies, it is designed as a tool that supports persons involved in certain decision-making processes rather than being a holistic system that substitutes them.

WEAP

The Water Evaluation and Planning System (WEAP, see www.weap21.org for more details) has been developed by the Stockholm Environmental Institute (SEI) as a planning tool for water resources management and is distributed free-of-charge for government- and non-profit organizations in developing countries.

The program calculates groundwater and surface water balances and current and future demands (irrigation and others) at a catchment, subcatchment or landuse class scale level. For the soil water balance and irrigation demand calculation the user can choose from three different built in algorithms or enter own expressions:

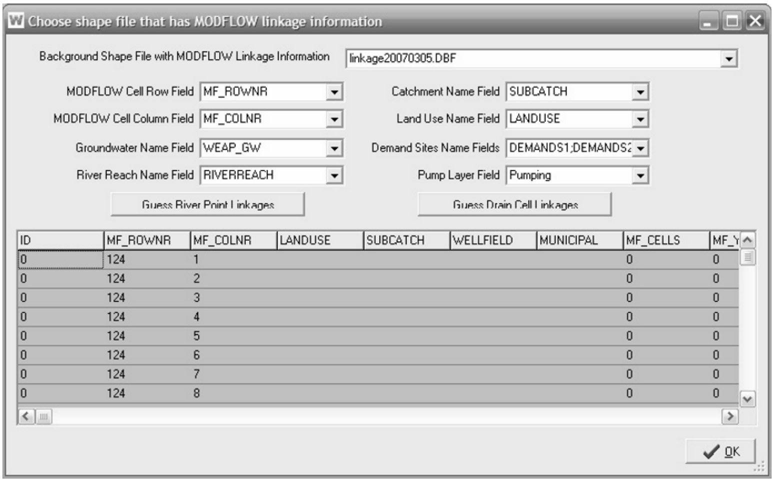
- FAO Crop requirements only (input parameters: reference crop evapotranspiration, crop coefficient, irrigation efficiency, effective precipitation)
- FAO Rainfall runoff method (input parameters: like above plus the surface runoff fraction is entered by the user manually)
- Soil moisture method (input parameters: detailed crop, climate, soil, slope and irrigation parameters)

Its Graphical User Interface is easy to use and setting up model constraints is straightforward. Physical dependencies between modelling units can be defined, reordered or removed by drag and drop operations on a drawing surface. Modelling data can easily be changed or updated either directly within the GUI, by importing spreadsheet-data or by linking WEAP to an external database management system using WEAP's Application Programming Interface (API).

Based on a reference year multiple development scenarios can be designed (incorporating prediction data or functions) and the respective water balance results can be visualized, compared and evaluated as graphs or tables by the user and then support respective decisions for the best or most likely planning scenario.

MODFLOW

MODFLOW is a computer program developed by the U.S. Geological Survey (USGS), which numerically solves the three-dimensional ground-water flow equation for a porous medium by using a finite-difference method. It is one of the most popular and comprehensive deterministic groundwater models available. The basic model uses a block-centered finite-difference grid that allows variable spacing of the grid in three dimensions. Flow can be steady state or transient. Layers can be simulated as confined, unconfined, or a combination of both. Aquifer properties can vary spatially and hydraulic conductivity (or transmissivity) can be anisotropic. Flow associated with external stresses, such as wells, spatially distributed recharge, evapotranspiration, drains, and rivers, can also be simulated using specified head, specified flux, or head-dependent flux boundary conditions. There are several commercially available pre- and post-processing packages; some of these operate independently of MODFLOW, whereas others are directly integrated into reprogrammed and (or) recompiled versions of the MODFLOW code. More details are available on McDonald & Harbaugh (1988), Harbaugh & McDonald (1996) and Harbaugh et al (2000).



Background Shape File with MODFLOW Linkage Information: linkage20070305.DBF

MODFLOW Cell Row Field: MF_ROWNR
MODFLOW Cell Column Field: MF_COLNR
Groundwater Name Field: WEAP_GW
River Reach Name Field: RIVERREACH
Catchment Name Field: SUBCATCH
Land Use Name Field: LANDUSE
Demand Sites Name Fields: DEMANDS1;DEMANDS2
Pump Layer Field: Pumping

ID	MF_ROWNR	MF_COLNR	LANDUSE	SUBCATCH	WELLFIELD	MUNICIPAL	MF_CELLS	MF_Y
0	124	1					0	0
0	124	2					0	0
0	124	3					0	0
0	124	4					0	0
0	124	5					0	0
0	124	6					0	0
0	124	7					0	0
0	124	8					0	0

Fig. 3.1.2. The link setup window inside WEAP.

Dynamic link between MODFLOW and WEAP

ACSAD, BGR and SEI jointly agreed to build and fund a powerful DSS by incorporating a dynamic link (developed by SEI) between MODFLOW and WEAP. For each time-step, results of the one model are transferred as input data to the other. MODFLOW calculates groundwater heads, storage and flow, whereas WEAP calculates groundwater recharge, river stage, irrigation demand and the remaining water balance components.

Contrary to MODFLOW, WEAP does not take into account any spatial relationship between its interior model elements like groundwater nodes, sub-catchments or rivers. In order to ensure that WEAP results address the correct MODFLOW grid cells as well as that MODFLOW results are assigned to its corresponding WEAP-elements, the link has to contain information of both models and act as a dictionary between them. This has been achieved by designing a „linkage-shape-file“ (link-file), which consists of rectangular polygons that are identical to the MODFLOW grid cells. All polygon features are enumerated in the same order as MODFLOW internally enumerates its cells and have this enumeration stored as specific row-and-column values. This address acts as a unique identifier to each polygon (Fig. 3.1.2).

Additionally, each polygon holds values of WEAP-elements like respective groundwater nodes, subcatchments, landuse classes, demand sites and from which cells and layers groundwater abstraction should come from (assigned to .wel-file in MODFLOW).

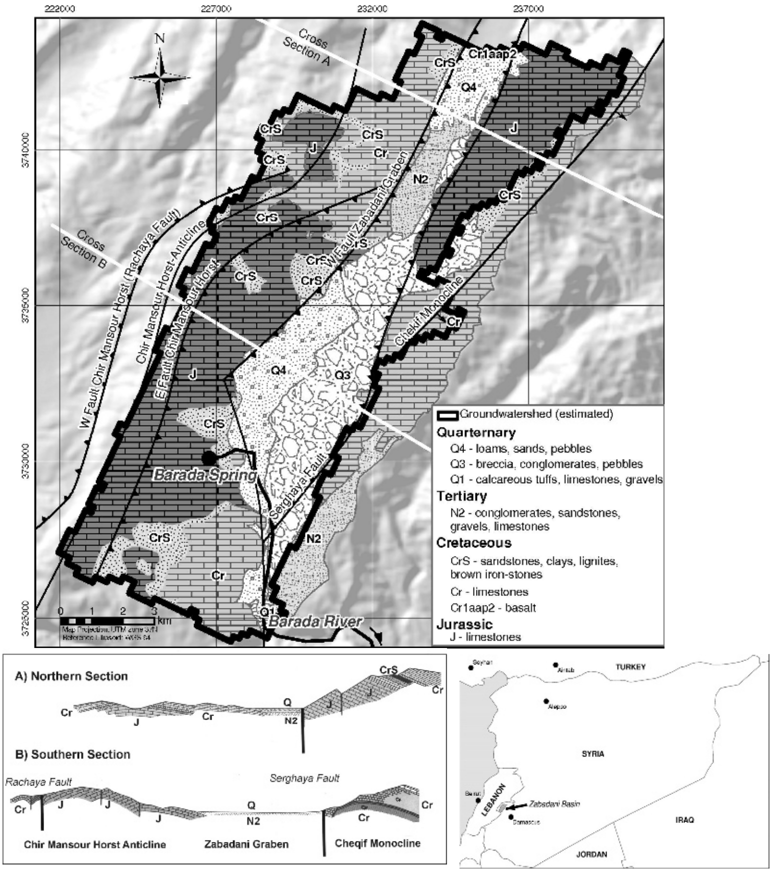


Fig. 3.1.3. Simplified geological map and sections of the Zabadani basin (modified from Dubertret, L. & Vautrin, H., 1950).

Additionally, if the river- (groundwater-surface water interaction) and drain-packages (used to simulate springs) are implemented in the MODFLOW-model, respective attributes have to be assigned in the linkage-shapefile. In WEAP a river flow-stage-width relationship has to be defined to make the MODFLOW river package working.

Initially the outlines of subcatchments and landuse classes for WEAP have been digitized following natural properties like watersheds. The assignment of WEAP area attributes to the rectangular polygons of the link-file was done by performing spatial intersections of WEAP areas against the polygons, where the value assigned to the link-file's polygon was the one that held the largest area share of all WEAP areas intersecting it. To ensure methodical consistency, codes have been programmed for many of the necessary GIS-tasks (create grid-shape-file, get attributes from other shape-file data sets by respective weighting method, etc.) and were integrated in a compact VB.net tool (Beta).

After the link-file has been chosen and the fields within it containing the linkage information have been specified, WEAP will be able to link the MODFLOW cells to the WEAP items and returns an on-screen report about the linkage status and possible errors.

3.1.3 Pilot study Zabadani Basin, Syria

The Zabadani Basin is located in the Antilebanon mountains covering an area of about 140 km. Geomorphologically it can be subdivided into three NNE-SSW trending units: the Chir Mansour Mountain range in the W reaching up to 1884 m a.s.l., the Zabadani and Serghaya grabens ranging from 1080 m a.s.l. to 1400 m a.s.l. and the Cheqif Mountain range in the E reaching up to 2466 m a.s.l. The basin is drained by the only perennial stream of the region, the Barada river with the Barada spring at 1095 m a.s.l. as its source (Fig. 3.1.3). The mean annual rainfall is about 700 mm.

There is already a water competition in the area between municipal drinking water suppliers of the area (DRA), Damascus city water supply authority (DAWSSA), agricultural and touristic (population doubles or triples in the summer) activities. In dry years Barada spring (average discharge 3.8 m/s) ceases during summer months completely, raising conflicts between the farmers (relying on the river discharge) and the drinking water suppliers operating well fields around the spring.

The Antilebanon mountain range is mainly built of Jurassic and Cretaceous limestones, minor basaltic, sandstone and claystone intercalations at the base of the Cretaceous, Neogene conglomerates and Quaternary alluvium (Fig. 3.1.3).

The regional tectonic pattern of the Antilebanon mountains is very complicated as the major branches of Red Sea – Dead Sea transform fault system are cutting the area. In the study area the Serghaya fault is not only a normal fault separating the Zabadani graben from the Cheqif mountain range, with an offset of more than 2 km, but also represents a major branch of the sinistral transform system with an offset of tens of kilometres (Dubertret, L. & Vautrin, H., 1950, Kurbanov, N., Zarjanov, Y. & Ponikarov, V.P., 1968; Russian Study, 1986). Fig. 3.1.3 shows the major folds and faults and respective geologic cross sections.

From NW to SE the area can be subdivided into 3 tectonic and hydrogeologic blocks: the Chir Mansour horst-anticline (Chir Mansour mountain range), the Zabadani graben and the Cheqif monocline (Cheqif mountain range). The patterns of these blocks are described in more details in Table 3.1.2. The Jurassic limestones represent the best aquifer of the region differing from the Cretaceous limestones and sandstones by one magnitude and regarding the Quaternary and

Table 3.1.2. Hydrogeologic blocks of the Zabadani basin.

block location	Chir Mansour Range NW	Zabadani Graben CENTER	Cheqif Range SE
major geology	Jurassic limestones	Neogene conglomerates	Cretaceous limestones
thickness (outcrop units)	Jurassic: 1000m	Neogene: Max. > 600m	Cretaceous: > 2000m
strike	NNE-SSW	NNE-SSW	NE – SW
dip	WNW	unknown	SE
faulting	Chir Mansour is an uplifted Horst with intensive block faulting brittle deformation	step faults & fault zones	beginning of Qalamoun Range, ductile deformation in mainly cretaceous rocks
deformation style	brittle (in Jurassic rocks)	unknown	ductile (in Cretaceous rocks)
folding	anticline structure	unknown	monocline/ anticline structure
karstification	intensive	not	minor
transmissivity	+++	+	++
watershed: groundwater versus surface water	assumed to be identical with surface watershed due to intensive vertical jointing, however there might be additional GW inflow from S	identical to surface watershed	due to E dipping formations groundwater shed possibly W of surface watershed

Neogene sediments even by two magnitudes. All these units are hydraulically connected as proven by several deep boreholes and are representing the regional aquifer.

Based on archive and field survey data as well as discussions with local experts a groundwater contour map and the outline of the Zabadani groundwater basin could be drawn. The groundwatershed of the Zabadani basin is identical to the surface watershed except (Fig. 3.1.4):

- the eastern block seems to be an isolated perched aquifer whose western boundary was estimated by the contact Jurassic/Cretaceous and the trace of the Chir Mansour monocline/anticline axis.
- significant groundwater inflow from SW (proven by hydraulic heads) and maybe also at a minor scale from W (estimated) through the Jurassic aquifer

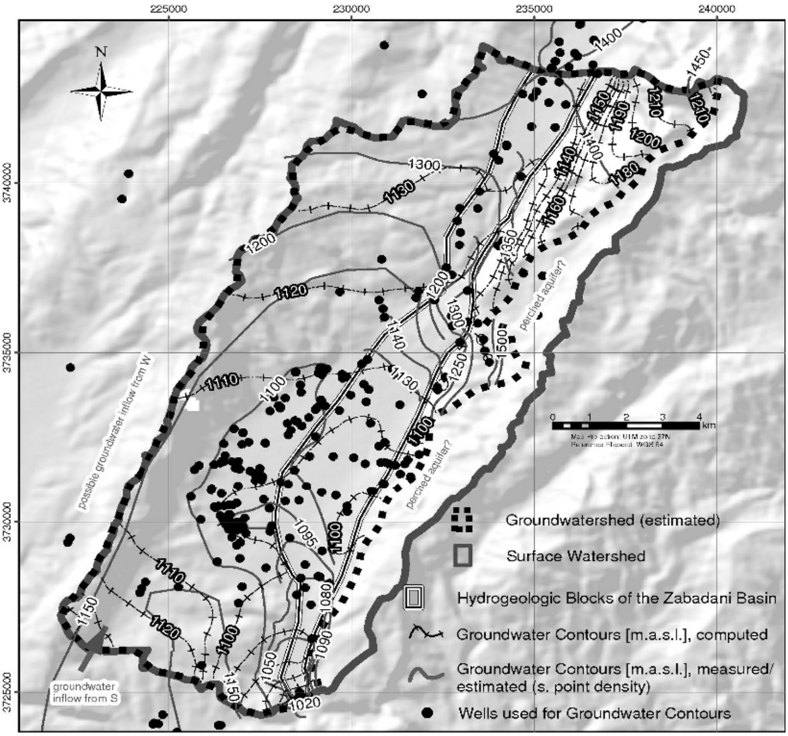


Fig. 3.1.4. Computed versus measured groundwater levels in the Zabadani basin.

The hydraulic year 2004/2005 was chosen as a reference year having average rainfall and fully recovered groundwater levels after the winter. Table 3.1.3 shows the main abstraction volumes and the direct recharge from rainfall. For this average year the preliminary water balance is negative and there might be additional lateral groundwater outflow from the basin shifting the balance even more to the negative side. Therefore there must be a groundwater inflow from outside the basin of more than 67 Mm per year. The lateral inflows and outflows as well as the groundwater – river water interaction have been calculated by the groundwater flow model (see below).

Table 3.1.3. Preliminary Water Balance for Zabadani basin.

Month	GW-Abstraction / Spring discharge				Rainfall	Recharge	BALANCE
	Barada Spring	Irrigation	Domestic	SUM			
10/2004	2.42	4.085	4.559	11.064	1.261	1.113	-9.951
11/2004	5.6	0.000	4.101	9.701	29.943	7.350	-2.351
12/2004	4.53	0.000	3.87	8.400	7.003	7.487	-0.913
01/2005	4.43	0.000	3.228	7.658	21.381	9.301	1.643
02/2005	7.52	0.000	0.766	8.286	27.494	11.408	3.122
03/2005	13.07	0.000	0.766	13.836	3.928	9.980	-3.856
04/2005	9.52	0.000	0.766	10.286	5.610	6.552	-3.734
05/2005	5.77	0.000	0.766	6.536	3.772	3.758	-2.778
06/2005	7.47	2.884	0.766	11.120	0	1.793	-9.327
07/2005	4.16	14.218	2.038	20.416	0	1.299	-19.117
08/2005	1.88	2.670	3.593	8.143	0	1.066	-7.076
09/2005	1.78	7.488	3.952	13.220	0	0.914	-12.306
SUM	68.15	31.345	29.171	128.666	100.393	62.022	-66.644

All units in Mm, irrigation and recharge volumes calculated in WEAP

Table 3.1.4. Hydrogeologic blocks and layers as applied in MODFLOW (relative permeability: - low, + intermediate, ++ high, +++ very high).

W - Block	Graben	E – Block	k-ranges [m/d]
Cretaceous/Jurassic +++ 400-600m	Neogene - 400-600m	Neogene/Cretaceous/ Jurassic +++ 400-600m	0.010 – 60.000
Cretaceous/Jurassic ++ 200-300m	Neogene/Cretaceous/ Jurassic - 200-300m	Cretaceous/Jurassic ++ 200-300m	0.005 – 1.500
Jurassic + 200-300m	Cretaceous/Jurassic + 200-300m	Cretaceous/Jurassic + 200-300m	1.000

3.1.4 Groundwater Flow Model

Conceptual Model and Boundary Conditions

The conceptual model has been designed according to the prevailing hydrogeological and geological conditions as described above and the lessons learnt from a previous groundwater model in the Zabadani valley (ACSAD, 2002). The regional aquifer has been subdivided into three layers (Table 3.1.4), which have different hydraulic properties but are hydraulically connected.

All boundary conditions have been considered as no flow boundary (GW divide), except the surface water outlet of the basin, which is a specified-head boundary.

As mentioned above there is a significant groundwater inflow from the southwest and probably also from the west. These inflows have been modeled as additional recharge along the respective boundary sections. An exact estimation of the amount and seasonal pattern of flow requires further investigations.

Input Data

The Zabadani basin numerical model grid consists of 124 rows, 27 columns, and 3 layers, i.e. 10044 cells, with 200m grid length and width respectively. The Groundwater Modeling System GMS 6 (www.ems-i.com/GMS/gms.html) was used as pre-processor of Modflow2000. The model was first calibrated in steady state, and then the parameters have been used as starting values for the transient model and further refined. All the stresses on groundwater have been entered in map module as different layers.

- Recharge: the respective groundwater recharge values have been calculated for each landuse class by WEAP, applying the „soil moisture method“ and then evenly assigned to respective model cells (positive recharge).
- Domestic groundwater abstraction: the respective well field abstraction rates have been assigned to respective model cells (*.wel-file).
- Irrigation groundwater abstraction: the respective groundwater abstraction data have been calculated for each landuse class by WEAP, applying the „soil moisture method“ and then evenly assigned to respective model cells (negative recharge).
- Barada spring discharge: the spring area has been modeled as drainage, assigning respective model cells as DRAIN-cells, where the bottom of each cell is equal to the spring outlet elevation of 1095 m.a.s.l. The discharge of Barada spring has also been used as a calibration target, giving a conductance value of 150 m^2/day/m as a result.
- Barada river stage (river package input): The stage of the river was taken from the measured values at Ramleh and Tekije stations and interpolated by GMS to change linearly between these stations.

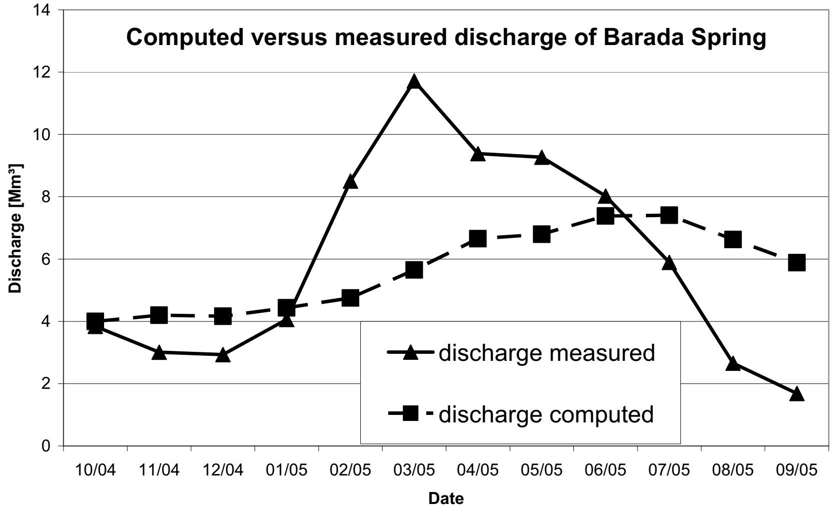


Fig. 3.1.5. Computed (MODFLOW) versus measured discharge of the Barada spring.

- The water balance deficit was balanced by assigning a groundwater inflow from outside the basin as extra recharge (see Fig. 3.1.6) to the respective model cells and to calibrate the model using the Barada spring discharge.
- Hydraulic properties of the layers: this was the most difficult part of the modeling work because of the complex hydrogeology and the data scarcity at the mountains and mountain slopes. The layers were divided into several hydraulic conductivity (k) zones according to hydrogeology, tectonics and available pumping test data. The k values range from 0.01 to 60 m/day in the top layer (most permeable layer). The values of k vary according to the type of formation, density of lineaments, dipping of the formation, and expected groundwater gradients.
- Starting groundwater head: the groundwater levels in May 2005 have been used as starting heads (see Fig. 3.1.4).

Results

It was assumed that the year 2004-2005 was at steady state as it was an average precipitation year with full recovery of the groundwater levels after the winter rains, and similar heads at the end of the irrigation seasons in November 2004 and November 2005. Using this assumption the model was run under steady state conditions and the hydraulic parameters have been calibrated and the water balance balanced (in- and outflows, Table 3.1.5). This calibration was then utilized to run a transient state model with a monthly time step for the hydrologic year 2004/ 2005.

Table 3.1.5. Transient state groundwater balance (volumes in Mm as calculated by MODFLOW).

DATE	OUTFLOWS						INFLOWS			BALANCE
	B. SPRING	IRR	DW	GW OUT	GW-RIVER	OUT	RIVER-GW	GW-RECH	IN	
10/04	4.494	4.085	4.588	1.129	0.940	15.236	0.061	1.304	1.365	-13.871
11/04	4.652	0.000	4.007	1.143	0.998	10.800	0.061	12.626	12.687	1.887
12/04	4.957	0.000	3.897	1.196	1.115	11.165	0.061	21.453	21.514	10.349
01/05	5.172	0.000	3.328	1.207	1.130	10.837	0.064	28.929	28.993	18.156
02/05	5.688	0.000	0.895	1.177	1.117	8.877	0.059	33.565	33.624	24.747
03/05	5.756	0.000	0.987	1.147	1.161	9.051	0.051	26.479	26.530	17.479
04/05	6.119	0.000	0.863	1.197	1.248	9.427	0.051	13.250	13.301	3.874
05/05	6.431	0.000	0.889	1.237	1.264	9.821	0.071	9.244	9.315	-0.506
06/05	6.333	2.884	0.705	1.191	1.224	12.337	0.076	1.141	1.217	-11.120
07/05	6.313	14.218	2.005	1.225	1.297	25.058	0.070	0.284	0.354	-24.704
08/05	5.987	2.670	3.568	1.221	1.336	14.782	0.061	0.955	1.016	-13.767
09/05	5.452	7.488	3.827	1.178	1.288	19.233	0.057	0.743	0.800	-18.433
SUM	67.355	31.345	29.559	14.248	14.119	156.626	0.743	149.974	150.717	-5.909

Outflows to: Barada Spring (B. SPRING), irrigation (IRR), domestic groundwater abstraction (DW), lateral groundwater outflow (GW OUT), flow from the aquifer to the river (GW-RIVER).

Inflows to: from the river to the aquifer (RIVER-GW), groundwater recharge (from rainfall + irrigation return flow + lateral groundwater inflow „extra recharge", GW-RECH)

Fig. 3.1.4 shows the computed heads versus the measured/estimated ones. In the plain area of Zabadani the residuals are within 5 m, going north and to the margins they increase significantly. With the available data and hydrogeologic model this was the best obtainable match so far. Jointly with the local institutions, drillers and farmers more data need to be collected in order to get a better understanding of the system and to refine the model towards a higher accuracy. However, the main abstraction and water competition area is the area adjacent to Barada spring and the Zabadani valley, so even at this stage the model is considered as a valuable and fairly accurate tool to model groundwater flow, head and spring discharge for this region.

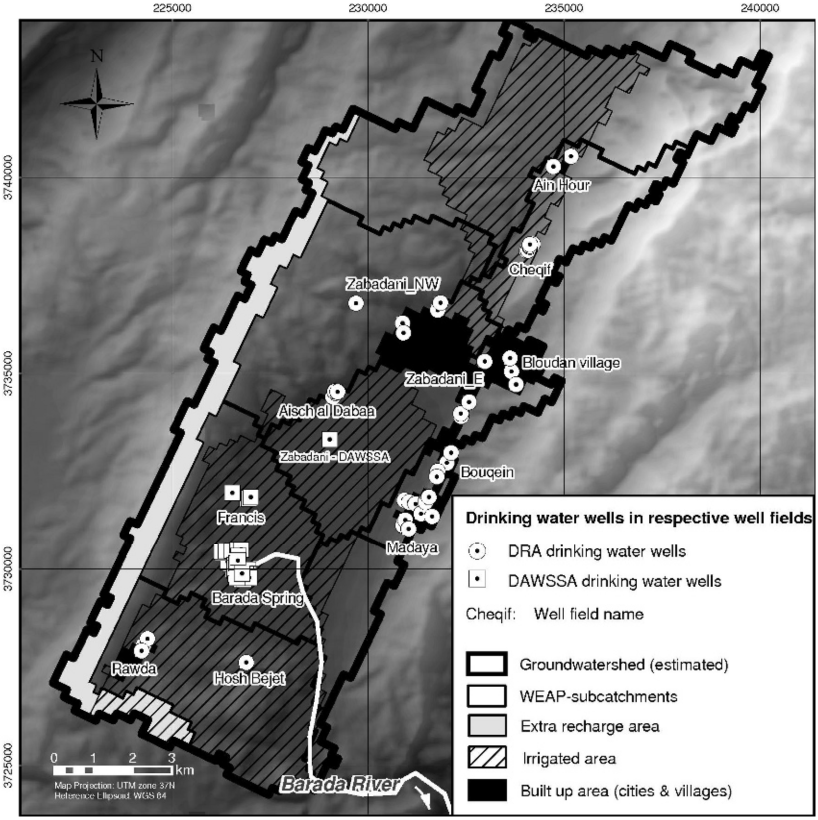


Fig. 3.1.6. Well fields, subcatchments and irrigated, built up and extra recharge areas in WEAP.

Fig. 3.1.5 shows the correlation of the computed versus the measured spring discharge. The yearly volume was also calculated correctly, only in the monthly values there are some differences indicating rapid and slow moving components feeding the Barada spring, typically for a karstic system, which cannot be exactly modelled at this stage. Future studies in delimitating the exact groundwater catchment area and respective rainfall and infiltration data will improve the spring discharge and groundwater flow model.

3.1.5 WEAP-model

The WEAP21 (www.weap21.org) software was used to build a planning and evaluation model, which then has been linked to a MODFLOW groundwater flow model as component of the DSS. For this approach spatial integrity and identical time steps between the models are very important. Spatial units in WEAP must follow the outlines of the MODFLOW cell boundaries. Inside WEAP21 the „one bucket" soil moisture method was chosen to calculate the soil water balance, groundwater recharge and the irrigation demand. The hydraulic year 2004/2005 was used as a reference year.

The initial task has been to divide the basin into spatial subunits. Together with the members of the DSS steering committee the Zabadani basin was subdivided into 11 subcatchments, being crucial to the water management planning. Their outlines have been determined by aggregating the major drinking water well fields and if possible follow surface watersheds (Fig. 3.1.6).

Besides areal, also climate data are assigned at subcatchment level. Each subcatchment is then further subdivided into respective landuse classes and irrigation pattern, crop coefficient, leaf area index, root zone conductivity and soil water capacity values have been assigned to them. The basis for the landuse mapping has been high resolution aerial colour photographs, geological information (Kurbanov, N., Zarjanov, Y. & Ponikarov, V.P., 1968) and data from the Syrian Ministry of Agriculture and local farmers. Regarding the irrigation practices seven different landuse classes have been mapped.

Inside WEAP the domestic demand sites have been integrated as nodes and respective annual water use rates have been entered. The agricultural demand (rainfed and irrigated agriculture) is calculated in WEAP for each landuse class polygon depending on the respective crop types, climate and soil parameters. Linking demand and supply is done simply through the graphic user interface by digitizing transmission links between respective demand sites and groundwater nodes (or other supplies). In the transmission link additional characteristics can be assigned like losses (to evaporation or to groundwater), maximum flow limits or minimum hydraulic heads for pumping groundwater.

Linking & calibrating the models

Groundwater is the main water resource of the Zabadani basin and groundwater recharge is the most important calibration parameter for both models (WEAP and MODFLOW). However it is also the most difficult parameter of the water balance to be calculated or estimated, as there are no direct measurements available.

As mentioned the „one bucket soil moisture model" was used to calculate groundwater recharge and irrigation demand inside WEAP. There is a limited range of input variables beside the meteorological parameters (precipitation, temperature, humidity, wind speed): two soil hydrological parameters (topsoil water holding capacity and saturated hydraulic conductivity) and two plant parameters

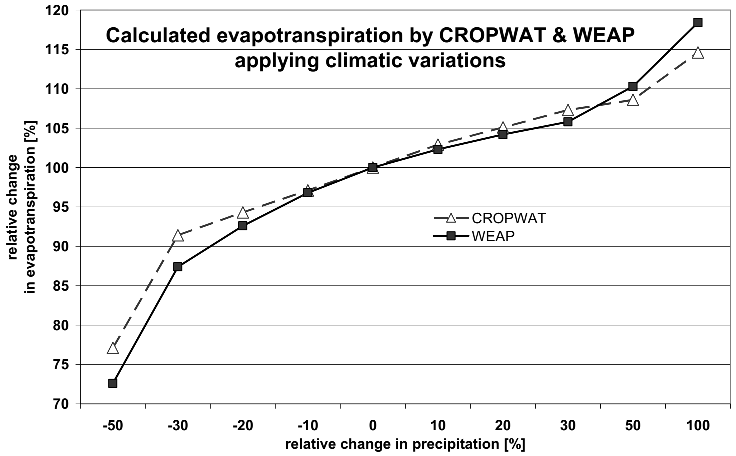


Fig. 3.1.7. Calculated evapotranspiration of CROPWAT versus WEAP applying climatic variations.

(crop coefficient and leaf area index). These parameters are WEAP-specific parameters in the empirical functions applied in WEAP, which depend also on the time step of the model. Soil and plant parameters taken from soil survey or literature data cannot be used directly as input parameters.

In order to calibrate respective soil and plant parameters external models have been utilized: CROPWAT (Clarke, D., Smith, M. & El-Askari, Kh.,1998 - for areas with vegetation cover, based on daily soil water balances and no stress for irrigated crops) and SWAP (Kroes, J.G. & van Dam, J.C., 2003 - for areas without vegetation and bare soil or rock cover, to calculate evaporation from the soil). The water balance was considered as:

precipitation = surface runoff + actual evapotranspiration + groundwater recharge

The actual evapotranspiration was calculated by CROPWAT (Fig. 3.1.7); surface runoff occurs only in January and February accounting about 12% of the yearly precipitation. This fraction was calculated by the difference between the Barada river discharge, at the basin boundary and the Barada spring discharge. The surface runoff was estimated to be evenly distributed in all subareas to be 12% of the yearly precipitation. Thus groundwater recharge could be calculated as the remaining fraction:

groundwater recharge = precipitation – 0.12 * precipitation – actual evapotranspiration

Fig. 3.1.7 shows a fairly good correlation between the calculated evapotranspiration (and similarly the calculated groundwater recharge) by CROPWAT and WEAP if the precipitation input is varied, validating the calibrated parameters for the reference year.

The irrigation demand was calculated also in CROPWAT applying the „no stress for crop“ irrigation scheme. The applied irrigation water volume causes an increase in evapotranspiration and groundwater recharge respectively. Inside WEAP the calculated irrigation volumes have been calibrated by adjusting the upper and lower irrigation thresholds.

Results

By the linked WEAP-MODFLOW models realistic soil-, groundwater balances and hydraulic heads for the reference year 2004/ 2005 could be calculated and the results can be visualized by WEAP in various scales from the total area down to the subcatchment and its landuse class levels (Fig. 3.1.8, 3.1.9 & 3.1.10).

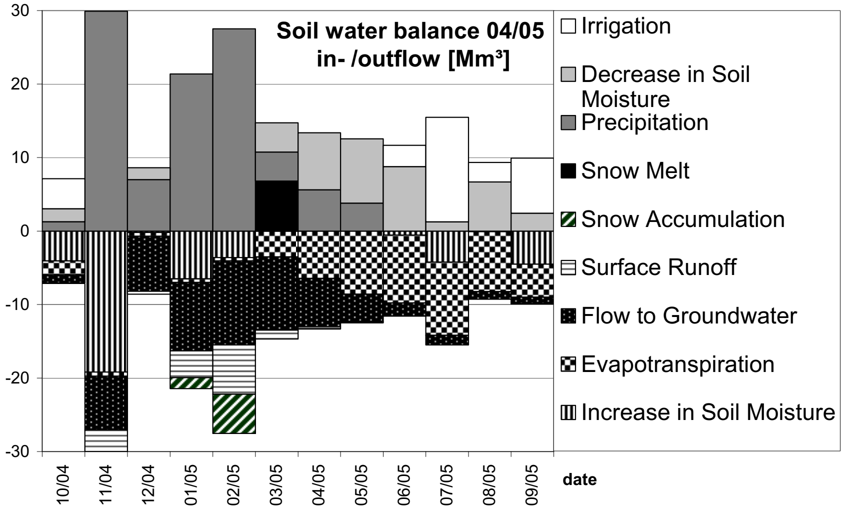


Fig. 3.1.8. Calculated soil water balances for the reference year 2004/2005.

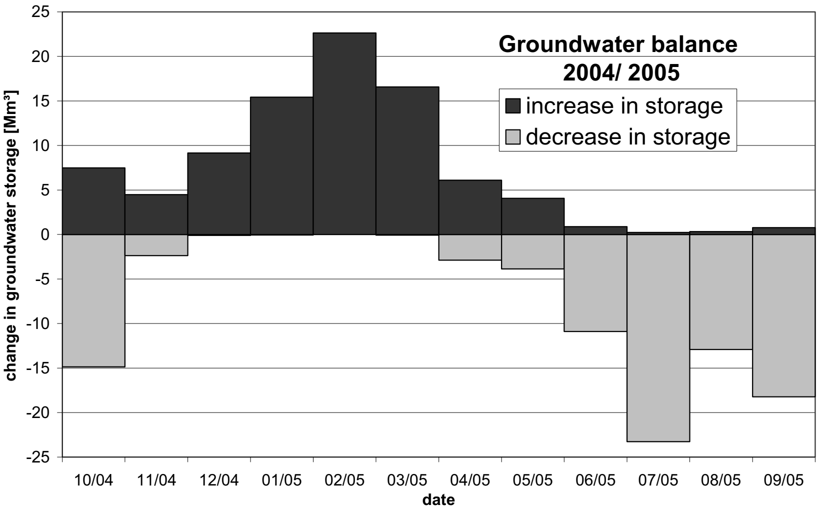
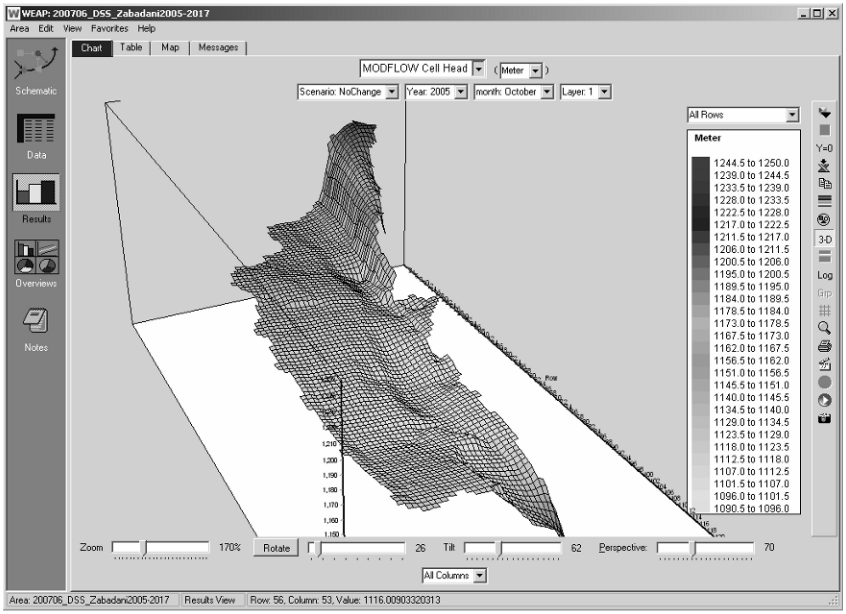


Fig. 3.1.9. Calculated groundwater balances for the reference year 2004/2005.



MODFLOW Cell Head (Meter)

Scenario: NoChange | Year: 2005 | month: October | Layer: 1

Meter

1244.5 to 1250.0
1239.0 to 1244.5
1233.5 to 1239.0
1228.0 to 1233.5
1222.5 to 1228.0
1217.0 to 1222.5
1211.5 to 1217.0
1206.0 to 1211.5
1200.5 to 1206.0
1195.0 to 1200.5
1189.5 to 1195.0
1184.0 to 1189.5
1178.5 to 1184.0
1173.0 to 1178.5
1167.5 to 1173.0
1162.0 to 1167.5
1156.5 to 1162.0
1151.0 to 1156.5
1145.5 to 1151.0
1140.0 to 1145.5
1134.5 to 1140.0
1129.0 to 1134.5
1123.5 to 1129.0
1118.0 to 1123.5
1112.5 to 1118.0
1107.0 to 1112.5
1101.5 to 1107.0
1096.0 to 1101.5
1090.5 to 1096.0

Zoom 170% | Rotate 26 | Tilt 62 | Perspective: 70

Area: 200706_DSS_Zabadani2005-2017 | Results View | Row: 56, Column: 53, Value: 1116.00903320313

Fig. 3.1.10. Calculated hydraulic heads in 3D-view.

Scenarios

Two sets of scenarios have been calculated by the DSS, a historic scenario (1998-2007) in order to check the calibration accuracy of the models and a planning scenario set (2005-2017) of three different climate/demand change scenarios.

Historic Scenario 1998-2007

In the past decade some extreme years have occurred (Fig. 3.1.11), from 1999 to 2001 have been three consecutive years in a row with less than 50% of the average precipitation, whereas 2003 has been a very wet year with 150% of the long-term average precipitation. The respective hydraulic heads (Fig. 3.1.13) and groundwater balances (Fig. 3.1.12) show clearly the impact of these extreme years compared to the average ones.

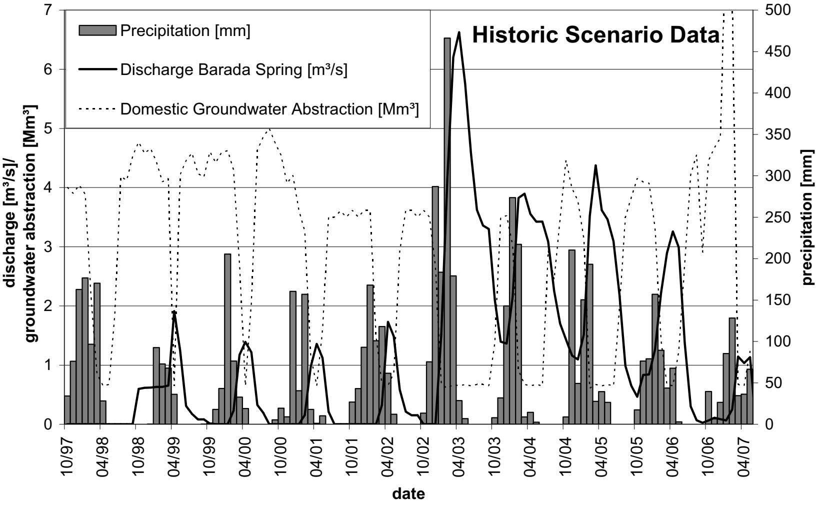


Fig. 3.1.11. Precipitation, Barada spring discharge and drinking water abstractions as input data for the historic scenario (in the winter months utilized spring water discharges outside the area are the reason for the decreases in domestic groundwater abstraction).

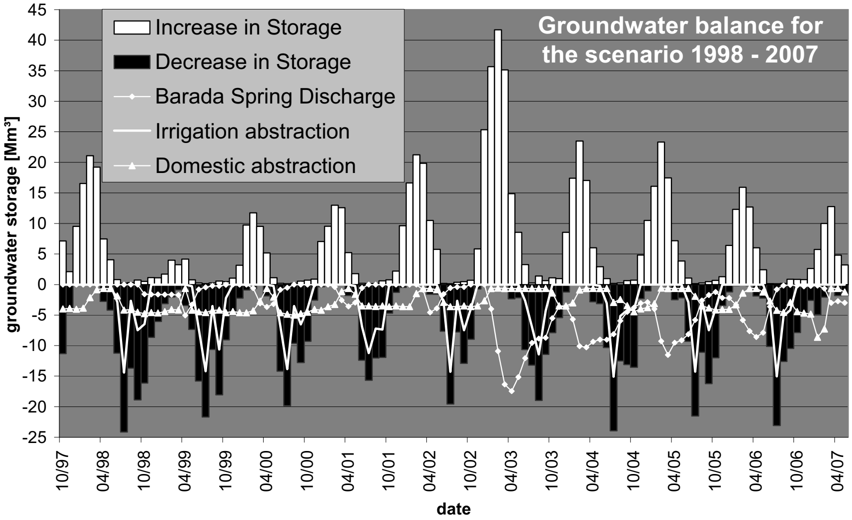
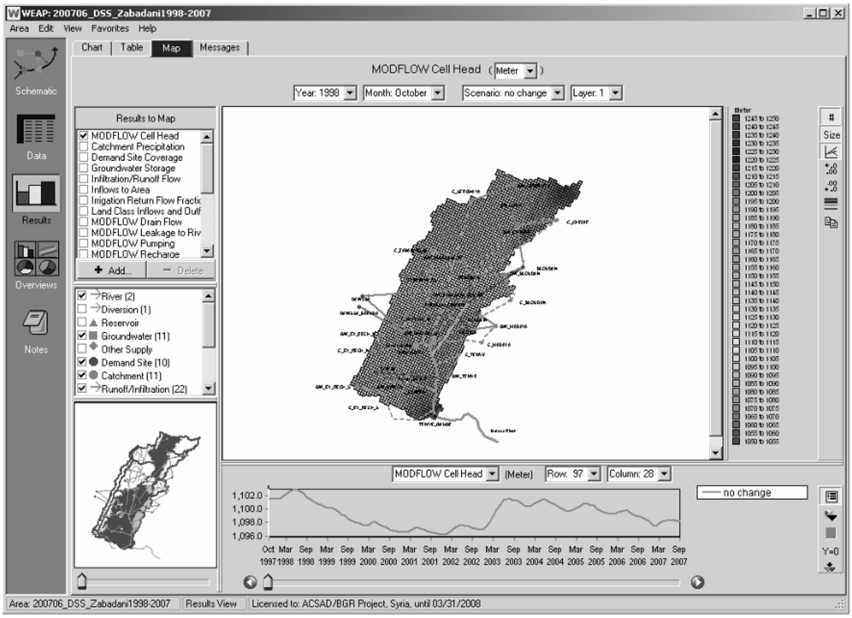


Fig. 3.1.12. Calculated groundwater balances for the years 1998 – 2007.


WEAP: 200706_DSS_Zabadani1998-2007

MODFLOW Cell Head (Meter)

Year: 1998
Month: October
Scenario: no change
Layer: 1

Results to Map
- ☑ MODFLOW Cell Head
- ☐ Catchment Precipitation
- ☐ Demand Site Coverage
- ☐ Groundwater Storage
- ☐ Infiltration/Runoff Flow
- ☐ Inflows to Area
- ☐ Irrigation Return Flow Fracti
- ☐ Land Class Inflows and Outf
- ☐ MODFLOW Drain Flow
- ☐ MODFLOW Leakage to Riv
- ☐ MODFLOW Pumping
- ☐ MODFLOW Recharge

- ☑ River (2)
- ☐ Diversion (1)
- ☐ Reservoir
- ☑ Groundwater (11)
- ☐ Other Supply
- ☑ Demand Site (10)
- ☑ Catchment (11)
- ☑ Runoff/Infiltration (22)

MODFLOW Cell Head (Meter) Row: 97 Column: 28

Area: 200706_DSS_Zabadani1998-2007 | Results View | Licensed to: ACSAD/BGR Project, Syria, until 03/31/2008

Fig. 3.1.13. Calculated hydraulic heads in the scenario 1998-2007.

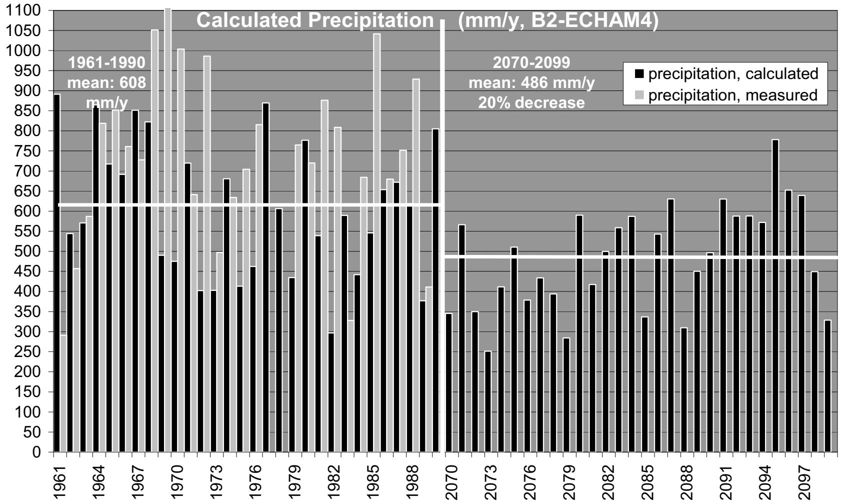


Fig. 3.1.14. B2-ECHAM4 climate scenario impact on the Zabadani basin.

Planning Scenario Set 2005-2017

Scenario A: Demand changes (DRA 2X DAWSSA 3X AGR 0.7): Jointly with the members of the Steering Committee of the Zabadani basin DSS realistic scenarios for the coming 10 years (13 years from reference year 2005) have been discussed. Each stakeholder contributed with his (institutional) estimates of the future water demand and supply:

DAWSSA:	increase in demand by 300 %
DRA:	increase in demand by 200 %
Agriculture:	change to drip irrigation, decrease in water demand by 30 %

Scenario B: Climate change scenario (80_rain): Long-term climate change impacts have been assessed by Kunstmann ET AL. (2007) by downscaling the global B2 climate scenario model of ECHAM4 to a resolution of 18km x 18km in the eastern Mediterranean/Near East region. Preliminary calculation results (daily precipitation data) have been derived for two thirty year (1961-1990 and 2070-2099) time periods. The calculated results for the Zabadani Basin are shown in Fig. 3.1.14. The graph indicates a decrease in precipitation and by averaging the yearly precipitations in the two time periods, a decrease in precipitation of twenty percent can be calculated. Up to now the climate model results on the historic data are not matching very well the measured values, however as a first hypothesis this decrease of twenty percent was applied to the planning scenario 2005-2017 in order to see on an even shorter time scale and more drastically the impact of possible decreases in precipitation. Further refinements of these climate models may give a better prediction basis.

Scenario C: Drought cycle scenario (50_rain): The historic precipitation measurements (Fig. 3.1.15, only the Damascus station has a continuous long-term precipitation record) show that there is roughly every five to thirteen years a „drought" year with less than half of the mean annual rainfall. From 1999 to 2001 there had been three „drought" years in a row, causing severe impacts on the domestic and irrigation water supply. Therefore an additional planning scenario was created by reducing the average precipitation of the year 2004/ 2005 to 50% and calculating the impacts of consecutive drought years.

For the three planning scenarios 2005-2017 Fig. 3.1.16 and 3.1.17 give the results of the impact on groundwater recharge and the hydraulic heads respectively. In Fig. 3.1.16 it can be clearly seen from which scenario year onward groundwater abstraction exceeds the groundwater recharge and thus overexploitation of the aquifer starts. The continuous drought scenario C has the most severe impact reducing the groundwater recharge also about 50% and a regional groundwater drawdown of about 10 m. The other two scenarios are less severe on basin scale, however in subcatchment-landuse class scale significant impacts on the water balances and hydraulic heads can be derived.

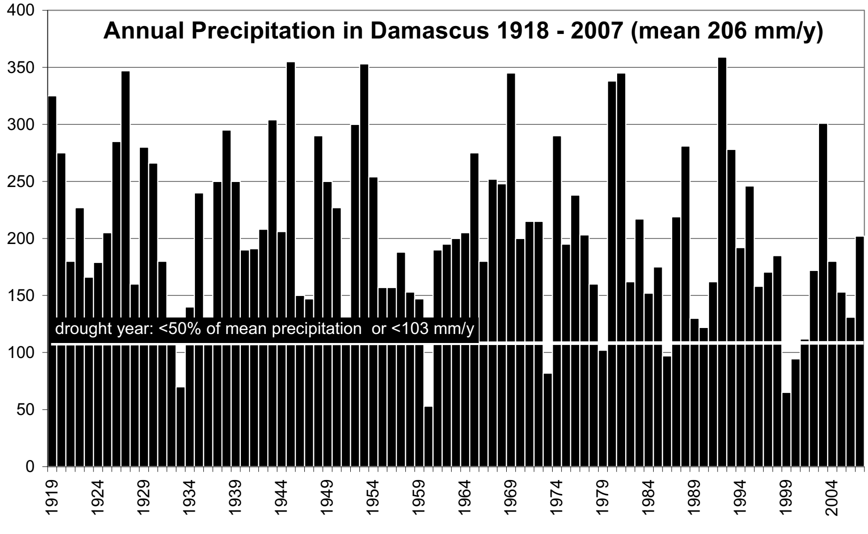


Fig. 3.1.15. Historic precipitation distribution recorded at the Damascus station.

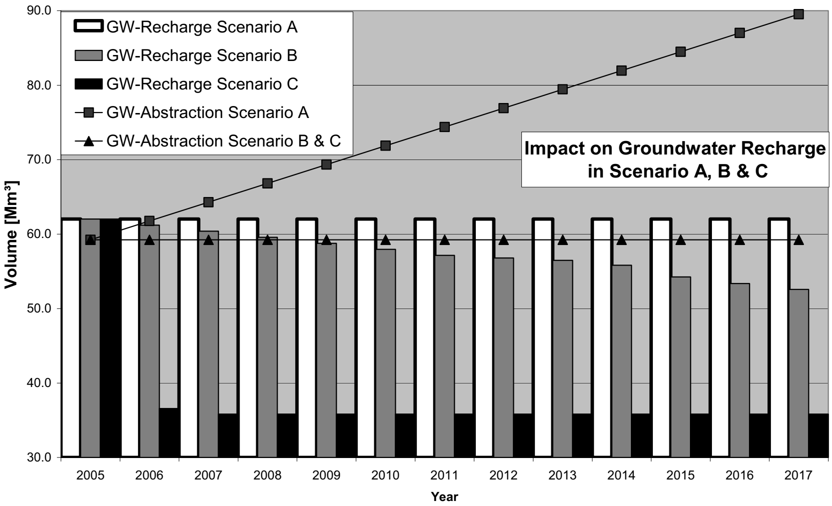
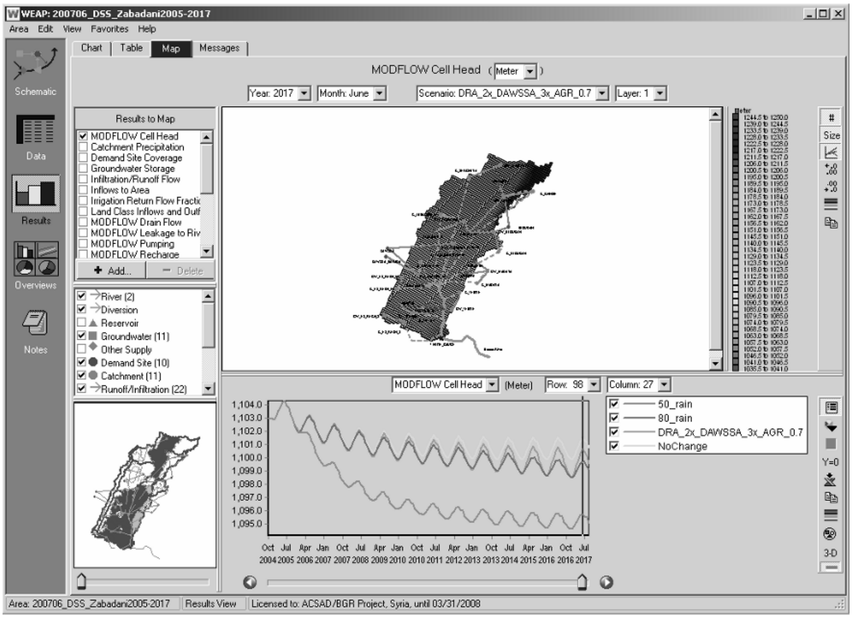


Fig. 3.1.16. Comparison of groundwater recharge and abstraction rates in the three planning scenarios 2005 -2017 (A, B and C).

.



MODFLOW Cell Head (Meter)

Year: 2017 | Month: June | Scenario: DRA_2x_DAWSSA_3x_AGR_0.7 | Layer: 1

☑ MODFLOW Cell Head
☐ Catchment Precipitation
☐ Demand Site Coverage
☐ Groundwater Storage
☐ Infiltration/Runoff Flow
☐ Inflows to Area
☐ Irrigation Return Flow Fractic
☐ Land Class Inflows and Outf
☐ MODFLOW Drain Flow
☐ MODFLOW Leakage to Riv
☐ MODFLOW Pumping
☐ MODFLOW Recharge

☑ River (2)
☑ Diversion
☐ Reservoir
☑ Groundwater (11)
☐ Other Supply
☑ Demand Site (10)
☑ Catchment (11)
☑ Runoff/Infiltration (22)

MODFLOW Cell Head (Meter) Row: 98 Column: 27

☑ 50_rain
☑ 80_rain
☑ DRA_2x_DAWSSA_3x_AGR_0.7
☑ NoChange

Area: 200706_DSS_Zabadani2005-2017 | Results View | Licensed to: ACSAD/BGR Project, Syria, until 03/31/2008

Fig. 3.1.17. Comparison of the calculated hydraulic heads for the three planning scenarios 2005 – 2017 (A, B and C).

3.1.6 Discussion

By the dynamic linkage of the three DSS-components a comprehensive and powerful tool for surface and groundwater management has been developed, applied and tested. A linkage-shapefile acts as a spatial, input and result data dictionary between MODFLOW and WEAP. Respective reference year and scenario results are calculated depending on the model grid size and the processor speed within a few minutes. The results like hydraulic heads, surface and groundwater balances can be visualized, compared and evaluated as graphs, maps or tables by the user and give more insight into the historic records and support respective decisions for the best or most likely future planning practices depending on the future constrains.

The Zabadani basin, Syria has been the first pilot area to apply the DSS. Due to the complex hydrogeology, unknown groundwater catchments, limits on time and human resources only a rough calibration of the MODFLOW groundwater flow model could be achieved at this stage. The results are acceptable in the Zabadani graben area with accuracies of the hydraulic heads of about 5m. Towards the northern margins of the basin the calculated heads are not matching reality. For the Barada spring the yearly discharge could be matched, however the monthly variations could not be calculated exactly. Further investigations in the coming months will be carried out for refinement of the model and can then lead to better calibration results.

However as stated above even at this stage the model and the DSS can be utilized for the reference year, historic data and future planning scenario calculations, taking into account that a good resolution is available in the Zabadani valley area and for the remaining region at least the general trends can be used in the planning process.

The most important input to the basin water balance is the groundwater recharge. If WEAP's soil moisture method parameters are calibrated by an external model like CROPWAT both model results are consistent and reliable as shown in Fig. 3.1.7. The open question remains, whether maybe in the future CROPWAT could be integrated directly into WEAP to allow any user to calibrate groundwater recharge by field or literature soil and plant parameters. The magnitude of groundwater recharge volumes is consistent with other regional studies using infiltration coefficient calculation and estimation approaches (El Hakim, M., 2005; Lamoreaux, P.E., Hughes, T.H. & Memon, B.A., 1989; Russian Study, 1986).

Using the same calibrated groundwater recharge as an input, WEAP and MODFLOW have been linked and used for respective scenario calculations. In the Zabadani basin the historic and the future planning scenario results have shown on the MODFLOW cell, landuse class, subcatchment or whole catchment scale: the groundwater balance (increase/decrease of groundwater storage) indicates time periods of over-pumping in the catchment (Fig. 3.1.12, negative storage 1998-2001 and 2004-2006) and significant groundwater drawdowns, which recover after the wet year(s) event. Additionally in the future planning scenarios the severe decrease in the groundwater recharge (climate impact) or the overpumping of the aquifer causing a negative groundwater balance can be seen as well as the respective fluctuations in the hydraulic heads. Especially the scenarios B and C give a first insight into climate change scenarios; the impacts as calculated by the global models (scenario B) and the ones by the „local models“ (simple statistic expectation of several drought years in a row) in scenario C can be seen. Together with the steering committee of the DSS Zabadani basin the scenario constrains have to be refined in order to incorporate also maximum allowed groundwater drawdowns and more details on demand management planning.

3.1.7 Conclusion

Within the framework of a technical cooperation project a Decision Support System (DSS) for water management as a user-friendly, inexpensive, efficient and easily shareable tool has been developed incorporating MODFLOW and WEAP as modelling components.

The user can manipulate inputs and evaluate and compare results of various current as well as future scenarios in the target area, such as:

- Human activities (population growth, urbanization, domestic demands)
- Agriculture activities (land use, crop types, irrigation practices)
- Climate impacts (climate change models, regional climate cycles)
- Network characteristics (transmission link losses and limits, well field characteristics, well depths)
- Additional resources (artificial recharge, waste water reuse)

The results are visualized as graphs, maps and tables (hydraulic heads, water balances, etc.) and support the decision making process among the relevant stakeholders and decision makers.

The DSS has been successfully tested in the Zabadani basin, Syria. For historic and future scenarios realistic results (hydraulic heads, surface and groundwater balance, etc.) on MODFLOW cell, landuse class, subcatchment or catchment scale could be calculated and visualized in graphs, maps and tables. After some remaining refinements the DSS will then be transferred to the respective basin agency and parallel capacity building and institutionalizing will continue to spread and apply the DSS-tool in Syria, Morocco and beyond.

References

Acsad (2002). Mathematical Model of el – Zabadani Basin (Syrian Arab Republic), [in Arabic]

Arlen W. Harbaugh, Edward R. Banta, Mary C. Hill, and Michael G. McDonald (2000). MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model—User Guide to Modularization Concepts and the Ground-Water Flow Process; Open-File Report 00-92; 2000

Clarke, D., Smith, M. & El-Askari, Kh. (1998). CropWat for Windows: User Guide.- Prepared by Land and Water Development Division of FAO, Institute of Irrigation and Development

Studies (IIDS) of Southampton University & National Water Research Center (NWRC) of Egypt. Download from: http://www.fao.org/waicent/faoinfo/agricult/agl/aglw/cropwat.htm

Dubertret, L. & Vautrin, H. (1950). Carte Géologique 1 : 50000, Feuille de Rayak, Notice explicative, [in French]

Dubertret, L. & Vautrin, H. (1950). Carte Géologique 1 : 50000, Feuille de Zebdani, Notice explicative, [in French]

El Hakim, M. (2005). Les Aquifères Karstiques de L'Anti-Liban et du Nord de la Plaine de la Bekaa: Caractéristiques, Fonctionnement, Evolution et Modélisation, d'après L'Exemple du Système Karstique Anjar-Chamsine (Liban). PHD Thesis, University Montpellier II & University Saint Joseph, Beirut, Lebanon.
http://www.fi.usj.edu.lb/webSiteCreen/c_publications_2005.htm, [in French]

Harbaugh, A.W. and McDonald, M.G. (1996). User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model. U.S. Geol. Survey Open-File Report 96-485.

Kroes, J.G. & van Dam, J.C. (Eds.), (2003). Reference Manual SWAP Version 3.0.3. – Alterra-report 773. Alterra, Wageningen / The Netherlands.

Kunstmann, H., Suppan, P., Heckl, A. & Rimmer, A. (2007). Joint high resolution climate-hydrology simulations for the Upper Jordan River catchment. Abstract IAHS-Conference 2007 in Perugia, Italy.

Kurbanov, N., Zarjanov, Y. & Ponikarov, V.P. (1968). The Geological Map of Syria, Explanatory Notes, scale 1:50 000, Sheets Zabadani and Rayak.

Lamoreaux, P.E., Hughes, T.H. & Memon, B.A. (1989). Hydrogeologic Assessment – Figeh Spring, Damascus, Syria. Environ. Geol. Water Sci., Vol. 13, No. 2, p. 73-127.

McDonald, M. G. & Harbaugh, A. W. (1988). A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Techniques of Water-Res. Invests. of the U.S. Geol. Survey, Book 6, Ch. A1.

Russian Study (1986). USSR all-union export-import association Selkhozpromexport: Water resources use in barada and auvage basins for irrigation of crops. Feasibility study stage I (Leningrad state institute for design of water resources development projects, USSR ministry of land reclamation and water management)

3.2 Management Strategies of Water Resources in the Arid Zone of South-Eastern Morocco

Hassane Jarar Oulidi[1], **Lahcen Benaabidate**[2], **Ralf Löwner**[3], **Alan Ernest Fryar**[4]

[1]Faculty of Sciences Dehar Mehraz, Morocco, jararhassane@yahoo.fr
[2]Faculy of Sciences and Technology Fez, Morocco, benaabidate@yahoo.fr
[3]GeoForschungsZentrum Potsdam (GFZ), Germany, loewner@gfz-potsdam.de
[4]Unviversity of Kentucky at Lexington, alan.fryar@uky.edu

Abstract

The Errachidia basin is located in the South Eastern part of Morocco and characterised by its typical arid climate. With an average rainfall of under 80 mm/year, the potential of water resources are very low in this part of the country. Because of its highly growing population, water is strongly required for agriculture (i.e. palms, vegetables…). Therefore, the management of water resources in the Errachidia basin takes priority.

The aim of the present work is investigating prospective groundwater reserves in the Cretaceous reservoir of Errachidia basin. The study uses Geographic Information System in combination with Geostatistics tools in order to produce a reliable map of potential groundwater resources.

Five basic spatial parameters in Raster and Vector format (Topography, Geology, Structures, Hydrogeology data and Hydrology) are used for this analysis. This spatial methodology required a probabilistic approach and the recourse to different statistical methods. The use of GIS for data preparation and interpretation combined with geostatistical tools is particularly useful in area where only few data have been collected.

The map of the potential groundwater resources generated through this model was verified with the yield data to ascertain the validity of the model. The verification showed that the groundwater potential zones predicted by the model are in agreement with the bore well yield data.

The present investigation demonstrates the capabilities of GIS in combination with geostatistical techniques in the demarcation of different potential groundwater zones. With appropriate adaptations, this method could be used in any other arid area.

Keywords: Arid basin, South East Morocco, Geostatistics, Groundwater mapping, Potential zone.

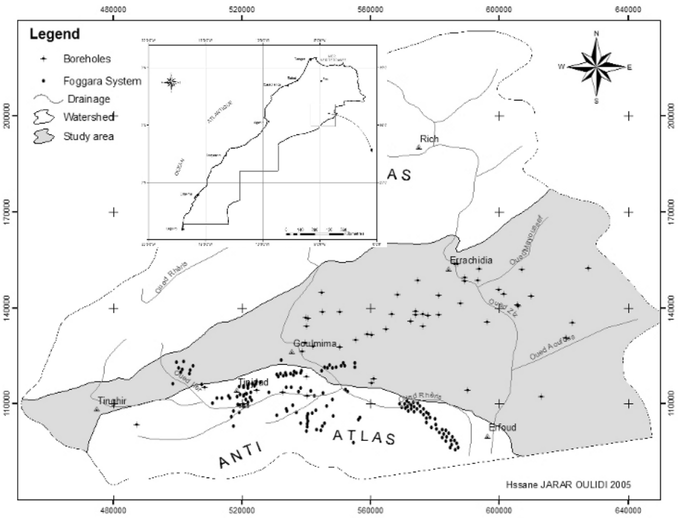


Fig. 3.2.1. Location map of study area.

3.2.1 Introduction

The study area is located in the Errachidia basin, which is bounded by longitudes 5°49’ E and 3°42’ E and latitudes 31°18’ N and 32°4’ N (Fig. 3.2.1). The area is marked by plateaus, valleys, and oases within an elevation range of 791-1455 meters. The area is hot for most part of the year. The region is arid, with precipitation less than 80 mm per year (Jarar et al., 2004) and water resources are scarce and mainly limited to groundwater. The traditional methods used to look for suitable sites of drilling boreholes have a very low rate of success. Consequently, these water wells dry up after a short period of exploitation. The concept of integrated GIS and geostatistics has proved to be an efficient tool in groundwater studies (Murthy, 2000). Inclusion of spatial information inferred from topography, hydrology, hydrogeology, and geology can give more realistic picture of the groundwater potential of an area. Hence, the present study attempts to delineate suitable locations for groundwater exploration using an integrated approach of geostatistical techniques and GIS technology.

3.2.2 The Groundwater Potential Model (GPM)

In order to define groundwater potential zones within the study area, different thematic maps at a 1: 50,000 scale were prepared from topographic maps, groundwater data and geologic maps (Fig. 3.2.2).

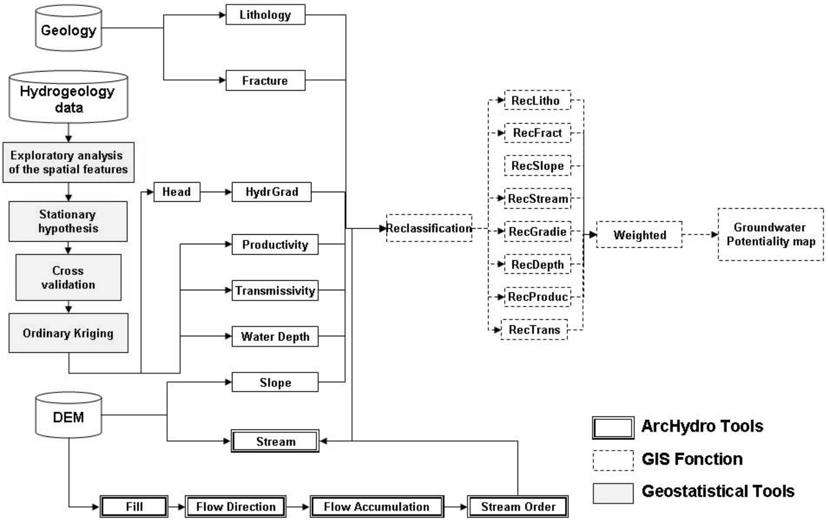


Fig. 3.2.2. Flow chart showing data flow and different GIS analysis operations followed in the present study.

- Surface data: all primary input maps (geology, lineament and contour) were digitized using GIS software, and the slope and drainage maps were prepared from a digital elevation model (DEM).
- Hydraulic data: several variables (transmissivity, productivity, hydraulic head and depth to groundwater) only locally known had to be regionalized by geostatistical modeling.
- Interpretation: thematic layers were converted into grids with related item weights, then integrated and analyzed using a weighted aggregation method. The grids in the integrated layer were grouped into different groundwater potential zones ((1) = poor, (2) = poor to moderate, (3) = moderate, (4) = moderate to good, (5) = good, (6) = good to very good, and (7) = very good).

3.2.3 Geology

The Errachdia basin can be divided into three broad permeable units, all of which are Cretaceous in age (Fig. 3.2.3). These include sandstone (Infracenomanian) in the southern part of the study area, limestone (Turonian) in the central part, and calcareous sandstone (Senonian).

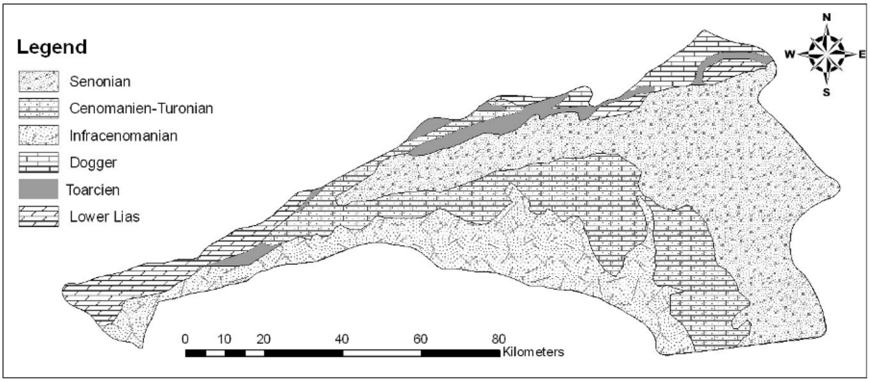


Fig. 3.2.3. Geological map of the basin.

3.2.4 Surface data

Topographic information has been collected from maps at a 1:50,000 scale and a DEM (Fig. 3.2.4) has been generated from elevation contours at 20-m intervals. A three-dimensional perspective model of the study area has been prepared using a triangulated irregular network (TIN) (Peucker et al., 1978) to understand the role of surface drainage patterns and topography in controlling groundwater conditions. A slope map (Fig. 3.2.5) was also prepared from the TIN and verified by superimposing drainage.

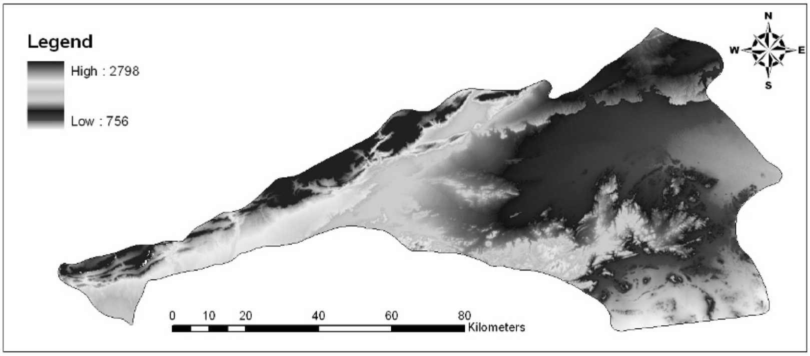


Fig. 3.2.4. Digital elevation model (DEM) of the study area.

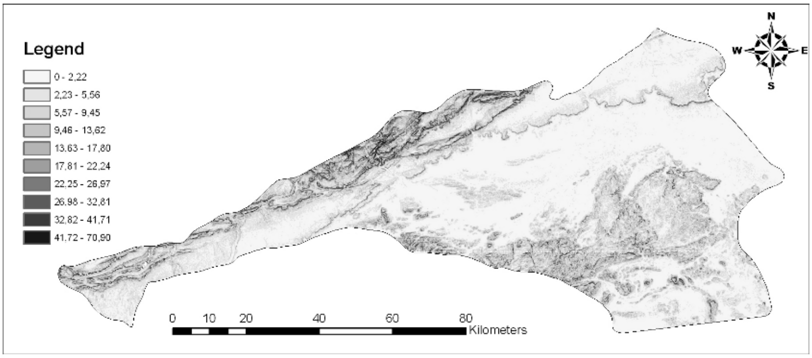
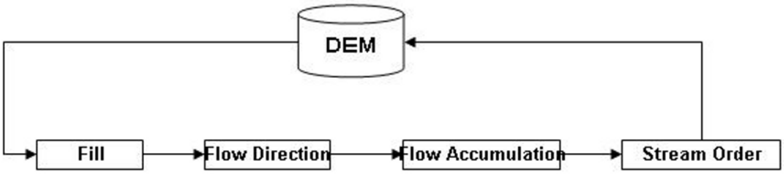


Fig. 3.2.5. Slope map of the study area.

3.2.5 Stream Network

The Hydro Tools is used to define stream networks. The following flowchart shows the process of extracting hydrologic information, such as stream networks and flow direction, from a DEM.

Stream networks can be delineated from a DEM using the flow accumulation output. Flow accumulation in its simplest form is the number of upslope cells that flow into each cell. By applying a threshold value to the results of Flow Accumulation using the Stream Networks. As feature dialog in the sample extension, a stream network can be delineated (Maidment, 2002).



3.2.6 Hydrogeologic data

The dataset used in this study includes:

- 160 measurements of hydraulic head h (m) and the depth to groundwater;
- 120 values of transmissivity T (m^2/s) and productivity (l/s).

In order to demarcate the groundwater potential zones in the study area, values of transmissivity, productivity, hydraulic head and depth to groundwater must be regionalized before being entered into the model. The first step (exploratory analy-

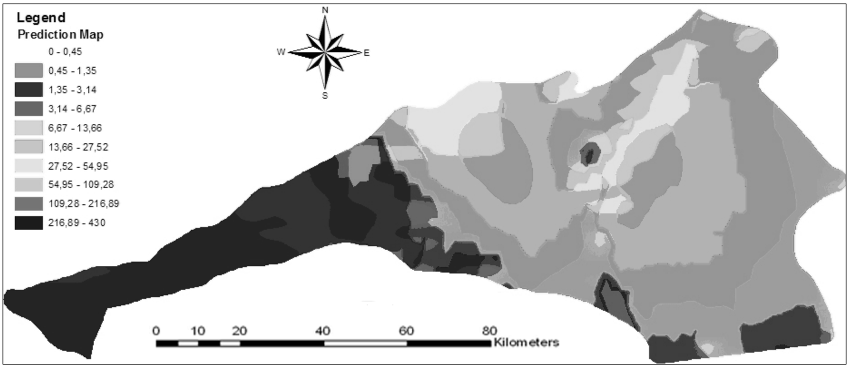


Fig. 3.2.6. Kriged map of the transmissivity field (× 10^{-3} m/s).

sis) in performing the geostatistics approach (Fig. 3.2.2) is to determine if the data sets respect the stationarity hypothesis (Isaaks and Srivastava, 1989). A random function is stationary if (Deutsch and Journel, 1992):

- its mean value (m) is constant, and
- the variance is the same everywhere.

The last step gives us a generalized variable by kriging that can be used for modeling through GIS.

Transmissivity

Statistical and geostatistical analyses of transmissivity yielded the following results: 20.3 x 10^{-3} m^2/s for the average, 10^{-1} m^2/s for the minimum, and 4.3 x 10^{-1} m^2/s for the maximum. The logarithm of the transmissivity was used to calculate the experimental omnidirectional variogram; we did not detect any anisotropy, which presents a nugget effect (sill = 0.04). The spherical model (range = 2003 m, sill = 0.3) was fitted to the experimental model at the maximal variance.

The transmissivity values were regionalized on a grid of 100 × 100 m using ordinary kriging, which allowed mapping of the estimated variable and the error of estimation (Fig. 3.2.6).

Productivity

Aquifer productivity (obtained by pumping test) was regionalized by kriging (Fig. 3.2.7). The basic statistics for productivity are 17,167 l/s for the average, 0.07 l/s for the minimum and 102 l/s for the maximum. The productivity variogram presents non-stationary spatial behavior. The recognition of structures is indirect and is made automatically in two steps (Geovariances, 1998). The first step consists of determining the degree of the drift by least-squares method. The second step con-

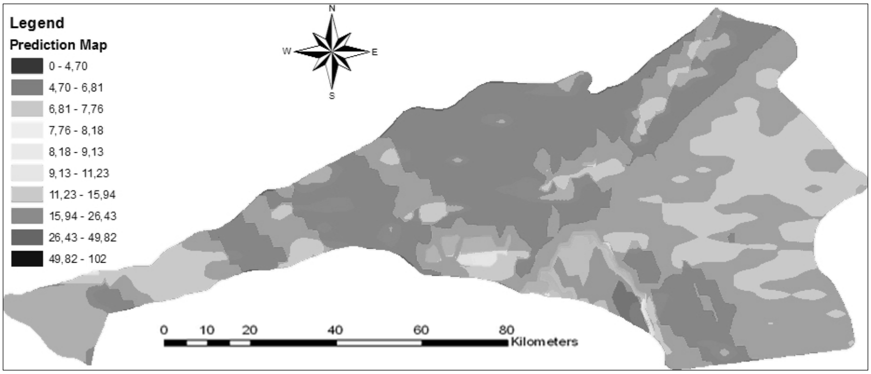


Fig. 3.2.7. Kriged map of the productivity field (l/s).

sists of adjusting models of covariance generalized by iterative regression and selection of the optimal model. The estimated productivity values were regionalized on a grid of 100 × 100 m using Geostatistical Tools (GT) ordinary kriging.

Hydraulic head

Hydraulic head (H) was interpolated by kriging (Fig. 3.2.8) using the 64 data points from the high water event of 2004. To reconstruct the H field a probabilistic approach developed by Matheron (1970) and applied to the groundwater sciences by Delhomme (1979) was used. The H variogram presents non-stationary spatial behavior characterized by a parabolic increase. It does not stabilize at great distance, reflecting the presence of a drift. As in the case of the productivity map, structural recognition of kriged H was indirect and was made automatically in two steps, and the hydraulic potentials were regionalized on a grid of 100 x 100 m using GT. This map shows that H generally decreases from north to south, following the topography. The map also shows the relationship between the aquifer and the river. As expected, the hydraulic gradient is greatest in the valley (Fig. 3.2.9).

3.2.7 Interpretation

Weighted Analysis is a simple method for the combined analysis of multi-class maps. A weight represents the relative importance of a parameter vis-a-vis the objective. The Weighted Analysis method takes into consideration the relative importance of the parameters and the classes belonging to each parameter. There is no standard scale for a simple weighted overlay method. For this purpose, the criteria for the analysis are defined and each parameter is assigned importance (Saraf and Choudhury, 1998). Determination of weighting for each class is the most cru-

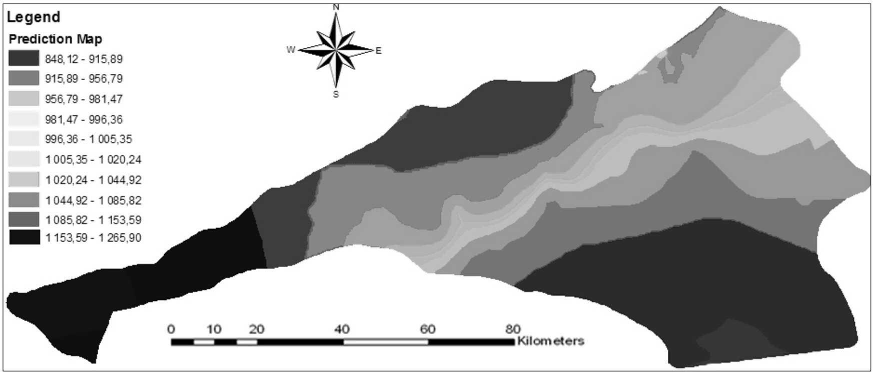


Fig. 3.2.8. Kriged map of hydraulic heads.

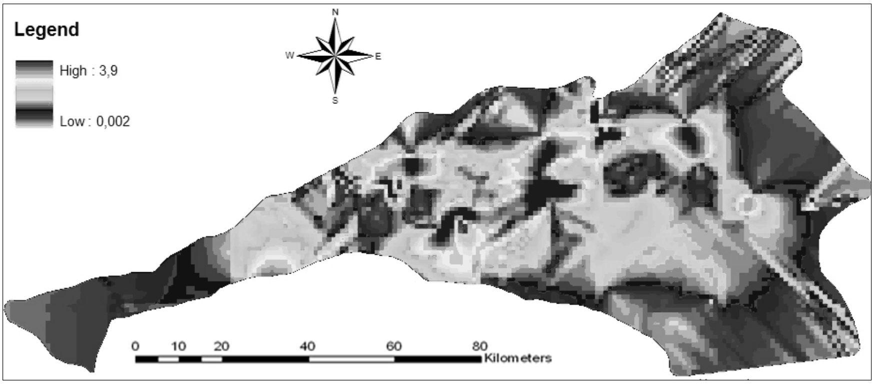


Fig. 3.2.9. Kriged map of hydraulic gradient (%).

cial in integrated analysis, as the output is largely dependent on the assignment of appropriate weights. Weighted indexing has been adopted (Table 3.2.1) to delineate groundwater potential zones (Fig. 3.2.10) considering eight parameters: geology, lineaments, drainage, slope, transmissivity, productivity, hydraulic gradient and depth to water.

The thematic layers were converted into grids with related item weights and integrated through GIS. The total weights of the final integrated grids were derived as a sum of the weights assigned to the different layers based on suitability. The delineation of groundwater potential zones was made by grouping the grids into different zones (very good, good to very good, good, moderate to good, moderate, poor to moderate and poor).

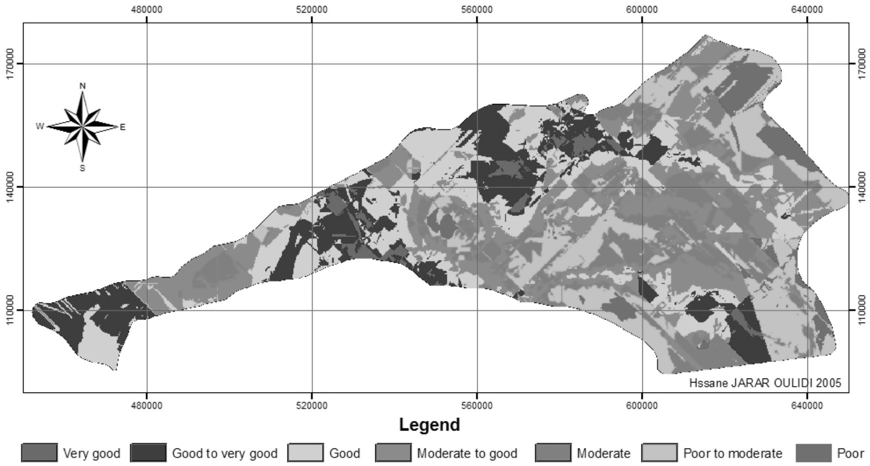
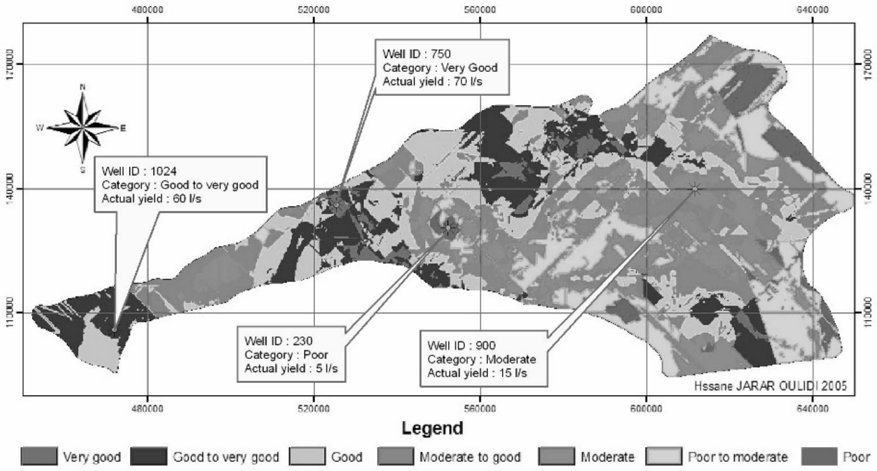


Fig. 3.2.10. Groundwater potential map of the study area.



Well ID : 750
Category : Very Good
Actual yield : 70 l/s

Well ID : 1024
Category : Good to very good
Actual yield : 60 l/s

Well ID : 230
Category : Poor
Actual yield : 5 l/s

Well ID : 900
Category : Moderate
Actual yield : 15 l/s

Fig. 3.2.11. Validation of model with actual water well yield data.

Table 3.2.1. Weights of different parameters for groundwater potential.

Sl. No	Parameters	Classes	Weight
1	Slope (degree)	0-0.22	5
		0.22-0.59	4
		0.59-1.11	3
		1.11-4	2
		> 4	1
2	Drainage	Order 5	3
		Order 4	2
		Order 3	2
		Order 2	1
		Order 1	1
3	Depth to groundwater (m)	49-91	1
		37-49	2
		27-37	3
		19-27	4
		6-19	5
4	Productivity (10^{-3} l/s)	2-7.54	1
		7.54-13.42	2
		13.42-18	3
		18-28	4
		28-46	5
5	Transmissivity (10^{-3} m/s)	0-0.45	1
		0.45-1.26	2
		1.26-2.64	3
		2.64-7.31	4
		7.31-25.11	5
7	Hydraulic gradient	0-0.36	1
		0.36-1.39	2
		1.39-3.7	3
		3.7-7.64	4
		7.64-15.35	5
6	Geology	Infracenomanian (Sandstone)	2
		Senomanian (calcareous sandstone).	2
		Turonian (Calcareous)	3
8	Lineament	Present	2
		Absent	1

Table 3.2.2. Validation of model with actual water well yield data.

Water well locations		Category of groundwater potential	Actual yield l/s
X	Y		
549170	135225	Poor	3
593740	108770	Poor	5
498440	118556	Poor to moderate	7
516920	123267	Good to very good	60
560766	145008	Very good	70
470176	105148	Moderate to good	20
584682	155879	Very good	75

3.2.8 Conclusion

The combined use of geostatistics and GIS technology is very useful for data preparation and interpretation, especially in areas where few data have been collected. The approach suggested in this paper was tested against real observations of well yield and good agreement was found, which validates the methodology for the study area (Fig. 3.2.11 and Table 3.2.2). This illustrates that the approach can demarcate groundwater potential zones in diverse geological settings and should be useful elsewhere, with appropriate modifications, for groundwater development and management.

References

Deutsch, C.V., and Journel, A.G., 1992. GSLIB - Geostatistical Software Library and User's Guide, Oxford University Press, New York, pp. 338.

Delhomme, J.P., 1979, Spatial variability and uncertainty in groundwater flow parameters, a geostatistical approach. Water Resources Research. 15, 269-280.

Geovariances, 1998. Isatis 3, The Geostatistical key. User's guide, Avon, France, pp. 120-123.

Isaaks, E.H., and Srivastava, R.M., 1998, An introduction to applied geostatistics. Oxford University Press, pp. 520-521

Jarar Oulidi, H., Benaabidate, L., and El Jaafari, S., 2004. Impact de la désertification sur les systèmes d’irrigation dans la plaine de Tafilalet, Journal International de l’Eau et de l’Environnement. 5, 52-60.

Maidment, D.R., 2002. Arc Hydro : GIS for water resources. ESRI Press, Redlands, Calif

Matheron, G., 1970. La théorie des variables régionalisées et ses applications, Centre de Géostatistique, Ecole des Mines de Paris, Fascicule 5, p. 211.

Murthy, K.S.R., 2000. Groundwater potential in a semi-arid region of Andhra Pradesh: A geographical information system approach, International Journal of Remote Sensing. 21, 1869 – 1884.

Peucker, T.K., Fowler, R.J., Little, J.J., and Mark, D.M., 1978. Triangulated irregular network. American Society of Photogrametry Digital Terrain Model (DTM) Symposium.

Saraf, A.K., and Chaudhary, P.R., 1998. Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharges sites, International Journal of Remote Sensing. 19, 1825-1841.

3.3 The Role of Groundwater During Drought in Tunisia

N. Gaaloul
National Research Institute for Rural Engineering, Water and Forestry (INRGREF)
Rue Hedi Karray, B.P.10, 2080 Ariana, Tunisia
E-mail: gaaloul.noureddine@iresa.agrinet.tn

Summary

This chapter focuses on the work done through the I.N.R.G.R.E.F to collect and analyses available information on water resources in Tunisia and the role of groundwater during drought. It presents the quantity and quality of groundwater resources data and the integration of the drought indicator information with groundwater resources. This chapter is based on review of the evolving situation during the drought years in Tunisia. It aims to raise awareness of the key linkages between groundwater and drought, and to identify appropriate technical and institutional approaches for improving the operational reliability of groundwater and the sustainability of groundwater resources. Droughts are a recurrent characteristic of the Tunisia climate, and in recent years they have become more frequent and more severe, lasting for longer periods. The repeated drought events, combined with the depletion of the aquifers, are causing acute water shortages, affecting the social life of the country, its economy and the environment. Another interaction between groundwater and droughts concerns groundwater storage and aquifer recharge. Groundwater is globally the most common water source for domestic supply and irrigation during the drought season in arid and semi-arid regions. Climate change, drought and desertification are interrelated, but these processes should not be confused or interchangeably referred to if we are to address the complex issues of drought and water management in the Tunisian region on a sound scientific basis.
Key words: Climate change, Groundwater, Aquifer recharge, Drought, Tunisia.

Resume

Ce chapitre résume le travail effectué par l'I.N.R.G.R.E.F pour recueillir et analyser les informations disponibles sur les ressources d'eau en Tunisie et le rôle des eaux souterraines pendant la sécheresse. Il présente la quantité et la qualité des eaux souterraines et l'intégration d'information d'indicateur de sécheresse avec les eaux souterraines. Ce Chapitre est basé sur l'examen et l'évolution des eaux souterraines pendant les années de sécheresse en Tunisie. Il vise à soulever la conscience des liens clés entre les eaux souterraines et la sécheresse, et identifier les approches appropriées, techniques et institutionnelles pour améliorer la fiabilité opérationnelle des eaux souterraines et la durabilité de ces ressources. Les sécheresses sont une caractéristique récurrente du climat de la Tunisie, et ces dernières années elles sont devenues plus fréquentes et sévères, s'étendant sur des périodes plus longues. Les évènements répétés de sécheresse, combinés avec la diminution des nappes aquifères, provoquent de fortes pénuries d'eau, et affectent la vie sociale et l'économie du pays, ainsi que l'environnement. Une autre interaction entre les eaux souterraines et les sécheresses concerne l'emmagasinement et la recharge de l'aquifère. L'eau souterraine est une source pour la provision domestique et l'irrigation, pendant les périodes de sécheresse dans les régions aride et semi-aride.

Mots-clés: Changement climatique, Eaux souterraines, Recharge des nappes, Sécheresse, Tunisie.

3.3.1 Background

Tunisia is situated to the south of the Mediterranean; it is bordered by Libya in the southeast, Algeria in the west (Fig. 3.3.1). Tunisia's surface area is of 164 000 km^2, its coastline totals 1300 km, its average altitude is 700 m and its highest point is the Jebel Châambi (1540 m). The population is relatively urbanised, with 58 % living in urban areas on the northern and eastern coast. Administratively, Tunisia is divided into 23 governorates, 136 counties, and 250 communes.

Tunisia shares many common features in terms of climate, water and land resources and development issues. These include arid and semi-arid climate, limited water resources, agricultural development limited by water availability and high economic and social value of water.

Like most countries affected by aridity and particularly within the Maghreb region, water resources represent in Tunisia the most precious environmental good. The climate varies from Mediterranean to semi-arid and arid; it is characterized by hot and dry summers and mild winters receiving the major part of the annual precipitation. Total rainfall and distribution is highly variable from year to year and from North to South. Average annual rainfall is around 600 mm in the North, 300 mm in the Centre, and 150 mm in the South; it is ranging from 1600 mm in the extreme North to less than 100 mm in the extreme South.

The annual average rainfall is estimated to 36 000 Millions cubic/year and is ranging from 11 to 90 000 Millions cubic. Average annual evapotranspiration is also high and water deficit is particularly significant from May to October. The annual evaporation varies between 1300 mm in the north to about 2500 mm and even more in the south.

Tunisia, a semi-arid country, faces climatic challenges because of irregular and inadequate rainfall, a fragile ecosystem, limited natural resources and the risk of over-exploitation of these few resources.

Recent studies show that 3 million hectares of land in the Centre and in the North suffer serious erosion and over 7 million hectares of land in the south suffer from wind erosion and secondary salinization. To reconcile the agricultural use of

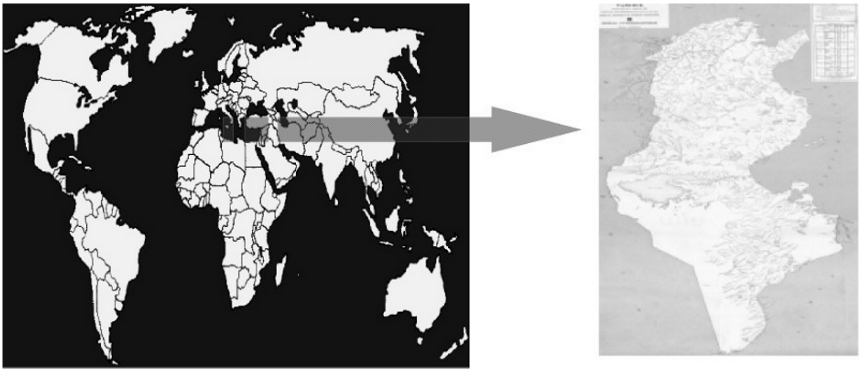


Fig. 3.3.1. Tunisia situation geographic and hydrographic network.

lands and soil protection against the different processes of desertification, Tunisia has, for several decades, developed several programmes for reforestation, pastoral improvement, dune fixation and the conservation of soil and water.

With its 1300 km of coast, the Tunisian littoral has various landscapes and important natural resources under a variety of pressure, including pollution, exploitation of sea resources and a concentration of human and economic activities along the coast causing environmental problems linked to the fragility of the marine ecosystems. The utilization of the coastline and adjacent spaces is monitored through various mechanisms with various institutions responsible for the environment, including the Ministries of Agriculture Water Resources and Environment.

Water resources and climate change in Tunisia

Water resources in Tunisia

The annual total volume of exploitable water resources in Tunisia is about 4800 Million Cubic Metres (MCM) of which about 56 % (2700 MCM) is surface water and the remaining 44 % (2100 MCM) groundwater (DGRE, 2005) (Table 3.3.1).

Table 3.3.1. Water resources distribution (Billion m^3) in Tunisia (DGRE, 2000a ; 2005).

	1970	1975	1980	1985	1990	1995	2000	2005
Surface water	2.3	2.4	2.6	2.6	2.7	2.7	2.7	2.7
Groundwater								
Shallow aquifers	0.2	0.3	0.5	0.56	0.69	0.74	0.74	0.7
Deep aquifers	0.6	0.9	1.0	1.1	1.1	1.2	1.2	1.4
Total	3.1	3.6	4.1	4.3	4.5	4.6	4.6	4.8

The water distribution resources in the three geographical regions is quite different:

- Most surface water resources are localized in the Northern region (81.2 %) which represents only 17 % of the total Tunisian area,
- The biggest part of the ground water resources are in the south, particularly in deep-lying aquifers with fossil water form,
- The Center is the poorest region on water resources.

Water resources are unevenly distributed across the country with around 60 % located in the North, 18 % in the Center, and 22 % in the South. Water quality, especially salinity, is a serious constraint.

Surface water has a generally low salinity (with the exception of the tributaries entering the Medjerda river from the south).

Groundwater are badly affected with 84 % of all groundwater resources having salinity levels of more than 1.5 g/l and 30 % of the shallow aquifers more than 4.0 g/l.

Fig. 3.3.2 shows a detailed classification of water resources in Tunisia according to their salinity. In Tunisia, 26 % of surface freshwater, 91.6 % of groundwater (shallow aquifers) and 80 % of groundwater (deep aquifers) have got water salinity of over 1.5 g/l. It is clear that a large percentage of these waters need to be desalted before they can be exploited. Out of the modest quantities of water available, only a small portion meets the standards for potable water due to high salinity levels. Only 8.4 % of the total shallow groundwater has salinity levels inferior to 1.5 g/l (Mamou and Kassab, 2000).

Ground water resources in Tunisia

Groundwater is divided into two main components: shallow and deep.

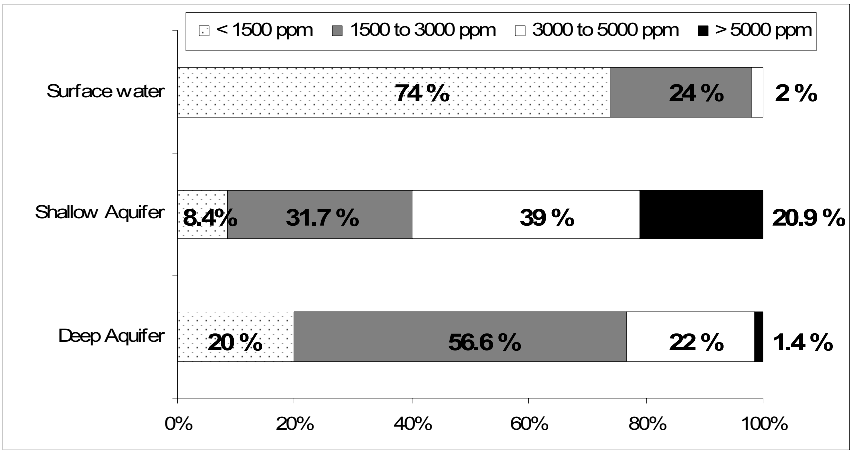


Fig. 3.3.2. Tunisian water resources classification according to salinity levels.

Shallow aquifers correspond to aquifers just under the ground surface. In Tunisia, shallow aquifers are located at less than 50 m depth.

Deep aquifers have depths between 400 and 500 m. There are also some exceptions of very deep aquifers in the South Region (between 1000 and 2000 m in the „Continental Intercalaire“ CI).

Groundwater resource exploitation is more advanced (Fig. 3.3.3) :

- 0.7 billion m^3/year from shallow aquifers, representing 106 % of renewable resources
- 1.4 billion m^3/year from deep aquifers, representing 77 % of renewable resources (including fossil groundwater)

Groundwater resources are exposed to various types of pollution and deterioration, increasing their vulnerability and scarcity.

Shallow aquifers are already over-tapped. Groundwater resources in coastal aquifers (Cap Bon, Sahel, and Gulf of Gabes) and in the chotts (Nefzaoua and Jerid) suffer from salinization problems due to seawater or saline water intrusion. As a result, the quality of these aquifers has deteriorated considerably. Pollution of some shallow aquifers by nitrates constitutes also a major risk for domestic requirements.

Generally, deep aquifer composition is rather stable over the year while the shallow aquifers one depends on location and season and is often salt-affected. Groundwater of the shallow aquifer is generally over exploited leading to lowering of water tables and the deterioration of water quality. The majority of the shallow aquifer is located in the north and the center of the country, while deep aquifers are mostly concentrated in the south.

The south of the country includes the fossil aquifer of the Sahara Aquifer System (SAS), shared with Algeria and Libya, with its two components: „Continental Intercalaire“ (CI) and „Complexe Terminal“ (CT).

Deep groundwater extraction rates are currently at 73 % of annual recharge, and shallow groundwater is at 97 % in the coastal and central regions. Excessive groundwater extraction in the coastal regions of Cap Bon, Soukra, and Ariana has resulted in saline intrusion in many areas leading to groundwater being rendered unsuitable for further irrigation.

Underground water reserves are very important in the south, especially deep water tables that represent 44.7 % of the underground water total. Potential fossil reserves represent 605 million m^3 that is 33 % (DGRE, 1997).

Given its modest water resources potential and the mediocre quality of most of its groundwater resources, Tunisia has no choice but to try to finding new sources of potable water. The total fresh water demand is expected to reach 877Mm^3/year by the year 2025 (Table 3.3.2). The increase in potable water demand is dictated by the population growth on one hand and the rise in the standards of living on the other. In addition, steady urbanization and industrialization processes contribute significantly to the increase in future water demand (DGRE, 2003).

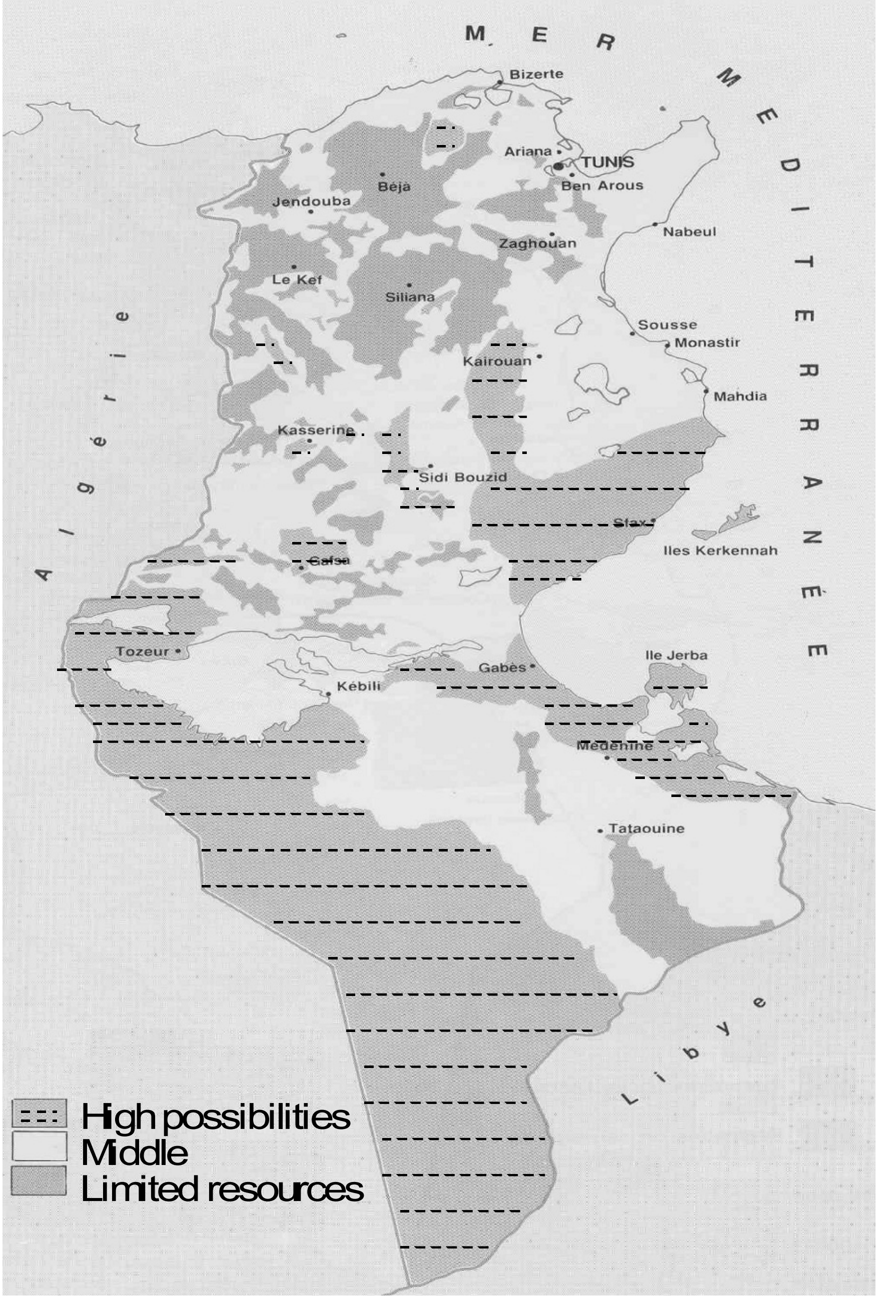


Fig. 3.3.3. Ground water resources in Tunisia.Shallow aquifers.

Table 3.3.2. Evolution of exploitation of shallow aquifers from 1980 to 2000 (DGRE, 2000a).

Region	Resources (Million m^3/year)					Exploitation resources (Million m^3/year)				
	1980	1985	1990	1995	2000	1980	1985	1990	1995	2000
North	287	324.4	371.6	395.2	386.1	227	300	382.1	406.2	405.1
Center	162	194.1	199.6	220.8	235.4	137	202.5	225.2	226.5	260.8
South	27	67.2	97.4	102.2	115.2	31	60.3	91.2	112.4	111.8
Total	486	585.7	668.6	718.1	736.7	395	562.8	698.5	744.9	777.8

Shallow aquifers

According to the 2000 inventory, the renewable potential of shallow aquifers (Table 3.3.2) is estimated at 736.7 million m^3/year. Their net rate of development is 106 % from 130 000 shallow wells. This number of wells was 60 000 in 1980 and 123 000 in 2000. Shallow water reserves are overexploited at the rate of 104 %. However, this average value hides some extreme overexploitation rates (120 to 130 %) in aquifers of the eastern coast of Cap Bon, and the Sahel of Sousse and of Sfax.

The majority of the shallow aquifer is located in the North (52 %) and the center (32 %) of the country. Water quality of ground water of shallow aquifers is based on its salinity level and can be divided in four classes.

Table 3.3.3 shows the shallow aquifers with saline water and significant renewable water resources classified at the level of regions.

In northwest of Tunisia, the Middle Valley corresponds to an alluvial plain where the Medjerda River receives its main tributaries from the north and the south. The groundwater salinity gradient, from less than 3 000 ppm on the margins of the plain, increasing towards the centre of the plain, in particular near the cities of Jendouba and Bou Salem, where it can reach over 10 000 ppm .

In the Center of Tunisia, the shallow aquifers is exploited; the rate of exploitation is of 111 %. The average salinity of the shallow aquifers in the center of Tunisia varies from 500 ppm to 10 000 ppm .

In the South of Tunisia, most of the shallow aquifers have a saline water higher than 3 000 ppm. The shallow aquifers relate to the aquifers known through the various wells of surface, which exploit them. They correspond to the first aquiferous levels met starting from surface. Fifty-five shallow aquifers are located in the South region of Tunisia. The average salinity of the shallow aquifers in the South of Tunisia varies from 1 000 ppm to 15 000 ppm (Fig. 3.3.4).

The main part of the ground water resources of Djerid is represented by the Jerid oasis (Djerid-Dhafria). The salinity of the Jerid oasis shallow aquifers varies from 4 000 ppm to 6 000 ppm and exceeds 8 000 ppm near Chotts.

Table 3.3.3. Shallow aquifers with saline water and resources of exploitation in Tunisia (Zebidi, 2003).

Region	Aquifer	Total renewable resources (Million m^3/yr)	Part of saline water resources (Million m^3/yr)	Total exploitation 1995 (Million m^3/yr)
North	Medjerda	9.2	6.8 (74 %)	8.1
	Mornag	23.6	4.7 (20 %)	24.1
Centre	Hadjeb-Jilma	14.9	5.5 (37 %)	18.6
	North Gafsa	9.5	3.8 (40 %)	17.3
South	Jerid Oases	16.5	8.3 (50 %)	24.5
	South Gabès	9.5	5.4 (57 %)	10.4

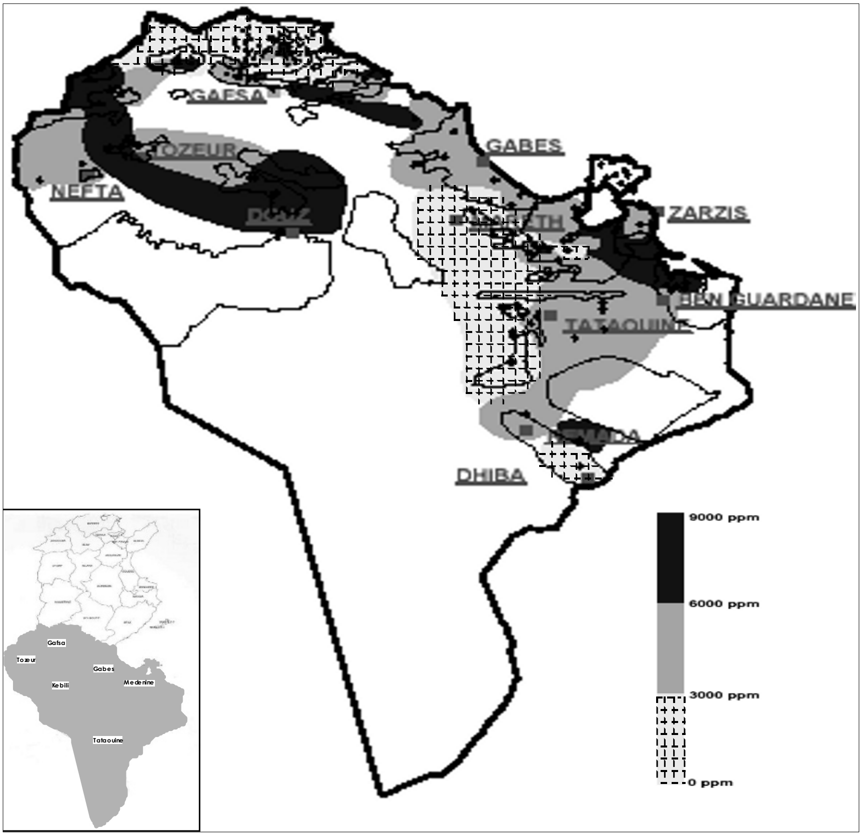


Fig. 3.3.4. Salinity of shallow aquifers in the south of Tunisia.

Table 3.3.4. Evolution of exploitation of deep aquifers from 1991 to 2003 (Millions m^3/year).

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
North	65	74.8	87.4	96.6	101.9	101.9	106.9	110.6	115.1	124.8	133.2	141.2	135.1
Center	169.5	169.8	169.1	189.9	200.9	177.6	175.4	187.9	191.8	215.8	230.8	239.8	229.4
South	599	616.7	625.6	632.2	624.8	717.8	722.8	715.2	723.7	737.8	754.6	753.8	744
Total	833.5	861.3	882.4	918.7	927.6	997.3	1005.1	1013.7	1030.6	1078.4	1118.5	1134.8	1108.5

Deep aquifers

The global exploitation of the deep aquifers in Tunisia during the year 2003 is 1108.5 Million m^3. It records thus an increase of 30.1 Million m^3 in comparison with the one of 2000. This exploitation represents 79.7 % of the total resources of the deep aquifers. Table 3.3.4 shows the evolution of exploitation of the deep aquifers in Tunisia from 1991 to 2003 (Gaaloul and Zouari, 2004).

A recent study distributed the exploited deep aquifers between several classes of salinity in connection with water use. Deep aquifers water has a better quality 22 % have a salinity degree lower than 1500 ppm, 57 % of resources with salinity between 1500 and 3000 ppm. The remaining part, or 21 % has salinity greater than 3 000 ppm (Table 3.3.5).

Based on the above table, brackish and saline deep groundwater (more than 5 000 ppm) exploitation represents 55 million m^3/yr, which corresponds to 5 % of the total annual groundwater withdrawal and is mainly allocated to industry and agriculture.

Brackish and saline deep groundwater resources are exploited mainly in the south of the country and in particular in:

- Algerian border to improve the production of El Borma petroleum wells.

Table 3.3.5. Annual exploitation in Million m^3/yr by class of salinity (DGRE, 2003).

Salinity ***(ppm)***	< 1500	1500 to 3000	3000 to 5000	5000 to 7500	> 7500	Total
Drinking water	97.5	61.6	15.1	9.7	0.0	183.9
Irrigation	147.8	555.2	142.8	14.9	0.1	860.7
Industry	8.7	16.3	17.2	12.0	14.9	69.1
Tourism	0.2	0.7	0.5	2.6	0.8	4.8
Total exploitation (Million m^3/yr)	254.2 (22 %)	633.8 (57 %)	175.6 (16 %)	39.2 (4 %)	15.8 (1 %)	1118.5 (100 %)

Table 3.3.6. Resources of not exploited deep aquifers in Tunisia (DGRE, 2000b).

Region	Aquifer	Resources (Million m^3/year)
Northeast	Jebel Ben Kleb (Jurassic)	0.5
	Jebel Ressas (Jurassic)	1.0
Sahel	Ksour Essaf Sidi Alouane	6.3
Southeast	Sandstone of Lower Triassic	6.3

- The coastal zone between Oued Akkarit and Skhira Village at the convergence of groundwater flows coming from the northern Sfax Plain Aquifer and the southern Northern Gabes Aquifer, for industrial purposes.
- The south part of the Jeffara Plain Aquifer in particular at the level of Jerba Island and Zarzis region, for desalination.

Some deep aquifers, which are not exploited due to groundwater salinity (Table 3.3.6).

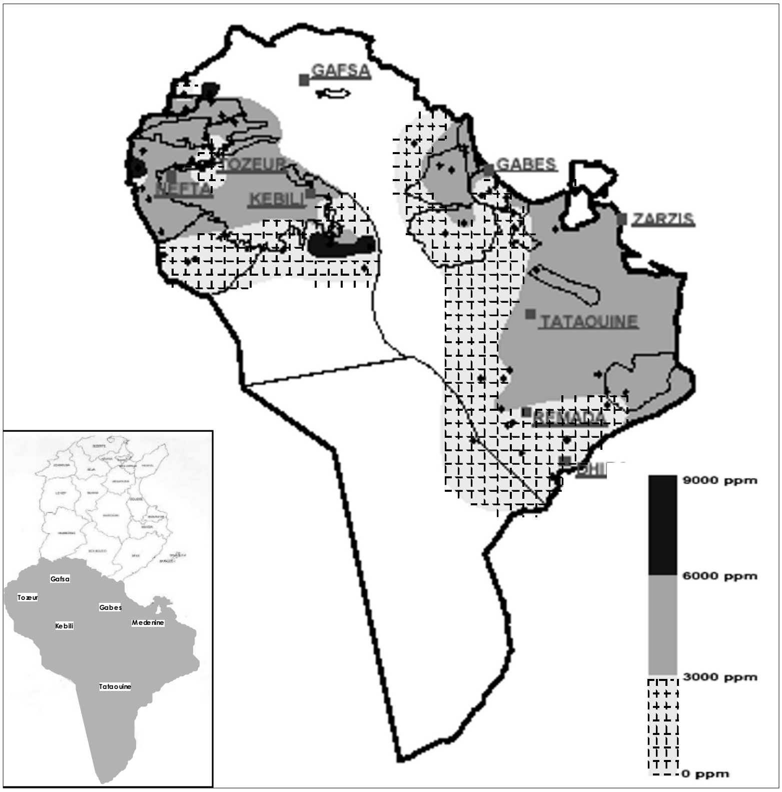


Fig. 3.3.5. Distribution of salinity of the „Complexe Terminal“ in the south of Tunisia.

The salinity of groundwater in the Center of Tunisia varies between 220 to 10.570 ppm.

The South region of the country is characterized by two aquifers, the largest in Tunisia (the medium aquifer or CT: „Complexe Terminal“, and the deep aquifer or CI: ‘”Continental Intercalaire”. These aquifers are the most important resources for the development of agriculture in the region, but they are rarely considered as renewable resources.

The aquifer is constituted by a geological series of which the age goes from Senonien to the Mio-Pliocene. His extension is of 350,000 km^2 of which a weak party only is located in Tunisia.

This phenomenon implies an inversion of the chemical gradient (Fig. 3.3.5) :

- The Chott El Gharsa North aquifer, obtained by Shili, krichet-naâm and Thelja drillings. The salinity varies from 4,180 ppm to 4,750 ppm;
- The Djerid aquifer, obtained by El Gouifla and Segui drillings. The salinity of groundwater of this aquifer varies from 6,350 ppm to 7,700 ppm.

The CI of the Chott Djerid is situated in the albiens sands and sandstone of Sidi Aich. The salinity of ground water of this aquifer is ranging between 2,000 ppm to 3,900 ppm (Fig. 3.3.6).

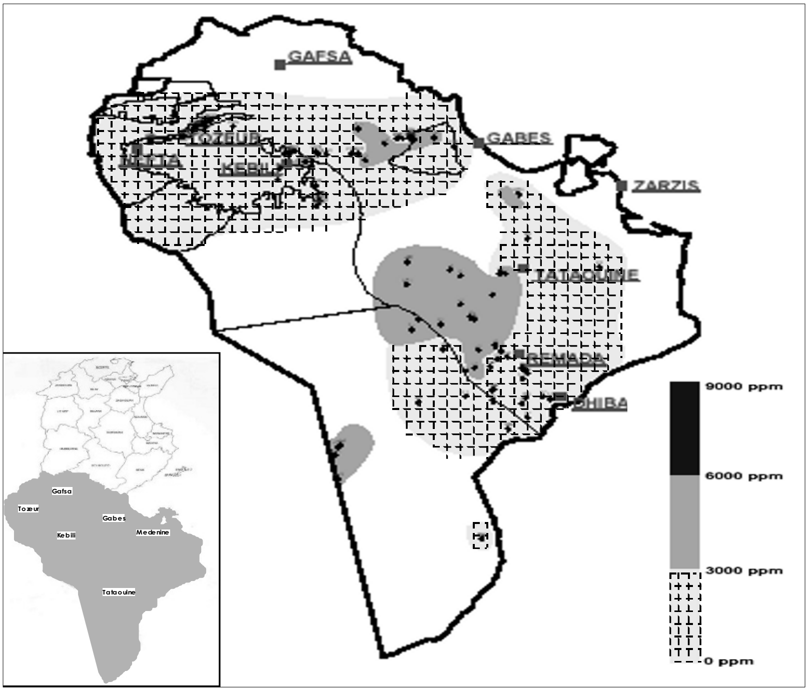


Fig. 3.3.6. Distribution of salinity of the ‘Continental Intercalaire’ in the South of Tunisia.

The impact of climate change on water resources depends not only on changes in the volume, timing and quality of streamflow and recharge but also on system characteristics, changing pressures on the systel, how management of the system evolves, and what adaptations to climate change are implemented. Nonclimatic changes may have a greater impact on water resources than climate change (IPCC, 2001).

Climate change challenges existing water resources management practices by adding uncertainty. Integrated water resources management will enhance the potential for adaptation to change. The key challenge, therefore, is incorporating uncertainty into water resources planning and management. Integrated water resources management is an increasingly used means of reconciling different and changing water uses and demands, and it appears to offer greater flexibility than conventional water resources management (IPCC, 2001).

In order to successfully cope with climate change and climate variability, an integrated approach to water resources management needs to be undertaken. Integrated water resources management implies a more holistic approach to the problem, by incorporating the relevant stakeholders as well as the climate and water resources infrastructure into decision-making. Coping with climate change & climate variability within water resource management in Tunisian means in general more efficient water use. To avoid wastage, the **„waster pays“ principle** could be introduced and applied to communities, industrial & domestic users and the agricultural sector. This „wastage“ charge could be used for grants to assist water saving efforts.

3.3.2 Climate variability, aridity and vulnerability to drought in Tunisia

Historic drought in Tunisia

Drought is a natural event and a normal part of the climate in any region of the world and may be defined as a rainfall deficiency, significantly below normal, which impacts human productive activities. As a natural hazard, drought imposes differential vulnerability on society and the compounded impact of hazard and vulnerability represents the risk associated with the drought event (Wilhite, 2000). Therefore, drought management should not be regarded as managing a temporary crisis as would think decision makers and drought managers in the region. Rather, it should be seen as a risk management process with emphasis on monitoring and managing emerging stress conditions and other hazards associated with climate variability. An important feature of the drought as a hazard is that it is essentially unpredictable and can only be monitored. Weather forecast does not mean drought predictability. While scientific advances in seasonal climate prediction have been made in many tropical regions with substantial opportunities for weather predictability (but not drought predictability), our global understanding of the climate system in the Mediterranean currently limits skill in this region to very modest levels. One thing is certain, however, the drought is a recurring event that affects the livelihood of millions of people in the Mediterranean, particularly in southeastern parts of the region.

In fact only an operational definition of drought helps hydrologists or water resources researchers and practitioners to identify the beginning, end, and degree of severity of a drought. This definition is usually made by comparing the current situation to the historical average, often based on a 30 year period of record (according to World Meteorological Organization recommendations).

Many definitions of drought are adopted in various fields, with reference to the components of the hydrological cycle considered in the analysis and to the different impacts on water users and ecosystems. The following categories of drought are usually considered:

Meteorological drought is usually defined on the basis of the degree of dryness (in comparison to some „normal“ or average amount) and the duration of the dry period. Definitions of meteorological drought must be considered as specific to a region since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region.

Agricultural drought links various characteristics of meteorological (or hydrological) drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, reduced groundwater or reservoir levels, and so forth.

Hydrological drought is associated with the effects of periods of precipitation (including snowfall) shortfalls on surface or subsurface water supply (i.e., stream flow, reservoir and lake levels, groundwater). The frequency and severity of hydrological drought is often defined on a watershed or river basin scale.

Although climate is a primary contributor to hydrological drought, other factors such as changes in land use (e.g., deforestation), land degradation, and the construction of dams all affect the hydrological characteristics of the basin.

Drought is a frequent climatic event in Tunisia. The decade 1990 watches a predominance of the drought (globally: 4 years dry, an alone humid year: 95-96 for the body of the country, 3 comparatively humid years and two average years except for the south that knew a rather dry decade). According to the frequency of the periods dry and the floods since the height century, the Tunisia knew 25 inundations and 46 periods of drought. In Tunisia, drought episodes have been traced back to the year 707 and in the period 1907-1997 alone, say the 20 th century, 23 dry years were observed. During the twentieth century characterized by a followed uniform of the rainfall, 12 inundations alternated with 17 drought periods. (Fig. 3.3.7).

In Tunisia, the drought affects particularly the arid and semi-arid regions characterized by unfavorable climatological and hydrological conditions. Low and erratic rainfall results in frequent periods of serious drought alternating with periods of floods causing major damages and soil erosion.

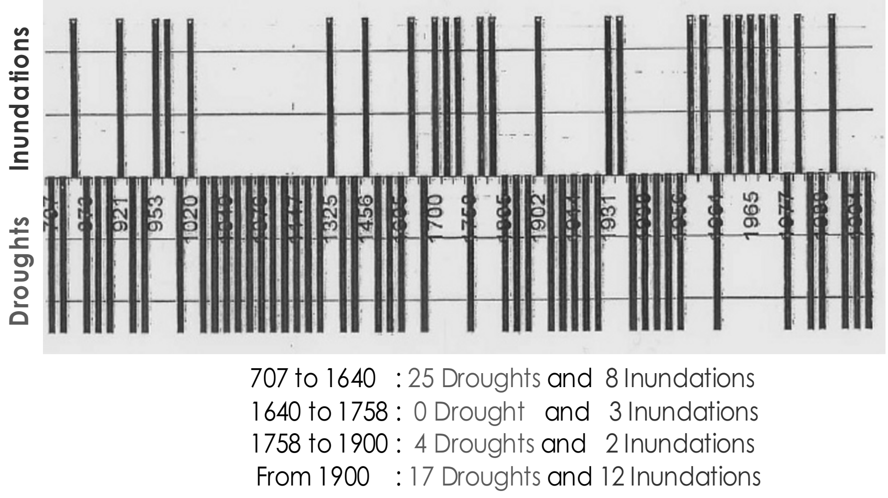


Fig. 3.3.7. Historic provision of drought and Inundations in Tunisia (707-2000) (DGRE, 2003).

Strong drought phenomenon is lived in Tunisia. A very dangerous natural phenomenon. It concerns population and all the economic system of the country. It is not predictable and not easy to manage negative influence on the aquatic and land ecosystems. The negative influence on the quality of surface and groundwater is salinisation.

The probability of apparition of a drought year's succession is resumed in Table 3.3.7.

The probability of drought in three successive years varies from 11 % to 34 % in Tunisia.

Table 3.3.7. Probability of apparition of a drought in Tunisia.

Region	Prob. Yr no drought / Yr no drought (%)	Prob. Yr drought / Yr drought (%)	Prob. 2Yr / Yr drought (%)
Tunis 127years	22	15	14
North West	19	11	11
North East	19	23	22
Center	23	24	23
Sahel (sea)	28	23	22
South West	25	35	34
South East	26	21	21

Some strategies to manage drought in Tunisia are as follows:

- Reinforcement of hydraulic equipment (dams, small dams and recharge aquifer's)
- Institutional reinforcement
- Research

Network of groundwater to control drought in Tunisia

Groundwater, as a natural resource and an element of the environment, used in human activities, is of a dual character. On one hand, it is a moving resource in the earth depths and abstracted out of it, on the other, it is a part or total water resource of the earth.

As a mineral resource, groundwater is a part of the depths and its safe yield is caused by geologic-hydrogeologic conditions of the territory. As a part of water resources, groundwater is directly connected with surface water and atmosphere. Due to this, groundwater safe yield depends not only on geologic-hydrogeologic but also on physical-geographical and human induced factors, connected with changes of water consumption and resulting in changes of groundwater recharge conditions, its quality and abstraction. The fact, that groundwater is a part of total water resources is the most important in estimating perspectives of fresh groundwater use. In spite of the fact that ground and surface water are separate components of total water cycle in the globe, they are, at the same time, closely connected.

Ground water is removed from storage when water is pumped from aquifers. The stored water in confined aquifers is derived from the expansion of water, the compression of the aquifer material, and compression of the clayey beds that are adjacent to and within the aquifer.

There is a growing recognition of the significance of the quantitative aspects of groundwater vulnerability since it is often difficult to separate the qualitative and quantitative aspects of vulnerability. Overexploitation of an aquifer system, therefore, needs not to be expressed only in quantitative terms but also in a changed composition of groundwater. Vulnerability in terms of quantity is of special importance in arid regions like Tunisia.

It would be equally pertinent to consider groundwater vulnerability to desertification and drought since desertification tends to increase runoff and decrease infiltration. However, because of low recharge the main quality problem is likely to be salinization. These concepts are of particular significance for groundwater protection in semi-arid regions. Groundwater indicators suggested for temperate regions need to be applicable to semi-arid regions.

In Tunisia groundwater is either the main source of freshwater or is vitally needed to supplement surface-water sources, especially in regions affected by recurrent droughts. However, there is a scarcity of regional groundwater information, and the understanding of the role groundwater plays in sustaining the livelihood of the population and related ecosystems. There is a critical need to assess and understand the coupled regional ground – and surface – water systems in order to manage optimally the resource, anticipate and mitigate impacts of droughts, and to reduce the risk of over exploiting the limited resource.

Drought is a major natural hazard and water resources and ecosystems are under great stress in times of drought. A thorough understanding of droughts and an assessment of their impact on the environment, society and economy are therefore important. As droughts normally cover large areas, and aquifers and rivers cross national boundaries, a transnational approach to hydrological drought estimation and management should be sought.

There is the need to enhance capabilities and scientific strengths of Tunisia country to address long-term and regional groundwater-resource assessment and management, while addressing immediate societal needs. In this context groundwater would be closely linked with an overall holistic approach to water resources management especially surface water and non-conventional water resources.

A major advantage of groundwater as a source of supply arises from the „buffering effect“ of aquifer storage in relation to climatic variability and changing demand, which (especially for irrigation) are often closely linked. Indeed, it is likely that the greater drought security of most wells compared to surface water sources is a major factor in explaining the normally far better economic productivity of land irrigated with groundwater.

While in most hydrogeological environments drought security will thus not be a significant concern, in certain situations the storage capacity is more limited and some wells may dry up altogether. A „groundwater drought“ may result, and absolute water shortages then replace crop failure as the most critical issue for the affected population.

In Tunisia, the piezometric monitoring started since the beginning of the twentieth century. It is solely in 1950s that piezometric networks were set up to supervise some aquifers. From 1960 onwards, the national network was improved. Today, it covers the totality of the aquifers.

The network piezometer was conceived for follow-up on the piezometer of the shallow and deep aquifers of the country. This network, managed by the General Direction of the Resources in Water, is constituted by piezometer, surface wells and accessorily by non-exploited drillings. The first global inventory of the realized network in 1994 to the ladder of the body of the Tunisia, showed that it was composed from 2540 points of follow by the superficial tablecloths (2400 wells and 140 piezometers) and of 310 points of follow by the deep tablecloths (240 piezometers and 70 drillings). In 1990, the shallow aquifers were exploited by 84060 surface wells (DGRE, 1998).

In Tunisia, the first networks, composed essentially wells, were selected among the wells networks of non-exploited surface that obtained the levels aquifers superficial. The most instructive one of these series (Fig. 3.3.8) is the Errissala well (Crétéville the former name gave to this region), followed on near of a century (Schoeller,1938; Tixeront, 1950; Ennabli, 1980).

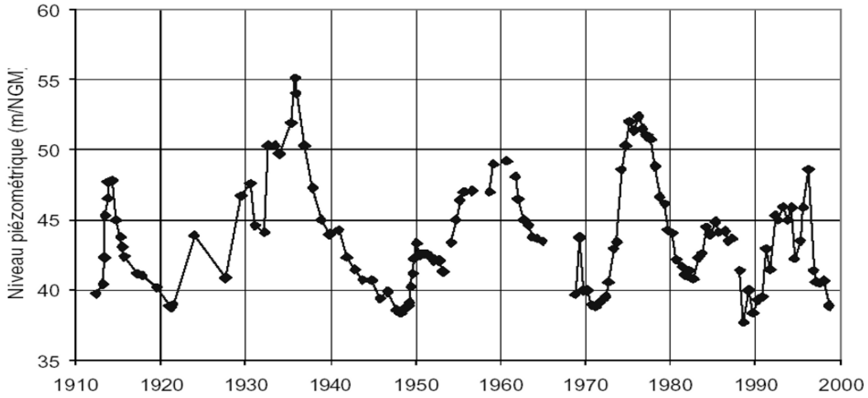


Fig. 3.3.8. Variation of the piezometer level of the Mornag aquifer (Errisala1 piezometer).

In Tunisia, the piezometric monitoring started since the beginning of the twentieth century. It is solely in 1950s that piezometric networks were set up to supervise some aquifers. From 1960 onwards, the national network was improved. Today, it covers the totality of the aquifers.

Tunisia has also experienced three serious droughts in the last decade that have affected agricultural growth and domestic consumption. With an increasing population, rapid urbanisation, and rise in living standards developing additional water resources is imperative. The last three Five-Year Plans (Government of Tunisia, 1987; 1992; 2002) have emphasised water harvesting and treated wastewater use. Since the severe drought in 1989, the use of treated wastewater in irrigation has been a part of the Government's overall water resource management strategy.

Climate change, drought and desertification

The vulnerability to climate variability in the Mediterranean has intensified with today's demographic, economic growth and resource use patterns, as a consequence the scale and urgency of the adaptation challenge has increased. Several studies indicate that global climate change will add more to the existing problems resulting from drought and desertification, especially in North African and eastern Mediterranean countries, where water resources are already limited and fragile. Climate change, drought, and desertification are interrelated, but these processes should not be confused or interchangeably referred to if we are to address the complex issues of drought and water management in Tunisian region on a sound scientific basis. Furthermore, in this region drought can no longer be considered as an exceptional event, but rather as a natural phenomenon linked to the climate of the region and to the hydrological system management.

The most recent IPCC reports, the Intergovernmental Panel on Climate Change, confirm small global warming in the region and forecast more over the next century but past changes in rainfall patterns and future predictions are not well established. Recent review of scientific basis for climate change in the region suggests that global models project little significant change to rainfall amount and its seasonal distribution for the next two decades, although models of run-off show slight reductions over the whole area, leading to reduce water availability.

Temperature increases will increase water stress on crops across much of the region from Morocco to Iran. Predicted changes to rainfall amounts and distribution are less reliable. Based on IPCC (2001) model simulations, projections indicate that water scarcity may be severely increased by future changing climatic patterns in the Mediterranean. Climate change, drought, and desertification are interrelated, but these concepts should not be confused or interchangeably used if we are to address the complex issues of drought and water management in the Tunisian region on a sound scientific basis.

Rivers flows in arid regions and semi-arid regions are very sensitive to changes in rainfall : A given percentage change in rainfall can produce a considerably larger percentage change in runoff. Confidence in estimates of change in water quality is determined partly by climate change scenarios (and their effects on stream flow), but additional uncertainty is added by current lack of detailed understanding of some of the process interactions involved (IPCC, 2001).

There are several indicators of water resources stress, including the amount of water available per person and the ratio of volume of water withdraw to volume of water potentially available (Falkenmark and Lindh, 1976). Water resources are inextricably linked with climate, so the prospect of global climate change has serious implications for water resources and regional development (Riebsame et al., 1995). The Magreb region is characterized by erratic and variable rainfall, with a high rate of evapotanspiration (almost 80 %). In addition, the Magreb region will have water scarcity by 2005 especially in Tunisia and Libya.

The United Nations Convention to Combat Desertification (UNCCD) defines desertification as „land degradation in arid, semi-arid, and dry sub humid areas resulting from various factors, including climatic variations and human activities“ (United Nations, 1994). Furthermore, UNCCD defines land degradation as a „reduction or loss, in arid, semi-arid, and dry sub humid areas, of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water, (ii) deterioration of the physical, chemical, and biological or economic properties of soil; and (iii)long term loss of natural vegetation.“

Desertification, in Africa has reduced by 25 % the potential vegetative productivity of more than 7 million km^2, or one –quarter of the continent's land area (UNEP, 1997). Desertification consists more of degradation of the productive capacity of patches well outside open –sand desert rather than the inexorable encroachment of open sand onto green lands. Arid lands can respond quickly to seasonal fluctuations (Tucker et al., 1991).

3.3.3 Groundwater Recharge and Resources

The intensive agricultural and economic activities induce the increase of the risk of groundwater quality degradation through high groundwater pumping rates. The salinization and contamination are the main sources of this pollution, especially in coastal aquifers.

Aquifers may recharge from rain-soaked ground, from lakes and streams, and, to some extent, from other aquifers. Significantly, certain human activities, such as irrigation operations, dike and canal building, and damming projects, may also recharge aquifers. Aquifer recharge is a function of both gravity and of the permeability of the strata lying between the aquifer and the source of the recharge. As a result, aquifers can also transmit to, and serve as, a source of water for lakes, streams, and other aquifers.

It will be noted from the foregoing that unconfined aquifers are sensitive to local climate change, abstraction, and seawater intrusion. However, quantification of recharge is complicated by the characteristics of the aquifers themselves as well as overlying rocks and soils.

A confined aquifer, on the other hand, is characterized by an overlying bed that is impermeable, and local rainfall does not influence the aquifer. It is normally recharged from lakes, rivers, and rainfall that may occur at distances ranging from a few kilometres to thousands of kilometres. Recharge rates also vary from a few days to decades.

Attempts have been made to calculate the rate of recharge by using carbon-14 isotopes and other modeling techniques. This has been possible for aquifers that are recharged from short distances and after short durations. However, recharge that takes place from long distances and after decades or centuries has been problematic to calculate with accuracy, making estimation of the impacts of climate change difficult. The medium through which recharge takes place often is poorly known and very heterogeneous, again challenging recharge modeling. In general, there is a need to intensify research on modeling techniques, aquifer characteristics, recharge rates, and seawater intrusion, as well as monitoring of groundwater abstractions. This research will provide a sound basis for assessment of the impacts of climate change and sea-level rise on recharge and groundwater resources.

Groundwater is the major source of water across much of the world, particularly in rural areas in arid and semi-arid regions, but there has been very little research on the potential effects of climate change.

The effect of climate change on stream flow and groundwater recharge varies regionally and among scenarios, largely following projected changes in precipitation (IPCC, 2001).

The results and experience gained in Tunisia on assessment of groundwater recharge is one of the key challenges in determining the sustainable yield of aquifers, as recharge rates are generally low in comparison with average annual rainfall or evapotranspiration, and thus difficult to determine precisely. The knowledge and experience gained by researchers in the National Research Institute for Rural Engineering, Water And Forestry (INRGREF) should provide excellent guidance to other countries in arid and semi-arid regions.

There are as many methods available for quantifying groundwater recharge, as there are different sources and processes of recharge. Each of the methods has its own limitations in terms of applicability and reliability.

The resources in water in Tunisia zones are characterized by their abundance relating to the North and their mediocrity to the Center and to the South. These aquifers have for principal discharge system the Mediterranean Sea. They are characterized by overexploitation that does not stop causing problems both quantitative and quality.

These aquifers are subjected to system exploitation intensive do to appear a generalized tendency downwards of the piezometric head independent of the runoff system. This decrease is more important and located more moved away from discharge. It some results a reduction in thickness of the water slice obtained by the surface wells and consequently a decrease in the productivity of these works.

By continuation of the decreasing in the hydraulic load, it some results a decreasing of the flows to the discharge and even an inversion of the flows. The latter translate themselves by invasion seawater and by total inversion of the role of certain Oueds crossing these aquifers. As well as the Oueds playing a drainage role on all or a part of their class, can in certain conditions, and following the geological context and hydro geologic, become alimentation axes.

As opposed to quantitative impact of the overexploitation of the tablecloth aquifers groundwater that amply shows itself in the zones upstream, quality impact does to feel most often in the downhill zones and very close to the discharges. It is in liaison with inversion of the hydraulic gradient that produces itself intrusion of salted bevel to interior of the continent and invasion by seawater of the fringes coastal of the aquifers.

The overexploitation of the aquifers cannot be identified that on the basis of a good comprehension of the hydrodynamic operation of the aquifer system. It is in the light of the alimentation mechanisms and of lateral or vertical communication. It is possible to ensure of extent of overexploitation and the incidences on evolution of the characteristics of the aquifer. The follow-up of the piezometric head and chemical quality of the aquifer is extremely instructive to include understand the reactions of the aquifer and to predict its future evolution. Surface well and piezometers constitute the network, to control the shallow and deep aquifer. This situation makes that the availability of this network for measurements is not always assured and certain of these wells, expose at the risks of deterioration, and should be diverted of their origin use. It is not possible to pumping in these wells and one would strictly hold them at ends of monitoring. This operation can be done only if it is possible to allow another source of water at the disposal of the farmer (drilling of water, water conveyance).

The follow-ups of the piezometric head and salinity of the groundwater are essential for a good management of their resources water; in which they cannot be carried out effectively without being able to predict their reactions live with-screw of exploitation. In addition, these follow-ups will allow the checking of the validity of estimate of the exploitable of water resources. In the same way the chemical follow-ups it will make possible to establish distribution maps of the water quality and to characterize the generated processes (salinization). Superimposed on the exploitation maps, these maps of water quality will make it possible to check quickly if the evolution of quality is ascribable with the exploitation or not. When with the use the groundwater of aquifer in irrigation, the chemical analyses are essential because they will make it possible to establish risks maps of use of this water; tools of decision-making aid very useful.

Artificial replenishment of the water table is strategies already applied which are paving the way towards efficient use of available water resources (Fig. 3.3.9). However, there is still progress to be made with respect to the optimal use and dissemination of new technologies and consumers' water-use habits. This replenishment is carried out using a broad range of techniques making it possible to optimize the local conditions of the site of injection. Thus, this operation is practiced along the beds of wadis having a good permeability, in basins arranged in this objective, through drillings and wells of surface, etc. The spreading of water along the permeable sections of the beds of Oueds remains the technique, which gives the best results. Indeed, this method revealed a good capacity of the surface formations making it possible to ensure the infiltration to the groundwater almost 70 % of the water used for the replenishment (DGRE, 1996).

Recharge aquifers is a new component of the water resources management strategy. So, artificial recharge is offered during raining year, their rate is depending on excess raining. During the period 1992 to 2000, 333 Mm^3 have been deducted from water resources and injected in the shallow aquifer with the aim of struggling against over operating (Fig. 3.3.9).

Seasonal recharge of the shallow and sandy aquifer of Nabeul has been performed since 1985. Activated sludge effluents that were not used for irrigation during winter season were infiltrated and stored into the aquifer, thus increasing the volume farmers can pump during summer season to irrigate citrus orchards. Groundwater recharge efficacy was proven not only by the increase of the water level in the wells but also by the improvement of the production of the surrounding wells. This experiment allowed an underground storage and an additional treatment step.

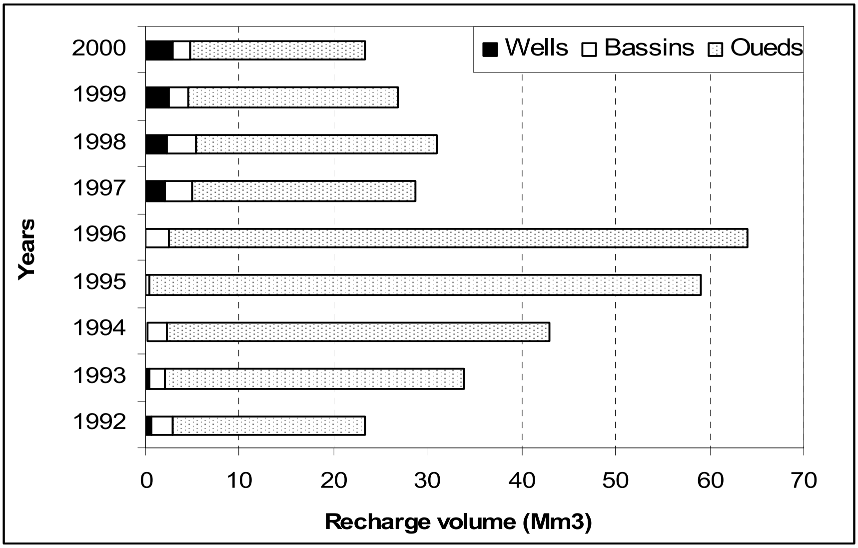


Fig. 3.3.9. Artificial recharge of Tunisian aquifers (millions m^3).

Performing coastal aquifer recharge, where the hydrogeological context is favourable, would make wastewater reuse well accepted by farmers. This subject is still under study and other sites are screened for further studies including the comparison of different treatment processes preceding recharge.

Although we don't know how climate change will affect regional water resources, it is clear that water resources are already stressed, independent of climate change, and any additional stress from climate change or increased variability will only intensify the competition for water resources. Current stresses on water resources around the globe include: growing populations, increased competition for available water, poor water quality, environmental claims, uncertain reserved water rights, groundwater overdraft, outmoded institutions and aging urban water infrastructure.

In all likelihood, the direct impacts of climate change on water resources will be hidden beneath natural climate variability. With a warmer climate, droughts and floods could become more frequent, severe, and longer-lasting. The potential increase in these hazards is a great concern given the stresses being placed on water resources and the high costs resulting from recent hazards.

The best advice to water resource managers regarding climate change is to start addressing current stresses on water supplies and build flexibility and robustness into any system. Flexibility helps to ensure a quick response to changing conditions, while robustness helps people prepare for and survive the worst conditions.

With this approach to planning, water system managers will be better able to adapt to the impacts of climate change, whatever they may be, and will also be better equipped for the climate variability we have now.

3.3.4 Modelling approaches to cost assessment

In the past few decades, modeling has become an important and powerful tool in many branches of science. Models allow engineers and scientists a way to test hypotheses in a manner that is non destructive to the actual problem.

Mathematical modeling plays an ever-increasing role in the quantitative analysis of the actual behavior of groundwater in terms of quantity and quality, and in the design of efficient protection and remediation scenarios.

The development of a model concept stands the origin of any modeling effort, and plays a key role in the success of the following steps. Carefully designed and understood conceptual model can save months of man work. Thorough analysis of the global hydrogeological situation, the flow direction and its seasonal variation, the system communication with other water resources, etc, are required at this level. All the information is represented in a form of simplified maps and cross-sections of the aquifer, though a better management (in space and time) is performed by storing and organizing these data in a computerized data base; linked with a general Geographic Information System (GIS) or at the best a custom GIS or a Hydrogeological Information System (HIS), managing all the data in easily graphic understood form (Gaaloul, and Cheng, 2003; 2007).

Computational hydrogeology is an emerging multi-disciplinary scientific discipline. It has its roots in board branches of sciences as illustrated in Fig. 3.3.10. These are, Groundwater Hydrology, Applied Mathematics and Computational Methods, and a Computer Science (Gaaloul, 1992).

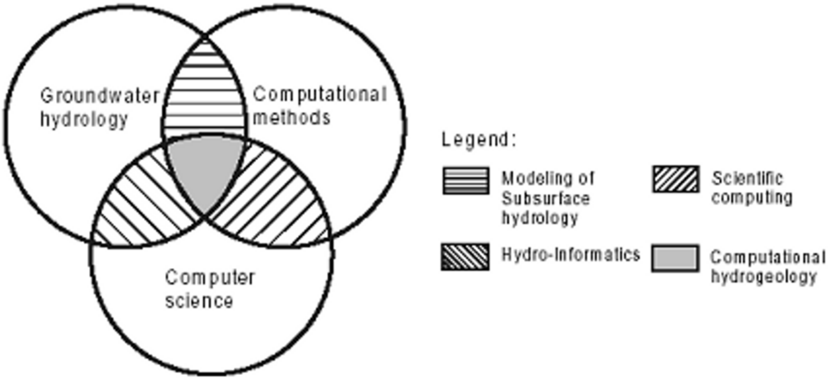


Fig. 3.3.10. Definition of computational hydrogeology.

Groundwater management models for aquifers should combine an accurate process model for seawater intrusion with an appropriate technique for solving the optimization problem.

The aim of modeling groundwater flow is usually to predict the aquifer piezometry under various groundwater stress situations. Modeling is indispensable in the field of ground water, as in the geosciences in general, as the accessibility of the objects of study is very limited. Because of the rather slow reactions of a ground water system to changes in external conditions, a tool for prediction and planning is necessary.

Groundwater models allow us to bring all available data together into a logical holistic picture on a quantitative basis. As the first step, the system with all its dominant processes must be understood. In this calibration phase observation data are integrated and parameters identified. Only a calibrated model can be utilized for predictions. In the prognostic application the strength of models lies in the ease with which scenarios can be compared to each other.

Provision of the Model for Integrated Management of the Ground Water Resources: The Example of the Cap-Bon

Groundwater in Cap Bon in the North of Tunisia is conserved through legislative measures and it is by the constitution the property of the State. The water resources management of coastal aquifers is undoubtedly one of the key priority issues not only because of the actual challenges of limited resources, but also because of the increasingly stringent quality standards and environmental sensitivities arising from the European legislation.

A numerical model that treats density-dependent variably saturated flow and miscible salt transport is used to investigate the occurrence of seawater intrusion in Cap Bon coastal plain of north-eastern Tunisia. We examine the effects of and interplay between pumping, artificial recharge, soil/aquifer properties, and the unsaturated zone. This study examines an approach for planning groundwater development in coastal aquifers. The seawater intrusion is controlled through a series of barrier extraction wells (Gaaloul, El Heni and Mechergui, 2007).

The multi-objective management problem is cast as a non-linear, no convex combinatorial model and is solved using a coupled simulation–optimisation approach. A density-dependent groundwater flow and transport model, Ground Water Vistas is used for simulating the dynamics of seawater intrusion. The Simulated Annealing algorithm is used for solving the optimisation problem (Guo, Langevin, 2002).

The data processing steps undertaken in this study are briefly de-scribed, and a critical assessment is given of the data avail-ability and of the requirements for successful monitoring and modelling of seawater intrusion risks in heavily exploited coastal aquifers such as those found in the semi-arid regions of the Mediterranean basin.

An idea of the extent of over-exploitation of the Grombalia and Oriental Coastal aquifers is obtained by examining the pumping and rainfall/infiltration data, and the simulation results support groundwater pumping as the mechanism for and seawater intrusion as the origin of the salt contamination observed in the soils and subsurface waters of the Grombalia and Oriental Coastal aquifers.

The physical characteristics of the coastal aquifer of the Cap Bon in the North of Tunisia, were determined by using GMS software MODFLOW Code (Zheng, 1990). This was helped in the quantification of the aquifer inflows and discharges as well as to the aquifer sustainability management, especially in the interaction between the Upper and Lower Aquifers for the area. The utility of the study is demonstrated through a trade-off curve between prioritising groundwater development and controlling seawater intrusion at desired levels.

Model simulations of the Oriental coastal aquifer that have been performed include preliminary sensitivity and calibration experiments and two scenarios to investigate the interplay between pumping regimes, effective infiltration, and artificial recharge.

Different boundary configurations, grid discretizations, and parameter combinations were tried, and it was observed that the model response was particularly sensitive to effective infiltration rates and saturated conductivities. In calibration trials based on steady state flow simulations, these parameters were varied, within the bounds of available field measurements, until an adequate match was obtained with the observed 1962 piezometric data (Gaaloul, El Heni and Mechergui, 2007).

The resulting pressure head distribution was then used as the initial flow condition for subsequent transient simulations using the fully coupled model (for the transport component in these transient simulations, a zero concentration initial condition was used throughout the domain).

Using numerical simulation to analyze some of the interactions and possible mechanisms for saltwater intrusion in the Oriental coastal plain of northeastern Tunisia. Further progress in managing and alleviating the presence of saltwater in the aquifer will need to rely on more exhaustive field investigations, including continuous monitoring, better aquifer and soil characterization, and assessment or confirmation of the suggested mechanisms for saltwater contamination and interactions between the soil zone, the aquifer, and the sea.

3.3.5 Conclusion

Groundwater has been the fundamental resource allowing the economical and rapid development of more reliable, improved quality, water supplies for a large proportion of the rural population across extensive areas of Tunisia. Groundwater has also provided security against drought in areas where irrigation with surface water resources has been deficient during dry years. Moreover, the use of groundwater can be a major factor in promoting increased irrigation water-use efficiency and agricultural water productivity.

An important aspect of groundwater behavior in drought conditions is the time-lag between recharge and response in groundwater levels and well yields, in contrast to the much more rapid response of surface waters. Because of the buffering effects referred to previously, meteorological drought may not always lead to groundwater drought. Where it does, several successive years of low rainfall may be required, and the response may even not become fully apparent until after the meteorological drought has ended by return of adequate rainfall.

The *time lag and severity of drought* impact on groundwater depend on:

- The duration of the drought episode;
- The type, design and sitting of groundwater supplies
- The demand on sources;
- The characteristics of the aquifer.

Thus, in conclusion, it is reasonable to briefly formulate the main tasks of further research scientific and practical investigations on the problem considered.

These tasks are the following:

- to improve the available and to develop new methods for assessing groundwater resources accounting for natural measures;
- to develop and put into practice nature-protecting criteria determining the acceptable impact of groundwater withdrawal on other components of the environment, and also the acceptable effect of anthropogenic activities on groundwater resources and quality;
- to perfect the available and to develop new methods for predicting changes in groundwater resources and quality under intensive anthropogenic activities and possible climate changes;
- to substantiate the principles of conducting groundwater monitoring in different natural climatic and anthropogenic conditions as a component of the general monitoring of water resources and the environment;
- to improve methods of assessing groundwater vulnerability to pollution in the main aquifers used for water supply;
- to perfect methods of artificial groundwater recharge and to use them more widely in active well fields;
- to develop mathematical models of interaction between ground- and marine water in different geologic-hydrogeologic conditions of the coastal zones and also methods for predicting marine-water intrusion into the aquifers under intensified groundwater withdrawal by coastal well fields;
- to develop and to put into practice legislative norms emphasizing preferred use of fresh groundwater of high quality primarily for drinking and domestic water supply.

References

DGRE, Direction Générale des Ressources en Eau (2005). Journée Mondiale de l'Eau. L'Eau et le Numérique, 22 Mars 2005.

DGRE, Direction Générale des Ressources en Eau (2003). Etude pour la mise en place d'un système d'information national des ressources en eau (SINEAU) – Phase 1: Bilan de l'existant, synthèse des besoins, orientation. Prepared by DHV Water/DHV Tunisie, October 2003.

DGRE, Direction Générale des Ressources en Eau (2000a). Situation de l'exploitation des nappes phréatiques en 2000. Publication de la Direction Générale des Ressources en Eau – Tunis.

DGRE, Direction Générale des Ressources en Eau (2000b). Annuaire de l'exploitation des nappes profondes en 2000. Commentaire global. Publication de la Direction Générale des Ressources en Eau – Tunis.

DGRE, Direction Générale des Ressources en Eau (1999). Étude du secteur de l'eau, 6 volumes.

DGRE, Direction Générale des Ressources en Eau (1998). Réseau National de Surveillance Piézométrique de Tunisie en 1998. DGRE.

DGRE, Direction Générale des Ressources en Eau (1997). Annuaire piézométrique de Tunisie, DGRE,Tunis, 455 p.

Ennabli M., (1980). Etude hydrogéologique des aquifères du Nord-Est de la Tunisie pour une gestion intégrée des ressources en eau. Thèse de Doctorat d'Etat. Univ. de Paris.

Falkenmark M., Lindh G., (1976). Water for a starving world. Westview Press, Boulder, CO,USA.

Government of Tunisia. (1987) Seventh Five-Year Plan, 1987–91, Ministry of Development and International Cooperation, Tunis, Tunisia.

Government of Tunisia. (1992) Eighth Five-Year Plan, 1992–96, Ministry of Development and International Cooperation, Tunis, Tunisia.

Government of Tunisia. (2002) Ninth Five-Year Plan, 2002–06, Ministry of Development and International Cooperation, Tunis, Tunisia.

Gaaloul, N., El Heni M., Mechergui M., (2007). Modélisation numérique des écoulements des eaux souterraines et de transport de soluté cas de la nappe phréatique de Grombalia. Colloque international sur l'eau et l'environnement, pp.77-85.

Gaaloul, N., Cheng A., (2007). Modélisation numérique des écoulements des eaux souterraines et de transport de soluté. Colloque Franco-Tunisien les milieux poreux CFT'07, pp.207-212.

Gaaloul N. Cheng A., (2003). Modeling Groundwater Flow and Seawater Intrusion : Concepts, Methods and Practices. Ed. University of Mississippi, Department of Civil Engineering – INRGREF. 72 p.

Gaaloul N. Zouari K., (2004). Harnessing Salty Water to Enhance Sustainable Livelihoods of the Rural Poor in Tunisia. Rapport de consultation. International Center for Biosaline Agriculture. ICBA, 40 p.

Gaaloul N., (1992). Modélisation mathématique du système aquifère multicouche application: Bassin Nord-Aquitain (Oligocène - Eocène). Thèse de Doctorat de l'Université de Bordeaux I en Sciences et Techniques de l'Eau, en collaboration avec le Bureau de Recherches Géologiques et Minières et le Centre d'Hydrogéologie de la faculté des Sciences de Bordeaux I. Novembre 1992, 283 p. Ed. BRGM Collection Etudes et Thèses 1992.

Guo. W., Langevin C.D., (2002). A Computer Program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow, User's Guide to SEAWAT, 77 p.

IPCC (Intergovernmental Panel on Climate Change) (2001). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Edited by J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson. Cambridge University Press, Cambridge.

Mamou, A.; Kassah, A. (2000). Économie et valorisation de l'eau en Tunisie Science et changements planétaires / Sécheresse. Vol. 11, No 4, décembre 2000 : 249-56.

Riebsame, W.E., Strzepek, K.M., Wescoat Jr, J.L., Perrit, R., Graile, G.L., Jacobs, J., Leichenko, R., Magadza, C., Phien, H., Urbiztondo, B.J., Restrepo, P., Rose, W.R., Saleh, M.,Ti, L.H., Tucci, C., and Yates, D., (1995). Complex river basins. In : As climate changes, International Impacts and Implications [Strzepek, K.M. and J.B. Smith (eds.)]. Cambridge University Press, Cambridge, United Kindom and New York, NY, USA, PP. 57-91.

Schoeller, (1938). L'abaissement du niveau d'eau dans les puits de Khélidia en 1938.

Tucker, C.J., Dregne, H.E., and Newcomb, W.W., (1991). Expansion and contraction of the Sahara Desert from 1980 to 1990. Science, 253, 299-301.

Tixeront, (1950). Manuscrit de données piézométriques relatif aux puits n°626/2 et 627/2 à Créteville.

United Nations. (1994). United Nations Convention to Combat Desertification (UNCCD). UN document number A/AC.241/27. United Nations, New York, NY,USA, 58 pp.

UNEP, (1997). World Atlas of Desertification, 2nd. Ed. United Nations Environment Program, Edward Arnold, London, United Kindom, 69 pp.

Wilhite, D.A. (2000). Drought as a natural hazards: Concepts and definitions. In D Wilhite (ed.) Drought, A Global Assessment, Volume I, Rutledge, London and New York.

Zebidi, H. (2003). Assessment of three North African countries: Algeria, Libya and Tunisia. February 2003. 44 p.

Zheng C., (1990). MT3D, A modular three-dimensional transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems, Report the U.S. Environmental Protection Agency, 170 p.

3.4 The Evolution of Groundwater Exploration Methods in the Moroccan Oases through History, and Managing Ecological Risk of their Present Pollution

Mohammed Messouli[1], Giuseppe Messana[2], Mohamed Yacoubi-Khebiza[1], Asma El Alami El Filali[1], Ali Ait Boughrous[1], and Mohamed Boulanouar[1]

[1] Département de Biologie, Laboratoire d'Hydrobiologie, Ecotoxicologie et Assainissement, Faculté des Sciences Semlalia, BP 2390, Marrakech, Morocco;
e-mail: messouli@ucam.ac.ma

[2] Istituto per lo Studio degli Ecosistemi del CNR; ISE-CNR, Sede di Firenze; Via Madonna del Piano 10; 50019 Sesto F.no, Firenze, Italy;
e-mail: messana@ise.cnr.it

Abstract

Moroccan Groundwater Systems in most oases are experiencing drastic changes due both to global scale stresses, and the cumulative effects of local and regional scale changes. The adaptive capacity and resilience of GW are severely affected because of the high magnitude of drivers.

The Tafilalt Oasis is located in the Sahara SE Morocco, with an area of about 1,370 km^2. Ramsar site no. 1483 which is part of UNESCO Biosphere Reserve is a site of Biological and Ecological Interest. It comprises a series of oases and the reservoir of one of the oldest dams in Morocco (Hassan Eddakhil). Significant atmospheric and desert Saharan events such as sand invasion often occur in the region affecting the world's climate. Irrigation in the oases mostly depends on a dense and intricate network of canals distributed across the oasis. In the northern part of the Tafilalt oasis, water for irrigation canals has, since the late-14th century, also been provided by khettara (subterranean channels draining perched water tables). Starting from the early 1970s, the remaining active khettaras experienced a flow reduction, and over the next two decades many more khettaras dried up and were abandoned. The diminishing and abandonment of khettaras is attributed to the Hassan Eddakhil dam and its new reservoir upstream from the Tafilalt oasis. The dam's control of downstream water releases has meant that many river channels downstream have water only during certain times of the year (thus affecting the Minimum Instream Flow), a phenomenon which is worsened by excessive water extraction for agriculture, human consumption and droughts that have become more common during the past two decades. Farmers are still not rapidly adopting techniques and equipment that economize water irrigation. The ground water (GW) mining in Tafilalt was enhanced by low-cost boring technology and cheaper imported and locally produced pumps. Pumps became a part and parcel of the green revolution and poverty alleviation but present development of uncontrolled GW markets threatens the sustainable use of GW reserves.

The valley's human growth is placing too many latrine systems too close to too many wells. The septic waste is seeping into drinking-water wells almost on every Kasbah, high levels of nitrates are showing up in water and most of sampled wells had bacteria contamination from septic wastes. Other poisons may be present, usually from septic waste that has polluted ground water.

Tafilalt Oases harbor important stenoendemic subterranean fauna. Major threats to regional freshwater biodiversity are: overexploitation; water pollution; flow modification; destruction or degradation of habitat; and invasion stygoxene species.

To the recent concept of the „new water culture“ involving a sustainable water use based on an integrated water management approach, we will consider the impact of man-induced contamination with regard to the different functions of the groundwater each with its own risk insight. Sustainable use can only be achieved if groundwater management is part of an integrated approach (surface water, environment, physical planning) and if instruments are available, providing information on the maintenance of potential functions and biodiversity.

Water management to date has been dominated by government agencies, and the necessary involvement of civil society (the general population, professional organizations, and selected non-governmental bodies) will take time to be organized.

3.4.1 Water resources and water management in the past and today

In southern Morocco, on the borders of the Sahara Desert, lies the Tafilalt oasis (Fig. 3.4.1, A), an historically important caravan crossroads and trading center. Sijilmassa (A.D. 757-1393), a great city whose remains lie in the center of the Tafilalt (near the modern town of Rissani), is one of the earliest Islamic cities established in Morocco. It used to play a crucial role in the gold trade from West Africa to the Islamic world during the medieval period. After the fall of Sijilmassa, the Tafilalt continued in a different form, ruled by the Alaouites who expanded the infrastructure through a large-scale irrigation network of dams and canals off the oueds (i.e., larger river channel) Ziz and Rheris (Lightfoot and Miller, 1996; Margat, 1959). Surface water for these canals is supplied by runoff from the Atlas Mountains, which increases during the Mediterranean-like winter experienced in the mountains, wanes in early summer, and is generally absent until autumn rain and winter snow return.

Irrigation has mostly been made possible through the use of earthen canals (seguias), and there is a very dense and intricate network of seguias in the Tafilalt. Most channels were traditionally filled with water diverted from the larger river channels (oueds or wadis), or from small reservoirs - intermittent pools of water - impounded behind a series of low-water dams across the Rheris and Ziz oueds. The channel which passes through the heart of the oasis, today called the Ziz oued, is

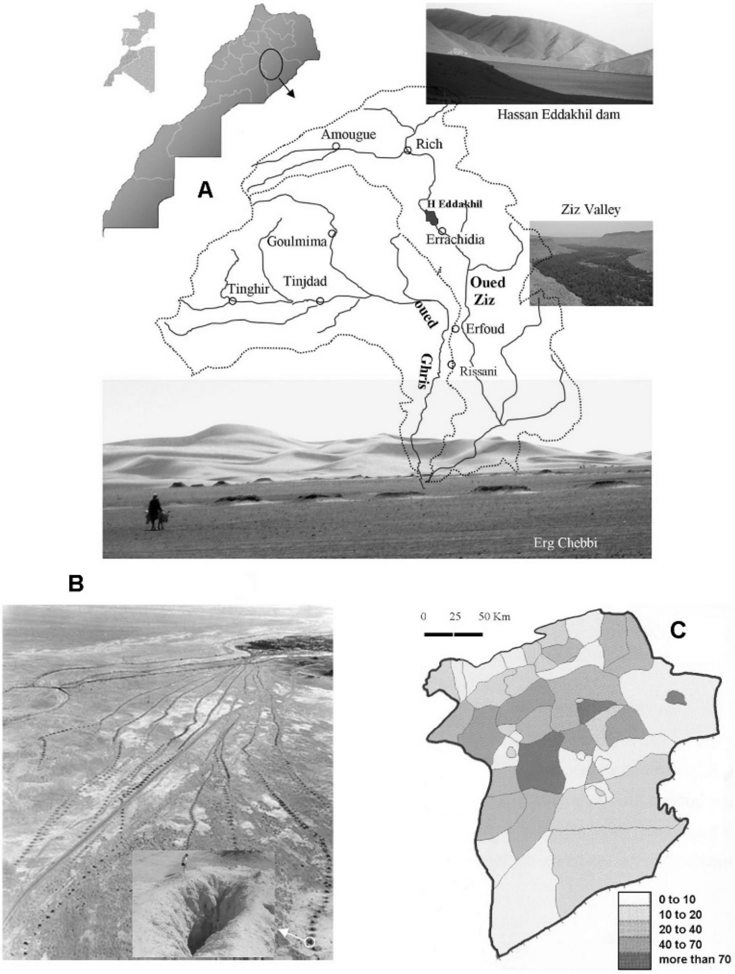


Fig. 3.4.1. **A**: Location of Ziz valley showing the hassan Eddakhil Dam the oasis and the sandy desert ,erg chebbi (photos Messouli);
B: System of khettara along the Tafilalet Valley (in Morocco, east of the High Atlas mountains); the water collected is used for irrigating the oasis visible in the background of the photograph. (source: www.francoravelli.it/cunicoli/images87/1.jpg);
C: percent of latrine use within the tafilalt oases (source: Atlas-Region Meknes-Tafilalet, MATEE).

itself a large primary channel built sometime after the mid-11th century by diverting water from the original Ziz, itself known as the Amerbouh in this stretch today (Lightfoot and Miller, 1996; Margat, 1959). Remains of the now- refashioned diversion dam lies in the Ziz channel near Erfoud. Eleven smaller dams on the Ziz, and two on the Rheris oued, were built and/or refashioned in this region by Sijilmassians, Alaouites, and the French empire. All of these ancient and historic dams have now silted up or breached and are useless for irrigation. In the northern part of the Tafilalt, water for irrigation canals was often provided by khettara, which will be discussed in detail in the next section. The availability and distribution of water in the Tafilalt changed dramatically after the 1971 opening of the Hassan Eddakhil dam near Errachidia, impounding the Ziz Oued about 75 km north of the Tafilalt. Water from the Ziz oued used to flow unimpeded into the Tafilalt basin and provided the primary source of water for irrigation since the time of Sijilmassa. Floods were not uncommon. Now water from the reservoir is released through government canals only three to four times per year, depending on reservoir recharge, with each water release lasting 20 to 23 days (to allot 10-12 hr of water flow per village) and timed to correspond to more critical periods in the growing season. This water contributes to the irrigation of about 9400 ha, more than 75 % of all arable land currently used in the Tafilalt, but the water is so thinly spread that fields can no longer be irrigated with water from the Ziz oued only.

Because of their ubiquity, private and cooperatively owned diesel-pumped wells have now become most important to Tafilalt irrigation. The first private motor pump was installed on a well in 1965 (information from the Office Regional de Mise en Valeur Agricole du Rissani). Seven larger, public pumps, irrigating about 950 ha, had been installed by the French in the 1930s. Some of these public tube wells were deepened after the early 1970s when the water table began to fall.

History of Khettara

An impressive 300 km network of khettara (Fig. 3.4.1, B) was excavated in the Tafilalt basin starting from the late 14th century. Some of these wells tap into the aquifer at the base of mountains along the western edge of the oasis. Others exploit the shallow water tables adjacent to major stream channels which pass through the basin. Eighty of these chains provided perennial water for 28 qsour (i.e., villages; sing. qsar) in the northern part of the oasis. The qsour and khettara simultaneously developed following the breakup of Sijilmassa (Lightfoot and Miller, 1996). Qsour in the central and southern oasis-where the water table was and is still much deeper-continued to rely on the same sources of water (wells and surface channels) for irrigation and drinking water that sustained Sijilmassa.

It is possible that khettara first came to Morocco from the Middle East following the Islamic revolution; the pattern of diffusion closely follows the historic diffusion of Islam. However, it is not certain if this technology was introduced by Muslims first to Morocco and later to Islamic Spain, or whether it first swept into Islamic Spain from North Africa, and then diffused back into Morocco (Goblot, 1979; Joffe, 1992). It appears that qanat technology had been earlier introduced to Roman Spain from the Middle East where the Romans, presumably borrowing Persian technology, had built and used qanats in Jordan and Syria, so there could have been an Iberian precedent to Morocco's filtration gallery systems (Fleming and Barnes, 1993; Glick, 1979).

Networks of dispersed villages with associated khettara appear to have emerged in the Tafilalt in the late 14th through the 16th centuries; a few of the Sifa district (northwest Tafilalt) khettara being originally constructed as late as the 1730s (Margat, 1961).

Khettara continued to provide the only reliable irrigation water for north Tafilalt qsour until the early 1970s, when new technologies and government policies forced changes in traditional water management. Insufficient water (from the dam) and non-sustainable methods of groundwater use (overuse of diesel pumps) have, since the early 1970s, resulted in a dramatic lowering of the water table underlying the oasis. Because they are proffered and subsidized by the government, these modern water technologies, continue to replace the few remaining khettara, which are abandoned as the water table drops.

Khettara: water as a renewable resource

Khettaras were widely used throughout the dry lands of the Old World until recently for several reasons. First, khettara are made of local materials. Second, they tap aquifers using no source of power other than gravity. Third, water is transported for substantial distances in these subterranean conduits with minimal loss of water through evaporation and with little risk of pollution. Water loss through percolation is reduced by lining the tunnels with clay hoops when they pass through loose sand, and by infusing their beds with layers of impermeable clay.

The rate of flow of water in a khettara is controlled by the level of the underground water table. Thus a khettara cannot drain an aquifer, because its flow varies directly with the subsurface water supply. When properly maintained, a khettara is a sustainable system that provides water to settlements indefinitely. Khettaras exploit ground water as a renewable resource.

The self-limiting features of khettara that make them a sustainable technology can, however, be their main drawback, particularly when they are compared with the range of technologies available today. First, the flow of water in khettara varies from year to year depending on the recharge rate of the aquifer. Second, water flows continuously in a khettara, and although some winter water is used for domestic use, much larger amounts of irrigation water are needed during the daylight hours of the spring and summer growing seasons in villages. Although this continuous flow is frequently viewed as wasteful, it can, in fact, be controlled to a large degree. During periods of low water use in fall and winter, water-tight gates can seal off the khettara opening damming up and conserving groundwater for periods of high use. In spring and summer, night flow may be stored in small reservoirs at the mouth of the khettara and held there for daytime use. Moreover, much perceived seasonal water loss infiltrates the soil beneath the khettara tunnel and thus recharges the aquifer.

Khettara in a Modern World

The competition between traditional and modern water systems is both environmental and cultural. Environmentally, diesel-pumped wells and government channels have led to the abandonment of a sustainable technology in favor of systems which are capable of providing greater quantities of water but are not sustainable. Culturally, the adoption of newer technologies has led to the abandonment of traditional technologies like khettara, altering the land use patterns which evolved through the historical reliance of villages on khettara. There has been some loss of local control over water resources because much of the water villages need comes only from the Errachidia reservoir and drinking water pipes, both regulated by the government. Khettara are qsour operated and collectively maintained, and intricate relationships have evolved to manage them and distribute their benefits according to each shareholder's inputs of land, labor, tools, and money. Diesel-pumped wells are often privately owned and, as a result, the traditional ties that bind village society are breaking down. Non-farm sources of income continue to draw young men away from villages and out of the oasis, disrupting the social organization of khettara systems. Furthermore, the traditional source of wealth in the oasis through the trade in dates has been irreparably altered. Only 60 % of the palm trees in the Tafilalt still produce a date crop today. The others no longer produce dates or have died as a result of periodic date blight and/or sustained desiccation.

3.4.2 Evidence of Climate Change in Morocco

Since 1970s, Morocco has experienced a general rainfall decline (Fig. 3.4.2). The Ziz-Rheris catchment is typical of a gradient from humid/sub-humid subtropical mountains to their arid foothills and finishing in the sandy desert (Sahara).

The trend toward a global warming of the Earth’s atmosphere is an important environmental force with significant implication for the state of GW ecosystems. The Earth’s surface temperature during the last two decades has increased by about 0.5° C and an ongoing rise with similar amplitude is expected up to 2025 (IPCC, 2001). The global warmth in 2001 was unusually high and is considered to be a consequence of anthropogenic greenhouse gases (Hansen *et al.* 2002).

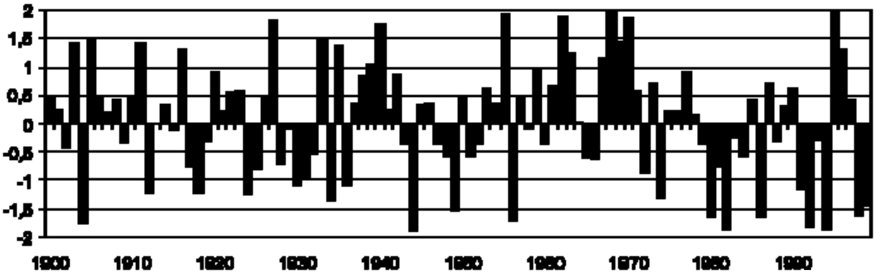


Fig. 3.4.2. Annual precipitation variability in Morocco throughout the 20 the century.

Table 3.4.1. Distributed changes on temperature and precipitation in Morocco.

		ΔT		Δp/p	
Climatic zones	Representative stations	range	mean	range	mean
		° C	° C	%	%
North-West	Tanger-Tetouan	0.6–0.8	0.7	-2.8 – -5.4	-3.3
Oriental	Oujda-Bouarfa	0.6 – 0.9 0.8 – 1.1	0.7 0.9	-1.8 – -5.5 -7 – 0	-2.3 -4.2
West	Kenitra	0.6 – 1	0.8	-7 – 0.1	-3.8
Oum er Rbia Tensift	Marrakech	0.8 – 1	0.9	-7 – 0.1	-4.3
Middle and High Atlas	Ifrane Beni Mellal	0.8 – 1.1	0.9	-7 – 0	-4.3
Sous-Draa	Agadir	0.8 – 1.1	0.9	-7 – 0.1 -11.7 – +2.8	-4.3 -10
South-East	Ouarzazate Errachidia	0.8 – 1.1	1	-7.5 – 0 -11.7 – +2.8	-4.3 -11
South	Laayoune, Dakhla	0.8 – 1.1	0.9	North: -8– -1 South:+1– +4	

Source: Bennani *et al.* 2001

These climate changes will act negatively on the GW reserves of many aquifers. In the semi-arid and arid zones the recharge of aquifers will be reduced through decrease in runoff and through higher human water consumption, especially for agriculture. The GW reserves will continue to shrink. In areas with a high net humidity, the surface run-off will increase, but because of fast flow the water will not optimally recharge the depleted aquifers.

Bennani *et al.* (2001) developed the climatic scenarios for Morocco following the IPCC methodology with „mid-range“ emissions scenario (scenario „IS92a“) and the MAGICC-SCENGEN software (Hulme *et al.* 2000). The software outputs are presented in Table 3.4.1 (Bennani *et al.* 2001)

The scenarios developed by Bennani *et al.* (2001) suggest that for Morocco as a whole:

- Mean annual temperature will increase by 0.6° C to 1.1° C between 2000 and 2020
- Annual precipitation volume will decrease by 4 percent between 2000 and 2020

The data indicates that the impact of future CC on water resources at smaller scales such as smaller river basins, specific water resources and irrigation systems has to date not been properly addressed and, therefore, constitutes a niche for immediate research. This is, especially relevant in areas such as the Mediterranean region, which is predicted to be particularly affected by CC in the future. The preliminary trend analysis of available rainfall data suggests that the possible future CC impacts will decrease the precipitation in parts of the Atlas Mountains, which is the main source of water supply in southern Morocco (Chaponniere, A.; Smakhtin, V. 2006).

3.4.3 Water distribution, rights and conflict

Water as a vital but scarce resource determines the everyday-life in the Tafilalt Valley. Especially in the southern Oases, the arid environment is the limiting factor for economic development. The results of interdisciplinary research demonstrate that water resources are decreasing both as a consequence of environmental constraints and anthropogenic influences, while the degradation of soils and vegetation is increasing. The recent droughts have further aggravated these conditions.

In addition to the gravity of the scarcity of natural resources and the limited options for the local population to manage these resources, the increasing speed of social change due to external forces is one of the major problems in coping with the local conditions. Socio-economic changes on the national level alter modes of access to resources on the local level, particularly by modification of production systems and production relations, by technological innovation, and through new modes of commercialisation. On the local level, a rising demand for water, an increasing individualisation of property, and a weakening of social relations and social ties within the communities are consequences of this development.

Case studies from Tafilalt Valley point to a tendency towards smaller households, often accompanied by residence in „better“ equipped domiciles/ houses, and an increasing domestic water demand. A similar pattern can be found not only in urban centers like Errachidia and Erfoud, but also in rural settlements. This development is closely linked with labour-migration; which was identified as a major factor in the socially embedded negotiation about water use, with an increasing significance in recent years.

In Tafilalt local decision making structures are characterized by the co-existence of modern state institutions and local or tribal (q’bila) institutions. In order to understand patterns of emerging conflicts and conflict settlement concerning water rights and use, this co-existence must be analysed thoroughly before any recommendations can be made.

Technological innovation like the massive introduction of motor pumps, often financed by labour migrants, led to a barely controllable abstraction of groundwater and weakened traditional structures of water distribution and water ownership. The resulting modification of income distribution is one factor that will alter rural

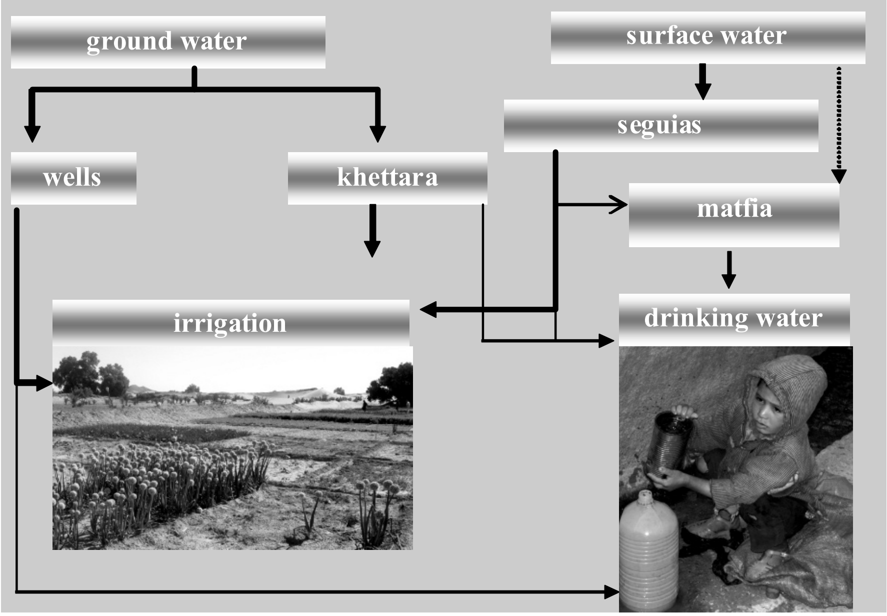


Fig. 3.4.3. Water distribution in main parts of the Ziz oasis (thick arrows indicate primary supply lines). Photos: M Messouli.

social structures. Yet, conservative kinship structures, group memberships, social status, and patterns of production that range from sedentariness associated with agricultural production to nomadic pastoralism, but also „non-traditional" economic activities, determine the handling of water resources. Therefore, to accomplish the task we are confronted with, it is essential to include social anthropological data. Otherwise, the impact of environmental and climatic change on the local populations cannot be investigated and understood fully. In addition, every intervention into an established setting needs a thorough understanding of the complexity of local traditions and the associated socio-cultural process of contemporary institutional changes. Any development cooperation can only be sustainable if the historically rooted cultural norms, values and strategies of survival are considered in the early stage of planning. Consequently, the social-anthropological work packages are investigating the embeddedness of indigenous systems of water use in the spheres of religion, economy and socio-political institutions.

Water taps are irregularly distributed along Ziz valley, but many wells are generally equipped with motor pumps. Together with the covered cisterns (matfiya), they supply the villages with water for drinking and irrigation. Water is distributed according to the pattern shown in Fig. 3.4.3.

3.4.4 Managing groundwater systems: Trends and developments

The danger global change and warming pose to oases is a concept familiar to many but understood by few. The life-sustaining benefits of oases are being altered by human activities and widespread disregard for the environment. Once this relationship has been clearly established, it is feared that global change will have a disastrous impact on local and regional weather patterns and on oases services. As a result, the oases as we know them today will be forever changed.

In addition, most of our knowledge in understanding linkages and feedbacks has to do with the physical, biological, and biogeochemical aspects of the Oasis system rather than with its human dimensions. As a rule, studies of complex water systems have included society either as a driver of change or as a recipient of negative impacts of changes. The aim of studies, however, must be to include human activities and institutions as one of the core components of the Oases water system, interacting with physical and biological / biogeochemical components.

Effects of contaminants on subsurface ecosystems are hardly considered in actual management of groundwater resources. Recent developments in groundwater management show growing attention for regional specific solutions and integrated environmental management including spatial planning. The role of ecology in groundwater remains unclear.

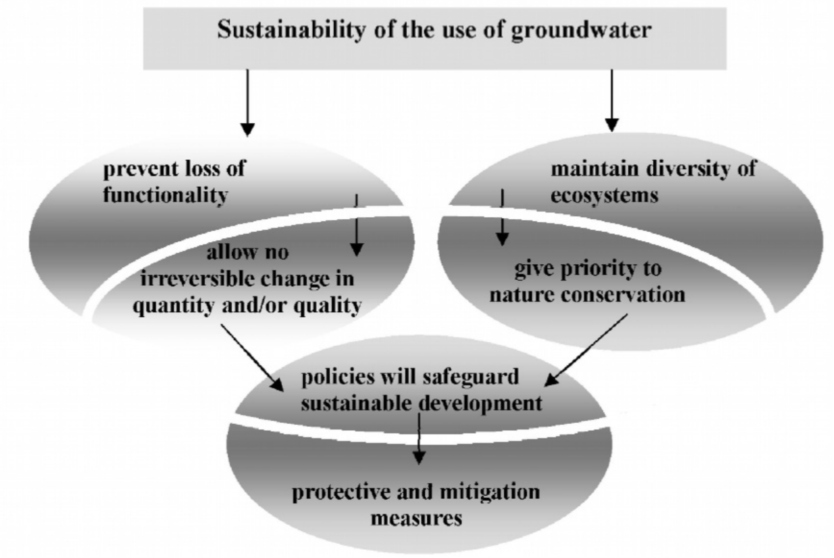


Fig. 3.4.4. Scheme for sustainable use of groundwater (modified after Notenboom, 2001).

Sustainability of the use of GW in Oases

The use of GW in a sustainable way is the maintenance of the integrity of structural and functional traits of groundwater ecosystems (Notenboom 2001). Within this framework we should consider not only the water aspects, but also the various species living within the subsurface. In order to achieve such a goal, we need to protect the environmental quality above and below the soil surface and apply a sound management strategy for the exploitation of water resources at relevant sites.

The problem of developing environmental policies for the implementation of sustainable GW systems and/ or for protection of such ecosystems requires two main approaches, one relying more on the socio-economic and political contexts and related to the sustainability of the water production, and the other insisting more on ecological criteria and related to the sustainability of the whole ecosystem (Fig. 3.4.4).

Analysis of environmental problems

Our paper follows the DPSIR framework (Driving forces, Pressures, State of Impact and Response), developed for environmental problems in the European Community (EEA [European Environment Agency] 1999; Notenboom 2001). This conceptual model encapsulates the idea that ecosystems, especially those impacted by human activities, change their structure and functions, leading to a diminution of ecosystem goods and services that they can offer to the biosphere.

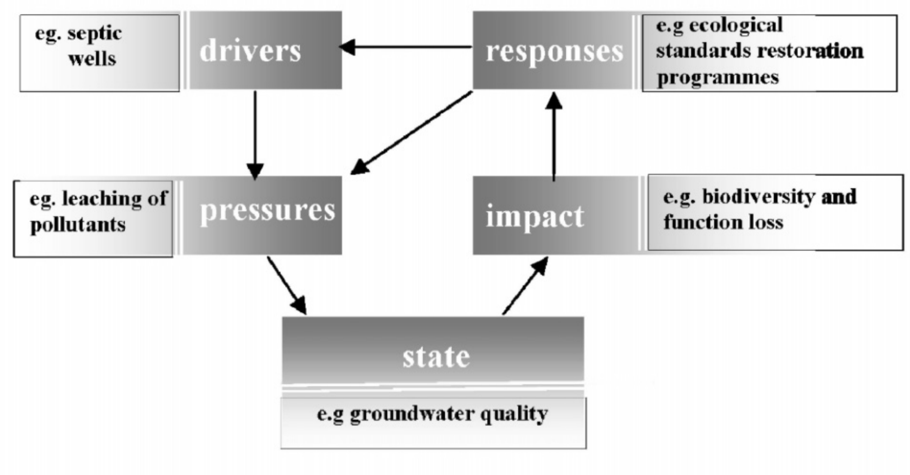


Fig. 3.4.5. The DPSIR framework applied to the impact of septic wells on the ecological properties of groundwater system onTafilalt oasis.

Table 3.4.2. Major global threats to the surface/ groundwater system in Oases and related issues (modified from Meybeck 1998 and Meybeck 2003). The scope and intersections of the numerous forcing and system impacts require an interdisciplinary and systematic research approach.
A : human health, B : water cycle, C : water quality, D : carbon balance, E : fluvial morphology, F : aquatic biodiversity, G : coastal zone impacts. Only the major links between issues and impacts are listed.

drivers	Major impacts	Global issues						
		A	B	C	D	E	F	G
climatic change	Change in flow regime (runoff volume and timing)		•	•		•		•
	Changes in wetland distribution	•	•	•	•		•	
	Changes in erosion and sedimentation				•	•		
	Change in chemical watering				•			•
	Accelerated salinization through evaporation	•	•				•	
	Development in non perennial rivers		•	•	•	•	•	•
Water management (including dams, diversions, and channelization)	Nutrient and carbone retention				•			•
	Retention of particulates				•	•		•
	Change in flow regime (runoff volume and timing)		•	•		•		•
	Stream flow variability and extremes		•					
	Loss of connectivity (L, V and H)						•	
Land use change	Wetland flling or draining		•	•	•		•	
	Change in sediment transport				•	•		•
	Change in vegetation cover		•					
	Alteration of first order streams					•	•	
	Nitrate and phosphate increase	•		•	•			•
	Pesticide increase	•		•				•
Irrigation & water transfer	Change in flow regime (runoff volume and timing)		•	•			•	•
	Salinization through evaporation		•	•				
Release of domestic wastes (latrines, manners)	Heavy metal increase	•		•				
	Eutrophication	•		•	•		•	•
	Development of water-borne diseases	•						
	Organic pollution	•		•			•	
	Persistent organic pollutants	•		•				•

The task of managers or decision-makers is to assess the driving forces, pressures, state and their ultimate impact. From the impact they must determine appropriate responses, in order to direct the final impact in the desired direction. These responses will influence the drivers, pressures and states, thus completing a feedback loop (Fig. 3.4.5).

Groundwater threats

Many of the driving forces, in Moroccan oases (Table 3.4.2), are leading to irreversible changes in the subsurface environment. The trend is that the subsurface is being used more and more for different functions. In densely populated areas in particular, along Ziz and Draa Rivers, these functions may conflict. Pressures are due to the presence of pollutants but also to changes in the natural physico-chemical conditions.

Latrines: groundwater contamination and impact on human health

It is important to distinguish point and diffuse sources of groundwater contamination. Environmental problems related to point sources are generally considered to be easier to bring under control, notwithstanding their seriousness. Diffuse sources are very difficult to bring under control and they need complex management solutions. Septic contamination is such a diffuse source of groundwater contamination. A basic threat assessment of this type of contamination for oases groundwater ecosystems is treated in the subsequent section.

Drivers

Tafilalt valley's growth is placing too many septic systems too close to too many wells. In several parts of the oasis along the Ziz River (Fig. 3.4.1, C)), people are using the underground as a place for waste disposal and a very large number of subsurface sites are therefore now highly contaminated.

More than 80 percent of the people in sub-Saharan Moroccan oases use ground water as their source of drinking water, and about one-third of the rural and waterfront population uses tanks systems for wastewater disposal. Tanks serve primarily as settling „wells“ removing solids from the sewage. In sand and gravel aquifers characterized by large pore sizes that allow for relatively easy and rapid transport of water and contaminants, concentrated plumes of dissolved constituents from tanks septic systems can occur in the shallow part of the aquifer and can affect the quality of drinking water withdrawn from domestic wells. There is a slight general decrease in total constructing of latrine as responses to the demographic and tourism demand.

The number of **Concentrated Animal Feeding Operations (CAFOs)** often called „factory farms“, is growing. On these farms, animals are raised in a small space. The large amounts of animal wastes/ manures from these farms can threaten water supplies. Strict and careful manure management is needed to prevent pathogen and nutrient problems. Salts from high levels of manures can also pollute ground water.

Table 3.4.3. Range of some characterestic water quality parameters in groundwater of me wells in Errachidia.

Parameters		max	min	mean
temperature	° C	25	20	22.2
conductivity	μS.cm^{-1}	4383	1515	2120
pH		7.95	6.9	7.2
dissolved O_2	mg.L^{-1}	10.32	0.0	5.12
OM	mg.L^{-1}	4.41	0.77	2.44
NH^{4+}	mg.L^{-1}	0.326	0.005	0.116
Na^+	mg.L^{-1}	361.4	67.5	210.8
K^+	mg.L^{-1}	101.6	3.85	16.05
Ca^{2+}	mg.L^{-1}	525.0	88.2	163.58
Mg^{2+}	mg.L^{-1}	180	25.5	108.9
Mn^{2+}	mg.L^{-1}	0.018	0.012	0.014
Cl^-	mg.L^{-1}	634	131.3	369.1
NO^{2-}	mg.L^{-1}	9.220	0.03	0.75
NO^{3-}	mg.L^{-1}	69.76	4.82	18.26
HCO^{3-}	mg.L^{-1}	451.4	180.0	245.2
SO_4^{2-}	mg.L^{-1}	1698	191.8	857.6
Fe (total)	mg.L^{-1}	0.106	0.064	0.079

Pressures

The quality of drinking water from shallow domestic wells potentially affected by seepage from septic systems was assessed by analyzing water samples for substances derived from septic systems. The effect of septic systems on water from domestic wells was demonstrated using a preliminary interdisciplinary approach involving the collection of physicochemical (Table 3.4.3), and biological data.

Domestic wells seemed to be most vulnerable to septic-waste contamination when they were sand-point wells within 50 m of a septic system and were less than 10 m deep in a shallow, thin aquifer.

States

The study illustrates that shallow wells, whether sand-point wells or cased wells, can be affected by septic waste if constructed near a septic field, the water table is shallow, and the saturated media consist mainly of sand and gravel. The study results also indicate that bacteria and nitrate concentrations may not always be the best indicators of contamination of drinking water with water and constituents from septic systems and that other indicators such as stygobites may be more valuable in some cases.

An impressive number of chemical and biological substances, mainly produced by human activities, accumulate in GW impairing the pristine quality of the water, producing changes in the structure and function of ecosystems and, very important, creating threats to human health. The spread of contaminants, especially nitrates and pathogens from septic tanks, is another widespread form of GW pollution that can impair the quality of drinking water and produce outbreaks of disease.

Impact

The study of the spatio-temporal distribution of meio- and micro-organisms was the only approach that provided evidence of the dispersion of contaminants throughout the less permeable parts of the aquifer during times of active groundwater recharge. This finding highlights the importance of integrating faunal investigations into the framework of interdisciplinary research programmes on groundwater contamination

Assessment of the impact of contaminants on biodiversity and ecosystem integrity is preferably based on system specific information on exposure, species sensitivity, population and community effects, and ecological recovery. This information is hardly available and no signs exist that applicable data and methods become available in nearby future.

Other human interventions in the subsurface

Acridian control: The Moroccan locust, *Dociostaurus maroccanus*, is an important pest in oases, affecting pasture and crops. Current control relies on broad spectrum chemical pesticides. Many thousands of hectares are sprayed each year, often in areas of major conservation value. Adverse effects on the environment have to be evaluated.

Fertilizers and Pesticides: Farmers use fertilizers and pesticides to promote growth and reduce insect damage. The chemicals in these products may end up in groundwater. Some underground agricultural drainage systems collect fertilizers and pesticides. This polluted water can cause problems to ground water and local streams and rivers.

Extraction of gravel creates GW pits through which contaminants (like nitrates) and pathogens pollute aquifers. Natural processes like climate change and polluted surface water infiltration put extra pressures on the GW. High amounts of phosphate and/ or nitrate infiltrate the subsurface water after drying out of streams and the rewetting of the channels under arid climate conditions (Stanley & Boulton 1995; Turner & Haygarth 2001). Infiltration of polluted water into the sediments along rivers also raises the concentration of dissolved organic matter and/or heavy metals in the shallow groundwater of riverbanks.

Deforestation: It is astonishing to notice that public baths (hammam) are still Morocco's largest consumer of fuel wood in spite of the negative impact of the deforestation. Landscape alteration, which can in the long term reduce the GW resources of an area, includes deforestation and reuse of the land for agriculture or urban activities, plantation of vegetation that extracts too much water from aquifers, dehydration of wetlands, and alteration of river courses through regulation of their channels and construction of dams, dykes and levies that contribute to isolation of the aquifer from riverbeds. In all these cases, the volume of recharged GW from surface run-off declines with time. UNDP Capacity 21 is supporting a number of projects focusing on more efficient use of fuel wood, including fuel-efficient stoves, solar water heaters for hammams, or public baths, as well as butane gas and rechargeable batteries.

Tourism: Tourism affects, and is affected by the environment. Mountains and Saharan tourism has grown and thus is expected to continue. In The High Atlas, the Isli and Tislit lakes are extremely sensitive mountain areas, represent important tourist destinations where water supply is rather scarce and sanitation poor. Tourism causes very high pressures on GW, especially because of the additional septic well, and water demand arising during the season when the GW situation may already be critical. In addition, tourism-associated waste and sewage represent a potential source of GW pollution in sensitive areas. This trend will certainly continue during the next decades and will extend to areas that, only recently, discovered the economic advantages of the tourism industry.

3.4.5 Oases groundwater ecosystems: structure and function

Wetlands on Tafilalt oases have close associations with groundwater. They depend on the outflow from an aquifer as a water source. In such case, the hydrology of the aquifer and the health of the wetland ecosystem are closely connected. Importantly, this relationship can be disrupted by changes either to the aquifer, such as by groundwater abstraction, or to the wetland, for example by reduced natural inundation of wetlands overlying aquifers.

One of the main functions of the water in the subterranean ecosystem is to transport energy and matter from the surface of the Earth and/or from underground and further distributes them through the subsurface. During the movement of the water through the subsurface, its chemical properties change due to physical, chemical and biological processes. The transport of water through the subsurface is studied mainly by hydrologists and hydro-chemists and is important for the understanding of the ecological dynamics of any GW system.

The groundwater of Ziz valley is inhabited by diverse micro-, meio- and macro-organisms (Fig. 3.4.6). They play an important role in the recycling of organic matter transported by water and in the redistribution of energy and matter; over areas ranging from few millimetres to metres (Ward *et al.* 1998). Secondary producers dominate GW ecosystems because of lack of light (Gibert *et al.* 1994). Primary producers are represented by chemoauthotrophic micro-organisms, namely Bacteria and Archea.

Many stygobitic species are relicts of animal groups that have disappeared from surface water systems. Such animals deserve protection within well functioning GW systems (Culver & Sket 2000). Shallow GW habitats, especially the hyporheal (the ecotonal zone connecting the surface-running water system to that of the deep subterranean) generally display high species richness, a mixture of surface dwelling and exclusively hypogean (stygobitic) taxa.

The key role of micro biota in the functioning of groundwater ecosystems

In pristine aquifers, micro-organisms are responsible for the major turnover of energy and matter. They play a key role in weathering and formation of minerals and they store in their biomass important quantities of carbon, nitrogen and phosphorus.

Moreover, they contribute to the development in the subsurface of microhabitats chemically distinguished by their redox reactions. In the context of strong human impacts on the environment, the high purification potential of GW ecosystems is of increasing interest and importance.

Understanding hydrological links between wetlands and groundwater

Hydrology controls the composition and functioning of aquatic and terrestrial subsurface ecosystems. The dynamic exchange processes between surface water and GW contribute much to the structure of subterranean communities.

Shallow subterranean ecosystems are directly connected to surface aquatic and terrestrial systems like rivers, lakes and wetlands. Hence the approach that ecologists now favour is to treat GW ecosystems within a holistic framework that integrates the connectivity between the subsurface and the surrounding terrestrial and aquatic systems (Danielopol *et al.,* 2003).

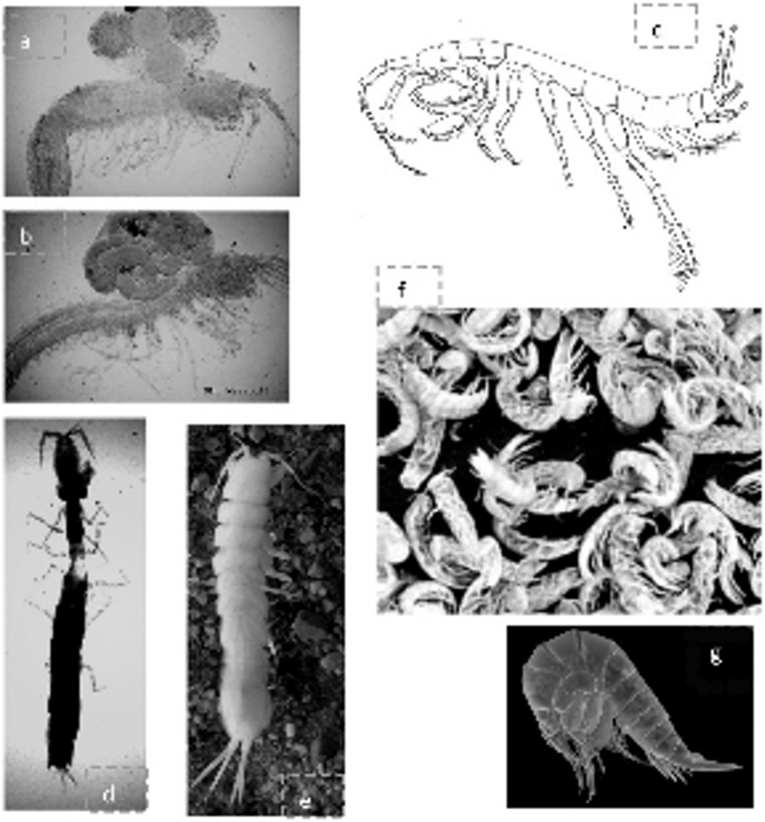


Fig. 3.4.6. Photographs and line drawing of representative unpigmented, blind, crustaceans from subterranean water of Tafilalt oases: (a) *Thetysbaena* cf. *atlantomaroccana* (1-1.5 mm) female carying larvae and (b) female with eggs on dorsal puch; (c) *Maghrebidiella* sp length 4.2 mm; (d) *Microcerberus remyi*; length 1.6 mm; (e) *Magnezia gardei*; length 10 mm; (f); *Typhlocirolana sp*; length 3-7 mm; (g) *Salentinella sp*; length 1.2 mm. (Photo and line drawing sources, a-d and f: Messouli; e: Messana; g: Messouli and Messana).

Into the relationships between GW and surface-water ecosystems it is important to integrate the ecological dimension played by human activities. In this enlarged ecological perspective we can better evaluate the actual ecological state of various GW systems viewed at different scales of generality from the local to worldwide.

3.4.6 Causes of Biodiversity Change

Groundwater ecosystems harbour an impressive number of animal species that are known exclusively from subterranean waters (referred to as stygobites), such as the crustacean species belonging to the orders Bathynellacea, Thermosbaenacea, Isopoda etc ..., and family of Microparasellidae, Microcerberidae, and Salentinellidae. The ecological characteristics of subterranean animal assemblages offer in many cases information on the functional state of GW ecosystems and/or on the degree of connectivity, especially between above soil (epigean) and subsoil (hypogean) ecosystems (Malard *et al.* 1996; Boulton 2000). Many stygobitic species are relicts of animal groups that have disappeared from surface water systems (Humphreys 2000). Such animals deserve protection within well functioning GW systems (Culver & Sket 2000). Shallow GW habitats, especially the hyporheal (the ecotonal zone connecting the surface-running water system to that of the deep subterranean) generally display high species richness, a mixture of surface dwelling and exclusively hypogean (stygobitic) taxa.

The quantity and quality of the various kinds of pressures on GW systems are able to induce drastic changes in the diversity of organisms living underground. We assess two types of such changes, namely

1. decline in GW-dwelling organism populations leading to species extinctions and
2. penetration of alien species belonging to surface-water communities.

Both processes determine changes in the functioning of GW systems, generally reducing the efficiency of some ecosystem processes.

Comparative sampling of pristine and sewage-polluted wells showed that the contamination induced the disappearance of stygobites, promoted the colonisation of the aquifer by stygoxenes and modified the relative abundances of the different faunal groups. Wells of the unimpacted sites had faunal assemblages dominated by crustaceans, and they harbored a high number of stygobite species wich usually represented a major component of the total number of invertebrates. Polluted wells had significant relative abundances of oligochaetes and insects.

Hyporheic habitats along rivers, like the Draa or the Ziz, which are polluted especially by organic matter, display low biological diversity and are represented mainly by surface-dwelling taxa. River regulation combined with the negative effect of organic pollution alter GW habitats; for example, through stronger siltation and oxygen depletion of the interstitial voids, the free-moving crustaceans (such as stygobitic amphipods and isopods) are replaced by assemblages dominated by epigean animals such as insect larvae and oligochaetes.

Arid climates as well as damming rivers determine the drying of down streams and the interruption of water infiltration into adjacent-shallow subsurface areas. The fauna of hyporheic habitats in such cases is represented by a few epigean pre-adapted species that can survive the dry period until the next rewetting.

3.4.7 Concluding remarks

Khettara has a profound influence on the lives of the water users in Tafilalt oases. It allows those living in a desert environment adjacent to a mountain watershed to create a large oasis in an otherwise stark environment. The United Nations and other organizations are encouraging the revitalization of traditional water harvesting and supply technologies in arid areas because they feel it is important for sustainable water utilization.

GW ecosystems provide generally important services and goods to humans. The water filtration process in groundwater systems due to removal of microbial pathogens allows production of high-quality drinking water, a good of immense benefit to human welfare (Daily et al. 2000). The value of healthy GW systems has also to be seen as an intergenerational capital to which precautionary protective measures should be applied. The ecological consequences of natural and artificial recharges of aquifers need to be better understood for the effective management of GW reserves. Another ecological research area with important implications for the management of sustainable water resources lies in the protection measures required for GW systems.

Morocco's illiteracy rate and the poor school enrolment figures reflect higher poverty levels in rural areas and a large disregard toward environment. Consequences of inadequate supply of water and sanitation are very evident. However, they hit women most severely, as women are the traditional water carriers and family health care providers in many societies of the developing world.

Human population growth and increasing poverty will continuously exert pressure on the sustainable use of GW. Without fundamental changes in the relationship between man and environment, the possibilities for sustainable GW management programmes are limited. In the Tafilalt especially, urgent action is needed to reduce anthropogenic threats to GW systems and policy makers should tackle this problem at grass root level.

The irrigated agriculture has been the main economic drive in the Tafilalt. Sustainable use can only be achieved if groundwater management is part of an integrated approach (surface water, environment, physical planning) and if instruments are available providing information on the maintenance of potential functions and biodiversity.

References

Bennani, A., Buret, J. & Senhaji, F. 2001. „Communication Nationale Initiale a la Convention Cadre des Nations Unies sur les changements climatiques“ Ministere de l’Amenagement du Territoire, de l’Urbanisme de l’Habitat et de l’Environnement. pp.101.

Boulton, A.J. 2000. The subsurface macrofauna. In: Streams and Ground Waters, ed. J.B. Jones & P.J. Mulholland, pp. 337–361. San Diego, USA: Academic Press.

Brunke, M. & Gonser, T. 1997. The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology 37: 1–33.

Chapelle, F.H. 2001. Groundwater Microbiology and Geochemistry. New York, USA: John Wiley & Sons.

Chaponniere, A. & Smakhtin, V. 2006. A review of climate change scenarios and preliminary rainfall trend analysis in the Oum er Rbia Basin, Morocco. Working Paper 110 (Drought Series: Paper 8) Colombo, Sri Lanka: International Water Management Institute (IWMI).

Culver, D.C. & Sket, B. 2000. Hotspots of subterranean biodiversity in caves and wells. Journal of Cave and Karst Studies 62: 11–17.

Danielopol, D.L. 1983. Der Einfluss organischer Verschmutzung auf das Grundwasser-Ökosystem der Donau im Raum Wien und Niederösterreich. Bundesministerium für Gesundheit und Umweltschutz, Forschungsberichte 5/83: 5–160.

Danielopol, D.L., Griebler, C., Gunatilaka, A. & Notenboom, J. 2003. Present state and prospects for groundwater ecosystems. Environmental Conservation 30: 104–130.

Daily, G.C., Söderqvist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P.R., Folke, C., Jansson, A.M., Jansson, B.-O., Kautsky, N., Levin, S., Lubchenco, J., Mäler, K.-G., Simpson, D., Starrett, D., Tilman, D. & Walker, B. 2000. The value of nature and the nature of value. Science 289: 395–396.

Fleming, D. & Barnes, N. 1993. The worldwide distribution of filtration gallery systems and the social mechanisms underlying their construction and management, Culture and Environment: A Fragile Coexistence, Proceedings of the 24th Annual Chacmool Conference, 1991, Calgary, Alberta, pp. 363-369, University of Calgary.

Gibert, J., Danielopol, D.L. & Stanford, J.A., eds. 1994.Groundwater Ecology. San Diego, USA: Academic Press.

Ghiorse, W.C. & Wilson, J.T. 1988. Microbial ecology of the terrestrial subsurface. Advances in Applied Microbiology 33: 107–172.

Glick, T.F. 1979. Islamic and Christian Spain in the Early Middle Ages. Princeton University Press, Princeton.

Goblot, H. 1979. Les Qanats: Une Technique d'Acquisition de I' Eau. Mouton, Paris.

Hansen, J., Ruedy, R., Sato, M. & Lo, K. 2002. Global warming continues. Science 295: 275.

Hulme, M.; Wigley, T.; Barrow, E.; Raper, S.; Centella, A.; Smith, S. & Chipanshi, A. 2000. „Using a Climate Scenario Generator for Vulnerability and Adaptation Assessment.“ MAGICC and SCENGEN Version 2.4 Workbook, Norwich, U.K.: Climate Research Unit. pp.52.

Humphreys, W.F. 2000. The hypogean fauna of the Cape Range Peninsula and Barrow Island, Northwestern Australia. In: Subterranean Ecosystems. Ecosystems of the World Volume 30, eds. H. Wilkens, D.C. Culver & W.F. Humphreys, pp. 581–602. Amsterdam, The Netherlands: Elsevier.

IPCC. 2001. Climate Change 2001: the Scientific Basis, ed. J.T. Hougthon, Y. Ding, D.J. Griggs, M. Noguer, P.J. Van der Linden, X. Dai, K. Maskell & C.A. Johnson. Cambridge, UK: Cambridge University Press

Joffe, G. 1992. Irrigation and water supply systems in North Africa, Moroccan Studies, 2, 47-55.

Lightfoot, D.R. & Miller, J.A. 1996. Sijilmassa: The rise and fall of a walled oasis in medieval Morocco, Annals of the Association of American Geographers, 86, 78-101.

Malard, F., Plenet, S. & Gibert, J. 1996. The use of invertebrates in groundwater monitoring: a rising research field. Ground Water Monitoring and Remediation 16: 103–116.

Margat, J. 1961. Carte Hydrogeologique au 1/50000 de la Plaine du Tafilalt. Notes et Mémoires du Service Géologique, Service Géologique du Maroc, Rabat.

Margat, J. 1959. Note sur la morphologie du site de Sigilmassa (Tafilalt), Hesperis, 46, 254-260.

Meybeck, M., 2003. Global analysis of river systems: from earth system controls to anthropocene syndromes. Philosophical Transactions of The Royal Society of London Series B, 358, 1935-1955.

Meybeck, M. 1998. The IGBP Water Group: a response to a growing global concern. Newsletters, 36, 8-12.

Notenboom, J. 2001. Managing ecological risks of groundwater pollution. In: Groundwater Ecology. A Tool for Management of Water Resources, eds. C. Griebler, D.L. Danielopol, J. Gibert, H.P. Nachtnebel & J. Notenboom, pp. 248–262. Luxembourg: Office for Official Publications of the European Communities.

Ronen, D. & Magaritz, M. 1991. Groundwater quality as affected by managerial decisions in agricultural areas: effect of land development and irrigation with sewage effluents. In: Hydrological Basis of Ecologically Sound Management of Soil and Groundwater, ed. H.P. Nachtnebel & K. Kovar, pp. 153–162. Wallingford, UK: IAHS Press.

Schwille, F. 1976. Anthropogenically reduced groundwaters. Hydrological Sciences Bulletin 21: 629–645. Seckler, D., Amarasinghe, U., Molden, D., de

Stanley, E.H. & Boulton, A.J. 1995. Hyporheic processes during flooding and drying in a Sonoran Desert stream. 1. Hydrologic and chemical dynamics. Archiv für Hydrobiologie 134: 1–26.

Turner, B.L. & Haygarth, P.M. 2001. Phosphorus solubilization in rewetted soils. Nature 411: 258.

Ward, J.V., Bretschko, G., Brunke, M., Danielopol, D., Gibert, J., Gonser, T. & Hildrew, A.G. 1998. The boundaries of river systems: the metazoan perspective. Freshwater Biology 40: 531–570.

3.5 Investigating Unconsolidated Aquifers in an Arid Environment – A Case Study from the Lower Jordan Valley/Jordan

Mathias Toll
University of Göttingen; Department of Applied Geology; Goldschmidstraße 3;
D-37077 Göttingen
Mathias.Toll@geo.uni-goettingen.de

3.5.1 Introduction

General Information

Groundwater systems in semi-arid areas frequently are not being sufficiently characterized hydrogeologically and long-term data are generally not available. Long-term time series are necessary however to design future groundwater abstraction scenarios or to predict the influence of future climate change effects on groundwater resources. To overcome these problems an integrated approach for the provision of a reliable database based on sparse and fuzzy data is proposed. This integrated approach is demonstrated using the lowermost area of the Jordan Valley (Fig. 3.5.1). A conceptual model of flow is set up based on geological, hydrochemical, and geophysical methods. The water balance is calculated based on historical data, combined with remote sensing techniques. On the basis of these findings a steady-state numerical flow model was set up.

The Lower Jordan Valley is part of the Jordan Dead Sea - Wadi Araba Rift Valley, which extends from the Red Sea to Lake Tiberias and beyond with a major 107 km sinistral strike-slip fault between the Arabian plate to the east and the northeastern part of the African plate to the west. Due to extensional forces, a deep depression called - for historical reasons - the Jordan „graben“, has formed. During the modern geological history, it was filled by evaporites, lacustrine sediments, and clastic fluvial components (Niemi et. al. 1997).

Protected by the high mountain shoulders of the West and East Bank together with the low elevation of -300 to -415 m below mean sea level and the long and warm season in the Jordan Valley lead to a natural hot house condition. Therefore the area is intensively used for agriculture. Consequently hundreds of shallow wells were drilled and large amounts of groundwater abstracted. Since the 1960's, the groundwater quality has been rapidly deteriorating and signs of overpumping and increasing soil salinity became apparent. Along with heavy groundwater abstraction, replenishment of the Jordan Valley aquifers is reduced by diversion and storage of large quantities of fresh water, both in dams built along the major wadi outlets on the Jordanian site of the Valley and by diversion of most of the fresh water from Lake Tiberias.

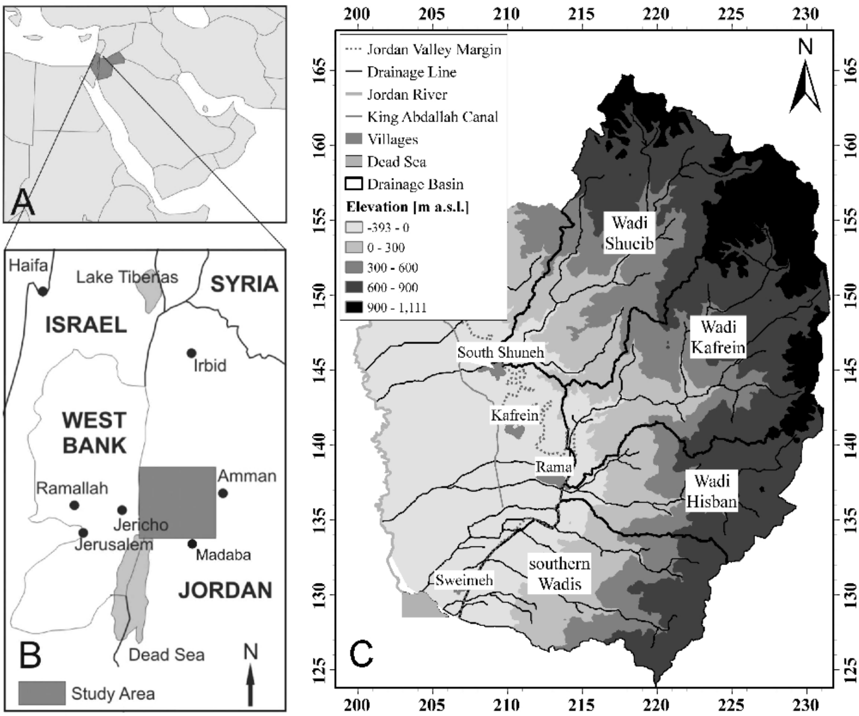


Fig. 3.5.1. Location of the study area. A: Middles East; B: Study area in the regional context; C: Study area.

The area of interest extends from the Dead Sea in the south to the city of Karameh to the north, from the Jordan River to the west up to the margin of the western hills of the East Bank in the east. Nevertheless the consolidated strata to the East were included in this study because it can be assumed that the major part of recharge to the unconsolidated aquifer originates from this area.

Integrated approach

In order to achieve a sustainable state of water resources and to quantify the impact of climate change on water resources a proper assessment of the groundwater resources as well as their quality is a prerequisite. Therefore the aim of this article is to contribute to a better hydrogeological understanding of the groundwater in the unconsolidated sediments of the Lower Jordan Valley/ Jordan. In order to sufficiently describe the complex hydrogeologic flow system an integrated approach, combining geological, geophysical, hydrogeological, historical and chemical methods was chosen. The aquifer geometry and composition is described with the help of geological, hydochemical, and geophysical methods. As far as the water budget is concerned, recharge to the aquifer is estimated with geological methods and available data sets, while the abstraction from the aquifer is estimated with the help of remote sensing techniques (Landsat data sets). A historical approach is used to detect the general conditions under which the groundwater system has been in the past. This information is then implemented into a flow model. This flow model must be able to describe the depicted stress periods on the groundwater systems in order to enable giving reliable predictions about the impacts of climate change scenarios on the groundwater system. The flow model provides the means for testing the consistency of the rather heterogeneous historical data set and allows the simulation of the future impact of management strategies as well as climate change scenarios.

Historical review of land use in the study area

The section „historical approach“ in designed to understand the different conditions under which the unconsolidated system was. The natural, anthropogenically unaltered flow system is addressed, as well as the effects of major stress periods in the 60ies, the influence of the events of 1967 and their aftermath, extreme rainfall events, and periods of drought on the groundwater system. A forecast groundwater flow model must be tested against these events in order to provide realistic predictions of future scenarios.

The lower Jordan Valley has a long history of human settlement and hence agriculture. Though periods of minor usage or even abandonment occur throughout its history. The city of Jericho, founded between the 9th to 8th millennium BC is known to be the oldest continuously populated city in the world and is located just 8 km west of the study area. Excavations in the Wadi Shueib dating back to the Neolithic Period demonstrate very early cultivation by humans.

The settlement and agricultural activities in former times are usually restricted to the availability of water resources and good farming land. Within the area of interest the Jordan River itself flows in a 15-30 m deep gorge (Arabic: Zor). Apart from the residues of former Jordan River flood plains, which can be considered as good farming land, the vicinity of the Jordan River flows in the the soft Lisan formation, which is unsuitable for farming due to its high salt content (e.g. Begin et al. 1974, Gibbs 1986, Landman et al 2002). As a consequence only places near the outlets of major wadis, where a perennial flow of water from the eastern hills provides enough water, are suitable for agricultural activities.

After the arrival of the first European and American explorers in the late 19th century the study area was described as a hot and uninhabited area, unsuitable for human settlement activities (Burckhardt 1822).

The first comprehensive report describing water use in the Jordan Valley was the report published by Ionides (1939) „The water resources of Transjordan and their development“. According to the report only 9 wells were drilled prior to 1938. In 1938 a Haifa based drilling company drilled 18 modern wells. Concerning the agriculture the author noted that farming is only possible through irrigation. Irrigation water came largely from perennial streams in the valley and only a few modern irrigation systems existed. Bedouins irrigated their farmland via earth channels diverting the water from the outlets of major wadis. Ionides described these channels as highly inefficient, since most of the water infiltrates or evaporates on the way to the farmlands. Wheat, barley, and corn were the dominant crops at that time.

A major transformation from an almost uninhabited area with only minor agriculture started after 1948. After the 1948 war Palestinian refugees along with increased engagement of major landowning Jordanian families resulted in the agricultural development in the Jordan Valley (Khoury 1981). This increase in farming activities is reflected by major increase in well drilling. According to Tleel (1963), the major phase of new well drilling started around the mid fifties and clear signs of overpumping could be seen by the beginning of the sixties. As a consequence first drilling restrictions were issued in 1961. Between 1953 and 1963 62 new wells were drilled in the Karameh area, 122 in the Shuna Nimreen, and 133 in the area of Sweimeh, Ghor el Rama and Ghor el Kafrein. The drilling of new wells and hence abstraction of larger quantities of groundwater reached its first peak in 1967. The political events of 1967 brought almost all agricultural activities to a halt. It was not before 1971 that agricultural activities began to increase again.

Two earth dams within the study area store excess runoff water from their adjacent wadis for irrigation. These dams are the 1968 built Wadi Shueib dam with a capacity of around 2.3 Mm^3 and the 1968 Wadi Kafrein dam with a capacity of 3.8 Mm, raised at the end of the 90s to 7.5 Mm^3 (Salameh and Bannayan 1993, MWI open files) both located at the outlets of major wadis (Fig. 3.5.1). Due to the ongoing deposition of sediments, transported mainly after heavy storm events, the capacity diminished. According to Lenz (1999) they also contribute to local recharge resulting from leakage.

The 1986 renamed King Abdullah Canal (KAC), previously known as East Ghor canal, is after its third extension (completed between 1984 and 1989) of 14.3 km the third allochthonous source of irrigation water in the study area (Fig. 3.5.1). The KAC carries water from as far as the Yarmouk River. Towards the south additional water from side wadis is added and water for domestic as well as irrigation purposes is diverted from the canal.

Today, groundwater is not anymore the major source of irrigation water within the study area and drilling new wells require a permit issued by the Ministry of Water and Irrigation (MWI). Nevertheless many illegal wells in fenced private farms still exist and extract unknown quantities of groundwater.

3.5.2 Development of a Conceptual Model of Flow

Geology and Hydrogeology

In this section the factors controlling the geometry and composition of the unconsolidated aquifer along with the connection to the consolidated strata to the east is described. The consolidated strata are important, since they control the recharge to the alluvial aquifer. The consolidated strata provide recharge to the studied Jordan Valley system insofar, that it drains runoff water in the major wadis towards the unconsolidated strata where the runoff water infiltrates along its flow path and by the inflow from groundwater from the bordering consolidated aquifers into the studied system.

A: Consolidated-rock stratigraphy and aquifers

Along the lower Jordan/ NE Dead Sea foothills area three consolidated sedimentary sequences can be identified, which are separated from each other and from the underlying crystalline basement by major unconformities. The Cambrian to Early Ordovician Ram Group represents a fluvial sandstone-transgressive siltstone/limestone-regressive mature sandstone cycle draping all over the crystalline basement with southward increasing thickness from an estimated 700 m around the Wadi Zarqa area to about 1 km near Madaba. It comprises the Disi Aquifer, which was encountered in well JICA No. 5, S of Kafrein.

The overlying Permian to Jurassic Hudayb, Ramtha, Azab Groups (formerly agglomerated as Zarqa Group) consists of unconformity-bounded marginal marine sandstone-carbonate-shale associations most of which are classified as aquitards. To the SE all of them wedge out so that a total thickness of an estimated 1 km around Wadi Zarqa is reduced to about 250 to 300 m south of Kafrein where the Jurassic Azab has tapered out completely and only the lower part (eg. Scythian to Anisian) of the Triassic Ramtha Group intercalated between the Ram Group and the following Cretaceous strata. SE of Wadi Naur-Wadi Kafrein the Ladinian and Carnian gypsiferous formations (Umm Tina, Abu Ruweis) were completely removed by pre-Cretaceous erosion (Bandel and Khoury 1981).

Above the early Cretaceous transgressive unconformity follows the sandy Kurnub Group (Neocomian), the limestone-marl sequences of the Ajlun Group (late-Albian to end of Turonian) and the predominantly chalky Belqa Group (Coniacian to Eocene). The fluvial to marginal marine sandstones of the Kurnub Group increase in thickness northwestward attaining 180 to 200 m at the NE end of the Dead Sea and 250 to 300 m in the Wadi Zarqa area. They form the Kurnub aquifer (Fig. 3.5.2) characterized by low salinities.

The lower Ajlun Group (Naur, Fuheis, Hummar, Shueib Formations; A1 to A6) with 300 m of subtidal to peritidal marls, nodular limestones, massive limestones reflect several transgressive to highstand cycles of a permanently submerged carbonate platform which however ends with a late middle Turonian lowstand gener-

Period	Epoch	Group	Formation	Hydrogeol. Unit		Brief Description	Regional Thickness
Quaternary	Holocene Pleistocene	Jordan Valley	Alluvium	Aquifer	Qal	Clastic sediments	
			Lisan	Aquitard	Jv3	Marl, Clay, Evaporites	0 - 300m
Teritary	Pliocene Oligocene		Ghor el Katar	Pleistocene Aquifer	Jv2	Conglomerate with silicious cement, sand, gravel	100 - 350m
			Shagur Conglomerate		Jv1		
Upper Cretaceous	Campanian Santonian Coniasian	Belqa	Amman al Hisa	Upper Aquifer	B2	Phosphorite, silicified limestone	100 - 350m
			Wadi Um Ghudran	Upper Aquifer	B1	Massive chalk & marlstone, fossiliferous	20 - 90m
	Turonian	Ajlun	Wadi as Sir	Upper Aquifer	A7	Thinlayered dolomite or massive gray limestone, fossiliferous. To the top more chertlayers	60 - 340m
			Wadi Shu'eib	Aquitard	A5/6	White crystalline limestone and Ammonites (A6), and thinlayered limestone and marlstone (A5)	40 - 120m
	Cenomanian		Hummar	Aquitard/ Aquifer	A4	Massive gray, sometimes yellowish limestone, often crystalline and cavernous	30 - 100m
			Fuheis	Aquiclude	A3	Thinlayered, marlstone, claystone	30 - 90m
			Na`ur	Aquitard	A1/2	Massive hard grey limestone + chertlayers (A2), and gray marlstone (A1)	90 - 220m
Lower Cretaceous	Albian Aptian Neocomian	Kurnub	Subeihi	Kurnub Aquifer	K2	Multicoloured sandstone	120 - 350m
			Aardo	Kurnub Aquifer	K1	White, yellow massive sandstone	
Angular unconformity							
Jurassic Triassic Permian		Zarqa	Azab	Aquitard	Z2	Marine sandstone-carbonate-shale associations	0 - 600m
			Ma'in	Aquitard	Z1		0 - 1250m

Fig. 3.5.2. Stratigraphic Table of Rock Units in the Study Area (modified, after Shawabkeh 2001).

ating upper Shueib F. shallow water dolostones and marls grading S-ward into supratidal gypsiferous claystones (Schulze et al 2003). Thus, mainly due to the Fuheis and the Shueib marls and claystones the lower Ajlun (A1 to A6) forms a multilayer aquitard, in some areas even an aquiclude with embedded aquifers e.g. the massive limestones of the upper Naur and of the Hummar Formations. In contrast, the overlying ca. 100 m of Wadi as Sir Formation (A7) of the area consists mainly of well bedded and massive limestones of a prograding and agrading carbonate platform and together with the basal Belqa Group forms the important Upper Aquifer (A7-B2 aquifer).

After an episode of non-deposition the pelagic chalks of the Wadi Umm Gudran and Amman cherty limestone Formations of the Belqa Group were deposited, which on the western-facing slopes are preserved in synclines. Only on the crest of the Transjordanian Mts. and beyond they form a gently eastward sloping continuous layer where they are overlain by bituminous marls and chalks of the B3 aquitard (Muwaqqar Fm.).

B: Unconsolidated rocks - Jordan Valley Group and aquifers

Two aquifers of local significance are located within the study area. These aquifers are hydraulically interconnected and consist of clastic components of Pleistocene to recent age.

Alluvial Aquifer (Holocene or sub-recent)

This aquifer is built up of sub-recent clastic deposits formed along the outlets of major wadis. These alluvial fans are still under accumulation as a result of large floods. They consist of debris from all neighbouring lithologies and are graded according to their transport energy, where the biggest components are found close to the apex and the smallest close to the fan margin. The transport normally takes place along alternating channels or after very heavy rainstorms as sheet flow. Thus permeable horizons alternate with impermeable lithological units within the deposits. It is believed that the thickness maximum is near the rift margins, thinning out towards the centre of the rift basin. Well depths in these deposits rarely exceed several tens of metres. Often the alluvial aquifer directly overlies the Pleistocene gravel aquifer and because of that is hydraulically interconnected with this aquifer.

Pleistocene gravel aquifer

The three members of the Pleistocene system (the coarse clastic, the silt and Lisan) are a vertical and lateral facies succession formed under terrestrial/fluvial, to deltaic/limnic and limnic/brackish lake environments. They reflect the Plio-Pleistocene depositional conditions. The Lisan Lake (60,000 - 18,000 year B.P.) reached up to an elevation of –180 m MSL. Lisan, the marl, gypsum and silt lacustrine unit is generally considered as an aquiclude, devoid of exploitable water. It is distributed mainly towards the centre of the graben. Al Ghor Formation consists of two members: a silt member underlying or interfingering with Lisan and a coarse clastic member further to the East that predominantly consists of gravel, interbedded with clay, sand and marl horizons. Al Ghor is hereinafter referred to as the „Pleistocene aquifer“. However, exploitable water resources are principally restricted to the coarse clastic member.

Meteoric recharge by rainfall is low. Therefore, the aquifer is mainly fed by inflows from neighbouring aquifers, namely the East Bank Mountain aquifers and by the infiltration of surface water originating from the wadis of the escarpment of the East Bank.

The water quality is variable, with low chloride concentrations near the areas of recharge and high values in areas under the influence of the highly saline Lisan Formation and hypersaline brines. The hydraulic gradient adjacent to the Jordan Valley escarpment is steep and becomes lower towards the west.

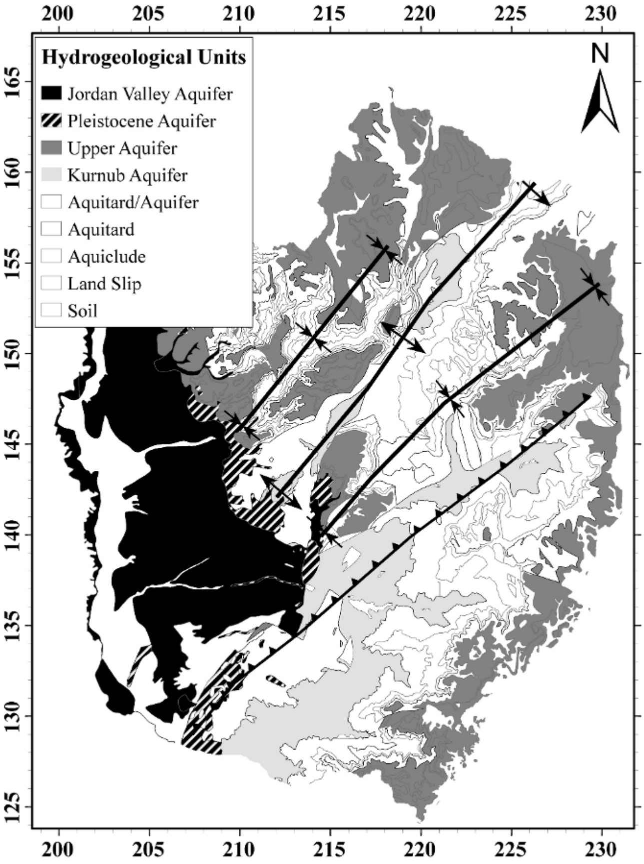


Fig. 3.5.3. Consolidated and unconsolidated aquifers within the area of interest including the main structural features depicted from available geological maps (Shawakeh 2001, Diabat and Abdelghafoor 2004) in the area of interest.

C: Geologic Structure

Pre-Cretaceous structural imprints on the subsurface rocks of the area are not known. Triassic and/or Jurassic phases of extension are indicated by a number of basaltoid dykes and sills in the Ramtha and Azab Groups, which did not intrude the Cretaceous cover (e.g.. Bandel and Khoury 1981). The structures most pertinent to groundwater flow probably originated during the late Cretaceous to Eocene Syrian Arc deformation episode and were modified during the following Miocene to present-day deformation associated with shear on the N-S-trending Dead Sea Transform Fault (DSTF) which in the area runs close to the Jordan River.

The Syrian Arc deformation produced the following fold and fault structures exposed in the eastern slopes of the southern Jordan Valley between Wadi Zarqa and the eastern shore of the Dead Sea. The major structural features can be found in Fig. 3.5.3. These features plus additional major structural features are listed from N to S:

- a dome-like structure around Salt where the base of the Cretaceous (bCr) rises to +400 m a.s.l.;
- the Wadi Shueib Syncline, where bCr drops to -500 m b.s.l. near Shuna;
- the Wadi Shueib NW -facing monoclinal flexure and associated normal faults;
- the Wadi Shueib composite anticline where bCr between Shuna and Kafrein rises to –250 m;
- the NNE-trending Kafrein normal fault and associated faults bounding the Kafrein syncline to the W;
- the Kafrein asymmetric syncline (bCr ca -400 to –800 m);
- the NE- to ENE- trending Amman flexure and associated faults facing toward NW;
- the gently warped dip slope SE of the Amman flexure where bCr rises again to about +300 m a.s.l.
- These structures are modified or enhanced by sets of normal faults trending NNW and NW, which may be regarded as syn- and antithetic to the subsiding Jordan Valley depression.

The network of Wadis discharging along the ecarpment toward the Jordan Valley depression seem fairly well controlled by the above structures of the Cretaceous rocks e.g. synclines parallel to Wadi Shueib and Wadi Kafrein. The wadis also follow a combination of structural dip with NW-trending antithetic or ac-faults on the dip slope SE of the Amman Flexure (Wadi Hisban/Ar Rama, Wadi al Muhtariqa, Wadi al Hiri E of Sweimeh). This may reflect some of the controls geologic structure exerts on subsurface flow paths of groundwater in the consolidated rock sequences.

D: Subsurface contacts between consolidated rocks and unconsolidated Jordan Valley Group sediments

Due to the spatial variability of the hydraulic potential and the multilayer nature of aquifers and aquitards in the consolidated rock sequence hydraulic contacts with the unconsolidated valley sediments play a major role in the water balance.

At the foothills of the highlands near Al Karameh, Shuna, Kafrein, Sweimeh the base of the Jordan Valley Group sediments (bJVG) crops out at an altitude of ca. –200 m b.s.l. A preliminary analysis of reflection seismics in combination with the deep wells JV1 and JV2 shows that the late Cretaceous structures continue beneath the younger Jordan Valley Group sediments (Heinrichs et. al 2004; AlZoubi et al. 2006). The same data reveal a drop of the bJVG along the Wadi Shueib composite anticline from –200 m at the surface to about –500 m b.s.l. at 4 to 5 km distance WSW of the outcropping contact. This dip corresponds roughly to the dip of the

Cretaceous strata E of the contact. It can therefore be concluded that up to this location on this anticline Naur and Kurnub Formations are directly overlain by unconsolidated sediments. Further W and toward SW seismic data suggest that higher stratigraphic levels of the Cretaceous are preserved and in contact with the unconsolidated sediments in spite of the bJVG dipping steeply toward W and toward the Dead Sea in the south. A similar inference can be made for the Wadi Shueib Syncline where the Wadi as Sir Formation should be continuous for some distance under the base of the unconsolidated sediments. At the moment low density of seismic information does prevent tracing the major faults into the subsurface of the Jordan Valley.

Hydrochemistry

In this section the water quality and fate of surface and groundwater entering the unconsolidated aquifer is described. By the application of hydrochemical methods, information about flow direction and water quality alteration along the flow path is attained. Groundwater quality of the unconsolidated aquifer in lower Jordan Valley displays a wide spectrum. Whereas the composition and concentration depends largely on the location of sampling points, the sampling date (because water quality varies both on a yearly and seasonal scale), and the pumping rate of the well. Sampling depth can also play an important role. Recharge to the unconsolidated aquifer comes from different sources: infiltration of surface water along the course of major wadis (mostly during the rainy season), inflow from different consolidated aquifers, irrigation return flow, and to a very small degree direct infiltration during rare single rainfall events. However, these singular events are believed to be negligible compared to other recharge sources, since the annual rainfall in South Shuneh is only 166 mm/yr and evaporation is very high (up to 2,000 mm/yr). In general, freshwater resources can be found close to the apex of the major alluvial fans. Along the groundwater flow path from east towards the west the groundwater quality deteriorates.

Distribution Maps

First comprehensive spatial water quality plots can be made for the 60s, when Tleel (1963) undertook the first extensive well survey in the Jordan Valley. Groundwater quality distribution maps were computed with the data provided by Tleel (1963), since from the beginning of the sixties the study area was intensively used for agriculture. Therefore recent well analysis would not deliver the natural flow system, but rather a strongly anthropogenically influenced picture of the flow system. The different distribution maps were drawn by author on the base of Tleel (1963).

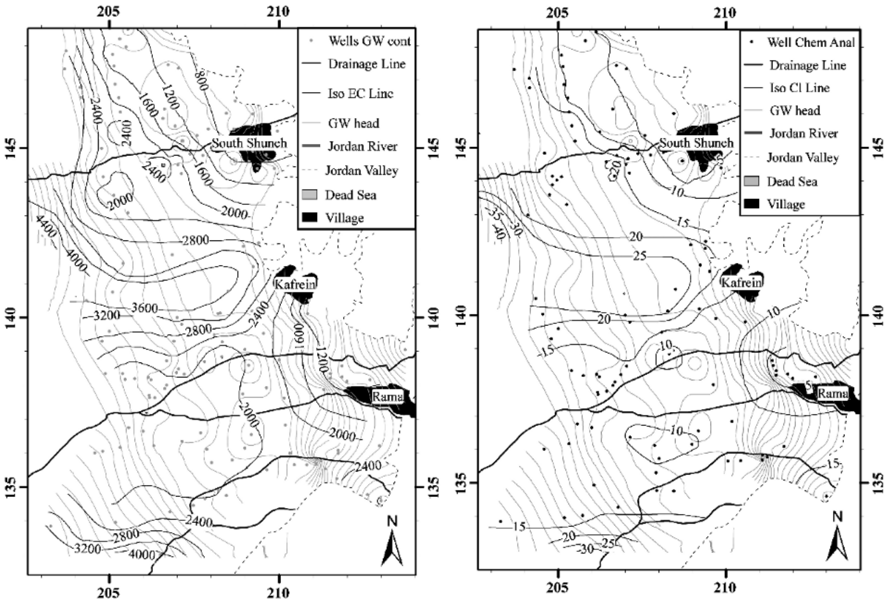


Fig. 3.5.4. Left: Relationship between groundwater contour lines (middle gray color) and iso- electrical conductivity lines (in S/cm; black color) of well water samples taken 1961 (data was taken from Tleel 1963). Groundwater contour lines are not labeled for better visibility of the iso- EC contour lines. Groundwater flow is from east to west; groundwater contour intervals are 5 m. The wells used for the generation of the groundwater contour map are shown as gray dots (Well GW cont).

Right: Relationship between groundwater contour lines (middle gray colors) and Iso- Chloride concentration lines (meq/L; black color) of well water samples taken 1961 (data was taken from Tleel 1963). The location of the wells, that were used to draw the EC and Cl- plots, are shown as black dots (Well Chem. Anal.). Groundwater contour lines are not labeled for better visibility of the iso- EC contour lines. Groundwater flow is from east to west; groundwater contour intervals are 5 m.

Fig. 3.5.4 left shows the relationship between groundwater contour lines (light gray colors) and iso- electrical conductivity lines (dark gray colors) for the year 1961. The groundwater contour lines are plotted in order to show the influence of groundwater flow on water salinity. Groundwater flows from east to west and groundwater level contour intervals are 10 m.

As far as the spatial distribution of EC values is concerned, the lowest values were found in wells located next to the outlets of the major wadis. Downgradient the salinity increases. The highest conductivity values were measured close to the Jordan River (west of Shunat Nimreen; around 143,000 PGN) and in the south to southwest (Fig. 3.5.4). Some wells regionally show high salinities. Between the alluvial fan sediments at the outlets of Wadi Shueib and the alluvial fan sediments of Wadi Kafrein and Wadi Hisban an increase in EC can be observed. Lacustrine sediments, mostly the Lisan Formation, accumulated more between the alluvial fans than on the fans themselves. The highly soluble salt of the Lisan Formation could be the reason for the increased conductivity between the two major flow paths in the study area. These two major flow paths are the Wadi Shueib alluvial fan flow path and the combined flow path within the alluvial sediments of Wadi Kafrein and Wadi Hisban. Groundwater flow is towards the west and almost no water flows between the two flow paths due to the low permeability of the Lisan Marls. However, Tleel (1963) already reported groundwater deterioration in wells with increased pumping activity. Therefore the „natural flow“ and its quality were already influenced by pumping activities and the interpretation of the distribution maps should be done carefully.

In 1961 several cones of depression started to form in the study area and first signs of overpumping were observed in the area northwest of Shunat Nimreen (PGE 206,500/ PGN 144,750), just east of Shunat Nimreen (PGE 208,000/ PGN 145,000), and 10 km west of the village of Rama (PGE 206,000/ PGN 139,000). Locally high salinities might be the result of inflowing water from the neighboring Lisan Formation as the cone of depression increases to the west and north, by upconing of salt water, or by return flow of higher saline irrigation water. In the southeast of the study area high salinities can be found. Since a large displacement fault is located directly in the vicinity of the sampled wells, these high salinities might be attributed to upconing water from the Zarqa or Ram Group.

Parameters like TDS and EC are only bulk parameters and are therefore not unique. Nevertheless, an increase in salt concentration along the groundwater flow path towards the west and the detection of two different major flow paths (Wadi Shueib and Wadi Kafrein/ Hisban alluvial fan flow path) could clearly be seen. In Fig. 3.5.4, right, the chloride distributions is displayed. Chloride was chosen as a parameter, since chloride is usually the most conservative ion. Chloride is easily dissolved from the rock matrix, but rarely precipitated. Therefore the concentration of chloride will increase or remain the same along the groundwater flow path. Only in case of mixing with fresher or more polluted water (e.g. water that contains dissolved rock salts from the Lisan Formation, or the inflow of groundwater from Ram Group Aquifer) the chloride content of the groundwater will change its composition. Generally, chloride concentration distribution maps should follow groundwater head distribution maps, as long as there are no sources or sinks concerning chloride. It should be noted, that this rule of thumb accounts only for waters up to brackish and saline quality and not for waters of brine concentration. However, no water of brine concentration was found neither in the studied literature, nor was measured in the field. Local high salinities might also derive from inflow of the highly pressurized Ram Group Aquifer. The Ram Group Aquifer has no outcrop within the study area, but was tapped by JICA Well No. 5 at 345 m depth (-422.5 m a.s.l.) and is believed to be tapped in Well No. 6 (-486.1 m a.s.l.).

Within the study area the aquifer is under artesian conditions. JICA Well No.5 penetrates the upper 50 m of this unit. While only small amounts of water discharged from the borehole during the drilling of the Zerqa Aquifer Unit, huge amounts of flowing water (100 l/s) flowed from the borehole after tapping the Ram Group Aquifer. The same happened in Well No. 6, where the base of the Zerqa was drilled at a depth of 275 m (-486 m a.s.l.). No rock samples could be taken from the depth of 275 m to the final depth of 298 m. But huge amounts of flowing water (20 - 300 l/s) were encountered at a depth of 275 m. This contrasts with the 1-2 l/s of flowing water during the penetration of the previous 11 - 274 m. Therefore, a penetration of the upper 23 m of the Ram Group Aquifer was assumed (JICA 1995). Due to the fact that a large contrast of flowing water between the Ram Group Aquifer and the overlying Zerqa Aquifer exists, a good hydraulic separation of these two systems can be assumed. However, leakage of groundwater into the Zerqa Group Aquifer along preferential flow paths, e.g. along open faults, might take place as a result of the high hydraulic pressure of the Ram Group Aquifer.

Fig. 3.5.4, right, shows a similar trend to the one shown in Fig. 3.5.4 left. The chloride distribution in the study area follows the groundwater head distribution. Areas, where cones of depressions formed, behave differently. An increased chloride content is apparent in the cones of depressions northwest of Shunat Nimreen and the one located 10 km west of Rama.

Geophysics

Complementary to the geological and hydrochemical methods surface geophysical methods can be used to provide information about flow paths and about the salinization of groundwater in unconsolidated materials. Especially in areas where no wells are drilled, surface geoelectrical methods can provide valuable information. Surface geoelectric resistivity soundings are a well-established method in the investigation of fresh-/saltwater environments. Notable contributions to this subject are Flathe and Pfeiffer (1964), Flathe (1967, 1968), van Dam and Meulenkamp (1967), Zohdy (1969), Ginzburg and Levanon (1976), Urish and Frohlich (1990), and Frohlich et al. (1994).

A large number of vertical electric soundings have been undertaken in lower Jordan Valley. The earliest and most extensive survey was conducted between November 1963 and February 1964 on the alluvial plains on both sides of the Jordan River. A total number of 173 VES with electrode separations of up to 680 m were conducted by a geophysical team of the Geological Survey of the Federal Republic of Germany (BGR) and the German Geological Mission in Jordan (Flathe et al. 1965). The soundings were arranged along the estimated groundwater flow direction in east-western profiles, whereas the shot point separation was around 1,000 m (Flathe 1968). The second major geoelectric sounding campaign was also operated by geophysicists of the Geological Survey of the Federal Republic of Germany (BGR 1985). The soundings were undertaken during February until March 1985 and concentrated on two north-south profiles, one in the vicinity of the Dead

Sea six kilometres northwards along the Dead Sea- Amman road and the second profile along the, at that time, proposed extension of the East Ghor Canal. This profile begins at the proposed end of the canal to around five kilometres north of it. In total 24 soundings were undertaken with a point separation of 400-600 m, an electrode separation of up to 1,200 m. The electrode spacing was perpendicular to the profile directions. The third major geophysical survey in the alluvial sediments of lower Jordan Valley was undertaken within the framework of „The study on brackish groundwater desalination in Jordan“ project, financed by Japan International Agency (JICA) and operated by a geophysical team of the Mitsui Mineral Development Engineering Co. Ltd., Tokio, Japan. In 1995 30 VES were conducted at selective points with an electrode separation of up to 600 m. Some VES were shot at three selective sites. Five VES soundings were made available by Prof Salameh, of Jordan University. The soundings were undertaken in the area north of the Dead Sea. Four VES, shot at a Jordan Fishery farm and were conducted by geophysical team of Jordan University in June 1998 (Abou Karaki 1998). Within the context of this study ten VES were conducted in February 2003 along a north- south profile, six kilometres north of the Dead Sea, along the road that leads to the baptism site at the Jordan River. The sounding point separation was 400 to 600 m, electrode separation up to 600 m, and the electrode spacing was perpendicular to the profile directions. The range in resistivity values covers three orders of magnitude, ranging from 0.2 to 400 Ωm.

For the study area, Toll (in preparation) demonstrated with the help of direct-push soundings, of sediment coring, and of the measurement of the soluble soil content of sediment samples, that the subsurface resistivity largely depends on the on the water saturation and on the concentration of the dissolved salt in the saturated and unsaturated zone and not on the nature of the rock material. Toll et al. (in preparation) compared geoelectric direct-push drillings to surface VES. They showed, that direct-push soundings are helpful to reduce the problem of ambiguity that occur when interpreting surface VES. Toll (in preparation) furthermore compared VES shot at different time steps. In almost all soundings a decrease in subsurface resistivity was found. However, the decrease in conductivity was rather low and the soundings stayed within a similar range.

On the base of these findings all available vertical electrical measurements, starting from the measurements in the sixties up to the soundings undertaken in early 2003 were revised and if necessary reinterpreted. The measurements were made by different investigators, who emphasized different aspects in their respective work. Therefore all available VES were assembled and processed by an individual geoscientist. Afterwards these interpretations are combined in a consistent manner together with the chemical analysis of well waters that show the spatial and temporal variations of the water quality in the lower Jordan Valley within the past 40 years.

In order to quantify areas of different electrical resistivity characteristics the VES interpretations were subdivided into different resistivity ranges. Dam and Meulenkamp (1967) determined the salinity of groundwater in western Netherlands. They considered 40, 12, and 3 Ωm as fresh, brackish, and saline water, respectively. Sabet (1975) estimated a range of 20 Ωm to several hundred Wm for the resistivity of clean sand and gravel saturated with freshwater in the southeastern region of Virginia. He also reported that the resistivity of the same sand containing silt, clay or brackish water is much lower. He concluded that freshwater is unlikely to be produced from horizons of resistivity less than 10 Ωm. A classification scheme for different resistivity ranges was developed by Zohdy et al. (1993) and modified by Nowroozi et al. (1999). Different resistivity values were correlated to different grain sizes and pore fluid salinity. Based on the findings the available shot point data was classified. Six different groups were distinguished. The different resistivity zones are characterized by the following characteristics:

0.1 – 1 Ωm (black colour)

In this very low resistivity zone groundwater samples, taken during the BGR survey showed the following typical characteristics: Mg^{2+}: 197; Ca^{2+}:157; Na^{+}: 725; K^{+}:138; Cl^{-}: 1,645; Br^{-}: 22,6; SO_4^{2-}: 154; HCO_3^{-}: 372 mg/L. The sediments consist almost entirely of the saline Lisan Formation. The sediments are saturated with saline groundwater. Only a few soundings showed such low resistivity values.

1-10 Ωm (70 % black colour)

Sediments consist usually of marl (Lisan Formation) or in areas of steady-state evaporation in the top soil caused by very shallow groundwater tables of silt. Groundwater from this zone (apparent electrical resistivity: 4,4 Wm) has the following typical composition: Mg^{2+}: 130; Ca^{2+}: 146; Na^{+}: 371; K^{+}: 41; Cl^{-}: 822; SO_4^{2-}: 193; HCO_3^{-}: 405 mg/L.

10 – 25 Ωm (50 % black colour)

Groundwater from this zone (apparent electrical resistivity: 12 Wm) has the following typical composition: Mg^{2+}: 119; Ca^{2+}: 78; Na^{+}: 225; K^{+}: 28; Cl^{-}: 521; Br^{-}: 0,1; SO_4^{2-}: 81; HCO_3^{-}: 421 mg/L. Sediments are usually of low permeability, like chalks, marls, shales, argillaceous fine clastics. However, the higher hydraulic conductivity in this zone, resembling coarser material and water of better quality from the major wadi outlets is higher than in the zone described above.

25-50 Ωm (30 % black colour)

Groundwater from this zone (apparent electrical resistivity: 30 Wm) has the following typical composition: Mg^{2+}: 74: Ca^{2+}: 78; Na^{+}: 146; K^{+}: 28; Cl^{-}: 425; Br^{-}: 0,1; SO_4^{2-}: 59, HCO_3^{-}: 187 mg/L. Sediments are usually less clayey and more sandy, typical for the mid-fan area.

50-100 Ωm (10 % black colour)

Groundwater from this zone (apparent electrical resistivity: 80 Wm) has the following typical composition: Mg^{2+}: 36: Ca^{2+}: 78; Na^{+}: 57; K^{+}: 5; Cl-: 102; SO_4^{2}-: 57, HCO_3^{-}: 320 mg/L. Freshwater prevails within these sediments. The sedimentary section is dominated by coarse alluvial material. These high resistivities usually occur only in the proximal fan area.

> 100 Ωm (white colour)

Sediments consist usually of dry alluvial components (sand and gravel). These high electrical resistivities are only found in non-saline environments close to the fan apex or close to the hinterland. This group is underlain by the 50-100 Ωm group described above.

Spatial information

The results of the VES classification and their respective shot points are shown in Fig. 3.5.5 and Fig. 3.5.6. Lowest resistivities are found in the west, close to Jordan River (black colour). The 1 – 10 Ωm group (70 % black colour) is found either in the west, the Lisan dominated area, as top soil layer in areas that undergo salt accumulation as a results of surface evaporation of shallow groundwater table, or, as in the case of the area of Rama, underlie fresh groundwater.

The 10 - 25 Ωm group (50 % black colour) prevails also in Lisan dominated areas, but more to the east than the 1 – 10 Ωm group. This includes also the areas between the alluvial fan of Wadi Shueib and Wadi Kafrein/Hisban. 30 % black colours (25 – 50 Ωm) in the transition zone between the more brackish water in the Lisan dominated areas and the freshwater dominated area in the vicinity of the major wadis and northeastern area of the study area. 10 % black colours (50 – 100 Ωm) can be seen in the freshwater dominated areas Rama and South Shuneh. White colours can usually only be found as top layer in the area of Rama, where they represent dry non-saline top soil. In the north of South Shuneh, the northeastern part of the study area, it can also represent low mineralized groundwater. However, their resistivity is only slightly higher than 100 Ωm. The low resistivity zone between the area of South Shuneh and Rama (alluvial fan dominated areas) is clearly visible. As a result of the soundings undertaken in the course of this study the downfan influence of Wadi Kafrein/ Hisban alluvial fan as continuation of a higher resistivity area into an otherwise lower resistive environment is clearly apparent.

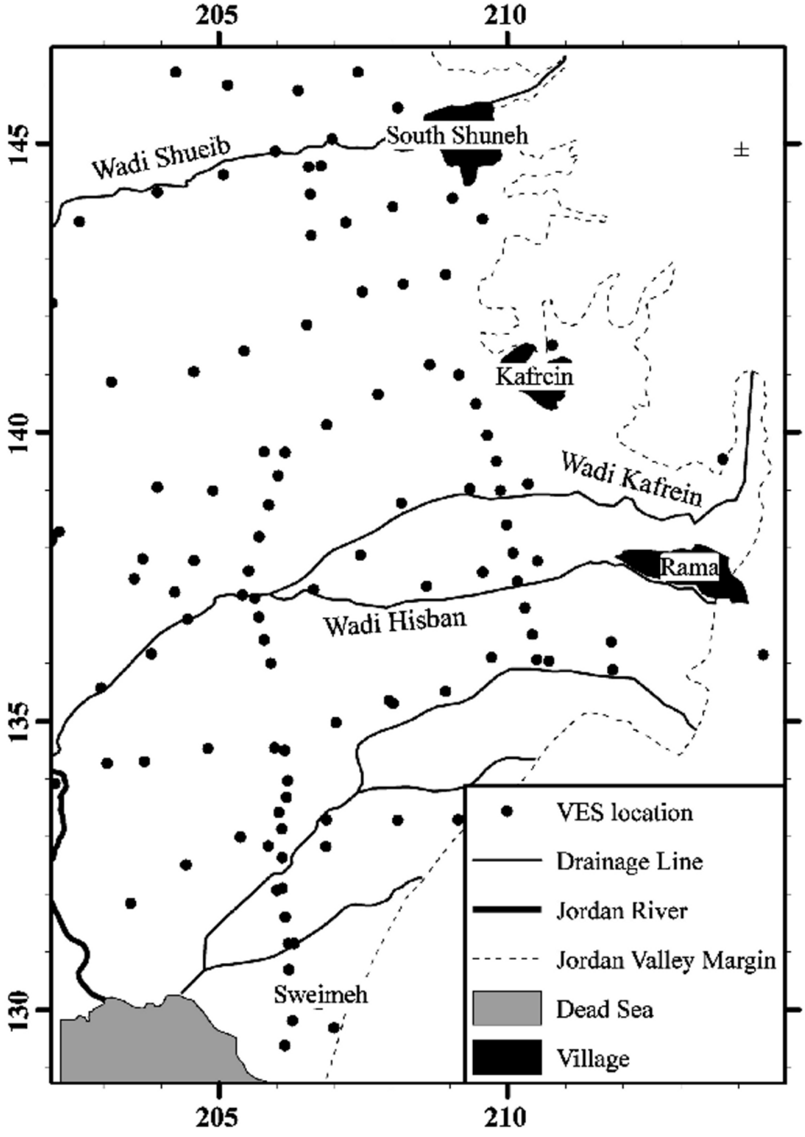


Fig. 3.5.5. Shot point location of all available VES soundings.

Conceptual Model of Flow

From the geological perspective the study area is characterized by an alternation of alluvial and lacustrine material. Only the unconsolidated aquifer is subject to the

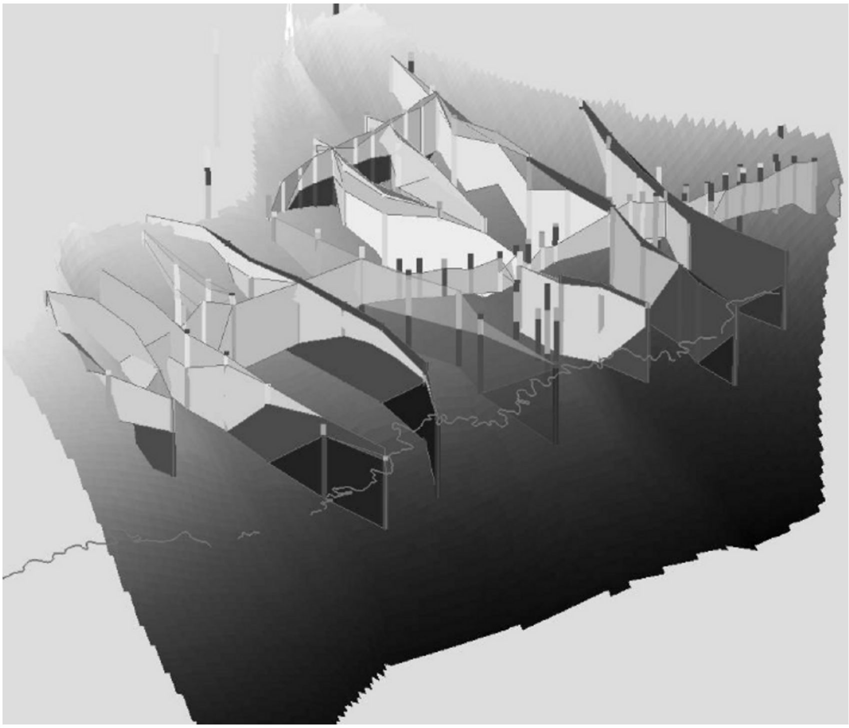


Fig. 3.5.6. 3-D cross sections of all available VES soundings, classified into six different classes; black colour = 0.1 - 1 m, 70 % black colour = 1 - 10 m, 50 % black colour = 10 - 25 m, 30 % black colour = 25 - 50 m, 10 % black colour = 50 - 100 m, white colour = > 100 m. The north-south flowing Jordan River (blue line), where north is on mid-bottom side and south on the middle-right side, is shown for orientation.

modelling process. The alluvial facies dominates the area close to the East Bank foothills, especially near the outlets of the major wadis. The lacustrine sediments dominate the western part of the study area and the area between the major alluvial fans. The general groundwater flow is from east to west, whereby the groundwater quality, in terms of total dissolved solids, deteriorates along its flow path. The groundwater system of the study area has undergone considerable change since its agricultural development of irrigation culture. The present-day flow system is in a transient state and is responding to stresses imposed on it. This is manifested in groundwater heads as well as in groundwater quality. The groundwater flow gradient (high groundwater flow velocities) is small in the area dominated by alluvial material and becomes steeper to the west and southwest of the study area. The steepest gradients (low groundwater flow velocities) can be observed in the vicinity of the Jordan River and the Dead Sea. This behavior was also verified by the direct-push drilling along a north-south profile in the vicinity of the Dead Sea. This can be attributed to a) a reduction in grain size of the alluvial material in the more distal area and b) to an increase of the lacustrine fraction in the distal fan area.

Flow Material

Alluvial fans are semi-circular (assumed for the Wadi Shueib fan), but with lateral constrictions, i.e. the influence of neighbouring fans (assumed in the case of Wadi Kafrein and Wadi Hisban fan), lead often to elongated fans perpendicular to the mountain front (Blair 1987). On elongated fans incised channels may transport sediment masses away from the mountain front to the active depositional lobes of their respective fans. Their presence highly influences the form of the fan. Alluvial fans generally have a planconvex geometry and slopes ranging from 2 to 6° in sheetflood dominated environments and up to 30 to 40° in the zone of freefall accumulations (Blissenbach 1954). But slopes within the study area might be lower due to the deposition of the lacustrine facies deposited to a higher extent in the mid basin and to smaller extents near the mountain fronts, thus reducing the general slope of the topography. Larger portion of alluvial material are deposited at the outlets of the major wadis. Along the depositional areas less alluvial and more lacustrine material accumulated. The area between the alluvial fans are dominated by lacustrine sediments. This assumption is undermined by lithological well logs.

System boundaries

Groundwater flow is from east to west, or east-north-east to west-south-west. The results of the hydrochemical and geophysical investigations indicated that in general no flow takes place from north to south or from south to north. Only in the influence area of heavy pumping activities a north-south flow might take place. Therefore the northern and southern boundaries can be regarded as no-flow boundaries. Groundwater inflow from the adjacent consolidated mountain aquifers into the studied unconsolidated aquifer takes place. Therefore a flux from east into the studied aquifer can be assumed. However, in the hydrogeological section it was described, that the flux is limited to the synclinal structures. The anticlinal structure between the synclines prevent the inflow of groundwater into the studied aquifer. Therefore a flux can only be assumed in the vicinity of the outlet of Wadi Shueib in the north and the outlet areas of Wadi Kafrein and Wadi Hisban and southeast of it. In the southwest and west of the study area (area of the Dead Sea and the Jordan River respectively) two different boundaries can be assumed: either a fixed head boundary or a flux boundary. Fixed-head boundaries were applied to the western boundary of the model domain. MERC (2004) estimated an inflow of groundwater from the study area into the Jordan River of around 3.5 Mm^3. Therefore the outflow of groundwater through the western boundary should be around the same order of magnitude.

Recharge to the aquifer system

Recharge to the unconsolidated aquifer in the study area derives from three different sources: inflow of groundwater from the adjacent mountain aquifers, percolation of stream water from intermittent streams and during occasional intensive rainfall events. Since rainfall in the study area is very low the amount of recharge from the third source can be neglected for the overall water budget. Different aquifers might contribute to the groundwater inflow into the studied aquifer. In the area of Shuneh the Wadi As Sir Formation (Upper Aquifer) underlies directly the unconsolidated aquifer. Further to the south, in the area of Rama and south of it, the unconsolidated aquifer is underlain by the Naur Formation. For the same area even a contribution of the Ram Group aquifer through an open fault system is possible. The largest portion of groundwater recharge however comes from infiltrating stream water that percolates along the flow course of the major wadis (Wadi Shueib, Wadi Kafrein, and Wadi Hisban). These intermittent streams flow seasonally during the winter rainy season and become dry towards the end of the summer season.

Groundwater abstraction

No water meters were encountered in the agricultural wells during the conducted field campaigns. Minimum groundwater abstraction rates were calculated using available remote sensing data. Together with information about plant growth, irrigation practices and irrigation water sources, an estimation of minimum groundwater abstraction for different time steps was performed. These estimations are addressed in the water budget section. A second major source of groundwater abstraction is evaporation. The reduction of groundwater transmissivities in the distal fan area leads not only to steeper groundwater flow gradients, but also to ponding of groundwater in the western area. Artesian conditions were reported in these areas prior to their development. In some areas the ponding of groundwater leads to constant evaporation from bare soils for high groundwater tables. These wet soils can be observed either directly in the field, on aerial photographs or in high resolution satellite images. Shallow groundwater under these wet soils were also encountered during direct-push soundings in the study area. The areas of groundwater evaporation are not steady, but vary with time. The largest area of groundwater evaporation from bare soils can be observed after the rainy season. From this time onwards the area of groundwater evaporation diminishes, but even at the beginning of the rainy season, large areas remain still under constant evaporation conditions. These areas were mapped from available remote sensing data and groundwater discharge of the aquifer system as a result of evaporation was estimated. However, evaporation losses might have been considerably larger in the past. Ionides (1939) reported many shallow hand dug wells, thus indicating very shallow groundwater conditions. With the beginning of the major development phase of the lower Jordan Valley groundwater levels declined and the hand dug wells fell dry. This can be taken also as an indicator that the area of the so-called „wet“ areas diminished thus reducing the extraction of groundwater by steady-state evaporation. Another reason may be attributed to the drop of the Dead sea level during the last five decades by about 27 m with the corresponding lowering of the groundwater levels in the surroundings as a result of the readjustment of the salt/freshwater interface and, in the vicinity of the Dead Sea, the lowering of the Jordan River bed along its flow path to the west of the study area.

3.5.3 Water budget evaluation derived from field and remote sensing data

Within the area of interest, groundwater levels of some selected wells are monitored by the Ministry of Water and Irrigation. During a well survey, undertaken in late 2004, no water meters were encountered at the private irrigation wells. Although only a certain amount of irrigation water is free of charge farmers abstract water according to their respective needs. Therefore, this section attempts to estimate the minimum water demand that is necessary to irrigate the cultivated areas. Estimations for certain periods of the past thirty years are prepared by undertaking the following steps: first, the land use and the kind of crops cultivated in the study area, are evaluated. Second, the irrigation techniques applied are presented. Third, crop water requirements, (the amount of water certain crops need during different growing stages), and the field water requirements (the amount of water needed to provide these plants with water without influencing the soil salinity) of the different crops planted in the study area are calculated. Fourth, Landsat data sets, made available by the Global Landcover Facilities, a NASA-funded member of the Earth Science Information Partnership at the University of Maryland, are used to identify the spatial extent of cultivated land during the past decades. Since these data sets were recorded at different periods during the year, they also give valuable information about seasonal planting practices. The area of cultivated land is calculated for different sectors in the study area. These different sectors are chosen according to their irrigation water sources. Fifth, on the basis of the findings above, the minimum agricultural water consumption of the study area is calculated for the different periods. Although the real water consumption of the area might be much higher, this method gives a minimum amount of the total water used for irrigation. At the end of this section a sample water budget for one year is set up by using the information gathered within this section.

A: Land-use in the study area

On the markets in Jordan banana fetch high prices. Therefore it is the favourite plant of the farmers in the study area and is planted there since the 60s. However, in terms of water demand, irrigation water quality, and soil quality banana plants are demanding plants. Every four to six years the soil needs to recover and the banana plot is switched to another part of the farmland (crop rotation). According to Philippe (2004) banana farms can be subdivided into three categories: large, smaller, and small family banana farms. Large banana farms consist of 200 to 400 dunums (0.2 – 0.4 km^2). In the study area members of the Al Edwan clan own all large farms. Commonly one fourth of these farms are planted with banana plants. In March and September seedlings are planted. Around 110 plants/ dunum are planted and each year two to three shoots are kept. In order not to leave the remaining three quarters of the farming area idle, vegetables are grown. Smaller farms consist of 100 to 200 dunum (0.1 – 0.2 km^2). Half of the farming land is planted with banana and the other half with vegetables. Every four to six years the plots are switched. The small familial banana farms are made up of 30 to 50 dunum (0.03 – 0.05 km^2). The land is divided into three plots. One plot is planted with banana seedlings and two with vegetables. The banana plot is switched every four to six years.

In places unsuitable for banana farming (high salt contents either within the irrigation water or the soil itself) vegetables like eggplant, zucchini, tomatoes, cucumbers, and pepper are grown. These places are located in the west and southwest of the study area. Some private farms also exist in the southwestern area. These farms were built for rich people from bigger cities like Amman or Salt and serve mostly recreation purposes. Most of these farms have an irrigation pool fed by well water. Farming exists only to a minor degree. Fruit and palm trees are grown (i.e. Guava and Mango). Vegetables are cultivated to a minor degree. Cheap labour workers, mostly Egyptians or Pakistanis, manage these farms as well as all other farms. Unlike the northern and middle part of the lower Jordan Valley, only few greenhouses exist. In these greenhouses vegetables, such as cucumber, tomatoes, and pepper are grown.

B: Irrigation techniques used in lower Jordan Valley

Two different irrigation techniques are applied nowadays in the lower Jordan Valley. Since its introduction in the eighties, drip irrigation is the most frequent method applied by the farmers. According to GTZ (2003) 70 % of all farms in the lower Jordan valley use this technique. In the study area drip irrigation is used almost entirely. However, drip irrigation systems require a pressurized pipe system. As stated above, different water sources for irrigation exist. But none of them delivers an on- demand pressurized system. In order to be independent, all farms possess irrigation pools where water can be pumped into the irrigation system on demand. Some pools are used to blend water from the Wadi course or the canal with more brackish well water. Although drip irrigation efficiency is often regarded to as 100 % efficient, evaporation losses in the storage pools, pipe losses and improper use of the system reduces the efficiency down to 80 % (GTZ 2003). Drip irrigation is mostly used in combination with plastic mulch to improve weed control and decrease evaporation, which would result in salt accumulation in the topsoil. Fertigation, the injection of dissolved nutrients/ fertilizers into the irriga-

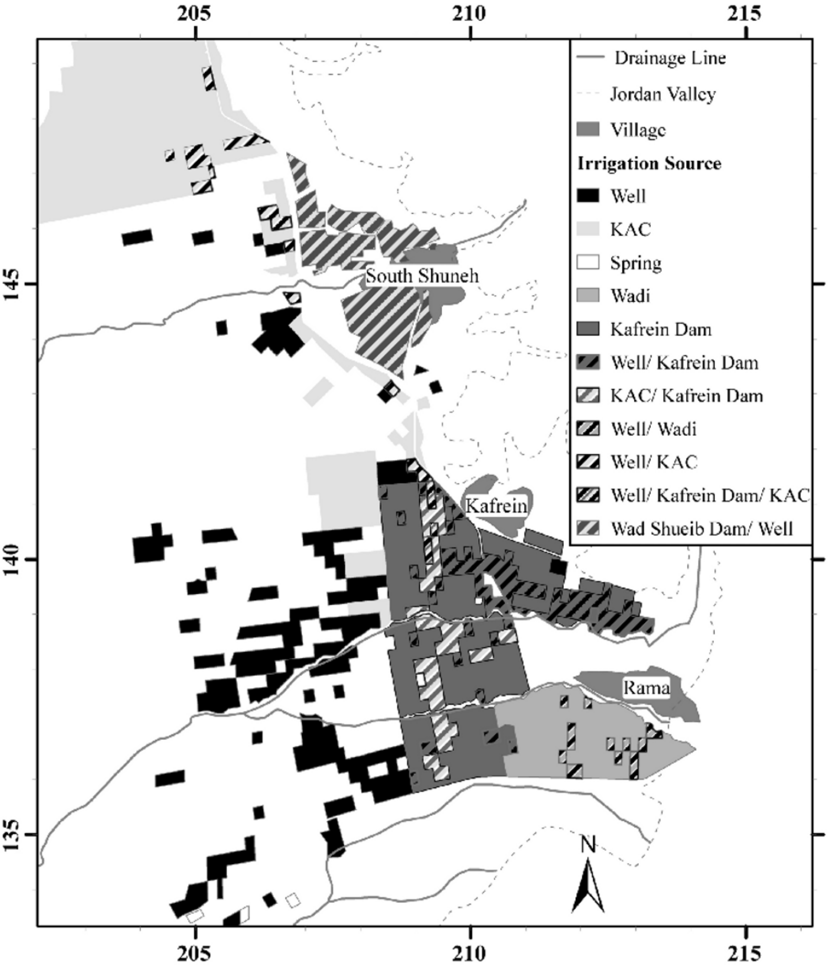


Fig. 3.5.7. Irrigation water sources 2002 (GTZ 2003).

tion water is the dominant fertilization practice. Since the drip irrigation system delivers the fertilizer directly to the planted crops fertigation is the most efficient fertilization method.

In some places near the KAC furrow irrigation or border irrigation is used. The efficiency of furrow irrigation is around 60 % (GTZ 2003), depending on the properties of the underlying soil and the length of the furrow channel to the farm. But, only very few farms using this technique were observed during the field campaigns. Irrigation water sources for the different parts of the study area can be seen in Fig. 3.5.7.

Table 3.5.1. FWR of the different fruit and vegetables grown in the study area in Mm^3/km^2 (after GTZ 2003). Min = minimum water demand planting season, max = maximum water demand growing season.

		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
		drip	drip	drip	drip	drip	Drip	drip	drip	drip	drip	drip	drip
Squash	min	0.0380	0.0490									0.0550	0.0430
	max								0.1300	0.1340	0.0850	0.0600	0.0000
Eggplant	min	0.0440	0.0550	0.1010	0.1190	0.1570	0.0880			0.0430	0.0770	0.0730	0.0470
	max	0.0440	0.0550	0.1010	0.1190	0.1570			0.1020	0.1210	0.1040	0.0790	0.0420
Tomato	min	0.0370	0.0570	0.1440	0.1120	0.0380							0.0100
	max	0.0000	0.0000	0.0720	0.1260	0.2060	0.2330						
Potato	min	0.0440	0.0340								0.0450	0.0630	0.0540
	max	0.0350	0.0580	0.1360	0.0970								0.0000
Sweet	min	0.0360								0.1040	0.1110	0.0900	0.0540
Corn	max	0.0000	0.0000	0.0880	0.1420	0.1920							
Wheat/	min	0.0560	0.0540	0.0220	0.0250	0.0340	0.0200					0.0190	0.0360
Barley	max	0.0320	0.0550	0.1320	0.0560	0.0340	0.0380						
Banana	1st yr	0.0980	0.0530	0.0990	0.1160	0.1540	0.2930	0.2980	0.3540	0.2870	0.2120	0.1500	0.0950
	>1st yr	0.1070	0.0800	0.1490	0.1750	0.2310	0.3450	0.3510	0.3840	0.3120	0.2310	0.1640	0.1020

C: Crop and field water requirement

The term crop water requirement is defined as the „amount of water required to compensate the evapotranspiration loss from the cropped field“. So crop water requirement refers to the amount of water that a specific crop needs to be supplied with at a specific growth stage. Values for crop water requirements by the FAO

1992 and Euroconsults 1989. However, the crop water requirements for the different fruits and vegetables planted in the study area vary only to a small extent: 0.6 in the early growth stage, 0.8 – 0.93 in the crop development stage, 1.0 – 1.25 in the mid season stage and 0.7 – 0.95 in the late season. The only exception are banana plants, since they need irrigation throughout the year. The crop water requirement highly depends on evapotranspiration:

$$\text{CWR} = \text{kc} * \text{ET}$$

CWR = Crop Water Requirement, kc = crop coefficient (depends on the growth stage), ET = estimated Evapotranspiration

The crop water requirement deals with the water requirements of the plant itself only. No irrigation water losses, or water required for soil leaching is integrated into the formula. Therefore the term field water requirement (FWR) was introduced:

$$\text{FWR} = \frac{\text{CRW}}{(1\text{-LF}) * E_{\text{IS}}}$$

LF = leaching fraction, E_{IS} = efficiency of the irrigation system in the farm reflecting all losses

For future calculations two different groups are considered: vegetables and bananas. FWR values for both groups are listed in Table 3.5.1.

D: Classification Results of satellite images

Landsat data are used to identify area of irrigated land in different years and different periods of the year. According to Werz (2006) it is not possible to distinguish between different crops or between cultivated land and pastures with a Landsat data set. Therefore, the only goal of the classification was to identify cultivated areas from uncultivated land. By post-processing the classification results the natural vegetation was removed and the area of cultivated land was subdivided according to its irrigation water sources. The area of each subdivision was calculated.

Pan-sharpening

The Colour Normalized (Brovey) sharpening was applied to all ETM+ image data sets (Vrabel 1996). The Colour Normalized sharpening technique uses a mathematical combination of the colour image and high resolution data (15 meter resolution panchromatic band). Each band in the colour image is multiplied by a ratio of the high resolution data divided by the sum of the colour bands. The colour channel combination 541 was found to be most suitable to identify irrigated lands. The Colour Normalized function automatically resamples the three colour bands to the high-resolution pixel size using nearest neighbour convolution. The output RGB images have the pixel size of the input high-resolution data (15 m).

Table 3.5.2. Water demand calculated for the available Landsat images. The different aras were chosen according to Fig. 3.5.3 right.

	March 2002		May 2000		August 1999		August 1987		January 1973	
	area	demand	area	demand	area	de-mand	area	demand	area	de-mand
	[km^2]	[Mm^3]	[km^2]	[Mm^3]	[km^2]	[Mm^3]	[km^2]	[Mm^3]	[km^2]	[Mm^3]
West Vegetable	11.82	1.26	7.49	1.05	3.57	0.41	2.21	0.26	-	-
Well/ KAC	17.77	1.90	17.49	2.45	1.24	0.45	1.41	0.52	13.69	0.81
Hisban	3.46	0.37	2.32	0.33	1.86	0.68	1.4	0.52	2.03	0.12
Shueib/Well	0.21	0.02	0.33	0.05	2.70	0.98	1.38	0.51	2.75	0.16
KafreinWell	6.80	0.73	9.19	1.29	8.29	3.01	8.34	3.08	6.01	0.36
total	40.07	4.28	36.82	5.16	17.65	5.53	14.74	4.88	24.48	1.45

Supervised classification

First, representative samples of two different ground cover types on the images were selected: vegetated areas and greenhouse areas. These ground cover types are also called classes of interest or regions of interest. The regions were chosen on the basis of field campaigns in Jordan. In order to obtain the results as accurate as possible, an adequate number of training areas for each class were graphically selected. Lillesand and Kiefer (2004) recommend a minimum amount of 10n to 100n pixel per training area, where n is the number of spectral bands used. The supervised classification method Parallelepiped was applied (Richards 1999). The Parallelepiped classification uses a simple decision rule to classify multispectral data. The decision boundaries form an n-dimensional parallelepiped classification in the image data space. The dimensions of the parallelepiped classification are defined based upon a standard deviation threshold from the mean of each selected class. If a pixel value lies above the low threshold and below the high threshold for all n bands being classified, it is assigned to that class. If the pixel value falls in multiple classes, the program ENVI assigns the pixel to the last class matched. Areas that do not fall within any of the parallelepiped classes are designated as unclassified. The results were exported as ESRI raster files.

Post Processing and Results

The ESRI raster files were imported to ArcGIS 9.1 and converted to ESRI shapefiles. The shapefiles were edited. An arid to hyperarid climate prevails in the study area. So, apart from some small bushes and a few trees, no non-irrigated vegetation exists in most of the area. The only areas, where natural vegetation exists are areas with very shallow groundwater tables and within some Wadi courses and in the area close to the Dead Sea. These areas were identified during field campaigns and erased from the supervised classification results. For the remaining cultivated land it was, as stated above, not possible to identify different crop types. As described above, the farmers in the test area use crop rotations. Therefore, it could not be assured that the existing crop types on the different images represent the vegetation during the acquisition of the training sites during the field campaign. However, in order to identify areas used for banana plantation, local farmers were questioned about crop plantation during field campaigns. All calculations depend on two categories: vegetables in general and banana. Since irrigation water has to be of good quality, only areas where irrigation water has good quality water are considered feasible for banana plantation. The areas where only poor irrigation water is available were classified as areas unsuitable for banana plantation and labeled as vegetable areas. This is necessary, because bigger groundwater abstractions can be expected in areas used for banana plantation than areas unsuitable for banana plantation.

The expansion of the irrigated land was calculated by area field calculations. The irrigated areas were subdivided according to their irrigation water source. The areas of irrigated land for each irrigation water source were determined and exported as database files (DBF). The results of the classification can be seen in Table 3.5.2.

E: Calculation of minimum irrigation water requirement

The data from above were combined and used to calculate the minimum irrigation water amount that was necessary to irrigate the farmland depicted from the satellite images. For the calculations the following assumptions have been made: during the

Table 3.5.3. Yearly water demand for the irrigated fields (excluding the portion irrigated areas from King Abdullah Canal).

	Jan [Mm^3]	Feb [Mm^3]	Mar [Mm^3]	Apr [Mm^3]	May [Mm^3]	Jun [Mm^3]	Jul [Mm^3]	Aug [Mm^3]	Sep [Mm^3]	Oct [Mm^3]	Nov [Mm^3]	Dec [Mm^3]
West Vegetable	0.62	0.78	1.26	1.32	1.05	1.05	0.35	0.26	0.11	0.93	0.81	0.61
Well	0.47	0.58	0.95	0.99	1.23	0.20	0.21	0.26	0.19	0.14	0.76	0.46
Hisban	0.18	0.23	0.37	0.39	0.33	0.12	0.12	0.52	0.11	0.08	0.30	0.18
Shueib/Well	0.01	0.01	0.02	0.02	0.05	0.40	0.40	0.51	0.38	0.28	0.02	0.01
KafreinWell	0.36	0.45	0.73	0.76	1.29	1.16	1.16	3.08	1.09	0.80	0.58	0.35
total	1.64	2.04	3.33	3.49	3.94	2.93	2.24	4.62	1.88	2.23	2.48	1.60

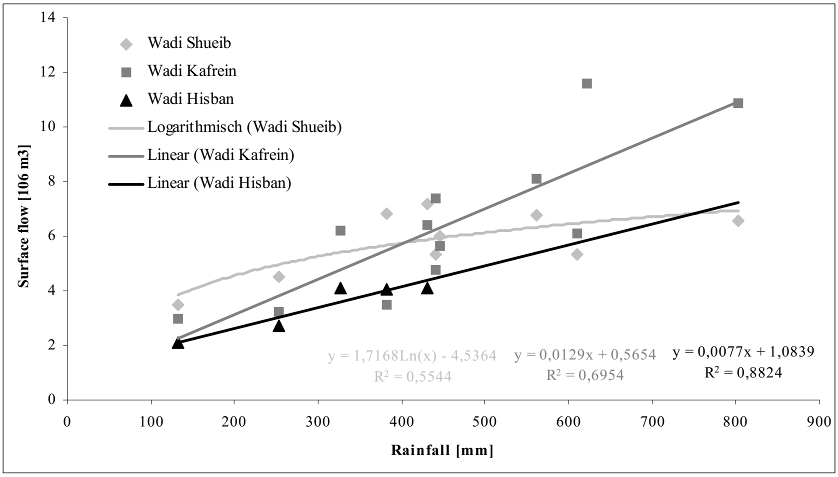


Fig.3.5.8. Yearly rainfall values of Naur climatic station versus available surface flow values (Rainfall data taken from Ministry of Water and Irrigation open files, surface flow data taken from GTZ 1977).

main cropping season, one third of the cultivated farmland is planted with banana plants (January, March, and May), in August no other plant except banana is grown, in 1973 furrow irrigation prevailed in the study area. It was not before the eighties, that drip irrigation was introduced in the Jordan Valley, except for the Landsat image of 1973, drip irrigation is the only way of irrigating cultivated fields

The minimum water requirement for irrigating the cultivated land was calculated for different sectors. Table 3.5.2 shows the calculated minimum water requirement results for the study area.

F: A sample water budget calculation for the study area

With the help of the information gathered above an average water budget for the period 1987 – 2002 will be set up. This budget will be later used to set up a steady state flow model. However, due to incomplete data records, the surface flow of the study area has to be estimated from older records (1956-1968; taken from GTZ 1977). A trend line approach will be used to estimate the yearly surface flow from yearly rainfall records. A water budget for the study area can only be set up by making certain assumptions. These assumptions are: (a) the rainfall runoff relationship remains constant from 1956 until 2002, (b)since the completion of the surface dams at the outlets of Wadi Shueib and Wadi Kafrein the whole surface flow of these wadis is used to irrigate the field shown in Table 3.5.3 right, (c) the fields which are irrigated with water from the King Abdullah canal are excluded from the

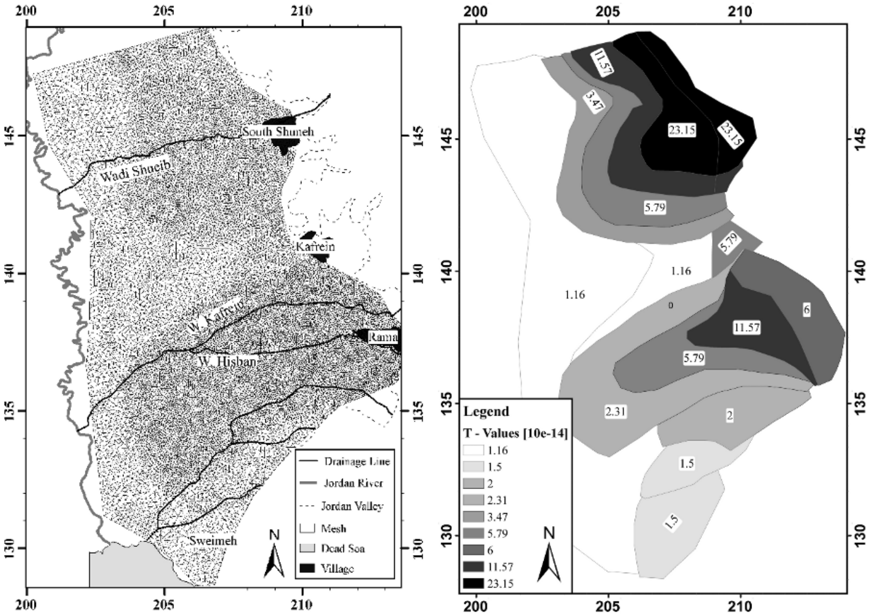


Fig. 3.5.9. Left: Finite element mesh of the study area. Note the mesh generation along the flow path of the major wadis.
Right: Transmissivity zones generated on the basis of the integrated approach.

water budget and the classification of the satellite scenes, and (d) the field water requirement of the area represents the water need of the plants, which means, that irrigation return flow is not take into account.

The water balance for the study area consists of the following components: input components into the study area are surface water stored in the Kafrein and Shueib dam, water flowing in Wadi Hisban and in some minor wadis in the southeast of the study area, and infiltrating groundwater from adjacent consolidated aquifers or the deep highly pressurized Ram Group aquifer; output components out of the study area are the water demand of the irrigated fields, which includes irrigation water from the storage dams and pumped groundwater, and outflow through the eastern border of the study area.

First, the amount of surface water available for irrigation in the study area is estimated. Since yearly rainfall for every period considered exists, the yearly rainfall (Naur Station) versus the available yearly surface flow (from the station in Wadi Shueib, Wadi Kafrein, and Wadi Hisban) were plotted in an x-y diagram. The equation for each wadi derived from trend line through the available points (Fig. 3.5.8) was used to estimate surface flow for the considered period. An average flow (for the period 1987 – 2002) of 5.5 MCM for Wadi Shueib, 5.3 for Wadi

Kafrein, 3.93 MCM for Wadi Hisban was calculated. For the remaining small wadis in the study area an average flow of 2 MCM was assumed (according to their relative small catchment area). This amounts to a total of 16.8 MCM for total available surface flow.

Taking the different planting and harvesting practices under consideration, the yearly field water requirement of the study area was calculated (Table 3.5.3). The calculation revealed that a total of around 31.5 million cubic meter of irrigation water is needed to irrigate the farmland in the model domain. Since no other information regarding planting activities exists for the study area this water demand is taken for the water budgeting.

The amount of pumped water in the study area can be calculated from the findings above. Since the water stored in the different dams together with the water flowing in Wadi Hisban are exclusively used to irrigated farmland within the study area, the deficit between the estimated field water requirement and the surface water flow represents the amount of groundwater that is necessary to irrigate the farmlands.

If a balanced budget for the study area is assumed, the groundwater inflow into the unconsolidated aquifer can be calculated as the water demand plus the outflow through the eastern boundary minus amount of available surface water. With the information gathered above a steady state flow model will be constructed.

3.5.4 Numerical Flow Modeling

A considerable amount of input data is required to construct and verify a distributed flow model. The information gathered in the previous sections will be used to set up a distributed flow model. The numerical flow model is based on the FEFLOW code (FEFLOW 5.2, WASY Inc.). Input parameters were pre-processed by the ArcGIS 9.2 software package (ESRI Inc.).

Two different areas were distinguished for the creation of the supermesh elements: areas dominated by the alluvial fan facies and areas dominated by lacustrine facies. The area dominated by the alluvial fan facies was estimated based on the hydrochemical and geophysical sections. Due to the active left lateral motion of the Dead Sea Transform Fault the elongated alluvial fans of Wadi Kafrein and Wadi Hisban experienced a north-south displacement. For the Wadi Shueib alluvial fan a semi circular shape was chosen, since most of the alluvial fan is located away from the main displacement fault. A triangular mesh of 29,438 elements with 14,960 nodes was generated on the base of the digitized results of the previous sections. The course of the different wadis, so that all triangular points are located in the course of each wadi (Fig 3.5.9 left). The mesh was refined in areas of high groundwater in- and output, e.g. along the flow course of the different wadis, and manually altered to avoid numerical problems with obtuse angles.

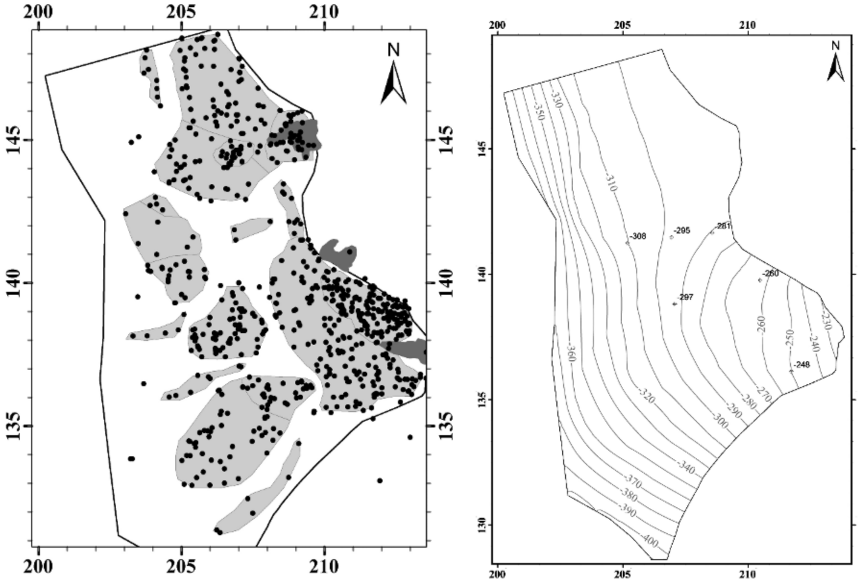


Fig. 3.5.10. Left: well locations in the study area and digitised extraction zone.
Right: Result of the steady-state simulation together with available groundwater heads.

The following boundary conditions were set: No-flow at the northern, southern borders, and, for reasons stated above, in the middle of the eastern border. Fluxes were applied to the upper and lower part of the eastern boundary to simulate groundwater inflow from the adjacent consolidated mountain aquifers. Fixed-head boundaries were applied to the western boundary of the model domain. The recharge to the aquifer by infiltration of surface water was given by flux boundary conditions along the wadi flow path.

The calibration of a model is always crucial. The main problem is non-uniqueness. In order to reproduce observed values, e.g. groundwater elevation contours, unknown or not sufficiently known transmissivity etc. have to be adjusted. Accordingly, an over-parameterized model is unlikely to predict the impacts of a change in the system correctly, no matter how high the correlation between the calculations and the observations are. Just as crucial as the number of calibration parameters is their selection. Highly dependant parameters can produce identical results with different combinations.

The constraints for the hydrogeological model are subject to the following consideration: the groundwater tables should be reproduced correctly. This comparison between predicted and measured data is an important measure for the reliability of the final model. The verified model can afterwards be used to demonstrate impacts on future water abstraction scenarios and climate changes on the groundwater resources.

The transmissivities have been measured at several locations. Pumping test data revealed changes in transmissivity between the upper fan area and the lacustrine dominated area (in an area that solely is made up of lacustrine formations in the distal fan area, no pumping tests were performed) are more than one order of magnitude. The information gathered for the setup of the conceptual flow model with regard to the flow materials was applied insofar, that the concentric zones of transmissivity (onion layers) were adjusted to the respective alluvial fan shapes (Fig. 3.5.9 right), where highest transmissivities were applied to the alluvial dominated areas in the upper fan area and lower transmissivity values in the lower to distal fan area. Lowest transmissivity values were applied to areas dominated by lacustrine sediments.

No recharge from rainfall was attributed to the model for reasons stated above. Recharge to the model domain was applied by flux boundary conditions either on the upper and lower eastern boundary or along the flow course of the different wadis (Wadi Hisban and the minor wadis southwest of it). The flux conditions on the eastern model boundary reflect the inflow of groundwater. The recharge to the unconsolidated aquifer from the infiltration of runoff and baseflow surface water is reflected by the flux conditions applied to the different wadi flow courses.

In order to simulate groundwater pumping in the study area extraction zones were created. These extraction zones were created since no information regarding pumping amounts and duration of pumping for the wells in the study area exists. The basis of these extraction zones are well locations. Around the well locations polygons were drawn (Fig. 3.5.10 left) and its area calculated with the help of the ArcGIS 9.2 software (ESRI Inc.). These areas were later imported into FEFLOW and used as sink (extraction of water per area of the polygon).

The last assumption to the transient model is related to the commissioning of the King Abdullah Canal in 1987. After its start of operation it serves a sole irrigation water source for most of the area north of South Shuneh. Therefore, starting with the commissioning of the canal pumping activities in its influence area seized.

Steady-state calibration and results

The goal of calibration is to obtain an optimal fit between the calculated and the measured data. In this approach, data consists of average groundwater heads (1987 – 2002) of available well data. The remaining parameters, like the transmissivity distribution, the inflow of groundwater from the adjacent mountain aquifers, the outflow through the western and southern boundaries, and the evaporation rate has been used for calibration. However, parameter ranges for each parameter have been defined and certain hydrogeological assumptions have been made.

A steady-state calibration was carried out. This steady-state calibrated model can be applied to different development stages of the study area and to simulate impacts of future climate change scenarios on groundwater resources in this highly important agricultural area. The results of the steady-state calibration can be seen in Fig. 3.5.10 right. A good fit between the calculated and observed data was achieved.

3.5.5 Summary and conclusions

In this paper an integrated approach is proposed that combines different types of available data and therefore overcomes data gaps common in many arid regions. This approach was demonstrated for the unconsolidated aquifer in the lowermost area of the Jordanian part of the Jordan Valley. The conceptual model of flow was set up based on geological, hydrochemical, and geophysical methods.

Geological methods were employed to determine the geometry of unconsolidated sediments, including the most important structural features of the study area. Furthermore the nature of the sedimentary deposits and their subsurface contacts to the consolidated mountain aquifers were identified. Contour maps of the electric conductivity and the chloride content of groundwater samples showed the different flow paths of the groundwater in the unconsolidated aquifer and their change of composition along the flow path. The plots were also used to distinguish areas dominated by hydraulically higher conductive material (alluvial deposits) from areas of lower conductive material (lacustrine deposits). It was shown, that no or almost no north-south flow takes place. A more precise picture of the subsurface and its salinity distribution is delivered by vertical electric soundings (VES). Furthermore VES can be applied in any area were no information about the subsurface exists and a more precise distinction of the areas dominated by lower saline sediments from those with higher saline sediments was possible. 173 VES sounding data or interpretation data were collected. Six different resistivity ranges were created, each representing different information about the subsurface and its groundwater quality range.

An average water budget for the period from 1987 to 2002 was set up. Since no information about water consumption, i.e. pumping rates and active wells exists, available information regarding planted crops, planting seasons, different irrigation water sources were combined with remote sensing data (Landsat data) to overcome this data gap. Agriculture in the study area is only possible with artificial irrigation. Minimum water demands were calculated by using the information about crops planted by the farmer in the area. With satellite images taken at different periods of the year, combined with information about planting and harvesting seasons the yearly minimum water requirement for the study are was calculated. Knowing the different irrigation water sources a water budget that contains the different sources of irrigation water was set up. A total minimum water demand of 31.5 million cubic meter (MCM) was calculated. This demand is covered to 53 % (16.8 MCM) by surface flow and to 47 % (14.7 MCM) by pumped groundwater.

The general conditions and the stress periods of the groundwater systems were identified by using a historical evaluation of the study area. In order to reliably predict the impacts of future climate change scenarios on the studied groundwater system a flow model must be tested against these constraints. A numerical flow model was set up by using the FEFLOW (Wasy Ltd.) software code. The geometrical and water budget information gathered with the integrated approach was incorporated into a steady state model. This numerical flow model simulates the average flow conditions between 1987 and 2002 and was calibrated with available groundwater heads. This numerical steady-state model is presently converted into a transient model to simulate the different effects on groundwater resources described in the historical approach.

Acknowledgements

The authors would like to express their thanks to the German Ministry of Education and Research (BMBF) and to the Israeli Ministry of Science (MOS) for supporting and funding the project: Water Resources Evaluation for a Sustainable Development in the Jordan Rift Basin, German – Israeli – JORDANIAN - Palestinian Joint Research Program. Project Number 02WT0161. Thanks to the Jordanian Ministry of Water and irrigation for interesting discussions and for providing the necessary data.

The author would like to thank Prof. Dr. Elias Salameh from Jordan University and Prof. Dr. Martin Sauter from Göttingen University for their continuous support and their helpful comments and advice during the formulation of this manuscript.

References

Abou Karaki, N. (1998): Geophysical resistivity survey in the Jordan Valley fisheries site. University of Jordan, Center for Consultation Technical Services and Studies, Amman.

Al-Zoubi, A., T. Heinrichs, M. Sauter and I. Qabani (2006): Geological structure of the eastern side of the lower Jordan Valley/ Dead Sea rift: Reflection seismic evidence. Marine and Petroleum Geology, 23, 473-484.

Bandel K and Khoury H (1981): Lithostratigraphy of the Triassic in Jordan. Facies, 4:1-26.

Begin, Z.B.; Ehrlich, A. and Nathan, Y. (1974): Lake Lisan: the Pleistocene precursor of the Dead Sea; Geol. Surv. Israel Report 63; Jerusalem; 30 p.

Blair, T.C. (1987): Sedimentary processes, vertical stratification sequences, and geomorphology of the Roaring River alluvial fan, Rocky Mountain National Park, Colorado. Journal of Sedimentary Petrology. 57, p. 1–18.

Blissenbach, E. (1954): Geology of alluvial fans in semi-arid regions; Geological Society of America 65, p. 175 - 190

Burckhardt JL (1822) Travels in Syria and the Holy Land, Association for Promoting the Discovery of the Interior Parts of Africa. London; 309p.

Diabat and Abdelghafoor (2004): Geological map of Amman - 3153-I, 1:50.000, The Hashemite Kingdom of Jordan, Natural Resources Authority, Geology Directorate; Amman

FAO (1992) Crop Water Requirements. Irrigation and Drainage Paper No. 24. Rome

Flathe, H. and Pfeiffer D. (1963): Outlines on the hydrology of the Isle of Madura (Indonesia): Subterranean Water (Proceedings of the General Assembly of Berkeley), p. 543–560.

Flathe, H.; Bender H. and Futian, A. (1965): Results from the hydrogeological and geoelectrical survey in the Jordan Valley. Jordan 1963 - 64. BGR, Hannover and Amman.

Flathe, H. (1967): Interpretation of geoelectrical resistivity measurements for solving hydrogeological problems. Econ. Geol. Report 26, p. 580–597.

Flathe, H. (1968): Geoelektrische Untersuchung der Grundwasserversalzung im südlichen Jordantal. Geologisches Jahrbuch Nr. 85, p. 767–782.

Frohlich, R.K.; Urish, D.W.; Fuller, J. and O'Reilly, M. (1994): Use of geoelectrical methods in groundwater pollution surveys in a coastal environment. Journal of Applied Geophysics 32, p. 139–154.

Gibbs, A. (1986): Karameh Dam Project – Final Report – Volume 5 – Ground Investigations for the Karameh Dam; Jordan Valley Authority of the Hashemite Kingdom of Jordan, Amman

Ginzburg, A. and Levanon, A. (1976): Determination of a salt-water interface by electric resistivity depth soundings. Hydrological sciences bulletin - Bulletin des sciences hydrologiques, Nr. XXI, p. 561–568.

Gtz (1977): National Water Master Plan. Surface Water Resources. Natural water Resources Authority of the Hashemite Kingdom of Jordan, Amman. Vol. III.

Gtz (2003): Guidelines for Brackish Water irrigation in the Jordan Valley. Ministry of Water and Irrigation Jordan Valley Authority Brackish Water Project Hashemite Kingdom of Jordan, Amman.

Heinrichs T, AL-Zoubi A, Sauter M, Salameh E and Qabbani I (2004) Structure of the Shuna (Eastern Jericho) Basin, Lower Jordan Valley - interpretation of reflection seismic data, preliminary results. 5th Int Symp Eastern Mediterranean Geol, Thessaloniki, Proc 3:1522-1525.

Ionides, M.G. (1939) Report on the Water Resources of Transjordan and their Development, Amman; 169p.

JICA (1995): The Study on brackish groundwater desalination in Jordan. Draft Final Report - Main report. Ministry of Water and Irrigation Jordan Valley Authority, Brackish Water Project, Hashemite Kingdom of Jordan, Amman.

Khoury, R.G. (1981) The Jordan Valley. Life and society below Sea Level. Longman Group Limited. London; 238p.

Landmann, G; Abu Qudaira, G.M.; Shawabkeh, K.; Wrede, V.; Kempe, S. (2002): Geochemistry of the Lisan and Damya Formations in Jordan, and implications for palaeoclimate; Quaternary International, 89; p. 45-57

Lenz, S. (1999) Hydrogeological Investigation along the Wadi al Kafrein and the Kafrein Reservoir. Unpubl. Masters Th, Dept Applied Geology Univ Karlsruhe, typescript, 108 p, 47 figs, 16 tables, 1 geol map 1:10.000.

Lillesand, T.M. and Kiefer, R.W. (2004): Remote Sensing and Image Interpretation.- John Wiley and Sons, New York, 763 p.

MERC (2004): Water Quality along the Jordan River: A Geochemical Perspective on the Sources of Salts – Final Report; Middle East Regional Cooperation Program (MERC); Project No.: M20-068; 170p.

Niemi TM, Ben-Avraham Z. and Gat JR (1997) The Dead Sea: The Lake and Its Setting. Oxford University Press, New York, USA.; 286p.

Nowroozi, A.A.; Horrocks, S.B. and Henderson, P. (1999): Saltwater intrusion into the freshwater aquifer in the eastern shore of Virginia: a reconnaissance electrical resistivity survey. Journal of Applied Geophysics, Nr. 42, p. 1–22.

Philippe, J. (2004): Reclamation's history of the Jordan river Basin in Jordan, a focus on agriculture: past trends, actual farming systems and future prospective, Volume II, open report, funded by the International Water Management Institute program „comprehensive assessment“; 185p.

Richards, J. (1986): Remote sensing digital image analysis, an introduction.- Springer, New York, 281 p.

Sabet, M.A. (1975): Vertical electrical resistivity sounding locate groundwater resources: a feasibility study: Water Resources Bulletin (73).

Salameh E and Bannayan H (1993) Water Resources of Jordan. Present Status and Future Potentials. Friedrich Ebert Stiftung, Amman; 183p.

Schulze F, Levy Z, Kuss J and Gharaibeh A (2003) Cenomanian - Turonian carbonate platform deposits in west central Jordan. Int J Earth Sci (Geol Rundsch) 92:641-660.

Shawabkeh KF (2001) Geological map of Al Karama - 3153-IV, 1:50.000, The Hashemite Kingdom of Jordan, Natural Resources Authority, Geology Directorate

Tleel JW (1963) Inventory and Groundwater Evaluation Jordan Valley. The Hashemite Kingdom of Jordan, Central Water Authority, Amman; 80p

Toll, M., Heinrichs T, Sauter, M. and Salameh E. (in preparation): An integrated approach for the hydrogeological investigation of the unconsolidated aquifers in lower Jordan Valley. In: Water Resources of the Jordan and Dead Sea Rift Valley, Springer; Berlin;17p.

Toll, M. (in preparation): An integrated approach for the investigation of unconsolidated aquifers in a brackish environment – A case study on the Jordaninan side of the lower Jordan Valley. Dissertation. Universität Göttingen, Angewandte Geologie

Urish, D.W. and Frohlich R.K. (1990): Surface elecrical resistivity in coastal groundwater exploration. Geoexploration, H. 26, p. 267–289.

Van Dam, J.C. and Meulenkamp R.K. (1967): Some results of the geo-electrical resistivity method in groundwater investigations in The Netherlands. Geophysical Prospecting. 15 (1), p. 92–115.

Werz, H. (2006): The integrated use of GIS and remote sensing imagery for groundwater risk intensity mapping in the Wadi Shu'eib, Jordan. Dissertation. Universität Karlsruhe, Angewandte Geologie.

Zohdy, A.A.R. (1969): The use of Schlumberger and equatorial soundings on groundwater investigations near El Paso, Texas. Geophysics 34, p. 713–728.

Zohdy, A.A.R.; Martin, P. and Bisdorf, R.J. (1993): A study on seawater intrusion using direct-current soundings in the southeastern part of the Oxnard Plain, California. U.S. Geological urvey. (Open File Report 93 - 524, 139p.).

3.6 Water Resources Protection Efforts in Jordan and their Contribution to a Sustainable Water Resources Management

Armin Margane[1], Ariane Borgstedt[1] & Ali Subah[2]

[1]Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, 30655 Hannover, Germany

[2]Ministry of Water and Irrigation (MWI), P.O. Box 2440, 11190 Amman, Jordan

Abstract

Jordan is facing a water crisis since several years. The available amounts are exploited to a large extent (surface water) or even overexploited (groundwater). With a rapidly growing population, these will not be enough to meet the future demand. A number of large projects are currently underway to overcome the consistent water shortage problems. However, some facts are often neglected when demand projections and management plans are drafted: the effects of deteriorating water quality and the possible effects of climate change.

The rapid agricultural and industrial development has brought about a considerable risk of pollution for the scarce water resources and in many areas the quality of water resources has deteriorated considerably. Only recently Jordan has adopted stricter water and environmental policies and regulations to counter these pollution risks. Since a number of years, technical cooperation projects between the Federal Institute of Geosciences and Natural Resources (BGR) and the Ministry of Water and Irrigation (MWI) are introducing measures which counter these pollution risks, encompassing groundwater vulnerability maps, the delineation of groundwater and surface water protection zones as well as the establishment of a legal basis for implementation of related landuse restrictions, giving support to the landuse licensing committee and the mining license committee and improving the national groundwater quality monitoring network. The aim of these measures is to achieve a sustainable management of the available water resources under present conditions.

The current climatic change scenarios suggest a considerable decrease of rainfall during winter and much hotter summer temperatures in Jordan. This could lead to a decrease in groundwater recharge of up to 30 % and higher evaporation from surface water resources (dams), so that water resources availability may be reduced to values as low as 550 Mm^3/a. Since the effects of such climate change are predicted to happen relatively fast, the Government of Jordan must urgently think about strategies to counter such possible decreased water resources availability in the near future. Under such conditions it may be unrealistic talking about sustain-

able management. Nonetheless should the Government presently try to achieve sustainability by the proposed measures. This will also help reducing costs when additional water sources are needed due to possible climate change effects.

3.6.1 Introduction

Jordan is currently facing severe challenges to meet the growing demand for water. The country has a population of approximately 5.5 million, a growth rate of 2.3 % (2005; Department of Statistics) and houses an additional 800,000 Iraqi refugees (2007; UNHCR). The available water resources, approx. 275 Mm^3/a of groundwater (safe yield) and around 530 Mm^3/a of surface water (MWI & GTZ, 2004), are developed to a high degree (surface water development around 400 Mm^3) or even overexploited (groundwater abstraction in 2005: 508 Mm^3) so that the Government is under an immense strain to provide more water in the future and to change its allocation policy. The water policy of Jordan seeks to meet future demand by:

- reducing water system losses (countrywide currently still around 50 %);
- increasing and promoting the reuse of treated wastewater in the agricultural sector;
- storing surface water runoff in all major Dead Sea and Jordan Valley side wadis (new dams: Wehdah dam, Karak dam, Wadi Ibn Hamad dam, Wadi Kufrinjah dam);
- providing additional amounts of drinking water through
  - desalination of brackish groundwater, surface water and sea water (Dead Sea side wadis runoff collector trunk line, collection of southern Ghor brackish groundwater (mainly from the Zarqa Formation) and Sweimeh desalination plant; Aqaba desalination plant; Red-Sea – Dead-Sea Canal);
  - establishment of a large groundwater abstraction scheme in the Disi area (fossil groundwater) and construction of a conveyor system to Amman and Aqaba.

However, in many scenarios for water resources management in the future two facts, which may lead to a reduction of the overall availability of water resources, are often not taken into consideration:

- the effects of climatic change on the water resources that may occur due to global warming; and
- the deterioration of water quality due to the growing number of environmental hazards.

Global warming is predicted to result in a rise of temperatures in Jordan of up to 7° C in summer and of around 2° C in winter in the time period 2070-99 (Kunstmann et al. 2006; Fig. 3.6.1; average annual temperatures would be around 3.5° C higher than in the time period 1961-90). According to the climate model this would go along with decreased precipitation in the northwestern part of Jordan of around 25 %. Since these are the areas presently receiving most of the regional rainfall, i.e. up to 500 mm in the area south of Irbid, groundwater recharge will possibly also decline considerably. In the past, snow melt was a major contributor to groundwater recharge in the northern and central highlands of Jordan, resulting in groundwater recharge rates of up to 30 % in years with extensive snow fall (Margane et al., 2002).

With rising temperatures, snow fall will occur much rarer than presently, so that groundwater recharge from snow melt will possibly disappear. Presently, groundwater recharge in areas receiving rainfall less than 200 mm/a is almost negligible. Since these areas will become more extended, the area where groundwater recharge can possibly take place in the future will be limited to a very small part of the country in the northern and central highlands. The effect on groundwater recharge might therefore be that total groundwater recharge will decrease even much more than 25 %, provided that this scenario of climate change is valid and correct. Water resources availability may therefore be reduced to a total of around 580 Mm^3/a. Moreover, with higher temperatures, especially during the summer months, evaporation from surface water resources will also strongly increase. This would affect the King Abdullah Canal (KAC) and, more importantly, the dams, many of which have been put into operation only recently in order to better regulate the surface water flow and make the year-round use of surface water more efficient. Thus a reduction of the total water resources availability to around 550 Mm^3/a (i.e. 2/3 of the present value) is a likely scenario.

Taking into account that climate changes have frequently occurred throughout the Quaternary, the Middle East had to adapt to their consequences numerous times. Some of these consequences are relatively well documented for the recent past and have made it possible to gain extensive insight into the climatic history (Issar & Zohar, 2004; Issar, 1990; Margane, 1990). However, with growing population numbers and increased dependency on the scarce water resources, it becomes more and more important to develop a strategy well in advance of possible water shortages. Regardless whether the climatic prediction presented by KUNSTMANN et al. (2006) are correct, the issue of climate change must be urgently addressed in water resources management in the Middle East.

Apart from the increased population, Jordan has faced a growing agricultural and industrial development over the past three decades, which has left its traces. The effect of groundwater quality deterioration is observed since a number of years, especially in areas of extensive agricultural cultivation. Levels of nitrate content and total dissolved solids have increased in many areas, such as the Badia region (east of Mafraq, along the Mafraq-Safawi road), the Dhuleil-Hallabat region, the Azraq area, and the area south of Amman. Moreover, groundwater has become bacteriologically polluted in some areas where collection and treatment of wastewater is lacking or insufficient. In some areas groundwater has become unusable for drinking purposes without prior treatment reducing the amount of available groundwater resources. This does not take into account contaminations by pesticides or toxic substances resulting from industrial production or commercial use and handling, mainly because these substances are still not sufficiently analyzed. Knowledge about the extent of this kind of contamination is weak.

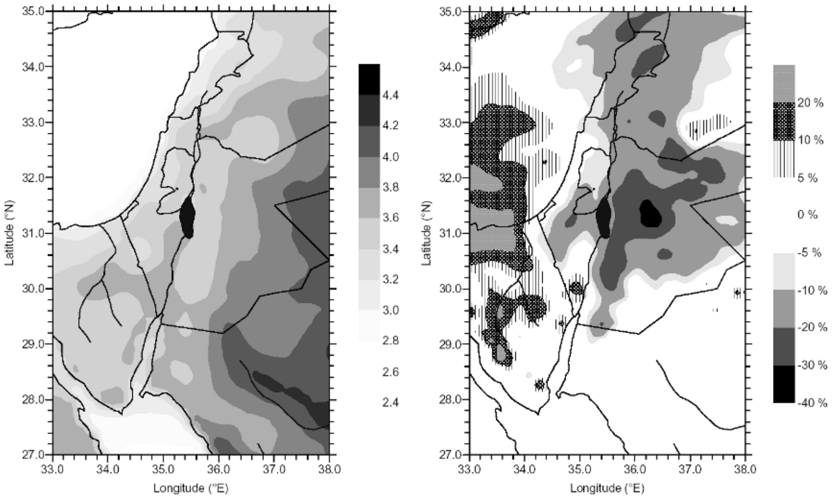


Fig. 3.6.1. Possible Consequences of Climate Change for the Middle East (adopted from Kunstmann et al., 2007; scenario B2 for a CO_2 concentration of approx. 600 ppm in 2100; left: absolute change in annual average temperature [° C], right: relative change in annual average precipitation [%]).

Whereas countermeasures against the effects of regional climate change can only be implemented through international agreements, measures against the deterioration of water resources quality can be implemented directly by the Jordanian Government. If fully implemented, these measures will help to conserve or even improve the quality of water resources and thus avoid future costs for water treatment, water conveyance from other areas/sources or more costly alternatives. They will also help to reattain a balanced and sustainable management of water resources.

3.6.2 Implemented Water Resources Protection Efforts

Within the framework of technical cooperation, the Federal Institute for Geosciences and Natural Resources (BGR) and the Ministry of Water and Irrigation (MWI) have jointly developed an approach to improve the protection of groundwater and surface water resources against contamination. The following measures have been introduced in Jordan :

- Several groundwater vulnerability maps were prepared showing to which degree the uppermost aquifer is naturally protected against pollution, focusing on those areas where a growing development is taking place or is expected to do so. These maps facilitate the assessment of risk for groundwater contamination emanating from existing or potential pollution sources (e.g. for environmental impact assessments, for the design of monitoring networks, or for future land reclamation projects). They also allow the determination of priority areas for drinking water exploitation. Furthermore they can be used in landuse planning to locate sites and activities which are potentially hazardous to groundwater.

- Groundwater protection zones have been or are in the process to be established for some major well fields and springs. A related guideline for the delineation of such protection zones has been elaborated by the Higher Committee with the support of the project and was officially issued by the Jordanian Government in July 2006.
- Protection zones for surface water resources will also be implemented by the project, focusing on large dams used for drinking purposes. The technical regulation was included in the above mentioned guideline.
- The Landuse Licensing Committee is supported by providing adequate geoscientific information in order to base its decisions on a thorough understanding of the possible negative effects of the proposed activities on the ground- and surface water resources.
- The National Groundwater Quality Monitoring Network is redesigned in order to provide decision makers with accurate information about the actual status of the groundwater quality and make proposals to maintain or improve the water resources quality.

The above mentioned water resources protection measures will provide protection for about 25 % of the drinking water resources, when fully implemented by the project.

The following chapters explain the realized measures and give recent examples. With these examples the degree of implementation is shown and possible consequences and further actions are discussed.

The above mentioned measures contribute together with continuous improvements in collection and treatment of waste water, supported by various donors (KfW, USAID etc.) to halt the deterioration in the quality of the water resources.

Groundwater Vulnerability Maps

Since 1995, four groundwater vulnerability maps have been prepared by the project for the following areas :

- Irbid (Margane et al., 1997, 1999; Margane, 1999);
- South Amman (Subah et al., 1999);
- Qunayyah spring catchment (Brosig, 2005) and
- Karak – Lajjun (Margane et al., 2005a, 2005b).

In all areas the same method has been applied. This method was introduced in the early 1990s in Germany (Hoelting et al., 1995) and modified for use in the Arab region (Margane et al., 1997). It uses the following parameters, which are readily available in Jordan for many areas, to calculate the „overall protective effectiveness“ of the soil cover and the unsaturated zone:

Parameter 1: S - effective field capacity of the soil (rating for ΣeFC in mm down to 1 m depth)
Parameter 2: W - percolation rate (groundwater recharge)
Parameter 3: R - rock type (consolidated/unconsolidated)
Parameter 4: T - thickness of soil and rock cover above the aquifer
Parameter 5: Q - bonus points for perched aquifer systems
Parameter 6: HP - bonus points for hydraulic pressure conditions (confined/artesian conditions)

Overall protective effectiveness (PT) is calculated using the formula: $PT = P1 + P2 + Q + HP$

P1 - protective effectiveness of the soil cover: $P1 = S * W$
P2 - protective effectiveness of the unsaturated zone (sediments or hard rocks):
$P2 = W * (R1*T1 + R2*T2 + ... + Rn*Tn)$

The establishment of such maps requires the use of a GIS system or other grid based interpolation and calculation software. The first three maps were prepared using ArcView and ArcGIS, for the most recent map SURFER was used. The most time consuming task in this context is the preparation of accurate structure contour maps of the relevant (hydro)geological units. The map scale used was 1:100,000 or 1:50,000, depending on the level of detail of the available information. Some further recommendations on groundwater vulnerability mapping with special reference to the Arab region are given in Margane (2002) and Margane (2003a).

Vulnerability maps are very helpful as a decision making tool in the landuse planning process. Areas of high vulnerability indicate areas with a high pollution risk. In this regard the question in focus is: which measures need to be implemented to protect the water resources against pollution? On the other hand areas of low vulnerability characterizes those with a low pollution risk. This helps to determine where sites and activities which are possibly hazardous to groundwater, such as waste disposal sites, wastewater treatment plants, industrial and commercial estates, power plants, etc. may be located.

Together with an inventory and a map of hazards to groundwater, it can be assessed where groundwater resources are at high risk to become polluted by existing or planned potentially polluting sites and activities. Water resources managers may also want to declare priority areas for groundwater exploitation, so that landuse planners can exclude these areas from other uses in their landuse plans. Concerning landuse planning, groundwater vulnerability maps provide a basis for an initial selection where to locate sites and activities which are potentially hazardous to groundwater and surface water resources. It must be emphasized, however, that for the final decision concerning the location of such sites, more detailed investigations are required because the applied scale for groundwater vulnerability maps is usually not detailed enough to support such a landuse planning decision.

Groundwater vulnerability maps may also be used as a basis for environmental impact assessments (EIA). However, also in this case a more detailed investigation will have to be carried out because such EIAs will require a more detailed mapping scale of between 1:10,000 and 1:1,000.

Furthermore, groundwater vulnerability maps may be used for the design of groundwater monitoring networks, both, for baseline groundwater monitoring and for monitoring of possible negative environmental impacts on the groundwater system resulting from existing hazards to groundwater.

For the preparation of maps of hazards to groundwater aerial photographs and satellite images are very helpful (both, recent and historical images) in order to obtain an overview of the development in a specific area and to detect possible sources of or an existing pollution. In most recent investigations Quickbird or IKONOS data have been used in Jordan because they provide an even better and more recent image than the available aerial photographs. In many cases images taken from Google Earth are the most time and cost efficient option in this respect.

An example of such a vulnerability map is shown in Fig. 3.6.2.

Vulnerability Map of the Irbid Area Groundwater

Critical points in the Irbid area are:

- Waste water treatment plant of Central Irbid;
- Disposal of domestic and commercial or industrial waste, especially hazardous waste.

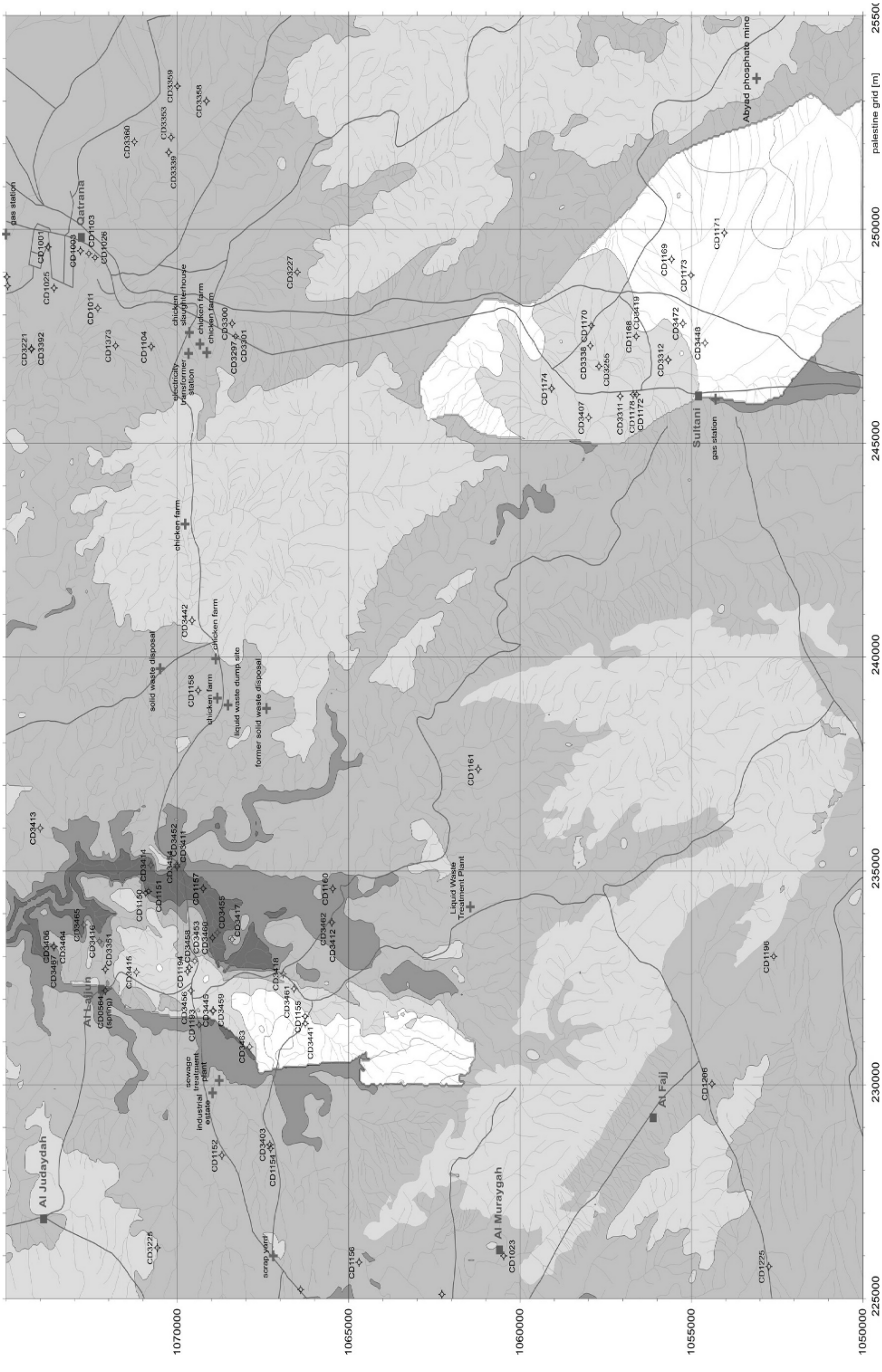
Because this was the first such map prepared by the project, implementation of the proposed measures was still weak.

Vulnerability Map of the Karak – Lajjun Groundwater

As main hazards this map shows the:

- liquid waste disposal of the municipality of Karak;
- old and new waste disposal sites of the municipality of Karak;
- wastewater treatment plant of the industrial estate;
- chicken farms; and the
- planned oilshale mine and processing plant.

Through a workshop, the decision makers and local population were made aware of the environmental problems in the area. The municipality of Karak has accepted that it will have to look for alternatives to the current waste dumping site. Concerning the liquid waste disposal, which was opened in November 2005, alternatives are currently discussed. Until now, no consequences are to be seen in the field. Further awareness campaigns are needed and will be held in connection with the implementation of groundwater protection zones for this wellfield.


Al Judaydah
Al Lajjun
Qatrana
Sultani
Al Faij
Al Muraygah
gas station
chicken slaughterhouse
chicken farm
electricity transformer station
solid waste disposal
liquid waste dump site
former solid waste disposal
Liquid Waste Treatment Plant
sewage treatment plant
industrial estate
scrap yard
Abyad phosphate mine
CD0564 (spring)
CD1001
CD1003
CD1011
CD1023
CD1025
CD1026
CD1103
CD1104
CD1150
CD1151
CD1152
CD1153
CD1154
CD1155
CD1156
CD1157
CD1158
CD1160
CD1161
CD1168
CD1169
CD1170
CD1171
CD1172
CD1173
CD1174
CD1178
CD1194
CD1196
CD1206
CD1225
CD1373
CD3221
CD3225
CD3227
CD3255
CD3297
CD3300
CD3301
CD3311
CD3312
CD3338
CD3339
CD3351
CD3353
CD3358
CD3359
CD3360
CD3392
CD3403
CD3407
CD3411
CD3412
CD3413
CD3414
CD3415
CD3416
CD3417
CD3418
CD3419
CD3441
CD3442
CD3445
CD3448
CD3452
CD3453
CD3454
CD3455
CD3456
CD3458
CD3459
CD3460
CD3461
CD3462
CD3463
CD3464
CD3465
CD3466
CD3467
CD3472
225000
230000
235000
240000
245000
250000
2550
1050000
1055000
1060000
1065000
1070000
palestine grid [m]

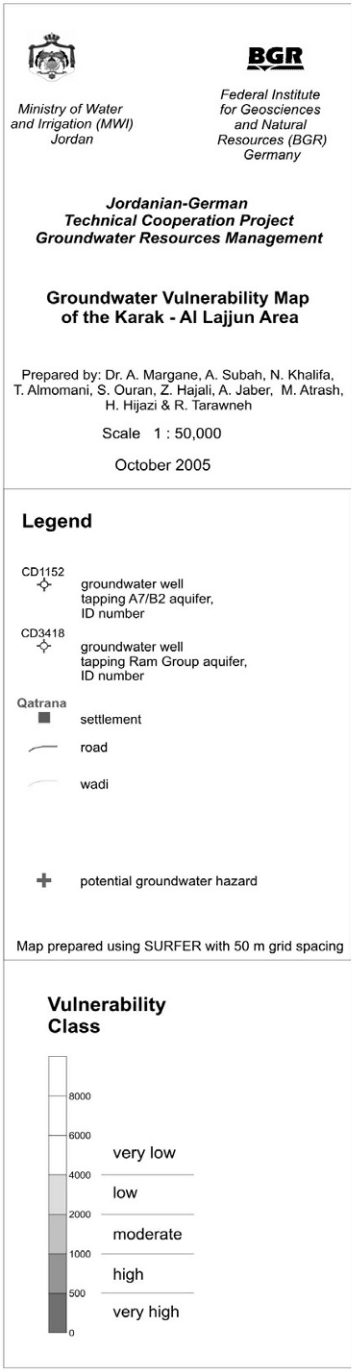


Fig. 3.6.2. Groundwater Vulnerability Map of the Karak–Lajjun Area (incl. page before).

The area bears large oilshale resources, which have been explored since the late 1970s. With increasing oil prices exploitation has now reached profitability so that currently several concessionaires are carrying out feasibility studies for oilshale exploitation and processing facilities. It has to be emphasized that before granting licenses to such projects, a thorough environmental impact assessment is required. Special precautionary measures will have to be implemented to provide a protection of the precious ground- and surface water resources. Groundwater resources are exploited through the Lajjun wellfield, which provides drinking water to Amman and surface water, also used as drinking water in Amman, is stored in the Mujib dam, located downstream of the envisaged sites.

Groundwater Protection Zones

The method of groundwater protection zoning was introduced in the late 1990s in Jordan. Four groundwater protection zones (GPZs) have been established and the work on another four is in progress:

- Pella (Tabaqat Fahel) spring (Margane et al., 1999);
- Qunayyah spring (Subah et al., 2004);
- Wadi al Arab wellfield (Hobler et al., 2006);
- Rahoub spring (Margane et al., 2006);
- Corridor wellfield;
- Hallabat wellfield;
- Lajjun wellfield; and
- Baqqouriah spring.

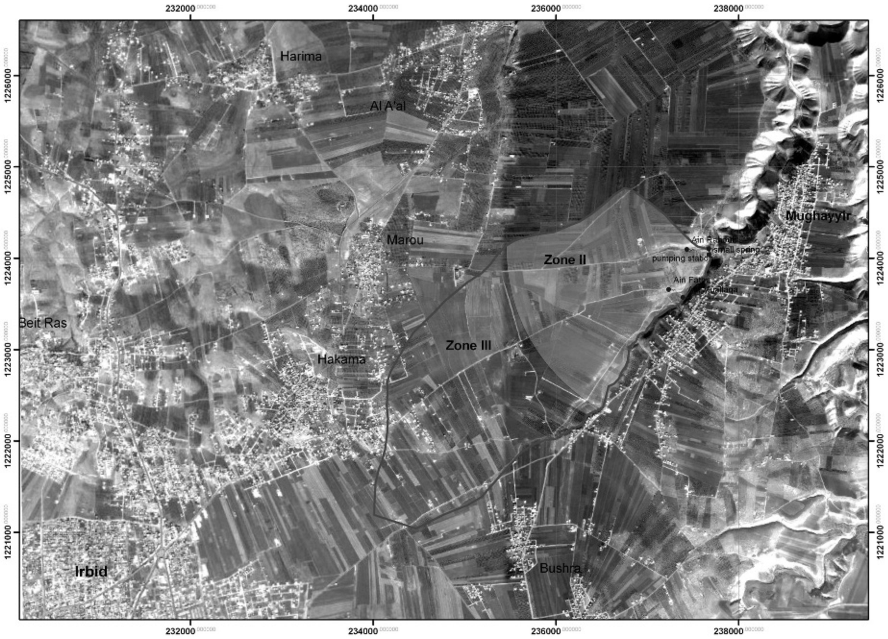


Fig. 3.6.3. Groundwater Protection Zones of the Rahoub Spring.

In 2002 the project wrote a proposal for a guideline and By-law concerning the establishment of GPZs (Margane & Sunna, 2002). This proposal was discussed by the Higher Committee on Groundwater Protection and finally accepted by all sides. The guideline was passed by the Cabinet and issued by the MWI in July 2006. The zoning system and landuse restrictions in place now contain the following:

Zone I:	corresponds to an area of about 1 dunum (1000 m²) around each public or private springs and wells and 2 dunums (2000 m²) around each public or private spring: 25 m in the upstream direction for wells and 50 m for springs, 10 m in the downstream direction and 15 m to both sides. No activities are allowed apart from those needed for water abstraction (operation and maintenance). For public supplies, WAJ will acquire the land and fence it.
Zone II:	the area is based on the 50-days travel time line but does not exceed 2 km upstream of wells or springs) Allowed activities for newly developed land - Residential areas with sewers or acceptable cesspit - Organic farming

Allowed activities for already developed land

- Residential areas (priority for establishing sewer systems)
- Organic farming
- Other activities have to ensure compliance with environmental sound practices

Activities in Zone II will be intensively monitored

Zone III: the area corresponds to the entire groundwater catchment area.

Allowed activities: All development, agricultural, industrial and social activities are allowed in this zone, under the condition that they comply with the laws and by-laws applied in Jordan and environmentally sound practices.

In this context it may be worthwhile mentioning that a similar but more detailed guideline for the delineation of groundwater protection zones in the Arab region has later been developed in cooperation with the Arab Centre for the Studies of Arid Zones and Dry Lands (ACSAD) that was later also published by UNESCO/Cairo (Margane, 2003b).

The maximum distance of 2 km for the outer boundary of zone II from the point of abstraction was a compromise among all stakeholders. Since in most conditions, the aquifer system is karstic and the groundwater flow velocity will be quite high along fractures and faults exceeding 40 m/d in karst conduits, the provisions of the guideline may not be adequate to guarantee bacteriological safety of the water at the abstraction point. If it turns out that bacteriological contaminations still occur at such locations, the guideline should be amended at a later stage.

The most recent example of such a GPZ is the Rahoub spring, located around 6 km northeast of Irbid (Fig. 3.6.3).

The Ministry of Water and Irrigation, including the Jordan Valley Authority (JVA) and the Water Authority of Jordan (WAJ), is responsible for the implementation of protection zone I. The Ministry of Water and Irrigation in coordination with the Ministry of Environment (MoEnv) is responsible to control and supervise zones II and III and will undertake the required measures according to existing regulations and laws. The Ministry of Water and Irrigation in coordination with the Ministry of Agriculture is responsible to control the agricultural activities in zone II and zone III and the requirements of protection zones II and III.

So far, however, there is no definition of what is understood under „compliance with environment sound practice“ and „organic farming“. The amendment proposed by the project therefore calls on the MoEnv to set up best management practice guides (BMPs) for all relevant activities which may negatively affect the environment and states that „no risk to the safety of the water resources may arise“ from organic farming.

Consequences of the Establishment of Groundwater Protection Zones

The first groundwater protection zone was successfully established for the Pella spring in the Jordan Valley in 1999. Most of the proposed measures were implemented. An illegal waste disposal site, located in protection zone II was completely removed and a fence was established around zone I. Spring flow was intercepted by shallow boreholes and water quality has improved considerably since 1999.

Concerning the Rahoub spring, the project has proposed to reestablish the fence, to improve the pipeline system diverting spring flow to the pumping station, to construct a new storage system, to construct a small building that allows only the responsible personnel to access the spring itself, and to construct a channel that would collect surface water runoff and bypass it along the road north of the spring. Most of these measures will be implemented with the support of the project.

Since a number of years fences are established around wells and springs used for domestic water supply. This protection perimeter corresponds more or less to protection zone I. However, some of these have been removed or vandalized in the meantime. The project has recognized a large demand for rehabilitation measures, to improve the protection of wells and springs. Based on this experience a related project component will be integrated into a KfW funded project in the future.

Surface Water Protection Zones

In July 2006 MWI issued the ‘Guidelines for Drinking Water Resources Protection’. They comprise provisions for the protection of surface water (dams, wadis and canals):

Dams
Zone I: corresponds to the land owned by JVA for operation and maintenance (fence around the lake with a distance of not less than 100m measured from the highest possible water level)
Zone II: its delineation depends on the geological and topographical situation of the area, but is not less than 2,5 km around the embankment of the dam and 350m on both sides of the main wadis recharging the aquifer
Zone III: corresponds to the entire catchment area

Wadis
Zone I: corresponds to the area of the wadi owned by the government
Zone II: delineation depends on the geological and topographical situation of the area but should not less be than 350m to both sides of the wadi

Canals (King Abdullah Canal)
Zone I: corresponds to the land owned by JVA for operation and maintenance (in total 40 m either on one or on the other side or equally on both sides of the canal)

Zone II: corresponds to an area within a distance of 15 m to both sides of protection zone I

Landuse Restrictions for all Surface Water Types
Zone I
Allowed: activities related to the operation and maintenance
Zone II
Allowed activities: organic farming
Allowed activities (already developed land):
residential areas (priority for establishing sewers)
organic farming
other activities have to ensure compliance with environmental sound practices
Activities in Zone II will be intensively monitored
Zone III
Allowed all the development activities if in compliance with environmental sound practices

It was recognized by the project that the guideline needs to be amended concerning dams, since a distance based zoning scheme will not provide adequate protection of the dams.

In surface water the main factors controlling travel time are:

- slope;
- land surface / channel shape;
- terrain / channel roughness (rock type);
- soil;
- vegetation cover;
- landuse and
- physical barriers.

In surface water regimes, movement is much faster than in groundwater regimes so it is impossible to maintain the same protection objectives especially pertaining to zone II (in groundwater: 50 days time of travel). In surface water it is not possible to set up a protection zone II with the objective to entirely prevent bacteriological contamination. Therefore it should be emphasized that bacteriological contaminants cannot be prevented from reaching the surface water resource and the corresponding source water has to be treated accordingly. The aim of setting up a protection zone II is to reduce the discharge of other contaminants, which are often not or not sufficiently treated by commonly used systems, into the surface water resource to a minimum. The main hazards to surface water in this context are hydrocarbons and other organic chemical components which have an effect on human health as well as fertilizers and pesticides used in agricultural cultivation.

Under the conditions typical in Jordan, the dominant parameter controlling travel time in surface water is the slope (Fig. 3.6.4). Therefore this parameter was integrated in the proposal made by the project (Margane & Subah, 2007) :

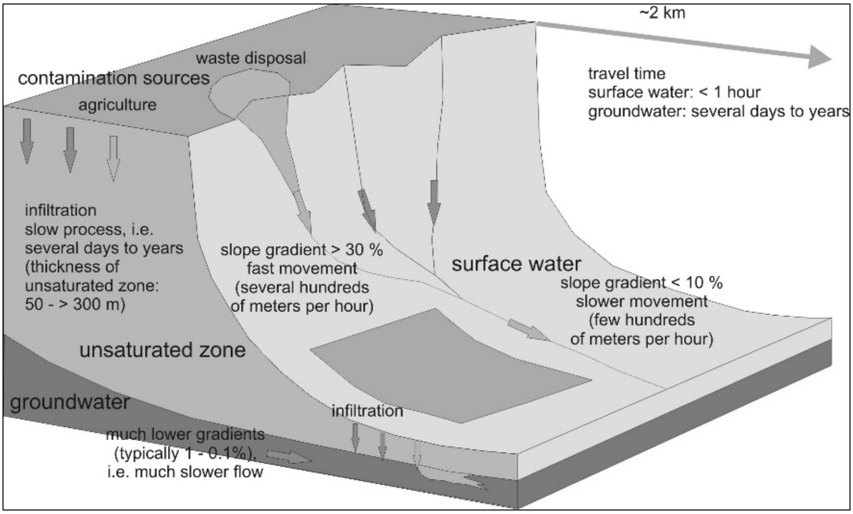


Fig. 3.6.4. Comparison of Flow Times in Surface and Groundwater under Typical Conditions given in Jordan (plumes and arrows indicate possible pollution pathways).

Zone I: buffer zone of 100 m around a reservoir, measured from the highest possible water level.

Zone II: buffer zone of 500 m around zone I, measured from the highest possible water level, if slope within this zone is below 2°. If the slope exceeds 2° at a distance of 500 m, zone II will reach to the point where the slope angle becomes less than 2°. In the upstream area, zone II will reach until a distance of a maximum of 5 km following the course of the main wadis discharging into zone I.

Zone III: Entire surface catchment area.

This system was based on simulations with different values of slope angle at the Wadi Mujib dam. The extent of protection zone II reached with threshold value of 2° is shown in Fig. 3.6.5. In the opinion of the authors it provides the best compromise between protection objective and practicability.

Protection zone III should provide protection against long-term contamination e.g. from hardly degradable substances. The main pollution sources in this respect are commercial and industrial activities.

Supporting the Landuse Licensing Committee

Since a number of years, a special committee, the so-called Landuse Licensing Committee (LLC) consisting of members from all major ministries and authorities regularly convenes to decide on requests for landuse conversions. Permission for

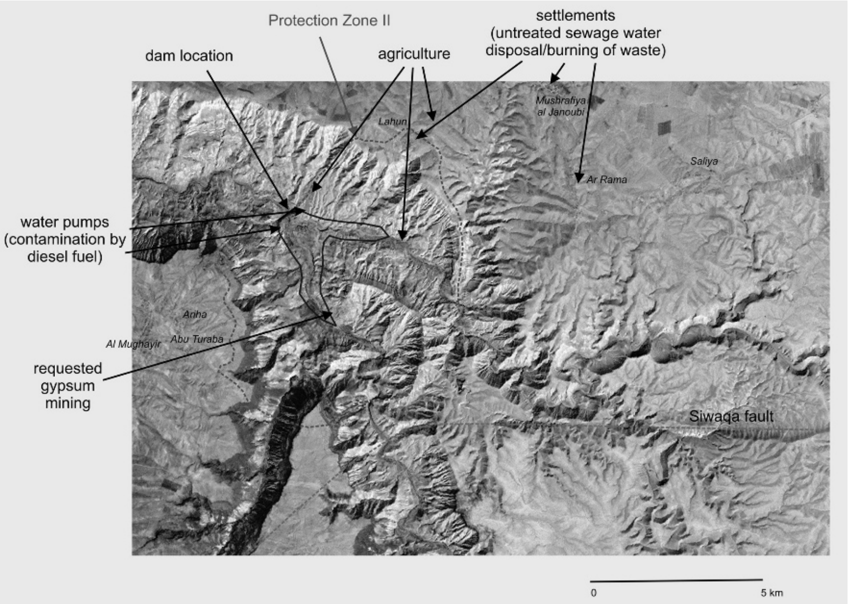


Fig. 3.6.5. Approximate Extent of Protection Zones at Wadi Mujib Dam using a Threshold Value of 2 Degrees.

landuse licensing has to be requested from the LLC for all activities that may negatively affect the environment. Another committee, the Mining License Committee (MLC), decides on requests for mineral exploration.

It has to be mentioned that with the issuance of the Environmental Protection Law N° 52 in 2006 the legal basis for water resources protection has become much stronger. Article 11 provides that: „It is forbidden to dump, dispose of, or collect any materials harmful to the environment, whether such materials are solid, liquid, gaseous, radioactive or thermal, in the sources of water.“ Article 13 states that any company which „conducts activities that negatively impact the environment is obligated to prepare an environmental impact assessment report“. By introducing the polluter pays principle the environmental law provides the legal basis for interventions against polluters.

In order to constitute a sound basis for such landuse decisions, the project provides relevant geo-scientific information to both of these committees. Since the number of such requests is quite high it is important to set up a database and GIS system that allows semi-automatic generation of the required maps. Many of these maps result from previous investigation programs that BGR conducted together with various Jordanian institutions in the framework of technical cooperation projects (e.g. Hobler et al., 1991; Hobler et al., 1993; Hobler et al., 2001; Margane et al., 2002).

Improving the National Groundwater Quality Monitoring Network

One of the tasks of the MWI is monitoring the status of the national groundwater resources. However, the current water quality monitoring system (WQMS), consisting of approx. 226 wells and 74 springs, is hardly appropriate to fulfill this task. Several attempts to improve the quality monitoring have been undertaken (e.g. USAID funded WQIC project in the Amman-Zarqa basin) but until now there exists no written monitoring plan. The BGR-MWI project aims to review the status and conditions of all existing monitoring wells on a national level, make proposals on how to improve the WQMS, help implementing this proposal, establish a monitoring plan and establish annual reports on groundwater quality.

There are several problems due to which the monitoring results are still unsatisfactory related to technical, organizational but also training and financial deficiencies (modified after Jousma et al., 2006, Margane, 2003d and Margane, 1995):

Technical deficiencies

- Often monitoring wells were not specially designed for this particular purpose. In such observation wells water level measurements might not be representative for water level fluctuations in the aquifer (wrong location of the well, wrong placement of the screens, corrosion or encrustation of the screens, etc.).
- The position, horizontal spacing, frequency of sampling, parameter set of many monitoring wells is not appropriately determined.
- A written monitoring plan is missing.
- There is no defined data storage, processing, interpretation, presentation, exchange and reporting structure.
- In some observation wells, the monitoring aquifer is not clear. Sometimes, the drilling penetrates more than one aquifer.
- Frequently monitoring wells have been vandalized as they are sometimes not sufficiently protected.

Organizational deficiencies

- There is a lack of qualified and trained personnel.
- There is often a lack of coordination between the sampling team and the laboratory, so that sampling, field analysis, preservation, transportation and storage are not conducted according to international standards.
- Analyses are often carried out several weeks and months after sampling without appropriate preservation and are thus incorrect.

- The incoming field data as well as the data entered to the database are mostly not checked sufficiently. Many of the hydrographs in the database had to be corrected considerably. In general, evaluation of the original recorder charts needs to be improved.
- Proper field reports of the technicians are not available and information on water level, pumping in nearby wells, maintenance requirements, etc. is commonly missing. This makes it difficult or impossible to interpret the results.
- Samples for groundwater quality are collected on different schedules, depending on the purpose and the constituents that are being monitored. In the past sampling was often imperfect (non reliable data, data gaps), so that historical data can only be used to a limited extent.

In order to achieve the optimal result, the project coordinates its activities with several other institutions, which also carry out water quality monitoring for other purposes, such as the Ministry of Environment, the Ministry of Health and several other institutes.

3.6.3 Summary

Jordan is facing a water crisis since several years. The available amounts are exploited to a large extent (surface water) or even overexploited (groundwater). With a still rapidly growing population, these will not be enough to meet the demand of the future. A number of large projects are currently underway to overcome the consistent water shortage problems.

However, some facts are often neglected when demand projections and management plans are drafted:

1. Effects of Deteriorating Water Quality: The rapid agricultural development, which started in the early 1970s, and the even more rapid industrial and commercial development since the early 1990s, has brought about a considerable risk of pollution for the scarce water resources. Only recently Jordan has adopted stricter water and environmental policies and regulations to counter these pollution risks. However, in many areas the quality of water resources has in the meantime deteriorated considerably, often rending them unusable for drinking purposes. Much more efforts are needed, especially concerning landuse planning and water resources management, in order to maintain and improve the water resources quality. The aim of the recent technical cooperation projects between the Federal Institute of Geosciences and Natural Resources (BGR) and the Ministry of Water and Irrigation (MWI), funded by the German Government, was and is to introduce measures which counter these pollution risks. These measures encompass:
    - groundwater vulnerability maps;
    - the delineation of groundwater protection zones and the establishment of a legal basis for implementation of related landuse restrictions;

- the delineation of surface water protection zones and the establishment of a legal basis for implementation of related landuse restrictions;
- giving support to the landuse licensing committee and mining license committee;
- improving the national groundwater quality monitoring network.

2. Effects of Changing Climate: The region has faced several climate changes over the past 30,000 years. The current scenarios for Israel and Jordan suggest a considerable decrease of rainfall during winter and much hotter summer temperatures. This could lead to a decrease in groundwater recharge of up to 30 % and higher evaporation from surface water resources, so that water resources availability may be reduced to values as low as 550 Mm^3/a. Since the effects of such climate change are predicted to happen relatively fast, the Government of Jordan must urgently think about strategies to counter possible decreased water resources availability in the near future.

   Under the given conditions and the above-mentioned constraints, it is likely that the already existing water crisis in Jordan will worsen even more in the near future.

   Despite all efforts of the Government to reduce water losses in the distribution system, reuse treated waste water, reduce water consumption in the agricultural sector, improve the collection and treatment of wastewater and improve the protection of the water resources, it might thus be unavoidable for the Jordanian Government to embark on large water supply projects such as the Red-Sea – Dead-Sea Canal or the exploitation of the Disi (fossil) groundwater resources.

   This is not to mean that the above described situation must occur (and it will only occur if the calculations of the climate research teams are valid and correct), but it would be wise for the Jordanian Government to be prepared for it.

References

Brosig, K. (2005): Groundwater Vulnerability Mapping in the Qunayyah Spring Catchment Area. – Final Unpublished Report, prepared for BGR by University of Goettingen, 121 p; Goettingen.

Hobler, M., Bender, H., Rashdan, J. & Schmidt, G. (1991): Groundwater Resources of Southern Jordan, Vol. 1-5. – Report prepared by Federal Institute for Geosciences and Natural Resources (BGR) and Water Authority of Jordan (WAJ), Technical Cooperation Project 'Groundwater Resources of South Jordan', Report No. 108652 and 107375; Amman.

Hobler, M., Margane, A., Almomani, M., Subah, A., Hammoudeh, A., Ouran, S., Rayyan, M., Saffarini, I., Hijazi, H. & Kalbouneh, A. (1993): Groundwater Resources of Northern Jordan - Vol. 3: Structural Features of the Main Hydrogeological Units in Northern Jordan. - Report prepared by Federal Institute for Geosciences and Natural Resources (BGR) and Water Authority of Jordan (WAJ), Technical Cooperation Project 'Groundwater Resources of Northern Jordan', Part 1: Report, Part 2: Appendices, Part 3: Annexes, BGR-Archive No. 112708; Amman.

Hobler, M., Margane, A., Almomani, M. & Subah, A. (2001): Groundwater Resources of Northern Jordan, Vol.4: Hydrogeological Features of Northern Jordan. - Technical Cooperation

Project ’Advisory Services to the Water Authority of Jordan’, BGR & WAJ, BGR archive no. 112708:5, 84 p.; Amman.

Hoelting, B., Haertlé, T., Hohberger, K.-h., Nachtigall, K.h., Villinger, E., Weinzierl, W. & Wrobel, J.-p. (1995): Konzept zur Ermittlung der Schutzfunktion der Grundwasserüberdeckung. – Geol.Jb., C, 63, p. 5-24; Hannover. - [translated into English by the Federal Institute for Geosciences and Natural Resources: Concept for the Determination of the Protective Effectiveness of the Cover above the Groundwater against Pollution. – Ad-hoc Working Group on Hydrogeology, 28 p.; Hannover]

Issar, A. S. (1990): Water shall flow from the Rock. – 213 p. Berlin, Heidelberg, New York (Springer Verlag).

Issar, A. S. & Zohar, M. (2004): Climate Change – Environment and Civilization in the Middle East. – 252 p.; Berlin, Heidelberg, New York (Springer).

Jousma, G., Attanayake, P., Chilton, J., Margane, A., Navarrete, C.M., Melo, M.T., Guerrero, P.N.L., Polemio, M., Roelofsen, F., Sharma, S.K., Streetly, M., Subah, A. & Al-yaqoubi, A. (2006): Guideline on Groundwater Monitoring for General Reference Purposes. – IGRAC/UNESCO, 165 p.; Utrecht.

Kunstmann, H., Suppan, P., Heckl, A. & Rimmer, A. (2007): Regional Climate Change in the Middle East and Impact on Hydrology in the Upper Jordan Catchment. - Proceedings of Symposium HS2004 at IUGG2007, IAHS Publ. 313, 9 p.; Perugia/Italy.

Margane, A. (1990): Paleoclimate and Groundwater Recharge in Jordan over the past 30,000 Years. – BGR archive no. 107712, 37 p.; Hannover. [in English and German; Paläoklima und Grundwasserneubildung in den letzten 30.000 Jahren vor heute in Jordanien]

Margane, A. (1995): Groundwater Resources of Northern Jordan, Vol.2, Part 2: Monitoring of Groundwater Levels in Northern Jordan. - Technical Cooperation Project ’Advisory Services to the Water Authority of Jordan’, BGR & WAJ, BGR archive no. 118701:2, 71 p., 3 app., 3 maps; Amman.

Margane, A. (1999) : Mapping of Groundwater Vulnerabilty and Hazards to Groundwater in Developping Countries. – Proc. 29th IAH-Congress 6-10 Sep 1999, 87-92; Bratislava.

Margane, A. (2002): Criteria for the Preparation of Groundwater Vulnerability Maps. - Technical Cooperation Project ‘Groundwater Resources Management’, Technical Report No. 2, prepared by BGR & MWI, BGR archive no. 0125646, 118 p.; Amman.

Margane, A. (2004): Guideline for Groundwater Monitoring. – Technical Cooperation Project ‘Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region’, Technical Reports Vol. 7, prepared by BGR & ACSAD, BGR archive no. 122917:7, 318 p., 1 CD; Damascus.

Margane, A. (2003c): Guideline for Sustainable Groundwater Resources Management. – Technical Cooperation Project ‘Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region’, Technical Reports Vol. 6, prepared by BGR & ACSAD, BGR archive no. 122917:6, 235 p., 1 CD; Damascus.

Margane, A. (2003b): Guideline for the Delineation of Groundwater Protection Zones. – Technical Cooperation Project ‘Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region’, Technical Reports Vol. 5, prepared by BGR & ACSAD, BGR archive no. 122917:5, 329 p., 1 CD; Damascus.

Margane, A. (2003a): Guideline for Groundwater Vulnerability Mapping and Risk Assessment for the Susceptibility of Groundwater Resources to Contamination. – Technical Cooperation Project ‘Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region’, Technical Reports Vol. 4, prepared by BGR & ACSAD, BGR archive no. 122917:4, 177 p., 1 CD; Damascus.

Margane, A., Borgstedt, A., Subah, A., Hajali, Z., Almomani, T. (2006): Delineation of Groundwater Protection Zones for the Rahoub Spring. – Technical Cooperation Project ‘Groundwater Resources Management', Technical Report No. 7, prepared by BGR & MWI, 97 p.; Amman.

Margane, A. & Hobler, M. (1994): Groundwater Resources of Northern Jordan, Vol.3: Structural Features of the Main Hydrogeological Units in Northern Jordan. - Technical Cooperation Project 'Advisory Services to the Water Authority of Jordan', BGR & WAJ, BGR archive no. 118702:1-3, 57 p., 30 app., 38 ann.; Amman.

Margane, A., Hobler, M., Almomani, M. & Subah, A. (2002): Contributions to the Groundwater Resources of Northern and Central Jordan Jordan. - Geol.Jb., C. 68, 52 p.; Hannover.

Margane, A., Hobler, M., Droubi, A., Subah, A. & Khater, A.R. (2004): Groundwater Vulnerability Mapping in the Arab Region. – In: Zereini, F. & Jaeschke, W.: Water in the Middle East and North Africa – Resources, Protection and Management, 145-155; Heidelberg (Springer).

Margane, A., Hobler, M., Ouran, S. & Al Zuhdy, A. (1999) Groundwater Resources of Northern Jordan – Special Report No. 5: Hydrogeological Proposal for the Delineation of a Groundwater Protection Area for the Tabaqat Fahl (Pella) Spring. - Technical Cooperation Project 'Groundwater Resources of Northern Jordan', BGR & WAJ, BGR-archive no. 119256; Amman and Hannover.

Margane, A., Hobler, M. & Subah, A. (1997): Groundwater Resources of Northern Jordan, Special Report No. 3: Mapping of Groundwater Vulnerability and Hazards to Groundwater in the Irbid Area. - Technical Cooperation Project 'Advisory Services to the Water Authority of Jordan', BGR archive no. 118708, 50 p., 10 app., 4 ann.; Amman.

Margane, A., Hobler, M. & Subah, A. (1999): Mapping of Groundwater Vulnerability and Hazards to Groundwater in the Irbid Area, N-Jordan. - Zeitschr.Angew.Geol., 45, 4, 175-187; Hannover.

Margane, A. & Subah, A. (2007): Guideline for the Delineation of Surface Water Protection Areas. – Technical Cooperation Project 'Groundwater Resources Management', Technical Report No. 6, prepared by BGR & MWI, 117 p.; Amman.

Margane, A., Subah, A., Khalifa, N. & Almomani, T. (2005b): Groundwater Vulnerability Mapping in the Karak – Lajjun Area. – Proceedings of UNESCO-IHP Jordan Workshop on Aquifer Vulnerability, 11 p.; Zarqa (Hashemiyya University).

Margane, A., Subah, S., Khalifa, N., Almomani, T., Ouran, S., Hajali, Z., Ouran, S., Jaber, A., Atrash, M., Hijazi, H. & Tarawneh, R. (2005a): Mapping of Groundwater Vulnerability and Hazards to Groundwater in the Karak – Lajjun Area. – Technical Cooperation Project 'Groundwater Resources Management', Technical Report No. 5, prepared by BGR & MWI, 138 p.; Amman.

Margane, A. & Sunna, N. (2002): Proposal for a National Guideline for the Delineation of Groundwater Protection Zones. – Technical Cooperation Project 'Groundwater Resources Management', Technical Report No. 1, prepared by BGR & MWI, BGR archive no. 0125645, 161 p.; Amman.

MWI & GTZ (2004): Digital Water Master Plan. – Unpublished CD; Amman.

Subah, A., Hobler, M., Haj Ali, Z., Khalifa, N., Almomani, T., Atrash, M., Hijazi, H., Ouran, S., Jaber, A. & Tarawneh, R. (2006): Hydrogeological Proposal for the Delineation of a Groundwater Protection Area for the Wadi Al Arab Well Field. – Technical Cooperation Project 'Groundwater Resources Management', Technical Report No. 4, prepared by BGR & MWI, BGR archive no. 0126796,
57 p.; Amman.

Subah, A., Hobler, M., Haj Ali, Z., Ouran, S., Khalifa, N., Rayyan, M., Atrash, M., Jaber, A., Hijazi, H., Almomani, M. & Almomani, T. (2006): Hydrogeological Proposal for the Delineation of a Groundwater Protection Area for the Quanayyah Spring. – Technical Cooperation Project 'Groundwater Resources Management', Special Report No. 7, prepared by BGR & MWI, BGR archive no. 0126726, 30 p.; Amman.

Subah, A., Hobler, M., Rayyan, M. &. Hijazi, H. (1999): Mapping of Groundwater Vulnerability and Hazards to Groundwater in the Area South of Amman. - Unpubl. report prepared by Technical Cooperation Project BMZ No. 89.2105.8, BGR-Archive No. 112708, 62 p.; Amman.

3.7 Model Investigations on the Groundwater System in Jordan – A Contribution to the Resources Management (National Water Master Plan)

Gerhard Schmidt

Federal Institute for Geosciences and Natural Resources (BGR), Hannover

Ali Subah & Nidal Khalif

Ministry of Water and Irrigation (MWI), Amman

Summary

In Jordan, groundwater is one of the major water resources and depends strongly on the regularity of the seasonal precipitation. Although there is a considerable annual precipitation its contribution to the groundwater recharge is limited in time and quantity. Precipitation is highly variable and drought periods occur frequently. Therefore, climate changes and the future groundwater development are of vital interest for this country under semi-arid to widely arid weather conditions.

In fact, Jordan faces a critical water shortage, and the groundwater system is over-exploited since many years. A high population growth rate and the concentration of population in the urban centres of the northern part of Jordan lead to a deterioration of the situation. Consequently, there is an urgent need of countrywide regulations, including the establishment of sustainable groundwater production and protection schemes as an integrated part of the National Water Master Plan (NWMP), as prepared by the Ministry of Water and Irrigation in Amman.

As a contribution to the National Water Master Plan the comprehensive numerical simulation model for Jordan has been established in order to provide a tool for the groundwater resources management. The countrywide simulation model of this complex groundwater system covers an area of about 100,000 km^2. It includes the major hydrogeological formations, which are composed either of basalt, marl, limestone, or sandstone. Due to hydrogeological and hydraulic reasons and with respect to plausible hydraulic model boundaries, some parts of Saudi Arabia (e.g. the entire Wadi Sirhan area) are included, whereas in Jordan the Wadi Araba and the Jordan-Valley have not been incorporated.

The regional development of the groundwater system during the past three decades has been simulated. So far, two long-term scenarios until 2050 have been calculated by assuming that either the recent groundwater production will continue or that the future groundwater production will be modified in accordance to projections taken from the National Water Master Plan, respectively. Applied for prognosis purposes the model delivers figures about possible future changes in groundwater flow and quantity.

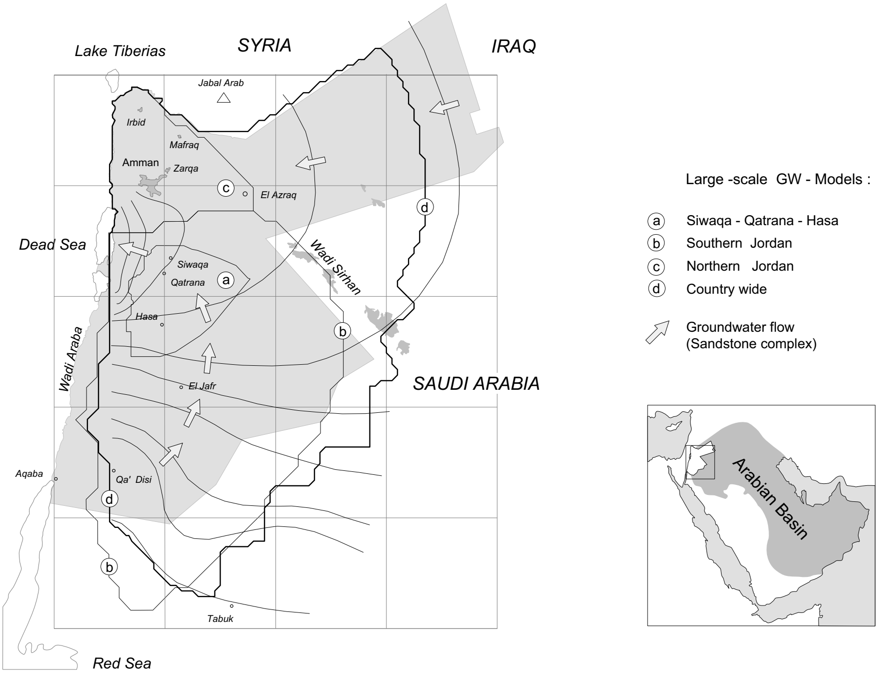


Fig. 3.7.1. The well fields of Siwaqa, Qatrana and Hasa (a) are located in the central part of Jordan. They contribute to the Amman water supply and meet the water demand of the phosphate industry. In the frame of the investigations on the groundwater resources of Southern and Northern Jordan corresponding simulation models (b and c) have been established respectively.

The model boundaries of the recent groundwater model (d) follow the outcrop areas of the sandstone complex in the western part, and in the eastern areas they refer to assumed groundwater flow lines. The groundwater contours are derived from a number of recorded water levels representing the water level of the deep sandstone complex. Constant heads are applied to the eastern and to the southern model boundary, namely in regions where the model boundary is located outside the Jordanian territory. The model covers an area of about 100.000 km^2.

3.7.1 Introduction

Groundwater represents the main water resource in most parts of the arid and semiarid regions of the Middle East and Northern Africa. Adequate groundwater management is a prerequisite for the sustainable use of the scarce water resources. Groundwater protection measures have to be incorporated in integrated water management activities as an important feature for sustainable development. To fulfil these requirements, the German Federal Institute for Geosciences and Natural

Resources (BGR) supports since several decades some national ministries and institutes as well as international organisations which are operating in the groundwater sector in this region.

In continuation of a long-lasting tradition in technical cooperation between the Hashemite Kingdom of Jordan and the Federal Republic of Germany, the German Federal Ministry for Economic Cooperation and Development (BMZ) commissioned Technical Cooperation projects in the water sector.

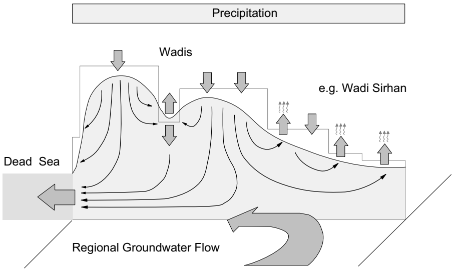
The idea of a comprehensive numerical model for the entire country has been initiated and encouraged by the fact that groundwater modelling has become a common tool in water decision projects in Jordan. Since about two decades several larger hydrogeological investigations have been completed by the application of groundwater models. As results from these activities models have delivered local and regional water budgets and consequently estimations about the amount of groundwater exploitable in future.

Among other activities in the water sector, the cooperation projects on groundwater resources in Southern and Northern Jordan finally led to a countrywide hydrogeological database. The projects were jointly conducted by the Federal Institute for Geosciences and Natural Resources (BGR) and the Water Authority of Jordan (WAJ), respectively the Ministry of Water and Irrigation itself, Amman.

The Southern and Northern Jordan models are fairly generalized numerical groundwater flow models for the entire system. They have been set up to improve the understanding of the overall hydraulic situation in Southern and Central as well as in Northern Jordan. In contrast to these, the Siwaqa-Qatrana-Hasa model has been prepared for the detailed study of the effects of groundwater withdrawal from the A7-B2 limestone aquifer in central Jordan. This type of model was aimed to be used as an efficient tool for well field management.

The groundwater model area Siwaqa-Qatrana-Hasa is located in the western highlands (900 to 1200 m above sea level) of Jordan some 50 km south of Amman. The well fields abstract groundwater from the A7-B2 limestone aquifer and meet a considerable proportion of the water requirements of Amman, approximately 11 to 15 MCM/a. Relatively large quantities (10 to 18 MCM/a) of groundwater are supplied to the phosphate industry near Hasa and Abiad and to local irrigation schemes. The model covers an area of about 5,700 km^2. In contrast to the deep sandstone complex the groundwater flow of the A7-B2 limestone aquifer is directed from recharge areas in the western highlands to the north-east towards Wadi Sirhan.

The main model results confirmed that water table drawdown continued since 1984 and reached 20-30 m after 10 years and 30-40 m after 20 years in the main well fields. It was obvious that groundwater withdrawal created a mining situation. Based on these results a strategy for a more sustainable groundwater abstraction was developed. Due to severe water shortages in Amman, the Water Authority of Jordan was not able to follow these recommendations during the next few years.

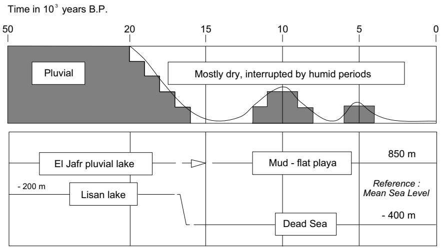


Under natural conditions the groundwater flow is characterised by short-term groundwater exchange at the shallow part of the upper aquifer system (recharge and seepage, springs) and by the long-term regional groundwater flow through the deep sandstone complex (fossil groundwater).

The depression of the Dead Sea forms the regional base level for the flow system in the deeper aquifer.

The model calculates the groundwater recharge in relation to the depth to water table (dynamic boundary condition) and in relation to the potential recharge rate, which depends on the precipitation and on the outcropping hydrogeological units.

Fig. 3.7.2. General sketch of the flow system.



The „South Jordan - Natural Aquifer Depletion Model" was planned as an overall evaluation of the groundwater potential of Southern Jordan with respect to the natural development of the aquifer system on a long term.

The calculations were based on the assumption that the whole system was filled with water at the end of the last humid period, approximately 5000 years ago.

Fig. 3.7.3. Long-term development of climate and surface water levels in the larger investigation area (after Ferrand).

It could be shown that the aquifer system in Southern Jordan is continuously under depleting conditions with a time-dependent decreasing outflow rate. The groundwater system is affected by the Wadi Sirhan depression at shallow to medium depths and by the Dead Sea at greater depths. The model gives a rough picture of the time-dependent behaviour of the flow system and the available groundwater resources in Southern Jordan. The calculated present distribution of groundwater levels compares fairly well with recent measurements of the groundwater level in the deep aquifer (Fig. 3.7.4). Since groundwater level observations are missing in larger areas of the model domain, a real calibration was not yet possible. Therefore, the model was one possible but plausible representation of the system.

The project „Groundwater Resources of Northern Jordan“ can be considered as a complement to the South Jordan Project. As part of the assessment of the groundwater resources, a flow model was developed that incorporates all major aquifers

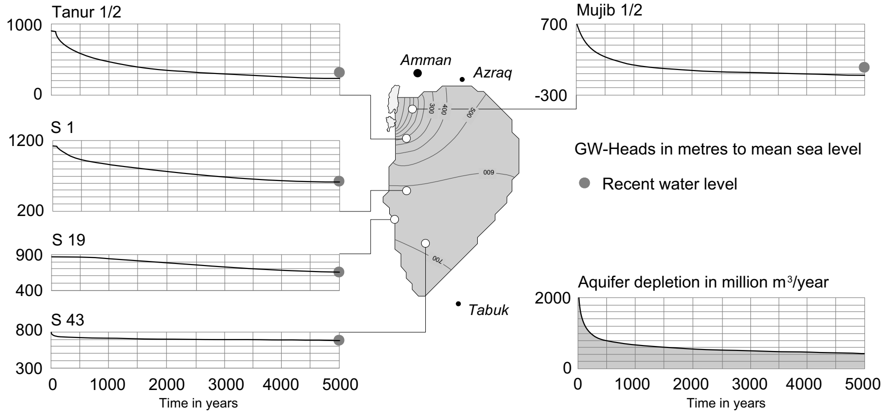


Fig. 3.7.4. Calculated groundwater-head contours of the deep sandstone complex as results of the three-dimensional South-Jordan model. After 5000 years of continuous depletion the calculated heads are close to the monitored water levels. During the recent time the calculated groundwater flow to the Dead Sea amounts to about 400 MCM annually.

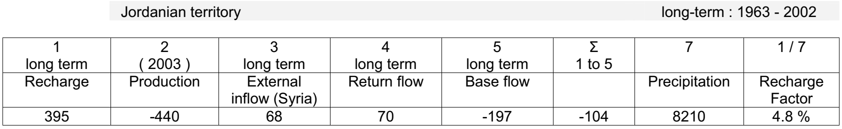
of northern Jordan. Other than with the more generic South Jordan model, the intention was to create the model as an instrument for advising the Water Authority in the safeguarding and improvement of the drinking water supply of Jordan.

3.7.2 Comprehensive groundwater model GSMO (NWMP)

Based on rough assumptions, the total potential groundwater resources in Jordan might be in the range of about 185,000 million m^3, giving the impression that enormous reservoirs of groundwater are available. Besides the general hypothetical background of such „magic“ figures, the exploitation of groundwater is restricted by several factors, as for example: the water quality, the depth of drilling (high drilling and pumping costs) and the distance between the areas of groundwater production and the areas of consumption, and of course less favourite hydrogeological situations at a local or regional scale.

The annual water demand (1200 million m^3 in 2002) is covered by surface water and groundwater, extending the sustainable annual rate of 750 million m^3 in total. The combined sustainable yield from rechargeable aquifers is about 395 million m^3 per year. The National Water Master Plan describes these deficits in the country-wide water balance in relation to the renewable groundwater resources referring to long-term hydrological records (from the MWI data base during the time period 1963 to 2002) and to recent groundwater production rates. In addition to the

Table 3.7.1. Mean annual budget of renewable groundwater in million m^3 Source: NWMP - MWI (2004). Source: NWMP - MWI (2004).



Jordanian territory long-term : 1963 - 2002

1 long term	2 (2003)	3 long term	4 long term	5 long term	Σ 1 to 5	7	1 / 7
Recharge	Production	External inflow (Syria)	Return flow	Base flow		Precipitation	Recharge Factor
395	-440	68	70	-197	-104	8210	4.8 %

groundwater production from the renewable resources about 80 million m^3 of fossil groundwater are annually abstracted from the sandstone aquifer (upper Ram group) in the southern region of Jordan.

Based on the long-term mean precipitation of about 8210 million m^3 and on the mean annual groundwater recharge of about 395 million m^3, a groundwater recharge factor is calculated to be in the range of up to 5 % (Table 3.7.1).

3.7.3 Model design and simulation

The GSMO (groundwater flow simulation model) program code allows the three-dimensional transient flow simulation in accordance to the Darcy-flow concept and refers to boundary conditions given either in terms of heads (constant head boundaries) or in terms of volumes (e.g., external groundwater inflow or abstraction). A variable triangular grid is used for the geometrical discretisation.

Shape and extension of the model area are adapted to a partially assumed groundwater flow pattern representing the deep sandstone complex. This flow pattern is based on groundwater head observations at several places in Jordan and includes head data (predominantly related to the southern region) from other external sources of information.

The numerical model incorporates all identified hydrogeological units from the basalt on top of the system down to the basement complex. It is assumed that the major groundwater flow follows a two-dimensional horizontal flow pattern, and vertical interflow through the units (up- or downwards directed leakage) is possible.

The hydrogeological structure maps originate from different sources, whereas important input for the model was derived from previous project results (groundwater resources projects in Southern and Northern Jordan). The structure contour lines for parts outside of Jordan mainly refer to extrapolations. The hydrogeological (conceptual) model matches with the lithological descriptions from a number of deep boreholes and includes also the major faults. For the deeper part of the system (below the Kurnub sandstone unit 006) the isopaches maps prepared by the NRA (National Resources Authority, Ministry of Energy and Mineral Resources) have been used in order to complete the hydrogeological model down to the basement complex.

Table 3.7.2. Stratigraphical units and their hydraulic significance.

	Group	Formation		Lithology (simplified)			Mean Hydraulic Conductivity in m/day
			BS	Basalt	001	AQ	20
TERTIARY	BELQA	Shallala	B5	marl, limestone	002	AQ	5
		Umm Rijam	B4	limestone			
UPPER CRETACEOUS		Muwaqqar	B3	Marl	003	AT	0.5
		Amman – Al Hisa	B2	Limestone	004	AQ	1
		Wadi Umm Ghudran	B1	marl, limestone			
	AJLUN	Wadi as Sir	A7	Limestone			
		Shuayb	A5/6	marl	005	AT	0.5
		Hummar	A4	limestone AQ			
		Fuheis	A3	marl			
		Naur	A1/2	marl, limestone			
LOWER CRETACEOUS	KURNUB	Subeihi Aarda	K	Sandstone	006	AQ	0.5
JURASSIC	ZARQA	Azab	Z_{01}	Silt-, sand-, limestone	007	AQ	1
TRIASSIC		Ramtha	Z_{02}	Silt-, sandstone, shale, limestone, anhydrite, halite			
PERMIAN		Hudayb	Z_{03}	Silt-, sandstone, shale, limestone			
SILURIAN	KHREIM	Alna	K_{01}	Siltstone, sandstone, shale	008	AT	0.0015
		Batra	K_{02}	Mudstone, siltstone			
		Trebeel	K_{03}	Sandstone			
		Umm Tarifa	K_{04}	Sandstone, siltstone, shale			
ORDOVICIAN		Sahl as Suwwan	K_{05}	Mudstone, siltstone, sandstone			
	RAM	Amud	R_{01}	Sandstone	009	AQ	2.5
		Ajram	R_{02}				
CAMBRIAN		Burj	R_{03}	silt-, sandstone, dolomite	010	AQ	2.5
		Salib	R_{04}	sandstone			
PRECAMBRIAN		Basement Complex		Clastics, volcanics, granite			

Hydraulic significance : AQ = Aquifer AT = Aquitard

Sources: Margane, A. et al., (2002); Contributions to the Hydrogeology of Northern Jordan; Andrews, I.J. (1991, 1992) Subsurface Geology - The Hashemite Kingdom of Jordan, Ministry of Energy and Mineral Resources

The calibrated values of the hydraulic conductivity K are in general within the range of the values as derived by previous model estimations. Modifications have become necessary for the units 005 and 007. For the unit 007 (Zarqa formation) the mean value of K has been increased in the model from 0.1 to almost 1.0 m/day. Slighter modifications have been carried out to the unit 005 (A1/A6), which has been considered so far as an extremely low conductive aquitard. As the A1/A6-formation includes the A4-formation with a rather productive groundwater potential the K-value of the unit 005 has been slightly enlarged.

The long-term precipitation (rainfall and snow) pattern is considered as a basic model input and is assumed as being valid throughout all the years simulated. This assumption has been made despite the fact that the areas, receiving major quantities of precipitation, might differ from year to year. For a simulation close to the real annual distribution of precipitation the exact and countrywide coverage with data would have been needed for all simulated time periods. In order to overcome this problem, the annual fluctuations of the total amount are incorporated into the transient flow simulations by applying the quotient of annual precipitation divided by long-term mean.

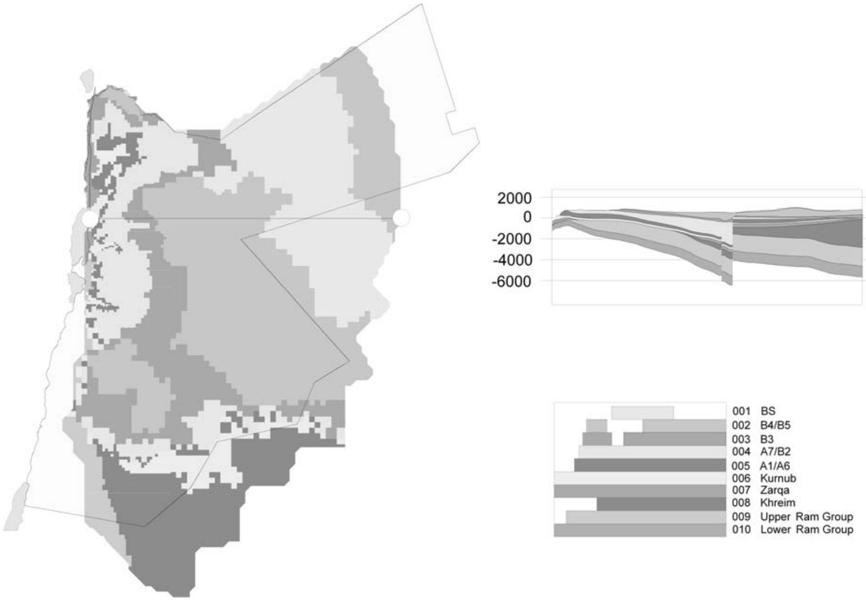


Fig. 3.7.5. Hydrogeological model: Outcrop areas and one selected cross section of the stratigraphical units as incorporate in the simulation model - coding refers to Table 3.7.2.

The long-term mean value of the precipitation amounts to 8326 MCM (million m^3) from 1938 - 2003 and to 7639 MCM during the time period 1980 – 2003. High precipitation rates occur predominantly in the relatively high elevated areas of North and Central Jordan and at the slopes of the Jabal Arab.

The potential groundwater recharge has been set into relation to the annually fluctuating model-precipitation and considers also the receiving soil / rocks. In relation to the outcropping hydrogeological unit higher rates are allowed for aquifers and lower values for aquitards, respectively. In the model, groundwater is recharged during the season from November to April gradually with a climax in January/February.

For each stress period the model delivers the hydraulic heads and the corresponding recharge rates in case that the corresponding model cell represents water table conditions. The calculated recharge might reach values equal to the potential recharge at a maximum. At cells where the water table intends to be higher than the land surface seepage (discharge) is calculated.

Major quantities of groundwater are abstracted from the A7/B2 limestone aquifer increasing from roughly 100 MCM in 1980 to almost 300 MCM in 2002. The production of fossil groundwater extracted from the Disi aquifer amounts to about 80 MCM in 2002.

A reasonable amount of groundwater is flowing from the basalt complex in the north (Jabal Arab) into the Jordanian aquifer system. A total amount of about 68 MCM per year has been assumed in the model as a constant inflow related to the relevant model cells of the units 001 (Basalt), 002 (B4/B5) and 004 (A7/B2) and gradually distributed to the groundwater basins of Amman-Zarqa, Azraq and Hammad (north-east). Additionally, the recent estimations about return flow from irrigations have been incorporated into the model. The return flow with relevance to the model area (note that the Jordan Valley basin is not included) amounts to 42 MCM/year.

The initial hydraulic situation is the result of a model groundwater head calculation and forms the basis for further simulation runs including the model calibration. This calculated situation should reflect the quasi steady state behaviour of the aquifer system under natural conditions, despite the fact that of course groundwater has been abstracted in Jordan before 1975.

A rather plausible initial hydraulic situation has been simulated under the assumption of the recent recharge conditions as derived from the long term mean annual precipitation. In relation to the aquifer parameters the aquifer system has been replenished in the simulation model within a period of hundreds to thousands years by this backwards orientated procedure until reaching a balanced quasi steady state.

In general, the model results are in a good accordance with the available information (e.g. on hydrographs), both in gradients and heads. Especially for the unit 001 (Basalt) in combination with unit 002 (B4/B5) and for unit 009 (upper Ram / Disi) the fitting between model results and observations has reached a high level. Sufficiently good accordance is to be reported for the other units. Under the view of regional aspects the results are considered as being plausible and acceptable.

Besides this, interesting side effects could also be obtained by the simulation of the deep sandstone complex, for instance in relation to travel time and with respect to previous estimations of the groundwater flow into the Dead Sea. Even under different geometrical aquifer conditions and for different values of effective porosities the calculated travel time for neutral particles in the deep sandstone reaches time periods of more than 20.000 years which is confirmed by results from the isotope hydrology for deep wells in the Qatrana area (Almomani et al., 2002), also indicating that vertical leakage into the deep system might be negligible.

3.7.4 Groundwater budgets

The groundwater flow components calculated by the model refer to the entire groundwater system including also the reservoirs of non-renewable groundwater. For the reason of the comparison of these model budget results to the findings from other investigations, the part of the rechargeable aquifer system is separated and extracted from the comprehensive model complex, consequently.

For each simulation run an external groundwater inflow of 68 MCM from Syria (equal to the values estimated by NWMP) is taken into consideration, as well as a total return flow from irrigation, etc. of 42 MCM, which is smaller than the NWMP-values, because the Jordan Valley is not included into the model as part of the shallow aquifer system.

The annual inflow from the north-eastern direction through the deep sandstone amounts to about 60 MCM. This complex is composed of the Kurnub (006) and Zarqa Group (007) formations. At the even deeper formations and below the Khreim aquitard another 30 MCM are flowing into the aquifer system through the Upper Ram Group (009). Due to the great drilling depths the deep groundwater flow is practically without any relevance for the water management of this region.

The groundwater discharge from the Zarqa Group (007) into the Dead Sea is calculated to be recently in the range of 1 MCM annually. As an effect of the groundwater exploitation from the Zarqa aquifer the calculated discharge decreased by 1 MCM since 1976. Under the assumption of hydraulical contacts of the Upper Ram Group to the Dead Sea totally about 210 MCM of groundwater are flowing into the Dead Sea annually through this formation. This amount of 210 MCM is comparable to the previous model results from the Southern Jordan Model (natural depletion) where no groundwater production is considered.

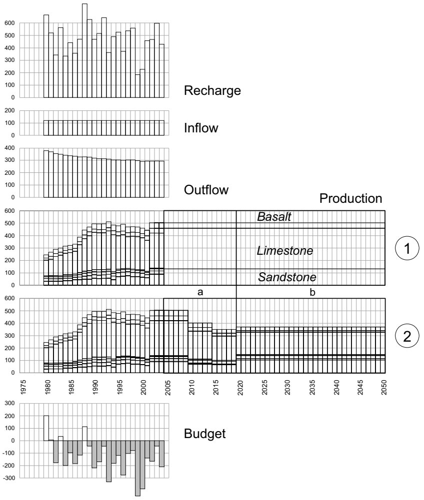
At the southern model boundary outside the Jordanian territory a relatively high inflow via the Disi aquifer of the Upper Ram Group is calculated. The average value is in the range of about 300 MCM per year. The calculated increase of the inflow of about 20 MCM during the last 30 years is recognised as being an indicator for the influences caused by the groundwater production in the Disi (and Mudawwar) area.

The calculated budgets for the time period from 1980 to 2004 show the dominant role of precipitation on the entire aquifer system. The seasonal fluctuations result in a long-term mean groundwater recharge of about 477 MCM with 185 MCM (in 1999) at a minimum and more than 700 MCM (in 1988) at a maximum which of course is responded by the aquifer system by the annual variations of the natural discharge (seepage). Due to the increasing groundwater production the seepage is decreasing continuously from about 370 MCM down to about 290 MCM (Table 3.7.3).

Table 3.7.3. Mean annual budget of renewable groundwater in million m^3 GSMO model result. Model area does not match with the Jordanian territory long-term : 1980 – 2004.

Model area does not match with the Jordanian territory long-term : 1980 - 2004

1 long term	2 long term	3 long term	4 long term	5 long term	Σ 1 to 5	7	1 / 7
Recharge	Production	External inflow (Syria)	Return flow	Base flow		Precipitation	Recharge Factor
477	-410	68	42	-312	-135	7418	6.4 %



Prognosis runs

Two scenarios in relation to future groundwater production have been simulated until the year 2050.

unreduced production rate until 2050

stepwise modified groundwater production as proposed by the NWMP until 2020 and constant after 2019

The recent mean annual precipitation and consequently the potential recharge conditions are assumed to be representative also in future until 2050.

Fig. 3.7.6. Groundwater Flow Simulation – Prognosis runs with assumed groundwater production.

As the long-term mean annual deficit in the groundwater balances amounts to -135 MCM in total also a surplus is calculated at the beginning (1980s) and during the exceptionally high rainfall season in 1988.

3.7.5 Groundwater prognosis

Production scenario 1: Under the assumption of a continuously unreduced production rate there will be a further continuous drawdown of all water tables. The additional regional drawdown will be in the range of up to 5 m for the B4/B5 (002) aquifer and of up to 10 m for the Disi (009) sandstone aquifer from 2005 to 2019, followed by an additional drawdown of 4 m (002) and 11 m (009) from 2019 to 2050. The additional regional drawdown for the limestone aquifer (004) might reach up to 40 m during 45 years, which most probably will cause a certain well exhaustion at some locations.

Production scenario 2: The simulation HEAD-02 (stepwise modified groundwater production as proposed by the NWMP) will also lead to further regional drawdown in general. However, also some recovery can be expected in future. This will happen in the Azraq-Wadi Sirhan area reaching values of recovery of about up to 10 m. In contrast to this, the sandstone (009) aquifer will be more stressed by extended groundwater production. In terms of additional regional drawdown the water table might drop by 13 m until the year 2019 because of intensive pumping from the deep wells in the central area (Lajjun). Another additional regional draw-

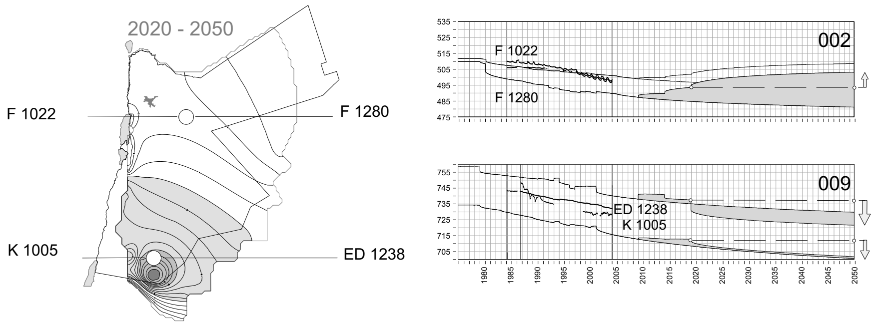


Fig. 3.7.7. Prognosis: Examples of calculated additional groundwater head drawdown in the deep sandstone complex caused by the future production of non-renewable groundwater between 2020 and 2050 (009). Reduced groundwater production from the Basalt and B4/B5 limestone aquifer might create a recovery of the groundwater table (002).

down of about 24 m has been calculated until 2050 as the result of future extended groundwater production in the Disi area. This expected drawdown also indicates that the cone of depression will extent to the south.

3.7.6 Conclusions

As seasonal precipitation recharges the groundwater, further sequences of drought situations as they might be caused in this region by climate changes would create severe problems for the national water supply.

The large-scale simulation of the groundwater system in Jordan has reached a calibrated status that enables the user to calculate groundwater heads and budgets at any location of the model aquifer system. Besides this, there is the feasibility of prognosis calculations at a regional scale, e.g. the calculation of drawdown and of the corresponding budget within groundwater basins and with respect to national management activities.

Considering groundwater modelling as an active and dynamic tool of the groundwater management, it is understood that a continuous up-dating is necessary with respect to water level observations and to exploration data on local geology. Major improvements of the model may be reached by incorporating hydrogeological information and data from areas, where the model mainly depends on assumptions.

As the groundwater system in Jordan expands to the three neighbouring countries Syria, Iraq and Saudi Arabia common activities should form the basis of common hydrological and geological understanding for an internationally shared groundwater resources management and might lead to a commonly shared benefit. Further information might enable and accelerate discussions on the selected model boundaries and the corresponding groundwater flow (e.g. in the basalt aquifer at the southern slopes of Jabal Arab or in the larger Wadi Sirhan area).

References

Ferrand, W.R. (1971) :Late Quaternary Paleoclimates of the Eastern Mediterranean Area in : The Late Cenozoic Glacial Ages, edited by Karl K. Turekian, New Haven and London, Yale University Press.

Andrews, I.J. (1991): Bulletin No. 2: Palaeozoic Lithostratigraphy in the Subsurface of Jordan
(1992): Bulletin No. 4: Permian, Triassic and Jurassic Lithostratigraphy
(1992): Bulletin No. 4: Cretaceous and Palaeogen Lithostratigraphy
The Hashemite Kingdom of Jordan, Ministry of Energy and Mineral Resources, Natural Resources Authority (NRA)

Hobler, M., Bender, H., Rashdan, J. & Schmidt, G. (1991): Groundwater Resources of Southern Jordan, Vol. 1-5.- Report prepared by Federal Institute for Geosciences and Natural Resources (BGR) and Water Authority of Jordan (WAJ), Technical Cooperation Project 'Groundwater Resources of South Jordan', BGR-Archive File No. 108 652 and 107 375, Hannover, Amman.

Almomani, M., Subah, A. et al. (2002): Environmental Isotope Application for Groundwater Utilisation, IAEA-Project, RAW/8/007. The Hashemite Kingdom of Jordan, Ministry of Water and Irrigation (MWI), Amman

Schmidt, G., Plöthner, D. & Mösta, W. (2002): Re-evaluation of the Siwaqa-Qatrana-Hasa Groundwater Flow Model.- Report prepared by Federal Institute for Geosciences and Natural Resources (BGR) and Water Authority of Jordan (WAJ), Technical Cooperation Project 'Validation of Groundwater Flow Models', BGR-Archive File No. 122 069, Hannover.

Almomani, M., Hobler, M., Margane & A., Subah, A. (2001): Groundwater Resources of Northern Jordan, BGR-Archive File No.: 112 708, Hannover, Amman.

Almomani, M., Hobler, M., Margane & A., Subah, A. (2002): Constribution to the Hydrogeology of Northern and Central Jordan, Geologisches Jahrbuch, Reihe C, Heft 68, 52 S.

Schelkes, K.; Hobler, M.; Schmidt, G. & Steinbach, V. (2004): Management, Protection and Sustainable Use of Groundwater – Results of Long-Term Technical Cooperation in the Middle East. - F. Zereini & W. Jaeschke (Hrsg.): Water in the Middle East and in North Africa: Resources, Protection and Management.

NWMP - National Water Master Plan (2004) - The Hashemite Kingdom of Jordan, Ministry of Water and Irrigation (MWI).

Schmidt, G. (2005): GSMO - Groundwater Flow Simulation Model - Contribution to the National Water Master Plan, Technical Cooperation Project 'Groundwater Resources Management', BGR-Archive File No.: 125 920, Hannover, Amman.

3.8 Seawater Intrusion in Greater Beirut, Lebanon

Mark Saadeh

3.8.1 Introduction

Seawater intrusion in the coastal aquifers of Greater Beirut has been largely a direct consequence of years of water mismanagement further exacerbated by a civil war which devastated the country for more than fifteen years. Significant and potentially irreversible deterioration of the quality of subsurface water in Greater Beirut continues, due to extensive aquifer over-abstraction by a population that probably exceeds one and a half million, causing the hydraulic gradient to reverse and encourage seawater encroachment.

Concurrent urban growth, and repeated natural drought conditions has amplified this phenomena. Seawater intrusion into Beirut's aquifers has mainly rendered the subsurface water unsuitable for any purpose (raising the salinity in some monitored wells to thousands of milligrams per liter).

In 2004, the World Bank published the Cost of Environmental Degradation (COED) report for Lebanon. The report indicates that the costs in the year 2000, was in the range of USD 565 million or 3.4 % of the GDP. Furthermore, the degradation of the country's coastal zone is the highest in the Mediterranean region.

The Ministry of Energy and Water (MoEW) is the authority responsible for the management of water resources in Lebanon, including coastal aquifers of as Greater Beirut. This ministry should set a clear strategy for developing solutions to mitigate the phenomenon of seawater intrusion along the entire Lebanese coast and not just Beirut.

3.8.2 Coastline overview

The unique coastline of Lebanon is characterized by low relief with a sharp increasing altitude as the western mountain range in the east is rapidly approached. The length of the entire coast of Lebanon stretches to about 200 km with about nearly 70 % of the population concentrated there and placing enormous stress on the limited available coastal water budget. The exposed aquifers of Lebanon cover an area of about 7,000 km^2 or 70 % of the total area, of those aquifers, 51 % belong to the Cretaceous, 15 % to the Jurassic and the remaining 2 % to the Eocene Period (Ghattas, 1975).

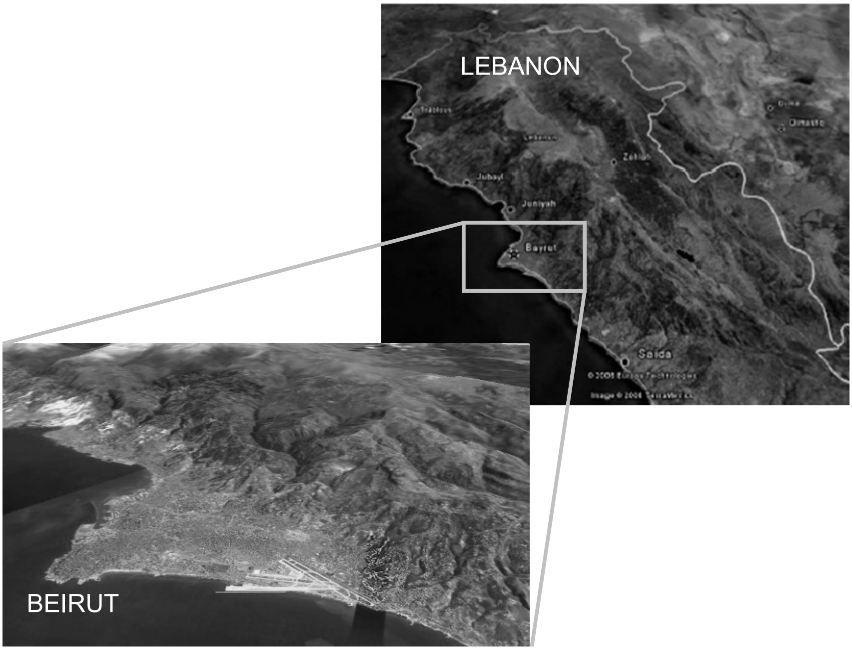


Fig. 3.8.1. Map of Lebanon and Beirut (Google Earth, 2005, not to scale).

Limestone karstification along the coast of Lebanon occupies about 70 % of the area (or nearly 3500 m2) and is heavily dissected with dense fault systems. The relatively high precipitation rate (average 900 mm) coupled with seaward dipping steep slopes and bedding planes, are conducive of a high loss rate in surface and ground water resources (Shaban, 2003).

The study area in particular, is dissected by numerous fractures which include faults, fissures, and joints, oriented in various directions as can be clearly seen in Fig. 3.8.2.

Among the seventeen different geological formations known in Lebanon, three are considered excellent aquifers, three are generally classified as being aquiferous, while the remaining formations are aquicludes. The aquifers of Lebanon are generally composed of dolomitic limestones to limestone while the aquicludes vary in composition from sandstone to marlstone.

The karstic aquifers prevalent in Lebanon, mainly consist of calcium carbonate and dolomitic rocks formed by the deposition of marine shells and corals. The primary porosity and permeability are low to moderate. Subsequent fractures and fissures make up the so called secondary porosity and permeability which is much more considerable.

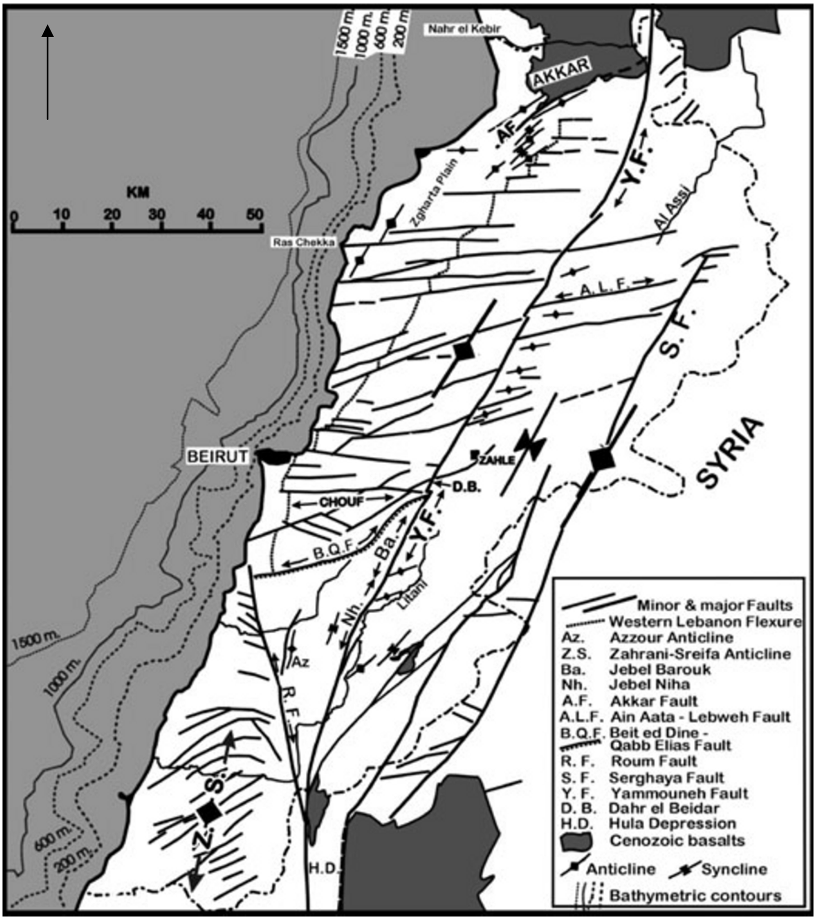


Fig. 3.8.2. Geological Faults of Lebanon (Walley, 2003).

In general, the greater the outflow of karst springs, the lower the salinity of the outflow water. Mixing of fresh and saline water takes place rapidly, rendering the out-flowing fresh water unfit for use. Mixing of fresh and saline water in karst regions takes place under a completely different regime compared to a homogeneous and isotropic porous media. Connective flow of fluids, not hydrodynamic dispersion, dominates the physical mixing. Thus the fresh-saline relationship in karstic regions only partly follows the Ghyben-Herzberg principle discussed in later sections. Altogether, description of this feature with mathematical formulas is complex or even impossible, unless very rough assumptions are permitted (Cotecchia, 1997).

Table 3.8.1. Average Monthly Precipitation and Temperature in Beirut (Central Administration for Statistics, 2004/5).

Precipitation (mm)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept	Oct.	Nov.	Dec.	Annual Total
2004	202.4	179.8	12.0	5.6	3.6	--	--	--	--	10.0	190.6	77.2	681
2005	127.1	92.6	40.0	19.0	8.7	1.0	0.4	--	--	119.5	114.6	136	659
Temperature (^{0}C)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept	Oct.	Nov.	Dec.	Annual Average
2004	15.2	16.2	17.7	21.1	26.1	24.8	26.9	27.3	27.8	26.6	19.4	15.1	22.0
2005	18.5	15.7	19.9	22.1	23.1	24.6	26.5	27.2	27.9	23.5	18.9	17.0	22.0

3.8.3 Meteorological data

A strong correlation was observed between Na^+ and CL^- in coastal precipitation as well as a strong correlation between sulfate and other elements of marine origin, which indicates that the Mediterranean Sea is the origin of these aforementioned elements in rain (Saad et. al., 2002).

The annual average precipitation in Beirut ranges from 800 to 900 mm between November and February (Majdalani, 1997), yielding about 495 million cubic meters (MCM) with nearly half lost to evapotranspiration (Shaban, 2003). The rest of the country receives more or less the same amount of precipitation depending on the local geomorphology.

The average monthly precipitation and temperature data for the years 2004/05, are presented in Table 3.8.1 below, and obtained on-line from the Central Administration for Statistics in Lebanon. This public service site includes meteorological data prepared by the Beirut International Airport as well as other locations throughout the country.

As can be noticed from the following figure of temperature versus precipitation variations in Beirut during 2005, the relative dry period would be between the months of March to September when the temperature curve exceeds the precipitation one for a reasonable period of the year. It is during this period, that the phenomena of seawater intrusion is magnified. It is noteworthy to mention that the dry months according to some sources (Koumair, 2005) extend between July and October. However, it is evident from the following figure that dry months for 2005, extended roughly between April and October. Longer than many recent estimates.

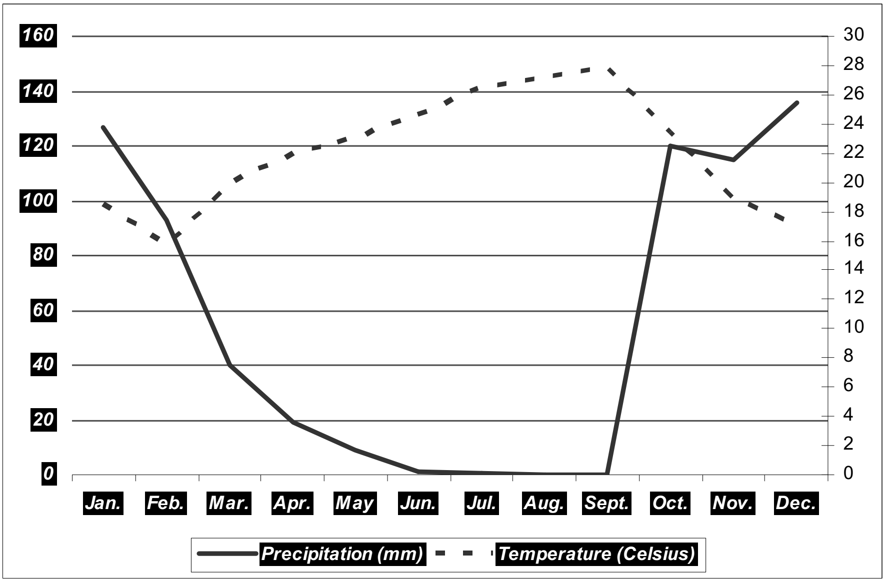


Fig. 3.8.3. Precipitation and Temperature Variations in Beirut, 2005.

3.8.4 Water budget

Lebanon, also known during the French Mandate as „Chateau d'eaux", has a surface area of 10,452 km^2, with a typical Mediterranean climate, and is considered among the most water rich countries in the Middle East. However, there is a conflict in the estimations of this precious resource, but most would agree that Lebanon's water reserve is under stress incurred mainly by a population that is growing at an average rate of 2 %.

According to many sources (CDR, 1997; UNDP & FAO, 1983; Jaber, 1995 and others), the renewable water resources in Lebanon (about 9000 MCM/ year from precipitation) are broadly classified as follows:

- 3500 MCM/ year flowing waters in 15 perennial rivers,
- 1250 MCM/ year flowing waters issuing from about 850 springs,
- 1350 MCM/ year estimated subsurface water resources.

Koumair (2005) estimated the total amount of water which Beirut and surroundings would require by the year 2030 will be in the range of 778 MCM (for domestic, industrial and agricultural purposes), however, these water requirements would be divided between agricultural consumption (15 %), industrial (20 %), and domestic (65 %).

During the dry period, the water need for domestic and other purposes are generally estimated to be around 25 L/capita/day, whereas during the rainy season, the estimated average could drop to about 200 L/capita/day or even less. Considering

Table 3.8.2. Water Budget in Beirut (Beirut Water Authority).

Beirut Water Budget	Available (m^3/day)	Delivered (m^3/day)	Demand (m^3/day)	Deficit (m^3/day)
Winter (7 months)	283,300	198,000	303,941	106,000
Summer (5 months)	183,000	128,000	303,901	176,000

Table 3.8.3. Water Storage in Beirut (Shaban, 2003).

Source	Surface Storage in Rivers (MCM/ year)	Springs' Discharge (MCM/ year)	Surface Storage in Lakes & Ponds (MCM/ year)	Greart Subsurface water Storage (MCM/ year)
Beirut	99	142	0.56	42

that Beirut's current population is estimated at 1.5 million, then the total required amount would be no less than 110 MCM annually. As for agricultural and industrial demand for water, the quantities required by Greater Beirut are insignificant in comparison to the total current domestic requirements.

The Beirut Water Authority has issued the following estimates for Beirut's water budget in recent years, summarized in the Tables 3.8.2 and 3.8.3.

3.8.5 Effects of seawater intrusion

As already mentioned, the devastating effect of seawater intrusion on a coastal urban center that relies heavily on its coastal aquifer is threefold, potable water, irrigation, and construction.

As for Lebanon, the most severe impact of seawater intrusion, would be on the quality of potable water, which is mainly abstracted from aquifers. Lebanon's coastal seawater contains approximately 22,000 mg/L of chloride. Therefore, it is evident that even a small amount of seawater intrusion can cause drinking water problems when mixed with fresh water aquifers such as the Miocene, Quaternary and Cretaceous which predominate in Greater Beirut.

A thesis completed by M. Abbud in 1986, entitled „The Aquiferous Formations of Lebanon through the Chemistry of their Typical Springs“, states that of all the aquiferous formations, the Miocene limestone (which is a coastal aquifer) has the highest chloride content reaching 1,800 mg/L. Furthermore, all coastal aquifers of Lebanon are brackish, contaminated by sea water intrusion attested by elevated salinity concentrations.

Drinking water standards established by the United States Environmental Protection Agency (USEPA) require that drinking water contain no more than 250 mg/L for chloride (commonly measured as salinity) and sulfate each, and 500 mg/L of Total Dissolved Solids (TDS). Yet, several public and private wells sampled in the study area of Greater Beirut have revealed salinities and Total Dissolved Solids (TDS) above 5,000 mg/L especially in the heavily populated southern suburbs. Even back in 1986, during Abbud's study, the coastal Miocene formation also revealed high TDS values attested by seawater intrusion.

Accordingly, since the demand of water needs in Lebanon is allocated mainly to agricultural use (estimated at over 65 %), the first and major victim of seawater intrusion and thus elevated subsurface water salinity are crops (Moujabber, 2002).

Furthermore, elevated concentrations of sulfate in subsurface water associated with seawater intrusion, also has a definite laxative effect on humans. In this way, it can be troublesome especially to infants. In addition to its laxative properties, sulfate water can induce water hardness.

Chloride-rich water will also corrode metal pipes, causing leeching and will reduce the lifespan of household plumbing. According to the American Society for Testing and Materials, ASTM C-94 standard, water used for concrete mixing and curing places very stringent restraints on chloride, sulfate and TDS concentrations. Non compliance with said concrete standard has adverse repercussions by reducing strength and durability of concrete mainly through corrosion of embedded reinforcement. Many apartment buildings inspected by the author along the coast of Beirut, have exhibited corrosion of household plumbing and concrete reinforcement within as little as three years of construction, in most cases due to uncontrolled abstraction from brackish wells.

Reports indicate that salinity of coastal wells have been on the rise since it was seriously investigated for the first time in 1964 by a UN study entitled: Report on Geoelectrical Investigations in the South of Beirut. Said report forewarned of a detected seawater-freshwater interface progressing evermore inland if left unchecked.

Generally, most academicians and engineers believe that there are well over 10,000 wells tapping into the coastal aquifers of Beirut. As such, a study on seawater intrusion of Beirut indicated that chloride concentrations from 125 randomly sampled wells, have steadily risen from 340 mg/L in 1970/1, to 1200 mg/L in 1979, to over 4200 mg/L in 1985 (Khair, 1992).

It should be emphasized that the presence of elevated concentrations of chloride alone is not by itself definitive proof of active seawater intrusion. Seawater intrusion is however indicated by increase in the chloride concentration of water samples collected periodically over time, rather than by a single or several measurements at one point in time. In addition, increase in sulfate concentrations is another reliable indicator of seawater intrusion.

This research of Greater Beirut's subsurface water, reports salinities of over 5,000 mg/L in some public and private wells being utilized for various domestic, industrial and limited agricultural purposes. With such high levels of salinity in coastal wells, seawater intrusion would theoretically indicate a mixing of no less than 10 %, placing it way past the 2 % irreversible contamination limit (Barlow, 2003) which would render subsurface water unsuitable for public supply.

Increasing chloride (or salinity) concentrations may well be the first indication of the approach of a seawater contamination front. In an area where no other source of saline contamination exists, high chloride concentrations in subsurface water can be considered rather definitive proof of seawater contamination.

3.8.6 Results

As such, the only approach to monitor this lateral movement is by directly taking measurements of this interface. For the purpose of this article, many hydrochemical parameters were selected to achieve this objective but only the following will be presented.

Chloride

The element in the forefront of seawater intrusion detection is, unequivocally chloride. Any rise in subsurface water salinity is always a cause for concern, and subsequent remediation measures.

When seawater intrudes into coastal aquifers, a transition zone of fresh and seawater mixing emerges. The boundary between the freshwater and seawater is not a sharp interface, but a transition zone with a width controlled, in part, by the aquifer properties. The Greater Beirut aquifer were mixing is occuring, this zone is no exception.

Chloride concentrations exceeding 500 mg/L are generally considered to be evidence of contamination with seawater. Throughout the study, four wells have consistently stood out over the rest with chloride concentrations exceeding the 500 mg/L threshold, namely G3, G2, P10 and P1.

Furthermore, Bear et al, states that a 5 % contribution of seawater intrusion would raise the salinity of subsurface water to over 1000 mg/L in chloride. As such, since G3, G2 and P10 wells have continually exhibited salinity concentrations over 2,000 mg/L, this would simply imply that seawater intrusion may very well have exceeded 5 % mixing in the aquifers tapped by these wells.

Total Dissolved Solids

Other measured parameters corroborate the presence of an advanced mixing front between salt water and fresh water. Mainly, the corroborative parameter includes Total Dissolved Solids (TDS).

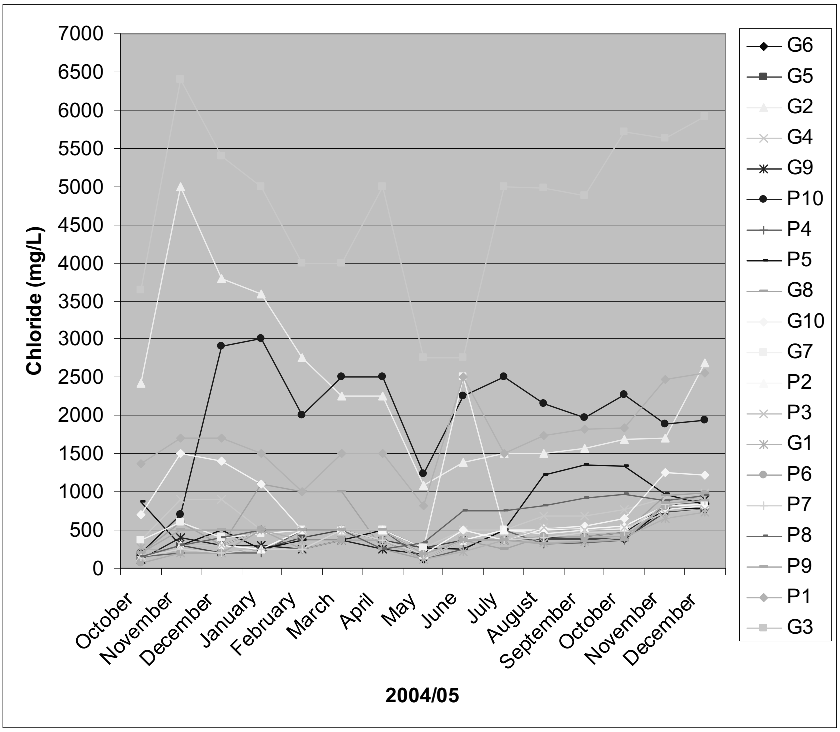


Fig. 3.8.4. Chloride Variations in Greater Beirut Wells.

From Fig. 3.8.5 for measured TDS values between October 2004 to December 2005, the fluctuations in said values closely conform to the previous ones on chloride concentrations especially true for the G3, G2, P10, and P1 wells which would provide further indication of potential mixing of seawater with fresh subsurface water.

The G3 well would be classified with respect to the TDS average concentration as moderately saline, rendering it suitable only for limited irrigation and livestock.

The G2 well with its average TDS in the range of 2,700 mg/L, would classify it as being slightly saline bordering on the moderately saline. Caution should be exercised when using said water for human consumption. The same would also hold true for P10 and P1 wells having similar TDS ranges.

Most of the remaining wells that were monitored during the study period are bordering on the fresh to slightly saline waters rendering them for the moment potable and useful for most domestic purposes.

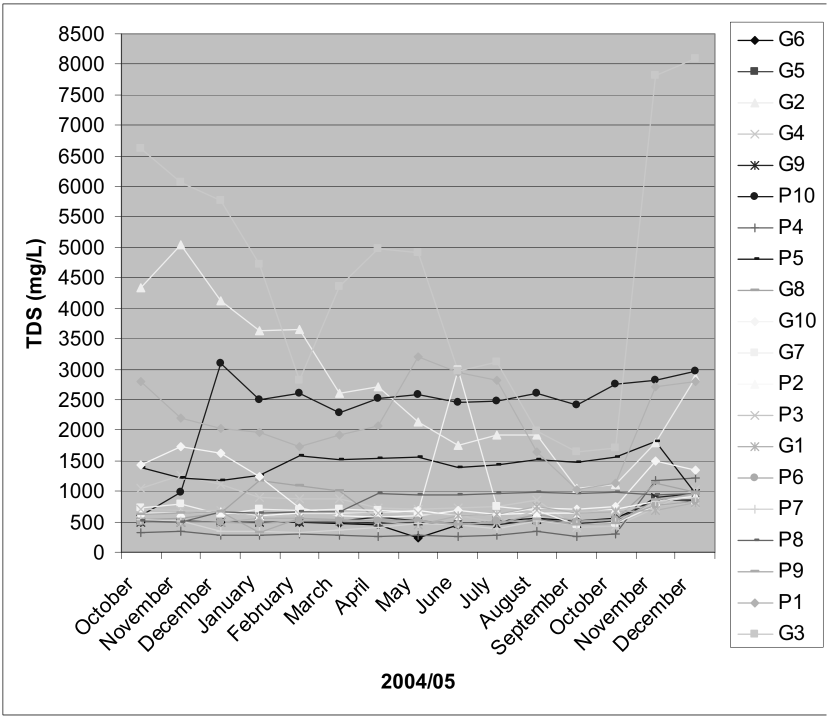


Fig. 3.8.5. TDS Variation in Greater Beirut Wells.

3.8.7 Conclusions

For the myriad reasons few today can dispute, Lebanon's climate is tending more to the semi arid, with drought periods imposing heavy taxes on the limited water resources in an already water scarce region.

With the ongoing trend of abstracting subsurface water beyond the safe yields of Lebanon's coastal aquifers, in order to combat said drought, the phenomena of seawater intrusion will impel Lebanon to one certain outcome; seawater desalination.

For the time being, the single most important element for staving off seawater intrusion, is by imposing a strict fee on coastal well abstractions. Progressive charges impose a self-control mechanism on the user and ensure that wasteful consumption is minimized. Penalties must be imposed for over-abstraction by the pertinent authorities, namely the Ministry of Energy and Water.

References

Abbud, Madeleine, 1986. Study of the Aquiferous Formations of Lebanon Through the Chemistry of their Typical Springs. Thesis, American University of Beirut, 108p.

Barlow, Paul, 2003. Ground Water in Freshwater-Seawater Environments of the Atlantic Coast: U.S. Geological Survey Water Resources Investigations Circular 1262, 120p.

Cotecchia, V., 1997. Karstic Coastal Aquifers. FAO Report; Seawater Intrusion: Guideline for Study, Monitoring and Control, 100p.

Council for Development and Reconstruction, Government of Lebanon, 1997. Regional Environmental Assessment Report on the Coastal Zone of Lebanon. Prepared by ECODIT-LAURIF, 250p.

Ghattas, Ilyas, 1975, The Geology and Hydrogeology of the Western Flexure of Mount Lebanon between Dbaiye and Jdaide. Thesis, American University of Beirut, 106p.

Khair, Kamal, et al., 1992. Hydrogeological Units of Lebanon. Geology Department, American University of Beirut, Lebanon, pp. 34-49.

Koumair, Fadi, 2005. Lebanon's Water: Between Loss and Exploitation. Dackash Publishing Company, 319p.

Majdalani, M., 1997. Seawater intrusion in the Cenomanian-Turonian Limestone Aquifers of Beirut. FAO Report; Seawater Intrusion: Guideline for Study, Monitoring and Control, 100p.

Moujaber, M. El, 2002.Assessment of Subsurface water Salination by Seawater Intrusion in a Typical Lebanese Horticultural Area. pp. 195-201.

Saad, Z. et. al., 2005. Chemical and Isotopic Composition of Rainwater in Coastal and Highland Regions in Lebanon. Journal of Environmental Hydrology. Vol.13, No. 29, Pp. 1-11.

Shaban, Amin, 2003. Hydrogeological Study of Occidental Lebanon: Through the Utilisation of Teledetection. PhD thesis. Bordeaux University, 200p.

3.9 Long Term (1970 – 2001) Eco–Hydrological Processes in Lake Kinneret and its Watershed

Moshe Gophen
MIGAL-Galilee Technology Center, Kiryat Shmone POB 831
Israel (11016)
Gophen@Migal.org.il.

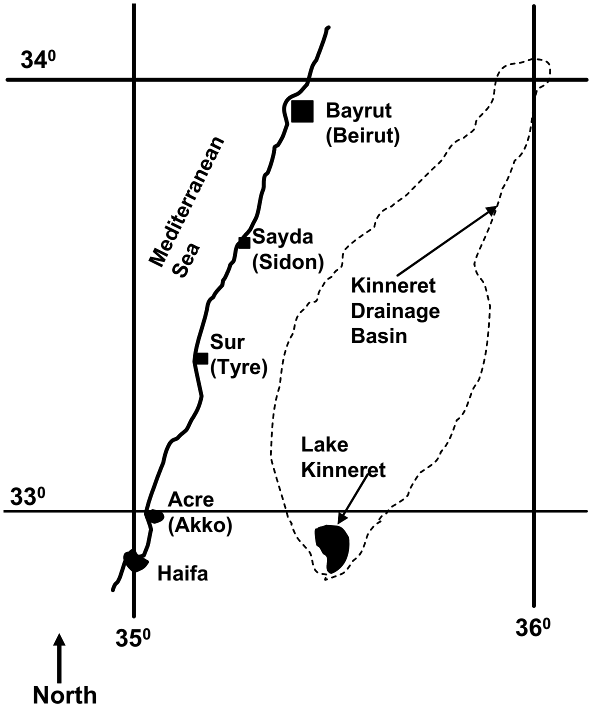
Introduction

Lake Kinneret (Sea of Galilee) is the only one natural freshwater lake in Israel. The lake is fed mostly (65 %) by Jordan river inflow from northern side and additional several smaller rivers from western, and eastern sides. The Kinneret-River Jordan system supply 16 - 30 % of the national water consumption and >50 % of the national drinking water demands. Therefore the Kinneret water quality is of a national concern (Gophen 2002; 2003b).River Jordan is crossing the Hula Valley (Maps 3.9.1, 3.9.2) before meeting the lake body of water. Consequently, human intervention in the ecosystem structure, climate changes significantly affect Jordan and Kinneret water quality. As a result of a long history of human activities and climate changes, ecological and limnological conditions of the Hula Valley and Lake Kinneret were changed. In this paper I present an ecological analysis of the Hula Valley and Lake Kinneret long term record aimed at evaluate man made and climate changes.

3.9.1 Background

Hula Valley (Maps 3.9.1, 3.9.2)

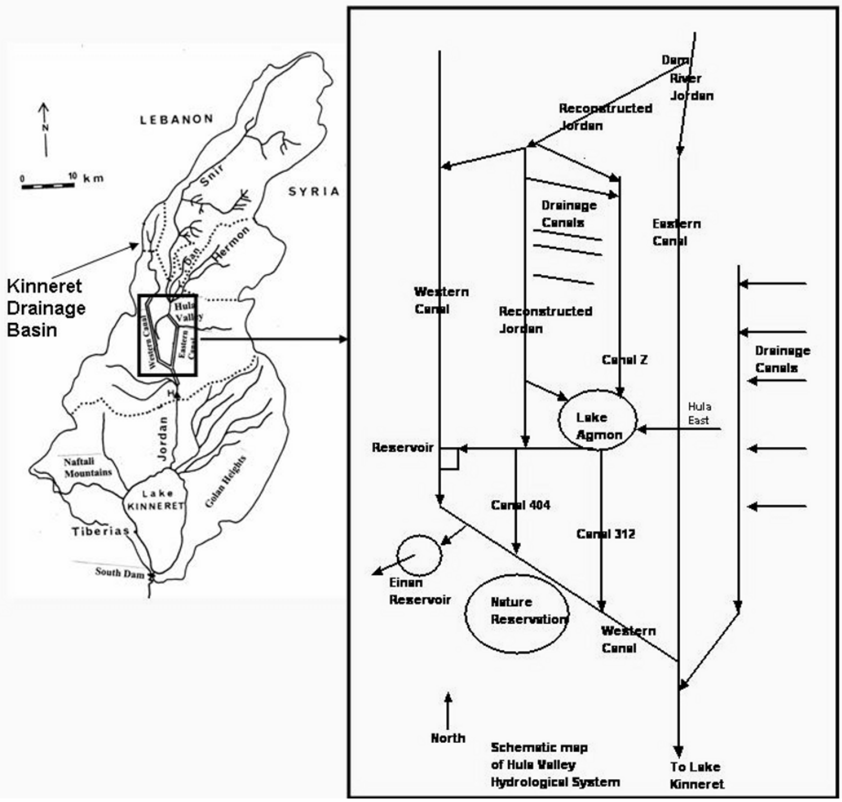
Until late 1950's, the Hula Valley was mostly occupied by old Lake Hula and swamps (Gophen 1998; 2002; 2003b). Most of this area was not cultivated, malaria was common, and densely covered by aquatic plants, mostly *Cyperus papyrus, Typha domingensis*, *Phragmites australis australis, Potamogeton spp. Ceratophyllum sp.* and others. As a result of a large area of uncovered water surface (old Lake Hula) and dense plant population (swamps), water loss by evapo-transpiration was high. Three major rivers, Hatzbani, Banyas and Dan, flow downstream from Mount Hermon in the north, joining together with several other streams, thus continuing to form the Jordan River (Rom 1999). During the 1950's, more than 6500 hectares of natural wetland areas and Lake Hula were dried, and converted to agricultural uses, which serve as an income source for residents of the Upper Galilee (Inbar 1982). Before Hula drying (1950's), the Jordan River crossed the swampy area by three major branches leading into old Lake Hula, and continued flowing into Lake Kinneret. After the drying the Jordan flow was shared between two



Map 3.9.1. Maps of the Lake Kinneret Watershed, the Hula Valley and the Hula Project area.

major newly constructed canals crossing the Hula Valley and joining at the south end of the Valley (Map 3.9.2). The Jordan River contributes about 70 % of total nutrient inputs, of which over 50 % originate in the Hula Valley region (Map 3.9.2).

Until late 1980's the dried area was successfully cultivated, and agricultural products were economically produced and the nutrient flux into Lake Kinneret did not threaten its water quality. Nevertheless, as a result of inappropriate management, the peat soil structure was damaged, consolidated and destructed, hence, influenced by frequent heavy dust storms. Consequently, subsidence of the soil surface occurs, and drainage canals were blocked, while underground fires were enhanced, together with rodent population outbreak, all of which caused severe damage to agricultural products (Levin and Shoham 1983; Neuman and Dasberg 1977; Sacham 1988). However, in some areas, agriculture lost its economic viability and the land remained uncultivated, therefore, increasing the threat on Kinneret water quality by nutrient fluxes (Levanon et al. 1987). One of the recommended operation for optimal management of the peat soil, to maintain high moisture and green cover throughout all year round, was administratively accepted recently by



Map 3.9.2. Maps of the Lake Kinneret Watershed, the Hula Valley and the Hula Project area.

the head of the Israel Water Authority and was implemented as a formal „Peat Soil Convention“ which was signed by all the Hula Valley partners: municipal, land owner (farmers), and water authority representatives. The peat convention ensure lower water price during dry seasons and summers to prevail soil moisture and summer crops.

In the early 1990’s, a decision was made to convert 430 hectares of the Hula Valley into a park, in which 110 hectares in the center of the former swamp lands would be re-flooded and the new Lake Agmon was constructed (Map 3.9.2). This was a partial change of the Hula valley concept: from agricultural development to an integrated management area of agriculture and tourism while preserving its ecological values (Gophen 1998; 2000a; Gophen and Levanon 1996). The Hula reclamation project was implemented during 1993 - 1997, and was aimed at reducing the pollutant contribution from Hula soil while retaining the economic utilization of the land through a shift from agriculture to eco-tourism. The new concept included principles of man made changes to the environment, combined with introduction of natural plants and animals, and reconstruction of the hydrological system structure and irrigation method over the entire valley. The construction of an underground 1.5 m diameter pipe which convey the treated sewage from the biggest city in the Kinneret watershed area (Kiryat Shmone) to an Operational Reservoir, asphalt paved car and cycling roads around Lake Agmon were completed. Public center with car parking area, rest rooms, administration facilities and four bird watching posts were constructed as well. The project area was closed for private cars and entrance in bus-shuttle against ticket purchasing is carried out. The essential collaborative maintenance of land use by the farmers, water managers and naturalists was implemented and a comprehensive study of the hydrology, pollutants and water migration, seasonal bird distribution, aquatic and terrestrial plant densities and trees performance was conducted (Gophen 1995-2006; 2000b; Gophen et al. 2001).

Lake Kinneret

Lake Kinneret supplies 16 % during drought and commonly 30 % of the Israeli water demands and >55 % of drinking water requirements. Fifty mcm/y are supplied to the Jordanian Kingdom. The drainage basin area of Lake Kinneret is 2730 km^2, located mostly northern to the lake of which „Hula Valley“ is about 200 km^2 (Map 3.9.2). The Hula valley’s altitude in its northern part is between 150 - 170 m and in the southern part of the valley 61 - 65 above sea level. River Jordan flow15 km from the Hula Valley southward, from +60 m altitude into Lake Kinneret with water level of 212.36 m (1.9.07) below sea level.

The warm monomictic Lake Kinneret is stratified from May through mid December (anoxic hypolimnion) and totally mixed during Mid December through April. During the last 60 years the Kinneret ecosystem has undergone several man-made modifications: construction of the south Dam (1932/3); salty springs diversion (1964); construction of the National Water Carrier (NWC) (operation -1964); implementation of the Hula Project (1994 - 1998), exotic and native fish stocking since 1930's and onwards, subsidized Bleak fishing (1994 - present), construction and operation of 1700 ha fish ponds (1960-70's) and restriction (450 ha) presently, and sewage removal within the drainage basin mostly by reservoir construction (total volume about 25 mcm). High ranged fluctuations of natural parameters such as water level fluctuations between 208.57 and 214.87 mbsl; high inflow discharges ($>10^9$ m^3 per annum) and droughts (<260 $x10^6$ m^3 per annum); low (333 mm/y) and high (1060 mm/y) precipitations; low (10-50 g/m^2) and high (170 – 412 g/m^2) monthly averages of the biomass of *Peridinium spp* during its blooming season; decline of zooplankton biomass during 1969 – 1993 and increase afterwards; low (1983, 1992) and high (1970, 1979, 1999) epilimnetic temperature.

The pattern of seasonal distribution of hydrological, chemical and biological parameters consistently represent subtropical climate conditions of the Kinneret region: high levels in winter and low in summer months but high hypolimnetic inventories of dissolved phosphorus, ammonium, sulfides and CO_2 in summer – fall period as a result of the thermal and chemical stratification (Gophen 2003a, c; 2004).

The lake is exploited for its fishing by ca 200 licensed fishermen which remove commercially an average of 1832 ton of fish (108 kg/ha) per annum. The zooplanktivorous Lavnun (Bleak, *Acanthobrama spp.*) comprised 40-60 % by weight of total catches and >50 % of the stock biomass (Walline et al. 1993). Only 8 species out of 24 recorded in the lake (Ben-Tuvia 1978) are commercially fished (Gophen 2003c; 2004).

Methods

A: Statistical analyses of long term records

Long term (1995-2005) data set of hydrology (discharge) and water quality of surface running waters in the Hula Valley canals and underground water table elevation (Migal, Hula Project Data Base) was analyzed as well as long term (1969-2001)data set of river Jordan discharge and water quality(Data provided by Mekorot Water Supply Co. Drainage Basin Monitoring Unit) and Lake Kinneret chemical and biological parameters (Kinneret Limnological Laboratory IOLR Co.'s Data Base)(LKDB). Hula Project data set include biweekly (hydrology and water quality) and monthly (ground water level) measurements; River Jordan data set include monthly averages of daily measurements. Kinneret data set include monthly averages of biweekly (biology) and weekly (chemistry) and hourly (temperatures) measurements in 5-8 sampling stations. Statistical analysis of all data sets was done by LOWESS (0.8) test (Stata SE 9.0). LOWESS (**LO**cally **WE**ighted **S**catterplot **S**moother) analysis is a robust smoothing procedure of weighted regression with level of tension of 80 to produce tight and straight curve with outliers robustness.

B: Land Use study (Meron 2006) meteorology and underground water level (GWL) monitoring (Tsipris, Orlov & Meron 2007)

Mapping and classification: Twice a year – March and August in 2004, 2005 and 2006 aerial photographs were taken scaling of 1:20,000 and 1:14,000, representing pixel footprints of 0.35 and 0.22 meters. They were digitized, rectified and registered to Israel TM grid (2039), using ArcView GIS. The pictures were classified on the RGB layers by a modified NDVI formula:

$$NDVI = (G-R)/(G+R-B)$$

This classification was later verified by supervised classification using the built-in method of the Image Analyst add-in of ArcView of the new version 9.1. Vegetative cover was defined as cropped / natural / un-cropped. Variation of soil fertility was evaluated in particular fields by vegetation density levels, to monitor changes over time, as soil salinization and fertility degradation became a major problem.

Field boundaries layer was included from the „Hula GIS“ project of the KKL, and annually adjusted to the cropping patterns of the farmers. The AGMON lake and surrounding area allocated for tourism purposes was treated at this stage as a single entity. Meteorological data was collected by a standard station located in the Hula Project area.

Monitoring of Under **G**round **W**ater **L**evel (GWL) in 55 drills in the Hula Valley was carried out monthly. Results are expressed as an altitude and/or distance from surface. Aereal cover of organic soil covering a fixed GWL depth was calculated by using the GIS system.

Results

Summarized Results of long term (1995 - 2006) research and monitoring of Hula Project (Gophen 1995 - 2006) are:

Agroforestry *(Atzmon et al. 2007)*

Windbreaks of planted trees were restored and their impact on wind velocities and dust production were measured.

Dust deposition measurements indicated 27 g/m^2 at the windbreak side which is exposed to the most common wind direction (westerly) at the end of December. In dust traps located on the opposite side of the windbreak (easterly), only 5.4 g/m^2 were harvested. In dust traps located close to the previously described traps but not protected by wind break, no differences were recorded between the two sides of the trees raw. Measurements of dust deposition which were harvested in March revealed different pattern due to direction change of the wind blow. Ally cropping experiments has indicated a remarkable differences between the survival rates of the different species at the end of the second year after planting. Pecan and Black walnut represented the highest survival rates (>50 %) whilst the Tuart tree - the lowest. The development of all tree species in this experiment was slow. Most of them were below 1 m. The survival rates varied between 91 % (Vine) and 49 % (Cypress). The growth rate of most planted tree species was moderate and lower. However, the growth rate of Vine and Eucalyptus was reasonably high.

Vegetation *(Kaplan & Meron 2007)*

The periodical dominance of plant species in lake Agmon, especially *Typha domingensis* (Gophen 2000b), *Potamogeton. nodosus* and two species of *Najas* were monitored since 1997. In recent years, *Najas delilei* disappeared abruptly, and *Cer-*

atophyllum demersum was the dominant submerged plant, together with *Najas mino*r and *P. nodosus*. Plant succession analysis documented these changes. A comparative computerized GIS mapping, indicated seasonal succession of plant species, but low densities of *Phragmites australis, T. domingensis* and *Ludwigia stolonifera* communities were documented.

The newly appeared *Cynanchum acutum* is a significant deteriorated „canopy's“ appearance of riparian plants, mainly on *Cyperus papyrus*, *T. domingensis* and other *Cyperus* species, which are important for canal banks protection.

Several soil analyses in the vicinity of Lake Agmon indicated high EC (**E**lectrical **C**onductivity). In previous studies it was shown that it was caused mostly by nitrates, and presence of nitrophilic plant species is typical. A high organic matter content was found, in most locations around Lake Agmon but not in those which are close to the reconstructed Jordan canal indicating the high variability of soil composition in the Hula Valley. In all locations, near by Lake Agmon, where soil contents were analyzed no halophytic plants, were found, which is probably due to the low level of sodium content. Most locations separated from water vicinity were characterized by sagetal and ruderal plant species. Some of them are nitrophilic, which grow on Nitrogen rich soil. These plants were also found in high densities in locations with high EC resulted in by increasing level of Nitrate.

Eco-Tourism *(Ben-Josef et al. 2007)*

The Agmon Site attracts during 2006, 160,000 ticket pay visitors and additional not counted non-paying visitors. The policy of not charging entrance fees with revenues on free choice of activities and services by the visitors has proven most successful. Over a rather short period, the management has attained a significant increase of revenue, almost balancing the cost of maintenance and operation. The visitor profile shows a high level of education and most of the visits occur in winter when migrating birds are crowded. Most of the visitors represent domestic tourism. The Agmon area is definitely a unique, successful and constantly developed ecotourism site while keeping a close watch on carrying capacity, fauna and flora response to visitors impact, observing principles of eco-system sustainability, carefully balanced with striving for maximum visitor satisfaction.

Avifauna *(Labinger & Alon 2007)*

Of the 215 total number of observed bird species, 67 are listed as nationally or globally threatened. It is important also to note that the status of many of the nationally listed species relates to their breeding status, and not to other times of the year when they maybe much more common. The bird community varied between different locations and years. Both factors were significant for both species richness and relative abundance. In general, diversity was highest during the migration seasons (spring and autumn) and areas with wetland habitat (Lake Agmon and riparian canals). In 2006, fewer water fowl species were recorded during autumn which may have been linked to relatively high water level of lake Agmon. Impacts of agricultural management activities such as vegetation mowing and dredging negatively affected birds distribution.

Crane management was successful and no crop damage was recorded. The trend of increasing number of wintering cranes continued, suggesting maximum population size as 50-60,000 birds. These increases in migrating and wintering populations have increased project costs. Migration patterns and stopovers of white Pelicans indicated 33,000 migrators through the Hula with approximately 10,000 stopping along the northern Israeli coastal plain. Fish stocking in Lake Agmon was not carried out in 2006 causing an increase in foraging pressure within the fish ponds at the Hula Valley.

3.9.2 **The Hydrology of the Hula Project Area** (Tables 3.9.1, 3.9.2; Fig. 3.9.1, 3.9.2)

A) Aerial Water Balance ($10^3 m^3$/year) (tcm/y) (2005):

Northern Peat soil blocks inside the following lines: North – New Northern Canal; West – Reconstructed Jordan; East – Eastern Canal; South – Lake Agmon – 400 ha:

Influx:	5050 tcm/y influx into New Northern Canal
	1780 tcm/y Rain
Total in:	6830 tcm/y
Outflux:	4600 tcm/y into Agmon through Canal Z
Transpiration	– 7980 tcm/y
Total out:	12580 tcm/y
Additional influx of:	12580 – 6830 = 5750 tcm/y probably originated directly from the „Western Dan“ water supply for irrigation.

Southern region limited by: North – Lake Agmon; East – Eastern Canal; West & South – Western Canal (400 ha):

Influx:	Jordan flow underneath Zero Canal – 3900 tcm/y
From Agmon into Z canal	– 4500 tcm/y
Rain	– 1780 tcm/y
Total in:	10210 tcm/y
Outflux:	From Canal 404 into western canal – 1600 tcm/y
From Canal 312/1 into western canal	– 3500 tcm/y
Evapo-transpiration	– 7980 tcm/y

Total out:	13080 tcm/y
Additional influx of:	13080 – 10180 = 2900 tcm/y probably originated from infiltration and direct pumping for irrigation from the Eastern and Western canals.

Total area balance, from the new northern canal as northern limit, including Lake Agmon to western canal in west and south and eastern canal in the east (910 ha):

Influx	– 21070 tcm/y measured in Kfar Blum Dam
Rain	– 4050 tcm/y
Total in	25120 tcm/y
Outflux	– From 404 - 1600, from 312- 3480, from Zero canal - 3720, evaporation - 18150 tcm/y
Total out	– 27000 tcm/y
Additional unmeasured influxes:	27000 – 25200 = 180 0 tcm/y probably originated from supplied un-measured irrigation waters but it is within the range of measured error (10 - 15 %).

Hydrological analysis of the Lake Agmon system (Fig. 3.9.1, Table 3.9.2) suggests an annual total infiltration of about 442 tcm m^3 of inputs exceeding the output infiltrated fluxes.

Monthly hydrological balances of the Lake Agmon system indicates 7 months of positive balance i.e. inflow > outflow (total input – 1526 tcm) and 5 monthly negative balances, inflow < outflow, (total output 1084 tcm).

Water migration between parts of the Hula Valley occur through measured and unmeasured pathways and the role of underground preferential pathways might be significant. Nevertheless, the comprehensive balance of the entire area under investigation (910 ha) is balanced (loss = gain) and therefore suggested as properly estimated by the discharge monitoring in the 12 stations included in the monitoring program.

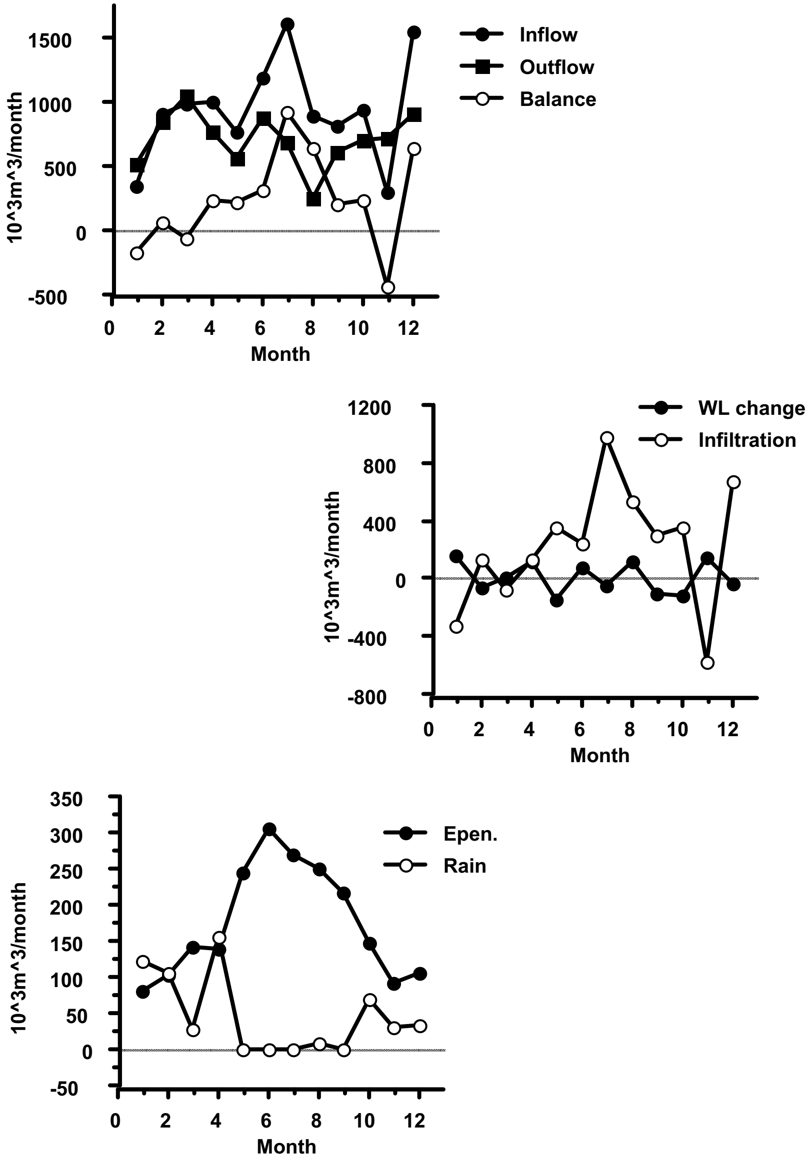


Fig. 3.9.1. Lake Agmon Hydrology – 2006 in 10^3 m^3/month.

Table 3.9.1. Hydrological parameters (10^3 m^3/month = tmc/m; & tmc/y) of the Agmon system during 2005:
Total influxes – 7742 tmc/y
Total outfluxes – 7100 tmc/y
Balance; 642 tmc/y;
(642 tmc/y) minus (200 tmc/y)= 442 tmc/y of influx by infiltration.

Month	Z Canal in	HE in	Jordan in	Agmon Outflow	Rain	Evaporation	Total in	Total out	Water level Change
1	46	3	124	135	107	112	280	247	-100
2	280	4	96	525	128	104	507	629	0
3	179	44	181	230	14	151	418	381	0
4	190	56	183	592	4	218	432	810	300
5	566	26	192	626	21	242	805	868	-80
6	811	8	134	756	0	263	953	1019	-40
7	480	50	306	212	0	262	836	474	10
8	820	20	229	593	0	250	1070	843	20
9	718	12	342	419	0	200	1072	619	40
10	119	22	196	463	19	177	357	641	-90
11	363	42	267	235	67	127	739	362	10
12	0	23	122	121	128	86	273	207	130
Total	4572	310	2372	4907	488	2192	7742	7100	200

Total annual influx into the Western canal through canal 404 was 1600 tcm/y.

Total annual influx into the Western canal through canal 312/1 was 3500 tcm/y.

Total annual flow through Jordan route underneath canal Zero was 3900 tcm/y.

Consequently 3900 minus 1600 = 2300 tcm/y were infiltrated from canal 404 into underground preferential water flows on its both sides.

Table 3.9.2. Hydrological parameters (10^3 mc/month and totals) of Lake Agmon System during 2006.

Month	Total gain	Total loss	WL change	Balance	Infiltration	E-Penman
1	344	519	154	-175	-329	79.9
2	899	841	-66	58	124	102.3
3	991	1053	11	-62	-73	142.1
4	1002	764	110	238	128	137.7
5	773	560	-143	213	356	244.6
6	1183	870	77	313	236	305.6
7	1613	686	-44	927	971	268.8
8	896	251	110	645	535	250.8
9	817	617	-99	200	299	217.6
10	939	709	-121	230	351	146.1
11	293	724	143	-431	-574	90.6
12	1550	910	-33	640	673	106.5
Total	11300	8504	99	2796	2697	2092.6

Month	Rain	Jordan in	Canal Z in	From HE	Outflow to Z	Outflow to Zero	Total outflow
1	121.6	51	148	24	11	439	450
2	104.7	234	550	10	750	0	750
3	26.8	236	714	14	829	92	921
4	156.6	317	526	3	551	86	637
5	0	406	368	0	155	172	327
6	0	366	802	16	155	420	575
7	0	603	981	28	11	417	428
8	8.1	100	698	91	0	0	0
9	0.8	75	684	57	11	398	409
10	70.2	419	409	41	301	92	393
11	30	234	0	29	408	238	646
12	34.4	223	1252	41	830	-15	815
Total	553.2	3264	7132	354	4012	2339	6351

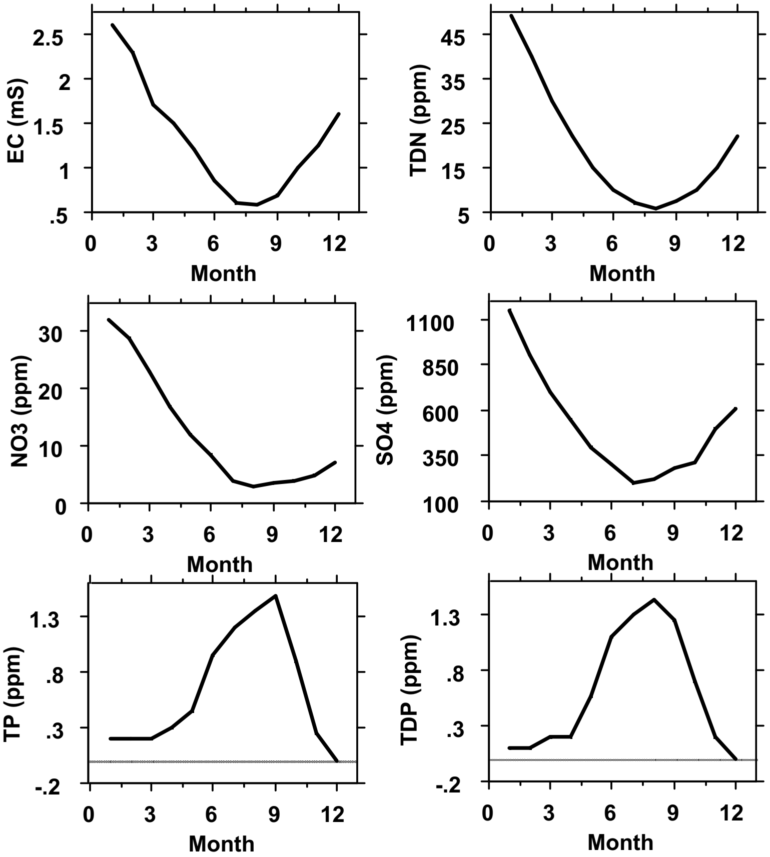


Fig. 3.9.2. Seasonal changes of EC (mS), and concentration (ppm) of SO_4, TDN, NO_3, TP and TDP in Canal Z waters during 1994 – 2006.

B) ***Annual Hydrological balance (mcm/y) of the Agmon system in 2006*** *(Tables 3.9.1, 3.9.2)*

Gain:	
Jordan in	3.3
Canal Z in	7.1
Hula East (HE) in	0.35
Rain	0.55
Total in	11.3
Loss:	
Measured outflow (to canals Z & Zero)	6.4
Penman Evaporation	2.1
Total out	8.5

Balance = In minus out	2.8
WL change	0.1
Infiltration = 2.8 – 0.1	2.7
Infiltration from Agmon outside	1.0
Infiltration into Agmon	3.7

C) ***Nutrients flux from Hula Project area*** *(Map 3.9.2; Fig. 3.9.2)*

TN, TDN, NO_3, NH_4 and SO_4 concentrations represented similar pattern of seasonal changes in all surface flows over the Hula Project area. During summer, nitrogen products accumulate in the soil and during the winter months they migrate by rain transporting through infiltration into the canal surface flows. At the beginning of the winter when soil loads are high the flux is intensive and gradually decline when the soil stock diminish. Phosphorus product concentrations represent an inverse seasonal changes: after the rainy season peat soil moisture start to decline and degradable P concentration increase and transported through infiltration of irrigated waters into the canal surface flows.

Concentrations of all Nitrogen species, SO_4, TDS, and EC values in the Lake Agmon outflow (data is not shown here) indicates similar pattern of seasonal changes: decline from January through August and slight increase later. This pattern is in accordance with the trends that were observed in other surface flows within the canals of the Hula Project. Winter declining of underground weakly bounded nutrient (N forms, SO_4) transport by rainy waters and irrigated waters inputs of P in summer. When the peat soil moisture is high (January – April) P concentrations in Agmon are low and increase abruptly as a result of both, vegetation degradation and underground transport in summer by irrigated waters.

It can be conclusively summarized as follows: During summer the peat soil moisture is low and soluble compounds like Gypsum and nitrogen forms are transportable (Avnimelech et al. 1978; Levanon et al. 1987; Tsipris and Meron 1998). The first rainy fluxes dissolve these compounds and transport them at a high rate and their concentration are therefore high in drainage waters. During the following rainy months the underground fluxes are saturated by dissolved products and their concentrations does not increase. From February the rain is declining and the flux of these compounds diminish.

The Phosphorus behave differently (Richardson 1985): as the peat soil moisture decline (in summer) the P compounds become available and transportable. Water supply for irrigation and high water table maintenance carry those P substances and therefore P increase was indicated in drainage waters in summer and decreasing was observed when water supply decline in fall season. During winter time the peat soil moisture is high and P is not transportable and its fluxes into water line is therefore minimal.

D) Nurtient Fluxes from the Drainage Basin into Lake Kinneret (Figs. 3.9.3)

Nutrient contribution from the Kinneret drainage basin is mostly due to the Hula region, including the eastern and western slops of the valley. Scientists from the Water Supply Co., Kinneret Limnological Laboratory and the Tel Hai Academic College analyzed the contributions of all regions of the catchment (among others, Rom 1999; Litaor et al. 2006). In this paper the local contribution of the Hula Project area is considered (Gophen 2000a, b, c; Gophen et al. 2001; 2003). During 2005 low contribution of nutrients from Hula Project area to Lake Kinneret was documented: TN – 42 tons, TP – 2 tons, Sulfate - 1200 tons, and 281 tons of TSS. A decline of discharges as a consequence of precipitations decreasing (Givati 2007) were documented in River Jordan during the 1990's and 2000's (Givati & Rozenfeld 2007, Gophen 2007, and Rom 1999). The concentrations of SRP in river Jordan increased and The TN and Organic-N concentrations declined. It is likely that influx of bio-available P (SRP) was enhanced and consequently the Kinneret epilimnetic stock; The drop of TN and Org. N was probably the result of sewage removal, fish ponds reduction and Hula Project constructions, in the drainage basin.

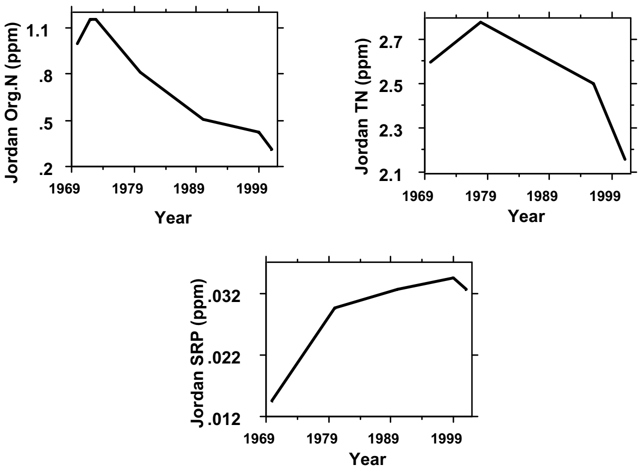


Fig. 3.9.3. Temporal changes of nutrient concentrations (ppm) in River Jordan during 1970-2001:TP, SRP, TN, and Organic- N.(Data source: Mekorot Water Supply Co.).

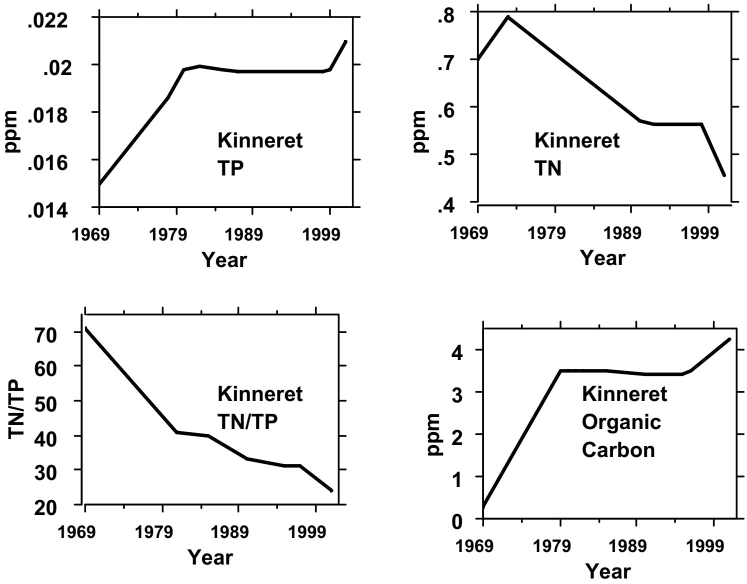


Fig. 3.9.4. Temporal changes in the Kinneret Epilimnion (1969 - 2001): concentrations (ppm) of Organic-Carbon, TP, TN; TN/TP mass ratio.(Data source: LKDB).

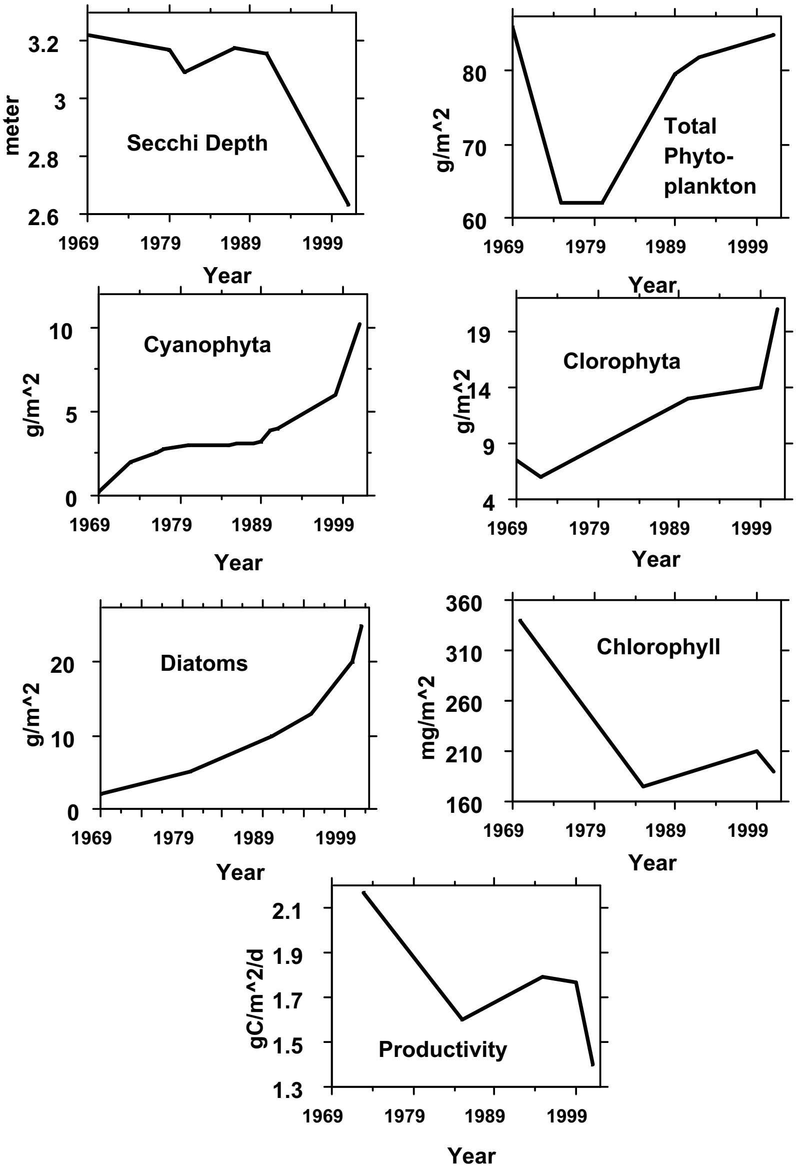


Fig. 3.9.5. Temporal changes in the Kinneret Epilimnion (1969 - 2001): Total Phytoplankton Biomass (g/m^2), Chlorophyll (mg/m^2), Secchi depth (m), Productivity (gC/m^2/day), Cyanophyta (g/m^2), Chlorophyta (g/m^2), Diatoms (g/ m^2).(Data source: LKDB).

Lake Kinneret (Figs. 3.9.4, 3.9.5; Table 3.9.5)

The Lake Kinneret data (Fig. 3.9.4, 3.9.5) refer to the epilimnion (0 - 15 m) and indicates the followings: Increase of organic carbon concentration; increase of TP concentration; decline of TN concentration; phytoplankton biomass enhancement from mid – 1970's; biomass enhancement of nano-phytoplankton (*Cyanophyta, Chlorophyta,* Diatoms); on the other hand, chlorophyll concentration, and primary production, declined. Secchi depths became shallower. The mass ration (Wt/Wt) of TN/TP declined. The community structure of phytoplankton represent a shift from large cell algae-Peridinium to a smaller cell size of nano–phytoplankton. It is likely that these changes caused an increase of water turbidity as reflected by the shallower depth of Secchi measurements. These changes are probably, also, reflected by the decline of chlorophyll concentration and reduction of primary production rate due to the decline of light penetration. Particle density was enhanced and size fraction became smaller resulted in higher cell surface area in relation to cell volume and therefore light reflection was enhanced. Decline of nitrogen accompanied by phosphorus increase (as mathematically computed as lower TN/TP mass ratio) enhanced N deficiency and P sufficiency resulted in by nitrogen fixixing cyanophytes blooms, as previously predicted (Gophen et al. 1999; Gophen 1999).

Decrease of zooplankton biomass (Copepoda, Cladocera) between 1969 and 1990 and increased later was documented by Gophen (2003a). The impact of the increase of the biomass of the zooplanktivorous fish, Lavnun resulted in by fishery pressure reduction and reproduction supportive climatological conditions were suggested (Gophen 2004). The implementation of recommendation to reduce Lavnun biomass by subsidized fishery resulted in the zooplankton biomass increase from early 1990's. The expected decline of nano-phytoplankton as a result of enhanced grazing pressure by zooplankton did not occur.

Global Warming effect (Fig. 3.9.6)

Data presents in Fig. 3.9.6 indicates cooling trend during 1970 – mid 1980's and warming (by 1.8 C^0) afterwards. The timing of temp. increase started earliest in upper layers (from mid – 1980's) and latest (end of 1980's) in deep layer. The analysis of the long term thermal dataset indicates warming process of Lake Kinneret by ca 1.8 C^0 throughout the entire water column from surface to bottom during the last 20 years. This warming trend came after a cooling period from 1960 to mid 1980's.Thermal measurements that were collected simultaneously 3 m above Kinneret water surface in a station located on the western side represent similar pattern of changes. Therefore I assume that it is probably partly the result of global warming process. It is also suggested that the shift of phytoplankton composition from large cells to small sized algae with higher particle density enhanced heat capacity (budget) of the Epilimnion. The implication of the warming process might have an

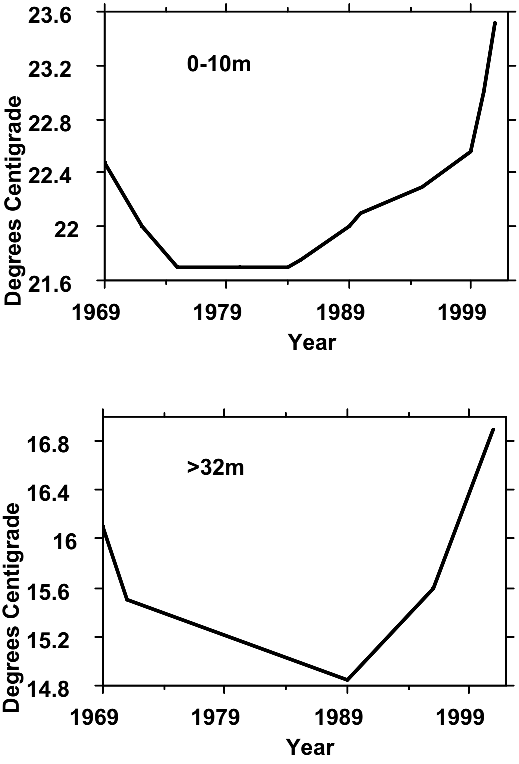


Fig. 3.9.6. Temporal changes of Kinneret water temperature (C^0) in 2 layers: 0 - 10 m, and >32 m during 1969-2001.

impact on the lake metabolism: enhancement of biological, microbiological, chemical and obviously physical rates of processes. These long term aspects require additional investigation.

Land Use-Land Cover (Meron et al. 2006) (Table 3.9.4)

The monitored area covers about 4000 ha, in the Hula Valley, of which about 440 ha out is allocated to tourism. Out of the 3600 ha allocated for farming, in 2004, 44 % were planted for winter and 66 % for summer crops. From the farmers view it looks like fair utilization of the land, however it is still far away from recommendations to keep the peat soil under plant cover and irrigation year around to retard oxidation and fertility degradation. About 9 % of the land was left fallow all year around (not included in the table). In 2005 water was allocated for irrigation aimed keeping the peat soil under high moisture condition year around. We will follow up the Soil fertility results in land blocks where recommendation of keeping the soil moisture condition high, will be analyzed upon completion of the 2005/6 survey.

Ground water level *(Tsipris et al. 2007)(Figs. 3.9.7 & 3.9.8)*

The maintenance of GWL (1.5 - 1 m below surface) in the northern region and in the vicinity to Agmon was efficient. In the northern part of Hula project area, GWL was maintained at 1 m under soil surface in February and 1.5 m in October. Next to Agmon, GWL was about 62 – 62.5 m, i.e. close to theAgmon water level. It was evidently confirmed that the hydraolic link between lake and this zone is existed. Since 2000 when renewal irrigation system (portable spray lines) was operated GWL range of fluctuations in the southern zone was slightly greater than 80 cm.

A clear trend of GWL decline in summer was observed in the south – east zone of the Hula project area: averages varied between 1.5 – 2.5 m (maximum 4 m). The winter precipitation enhanced increase of GWL and in the southern marginal regions. It is suggested that there is an underground preferential free space where winter rains abruptly accumulate. During vegetation growth period, evapotranspiration empties this water full space if irrigation does not fully recharge the water loss. Precipitations on the eastern part, close to the Golan Heights, are 25 % lower than on the western part of the Hula valley.

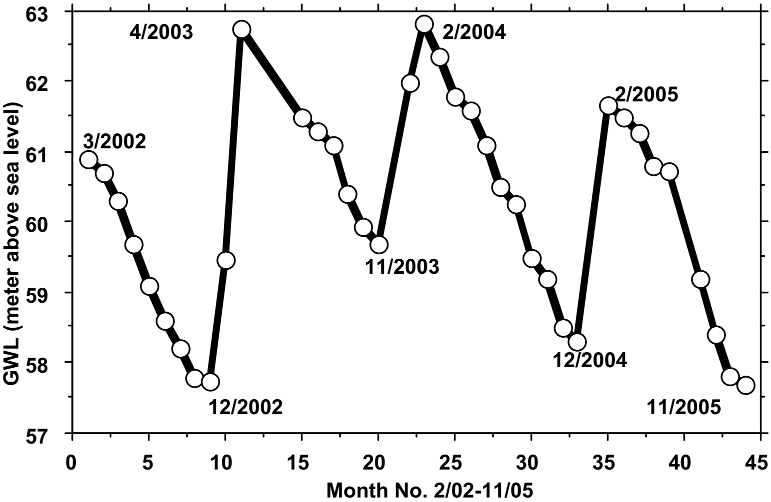


Fig. 3.9.7. Ground water level in a drill located in the eastern – south part of Hula Valley during April 2002 and November 2005 (Vertical axis: meter above sea level; Horizontal axis: month/year) (source: J. Tsipris unpubl. data).

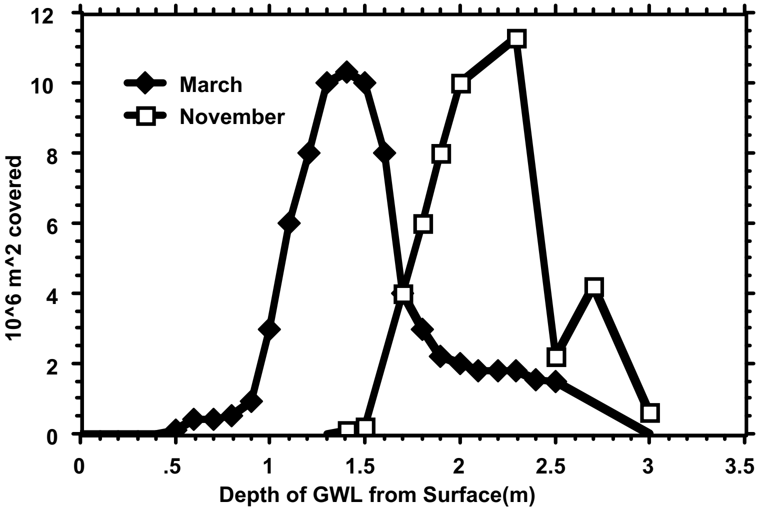


Fig. 3.9.8. Surface Area (dunams, 10^3 m^2) covering ground water level (m) in the Hula Project land during March (highest level) and November (lowest level) 2006. (Source: J. Tsipris, unpubl. Data).

Distribution of GWL within the organic soils area (Fig. 3.9.8) indicates a seasonal drop of 1.0 - 1.5 m (from 1.75 to 2.75 m from surface) during spring-summer season. Deeper depths of the GWD distributions (the „tails“ in Fig. 3.9.8) are those of the transition regions between organic and loamy soils and/or to the marl lake-bed soils.

The NWC impact (Fig. 3.9.9, Table 3.9.5)

The National Water Carrier (NWC, „Movil“), operation together with the previously (1932-33) operated south dam modified the hydrological management of the lake. Israel is located in a sub-tropical region where climate conditions are extremely changed between summer and winter. Results in Table 3.9.3 emphasize these extremes: high values of radiation, air temperature, wind velocities, evapotranspiration are significantly higher in summer whilst relative humidity, is lower and no precipitation in summer as well. Before the operation of the south dam and until the operation of the NWC most or all water inputs in winter were out fluxed through an open dam or naturally without dam regulation. Most of the nutrient rich winter influxes crossed the lake in the upper layer and major part of the nutrient inputs left the lake. After to 1964 the southern dam was opened only to release

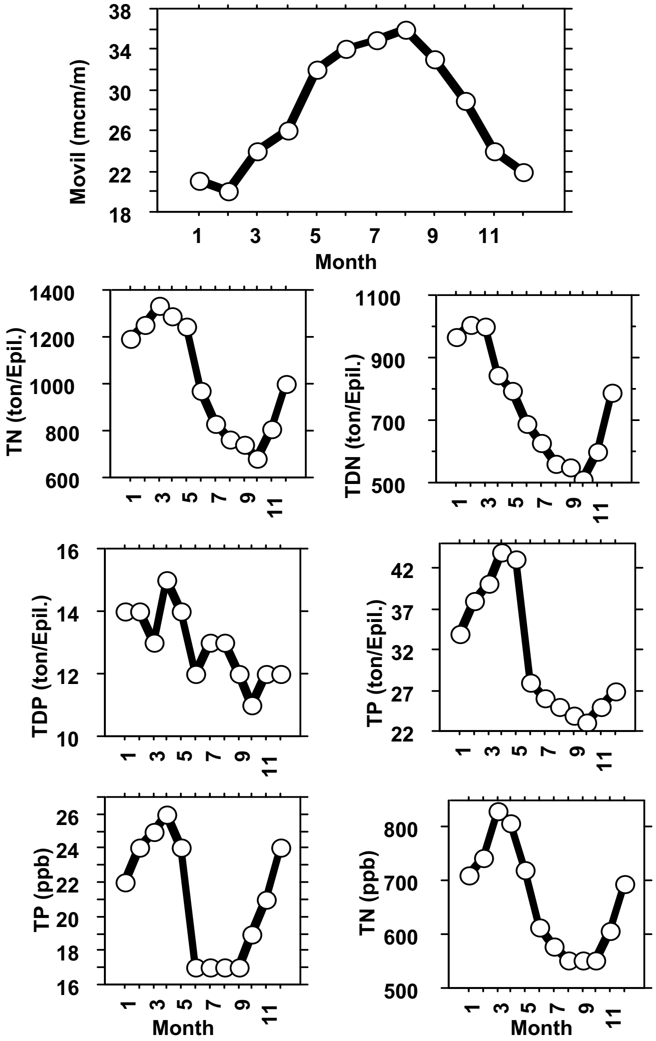


Fig. 3.9.9. Monthly means (1969-2001) of pumping regime in the National Water Carrier (Movil) (mcm/month)(Data source: Mekorot-Water Supply Co.); and Epilimnetic concentration and loads of nutrients: TDP and TP (tons/Epilimnion); TP and TN (ppb).

excess of water as part of the water level (WL) control and most of the external nutrient loads accumulated within the lake. In view of long term existence of the Eco-hydrological system of Lake Kinneret this parameter has a significance of

Table 3.9.3. Monthly meteorological data (2006). (Data Source: J. Tsipris, unpubl. Data).

	Radiation MJ	T air ° C	RH %	Wind speed m/s	Daylight ET mm	Precipitation mm
Jan	261	10.5	79	1.0	42.8	111.5
Feb	315	12.4	71	1.3	60.6	95.2
Mar	532	14.6	66	0.9	107.4	23.0
Apr	526	17.2	70	0.7	111.6	142.9
May	804	21.6	58	1.4	196.8	0
Jun	860	25.0	57	1.9	228.5	0
Jul	811	26.1	63	1.7	214.9	0
Aug	753	27.0	61	1.4	200.4	7.4
Sep	622	25.5	57	1.4	163.4	0.7
Oct	449	20.6	67	1.1	105.7	63.9
Nov	337	14.1	70	0.8	63.3	27.2
Dec	305	10.0	62	1.2	54.4	31.4
Total					1550	503

eutrophication factor. More over, since its operation, the NCW conveyed about 13 billion cubic meters (about 3 times of Lake Kinneret volume) of water which were supplied in Israel (from Haifa in the north to Ramon in the southern desert) for drinking (practically for house hold utilization of which only 5 % for drinking), agricultural irrigation, industry, and aquifers recharging. These NWC's waters transported also about 8 million tons of salts which significantly contributed to enhanced processes of salinization of soil and underground water (total quantities given in million tons: 3.1 – Chloride, 1.6 – Carbonate, 1.4 – Sodium, 0.4 – Magnesium, 0.1 – Potassium, 0.7 –Calcium, 0.7 – Sulfate).

For the study of the eutrophication NWC's effect two seasons were considered (Table 3.9.5): 5 winter months (December and from January through April) and 7 summer months (from May through November).It should be taken into a count that Israel is a sub – tropical region and the Eco-hydrology of Jordan-Kinneret ecosystem is mostly the result of these climate conditions but the impact of man-made modification might be significant.

Table 3.9.4. Land use and crop cover (Hectares) of winter (March) and summer (August) crops in the Hula valley in 2004 -2006. (Data Source: M. Meron & V. Orlov, unpubl. Data).

Owner	Owned Area	3/2004	8/2004	3/2005	8/2005	3/2006	8/2006
1	167.5	111.9	167.5	74.6	124.7	130.7	158.5
2	64.8	X	51.5	X	55.9	39.5	60.8
3	396.6	82.4	311.5	73.2	224.3	112.9	211.8
4	185.1	78.6	149.3	61.7	116.3	55.7	79.4
5	107.5	49.5	10.1	X	X	X	X
6	211.9	10.4	107.9	34.9	153.8	180.9	180.9
9	127.9	92.0	113.0	85.2	66.5	100.2	119.2
10	134.4	121.3	13.1	40.8	90.2	116.7	116.7
11	186.1	79.3	110.0	40.0	69.4	83.5	102.0
12	259.8	90.5	205.2	26.5	111.4	128.5	205.7
13	263.5	108.1	116.6	14.7	40.0	1,319	131.2
14	798.7	350.9	521.2	329.1	138.6	356.6	499.3
15	212.5	80.7	113.4	18.3	118.1	70.7	134.7
16	88.1	88.1	66.2	X	X	79.2	73.1
17	184.2	124.7	182.7	94.5	69.5	156.6	178.2
18	132.4	99.4	119.3	85.0	78.8	47.3	97.3
19	94.7	34.2	18.3	34.0	X	91.1	73.7
Total cropped(ha)	3615.8	1602.0	2376.7	1012.5	1457.4	1882.1	2422.5
(%)	89 %	44 %	66 %	28 %	40 %	52 %	67 %
Eco-Tourism	431.3 (ha)						
Total Area	4047.1(ha)						

X=No data

Eco-Tourism=Rainfed, Lake and Wetlands

When summer + winter exceed 100 % it is due to double cropping

Table 3.9.5. Multiannual (1969-2002) averages of total inflows (mcm/y), total outflows (mcm/y), Evaporeatin (mcm/y), and pumping through NWC (mcm/y) in Lake Kinneret (Data Source: Mekorot Water Supply Co.) and nutrient dynamics: Epilimnetic concentrations and loads and removal through NWC and no dam control (NDC) (t/season) (see text).

	Winter	Summer
	Hydrology	
Water inflows (mcm) (%)	459 (62)	279 (38)
Evaporation (mcm)	90	190
Outflow (no dam control)	369	189
	Annual NCW's	
pumping (mcm) (%)	115 (34)	224 (66)
	Epilimnetic loads in Ton & Concentrations (ppm)	
TN	1215 (0.8)	863(0.6)
TP	370 (0.024)	28 (0.019)
C-Organic	6694 (3.5)	7672 (4.1)
	Nutrient removal (T/y) by NWC (%)	
TN	86(7)	133 (15)
TP	3 (8)	4 (14)
C-Organic	405 (6)	914 (12)
	Nutrient removal (T/Y) by NDC (%)	
TN	295 (24)	113 (13)
TP	9 (24)	4 (14)
C-Organic.	1292 (19)	775 (10)

For the study of the NWC's eutrophication effect, multiannual hydrological and nutrient loading values were computed (Table 3.9.6). The outcome of these data are the following results:

Annual removal of nutrients (Tons/Year) by NWC and „No dam control“ (NDC, i.e. open dam all year around) policy are:

	NWC	NDC
TN	219	408
TP	7	13
C-Organic	1319	2067

Consequently, 11 – 16 % of the epilimnetic nutrients (TN, TP and C-Organic) remain in the lake ecosystem as a result of the man-made shifting from the natural NDC to NWC management. It is not impossible that during long term operation of the present NWC management enhanced eutrophication signal.

The long term trends of eco-hydrological changes in the Kinneret-Jordan ecosystem are presented in Fig. 3.9.3 for River Jordan and Fig. 3.9.4 and 3.9.5 for Lake Kinneret.

3.9.3 Discussion

Structural natural and man-made modifications in the Jordan – Kinneret ecosystem were carried out during the last 70 years. The most prominent factors are related to nutrient flux into Lake Kinneret with consequence changes within the lake. It is not always clear if both the two types of changes, natural and man-made did not confounded one each other. It is impossible to analyze the impact of Lake Hula and swamps drying on change of nutrient inputs from the Hula Valley into Lake Kinneret because of lack of information. On the other hand we documented changes of nutrient fluxes during the last 40 years as well as limnological modification in Lake Kinneret.

The seasonal pattern of nutrient fluxes from the peat soil was defined as well as the low contribution of the Hula valley and particularly the Hula Project region, as measured in runoff surface waters canal flows. Nevertheless, the underground peat-silty soils in the Hula Valley forms a complicated system where preferential pathways are very common and the information about underground discharges and chemical qualities is poor.

It is suggested that the Nitrogen loads in Lake Kinneret predominantly affected by external supply. Therefore, reduction of nitrogen concentrations together with discharge decline in River Jordan resulted in lowering of nitrogen loads in the lake. Because *Peridiniun* is sensitive to nitrogen availability its biomass was declined.

Phosphorus availability in Kinneret was enhanced and consequent proliferation of P limited nano-phytoplankton occurred from mid 1980's when grazing zooplankton biomass was suppressed by *Lavnun* fishes. Conclusively, P availability dominated nano-phytoplankton enhancement. It was suggested that reduction of Lavnun (started early 1990's) might indirectly as top-down effect, suppress nano-phytoplankton. But this was not the case: the grazers biomass increased and Diatoms and chlorophytes biomass was enhanced. It is suggested that due to optimal P availability the greater grazing pressure was insufficient. Benndorf et al. (2002) documented data which was concluded that fishery management, Biomanipulation, is insufficient if P is not reduced in mesotrophic-non-shallow and non-deep lakes The reasons for the reduction of nitrogen supply from the catchment are probably the result of man made operations. The increase of P availability in Lake Kinneret is probably the result of unknown or unmeasured sources within the catchment, such as, underground flows (Litaor et al. 2003; 2004; 2006), or dust deposition.

The agricultural management in the Hula Valley is ultimately needed for P flux reduction. This management include high soil moisture by GWL elevation and green crops cover throughout year around.

The bloom forming N_2 fixing cyanophytes were induced by conditions of nitrogen deficiency and phosphorus sufficiency. To improve water quality in Lake Kinneret by means of cyanophyte suppression it is suggested to achieve a better control of P supply. Such a management might also affect reduction of chlorophytes and diatoms but not with out supported policy of biomanipulation. i.e. biomass reduction of *Lavnun* by subsidizing its fishery.

It is also noticeable that the NWC management as operated by close dam might be a factor of eutrophication in long tem perspective.

3.9.4 Epilogue

The results of long-term study of the Hula Valley ecosystem indicates several positive developments: economically viable agriculture has been reestablished in spite of water scarcity; eco-tourism has been successfully implemented, particularly in Lake Agmon, and stringent regulation of public visits; the levels of pollutant flux flowing from Lake Agmon into Lake Kinneret were found to be minor, and the arrival of numerous bird flocks to the Hula area (Cranes, Pelicans, Cormorants, Herons, Storks, Kites and others) are attracting large number of visitors (ca 200.000 in 2006) (Ben-Josef et al. 2007; Labinger and Alon 2007). Nevertheless, the optimistic approach is not completely relevant. The professional and financial management requirements of all partners are not yet guaranteed and should be negotiated, discussed and achieved continuously. Improvements and operations of tourists facilities and prevention of damage to agricultural crops by wintering birds are very costly and fund raising is an unfinished job for the managers. It should be also considered that the preliminary goal of the Hula reclamation project was to ensure reasonable income to the land owners who agreed to convert their own land utilization from unsuccessful agriculture to Eco–tourism. The achievement of this objective is not yet implemented. The need for more information about underground water and nutrients migration and soil salinization mechanisms are ultimately required for the prevention of further soil deterioration and protection of the Kinneret water quality.

Acknowledgement

The whole story of man intervention in the Hula Valley was initiated, and operated since early 1950's and presently implemented by the Jewish National Foundation (Keren Kayemet Le'Israel)(KKL). The people who live in the vicinity of the Hula and cultivate its land and those who come to visit the site are deeply grateful to KKL.

I am grateful to E. Yasur for field observations and technical assistance; to H. Milard for discharge measurements; to the team of chemical laboratory in MIGAL, leaded by Dr. I. Bar–Ilan, and G. Melman for data computerization; to J. Tsipris and V. Orlov for field data collection of meteorology, and ground water level and together with M. Meron for friendly collaboration.

This project was funded by GLOWA research proposal to M. Gophen and M. Meron; Funds were also raised by National Water Authority and Jewish National Fund (KKL).

References

Atzmon, N., Z. Henkin, and A. Zuk. 2007. Agro-Forestry, in: UFSF 2006-Annual Report. Pp. 37 – 48.

Avnimelech, Y., Dasberg, S., Harpaz, A. and Levin, I., 1978. Prevention of nitrate leakage from the Hula Basin, Israel: A case study in watershed management. Soil Sci. 124-5: 233-239.

Benndorf, J., W. Boing, J. Koop, and I. Neubauer. 2002. Top-Down control of phytoplankton: the role of time scale, lake depth, and trophic state. Freshwat. Biol..47. pp.2282-2295.

Ben-Josef, I., N. Collins-Kreminer, H. Israeli. and A. Rapaport, 2007. Eco – Tourism, in: UFSF 2006-Annual Report, pp. 81-127.

Givati, A. and D. Rosenfeld, 2007. Possible impacts of anthropogenic aerosols on water resources of the Jordan River and The Sea of Galilee. Water Resource Research. (in press).

Gophen, M. (ed. and chapters): 1995 – 2006. Annual reports of Hula Project Research and Monitorin. MIGAL, Kiryat Shmone (in Hebrew).

Gophen M., 1998. From natural to man-made Hula Wetland (Israel) (1950-1998): utilization and nutrient removal. Proceedings- 6th International Conference on Wetland Systems for Water Pollution Control (S.M.T.Tornisielo, ed) 1998. 195-205.

Gophen, M. 1999. Prediction of an N_2-fixing cyanobacteria bloom in Lake Kinneret (Israel) based on N and P balance. Verh. Internat.Verein. Limnol. 27: 1239 – 1242.

Gophen, M., 2000a. The Hula Project: N and P dynamics in Lake Agmon and pollutants removal from the Kinneret inpurs. Science and technology Vol.42 No.1-2; pp117-122. Gophen, M., 2000b. Nutrient and plant dynamics in Lake Agmon Wetlands (Hula Valley, Israel): a review with emphasis on Typha domingensis (1994-1999). Hydrobiologia 00: 1-12.

Gophen, M. 2002. The management of Lake Kinneret (Israel): Water supply, water quality and food web structure perspectives. Proceedings (Volume 2) of The Water and Environmental Research ICWRER 2002 (G. H. Schmitz, ed.), Dresden, Germany. Vol. 2 pp.275 – 285.

.Gophen, M. 2003a. Water quality management in Lake Kinneret (Israel): Hydrological and food web perspectives. J. Limnol., 62 (Suppl. 1): 91-101, 2003.

Gophen, M. 2003b. Hydrology and management of Lake Kinneret aimed at water quality protection. In: Water in the Middle East and in North Africa: Resources, Protection, and Management. Springer-Verlag. pp. 41-54.

Gophen, M. 2003c. Water Utilization in a semi-arid zone, the Hula Valley (Israel): Pollutant removal, agriculture and ecotourism management. in: Water in the Middle East and in North Africa: Resources, Protection, and management. Springer-Verlag, pp. 207-226.

Gophen, M. 2004. Ecohydrological management of Lake Kinneret: A case study. Ecohydrology and Hydrobiology. Vol.4, No, 4 397-408.

Gophen, M. and D. Levanon, 1996. The Hula Project: Environmental Perspectives. Preservation of Our World in the Wake of Change, Vol. vi A/B ISEEQS Pub., Jerusalem, Israel, 1996. Editor: Y. Steinberger, pp.652-655.

Gophen, M., Val H. Smith, Aminadav Nishri and Stephen T. Threlkeld, 1999. Nitrogen deficiency,phosphorus sufficiency, and the invasion of Lake Kinneret, Israel, by N_2-fixing cyanobacterium Aphanizomenon ovalisporum. Aquatic Sciences, 1, pp. 1-14.

Gophen, M., D. Kaplan, Y. Tsipris, M. Meron, & I. Bar-Ilan. 2001. The newly constructed wetland ecosystem of Lake Agmon (Hula Valley, Israel): Functional perspectives. In: Treatment Wetlands for Water Quality Improvement; Quebec 2000 Conference Proceedings (selected papers).(compiled by: J. Pries, CH2M Hill Canada Ltd.pp.53-62.

Gophen, M. Y. Tsipris, M. Meron and I. Bar–Ilan, 2003.. The management of Lake Agmon Wetlands (Hula Valley, Israel). Shallow Lakes Conference, Lake Balaton, Hungary, June 2002. Hydrobiologia, 506 (1): 803-809.

Inbar, M. 1982. Spatial and temporal aspects of man-induced changes in the hydrological and sedimentological regime of the Upper Jordan River. Isr. J. Earth Sci. 31:53-66.

Kaplan, D. and M. Meron, 2007. Vegetation, in: UFSF-2006 Annual Report, pp.49 – 80.

Labinger, Z. and D. Alon. Avifauna, in: UFSF-2006 Annual Report. Pp. 128-171.

Levanon, D., Levin, I., Kipnis, T. and U. Cohen. 1987. The effect of high yielding perennial crops on biological degradation and nitrate accumulation in peat soil. Experimental Agriculture 23:69-74.

Levin, I. and Shoham, D., 1983. Ground surface elevation loss in the reclaimed Hula Swamp in Israel during the period 1958-1980. 2^{ND} Int. symp. Peat in Agric. and Horticult. Bet Dagan Proc., pp. 61-69.

Litaor, M.I., O. Reichmann, M. Belzer, K. Auerswald, A. Nishri, and M. Shenker. 2003. Spatial analysis of phosphorus sorption capacity in a semi-arid altered wetland. J. Environ. Qual. 32:335–343.

Litaor, M.I., O. Reichmann, K. Auerswald, and M. Shenker. 2004. The geochemistry of phosphorus in an altered wetland. Soil Sci. Soc. Am. J. 68:2078–2085.

Litaor, M. I., G. Eshel, O. Reichmann, M. Shenker 2006. Hydrological control of Phosphorus mobility in altered wetland soils. Soil Sci. Soc. Am J. 70:1975-1982

Meron, M., V. Orlov, and J. Tsipris, 2006. Land Use-Land Cover. In : UFSF-2005 Annual Report.pp39-43. Neuman, S.P. and S. Dasberg. 1977. Peat hydrology in the Hula basin, Israel: II. Subsurface flow regime. Jour. Hydro. 32:241-256.

Richardson, C.J. 1985. Mechanisms controlling phosphorus retention capacity in freshwater wetlands. Science 228:1424–1426.

Rom, M. 1999. The Kineret drainage basin---trends and changes in nutrients contribution 1970 - 1998. Mekorot, Jordan District (in Hebrew).

Sacham, G. 1988. The subsidence of peat soils in the Hula Valley. The Kinneret Drainage Authority, Zemach. 26p. (in Hebrew).

Stata (SE 9.0) 2005. Stata Statistical Software: Release 9. College Station, TX: StataCorp LP.

Tsipris, J., and M. Meron. 1998. Climatic and hydrological aspects of the Hula restoration project. Wetland Ecol. Manag. 6:91–100.

Tsipris, J., M. Meron, and V. Orlov. 2007. Hydrological Regime, in: UFSF-2006 Annual Report. Pp 172 – 178.

3.10 Transfer of the Concepts of the European Water Framework Directive to Arid and Semiarid Regions

Benedikt Toussaint
Prof. Dr. Benedikt Toussaint, D-65232 Taunusstein
e-Mail: b_toussaint@web.de; internet: www.hgc-toussaint.de

3.10.1 Background information and objectives

Our Earth, the „blue planet“, is a water planet. The total volume stored in the water cycle is almost $1{,}400 \cdot 10^6$ km^3. Theoretically available for human use is a water quantity of about $9.6 \cdot 10^6$ km^3 in rivers, lakes, marshes and aquifers or 0.69 % of total water. Potential groundwater reserves are estimated to have a quantity of about $9.5 \cdot 10^6$ km^3 or 0.68 % of the total water, including brackish and fossil groundwater (Gleick 1996). From the global-scale water budget study, it looks as thought there is more than enough fresh water to meet demands of human survival, both now and in the foreseeable future. However, water is often available in the wrong place, at the wrong time, or of the wrong quality. This uneven distribution is highlighted in the arid and semiarid regions in the Middle East and in North Africa. Beyond it, the hydrological cycle is disturbed by over-exploitation, depletion, or deterioration of the waters in rivers and aquifers.

Since 2002 water rights are human rights, explicitly acknowledged by the United Nations. But according to WHO analyses and checkups of other institutions about 440 million people are affected by severe water shortages or water stresses (Helvetas 2005). Water shortage means less than 1,000 m^3 renewable water per person and year, water stress means 1,000 - 1,700 m^3 renewable water per person and year (Roudi-Fahimi et al. 2002, Worldwater 2007). According to the World Bank this number will rise by 2025 to 1.4 billion people and by 2035 to 3 billion people.

Nearly all of the 19 countries of the so-called MENA-region (Middle East and North Africa: 16 Arab countries, then Iran, Israel and Turkey) are considered as the most water-scarce regions of the world. Home to 6.3 % of the world’s population, they contain only 1,4 % of the world’s renewable fresh water (Roudi-Fahimi et al. 2002). Furthermore, primarily the northern part of the around 3.1 million km^2 comprising Sahel which stretches just south of the Sahara across Africa is affected by water shortage or at least by water stress. In all these arid and semiarid regions rapid population growth leads to increasing urbanisation. Thus, the demand for water resources sharply rises in all sectors of the economy (agricultural, industrial, touristic, and domestic), has exacerbating the natural water scarcity today and even more in the future.

The hyperarid, arid and semiarid regions have a high precipitation deficit, receiving much less precipitation annually than would satisfy for climatologic demand for evaporation and transpiration. The temperature-dependent potential evapotranspiration can reach extreme rates of more than 5000 mm/year. This is mainly due to the high temperatures (during the hottest months sometimes until 45 - 50° C) and few storms bringing rainfall.

Hyperarid and arid lands are deserts, such as especially the Sahara, with 8.9 million km^2 the largest hot desert and one of the most arid regions on the world, and furthermore on the Arabian Peninsula the Arabian desert and the East Sahero-Arabian xeric shrublands occupying 2.3 million km^2 and stretching from Yemen to the Persian Gulf and Oman to Jordan and Iraq. The immediate reason of the development of these deserts is the subsidence of a warm and dry air column from the upper atmosphere in a broad belt within the latitudes 20° and 35° north roughly centred on the Tropic of Cancer. Thus the humidity is lowered and clouds are dispersed. Deserts in North Africa also occur on the leeward sides of mountain ranges, e.g. in Somalia or Djibouti (shadow deserts). A further type of deserts in Africa is induced by upwelling of deep cold seawater, driven by ocean coastal currents, e.g. the western seaboard sections of the African continent. In the deserts the amount of mean annual precipitation is less than 250 mm, at many places no more than 20 - 50 mm. Especially in hyperarid areas decades may pass without rainfall, and even in the highlands rainfall happens erratically and with unpredictable patterns, once every 5 - 10 years. Desert storms are often violent when they occur after long dry periods, which usually last for years. These multiyear droughts can have lethal consequences for livestock and men. Large Sahara storms may deliver up to 1 mm per minute. Normally dry stream channels, so-called wadis, can quickly fill after heavy rains, and violent flash floods make these channels dangerous.

The fringes of Sahara desert and deserts in the Middle East form a gradual transition from an arid to a semiarid (more humid) environment, making it difficult to define the desert border. These transition zones have very fragile, delicately balanced ecosystems. In the semiarid regions mean annual precipitation ranges between 250 and 500 (600) mm. Rainfall occurs primarily in the monsoon season between May and October and is characterized by great variation from year to year and from decade to decade. During the wet period, usually distributed over a 3 - 4 months period in a year, the rainfall is higher than evapotranspiration.

It should be stressed that in principle the widespread aridity of the subtropical arid and semiarid regions in the Middle East and in North Africa arise only partly from man-made circumstances, but is mainly dependent on deep-seated features of the general global atmospheric circulation. Dry deserts or lesser dry semi-deserts are unique, natural ecosystems.

In the Sahara region and in parts of the Arabian Peninsula the water supply relies predominantly or almost entirely on groundwater, especially irrigation is mostly supplied by groundwater. In the Arab West Asia countries mostly surface waters meet the demand; desalinated water, treated wastewater or agricultural drainage are subordinate (Al-Zubari 2002). About 80.1 % of the total freshwater withdrawal (freshwater comprises renewable surface water and groundwater supplies including surface inflows from neighbouring countries) account for agricultural use, the domestic use averages 16.5 % and industrial use 3.4 % (Al-Zubari

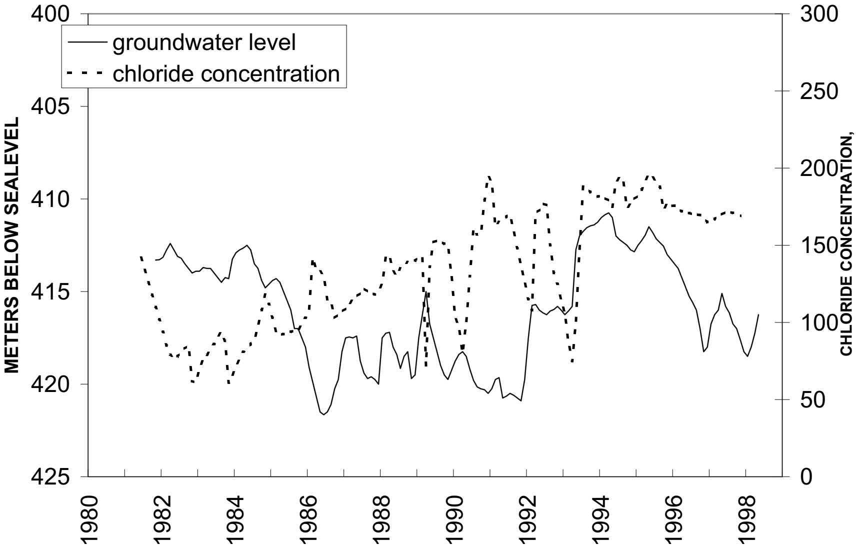


Fig. 3.10.1. During 1981-91, groundwater level (continuous line) in monitoring well 14518901 situated in the Eastern Aquifer (Cretaceous limestones and dolomites) east of Ramallah/Palestine declined about 8 m in response to groundwater abstraction, followed by a rise of about 10 m during 1992-93. The rise was in response to a period of heavy precipitation and snow melt that resulted in increased recharge to the aquifer. Chloride concentrations (dotted line) generally increased during 1981-94, and may be related to water-level fluctuations in the well (source: U.S. Geological Survey 1998, redrawn).

2002; Worldwater 2007). Due to escalating industrial, agricultural and individual water demands, at numerous places in the arid and semiarid regions being under consideration the amount of the used water is greater than the amount of the renewable water. In 1995 the following deficits were reported, amongst others: Saudi Arabia 13,558 million m^3, Syria 4,880 million m^3, Kuwait 200 million m^3, Jordan 140 million m^3, Gaza strip 65 million m^3 (Al-Zubari 2002; Gleick 2004). Speaking about groundwater, in many countries the resources are over-drafted, resulting in declining groundwater levels, in many cases at rates of 10, 20 or more cm per year. Over-extraction frequently results in a severe quality deterioration due to seawater invasion in coastal regions and deep connate water intrusion (Fig. 3.10.1).

Available water resources can also include fossil groundwater. The most famous example are the sandstones of Nubian facies which underlie most of the Sahara. Another example is the Disi formation in the south Jordan desert being equivalent with the Saq aquifer in Saudi Arabia. All these groundwater reserves are not or only marginally being replenished under current climatic conditions, but accumulated during periods of wetter climate in the Pleistocene glacial epochs. Traditional radiocarbon dating indicates that fossil waters were recharged between 20,000 and 40,000 years BP. Contrary to that, a new technique using the isotope Krypton-81 for tracing age results in the extraordinary findings that the palaeogroundwater contained for instance in the Nubian sandstone aquifer under the Sahara has residence times between 210,000 and 1 million years (IAEA 2007). By necessity, countries engaging in groundwater mining will come to a point at which they will have exhausted any fossil groundwater reserves and, presumably, have to look to alternative sources for maintaining standards of living, e.g. desalinated salt water (Murakami 1995).

Available or renewable water cannot be equated with potable (drinking) water. Most of the Middle East and North Africa countries are stressed by water scarcity not only caused by meteorological reasons but also due to quality problems, because surface water and (mainly shallow) groundwater resources are threatened and polluted by numerous point and diffuse sources of pollution generated by anthropogenic activities. Industrial activities producing water pollution are related amongst others to actual or abandoned industrial sites, landfills not reflecting the modern state-of-the-art, car repair shops, leakage of underground storage tanks and the adherent piping, discharge of poorly treated or untreated sewage and/or cooling water used for industrial processes, and surface and deep disposal of oil and gas brines. Another important risk factor is the agricultural land use being connected with saline and contaminated irrigation return flows with pesticides or fertilizers. Much nitrate leaches into deeper soil layers and into the groundwater.

Especially with regard to groundwater domestic effluents and the great number of uncontrolled municipal dumping sites constitute a high risk potential for the groundwater. Another problem is the frequent absence of sewage collection and treatment facilities particularly, but not only in rural areas. In small villages septic tanks and cesspits are commonly used to collect sewage and there is no connection to main sewerage pipes. The liquid effluents with high loads of nitrogen discharge into the soil via open-joint pipes or openings in pit wells and enter the groundwater sooner or later. Incremental increases in mineral content, high nitrate concentrations, and pathogen germs such as faecal coliforms are monitored in the groundwater under densely populated towns or cities. In the context with water quality the artificial groundwater recharge by injection or infiltration of more or less treated wastewater into the underground likewise seems not to be a good practice, especially not in karst terrains.

Many surface waters contain pesticides, fertilizers, spilled petroleum products or other hazardous compounds such as heavy metals adsorbed to suspended particles. Many rivers and creeks are subjected to chronic pollution due to non-treated domestic and industrial discharges (Fig. 3.10.2). Droughts lead to a deterioration of water quality because lower water flows reduce dilution of pollutants and increase contamination of remaining water sources at that region. Because of hydraulic interactions between surface water and groundwater a polluted influent watercourse will contaminate the groundwater and vice versa.

Fig. 3.10.2. Domestic wastewater draining into a creek.

Recapitulating one can say, that human and animal wastes on the one side and agricultural activities on the other side are the most important reasons for water pollution in the dry regions being under consideration. That means, that meteorologically respectively hydrologically caused scarce water resources are additionally reduced by quality reasons because of pollution of surface water and groundwater. That means that not all people have access to adequate supplies for safe water, that must meet the requirements of certain quality standards, especially of the WHO. The absence of adequate sanitation and any sewage disposal leads to diseases and in severe causes to deaths; especially children are affected.

In the Middle East, in North Africa and in European countries bordering the Mediterranean Sea droughts and water scarcity are a recurrent feature (Fig. 3.10.3). An extreme example is the Sahel, persistent droughts hit mainly its northwestern parts especially in the years 1969-1977 and 1982-1985. These multiyear droughts, which were responsible for the loss of several 100,000 human lives, for a long time were not interpreted as an early sign of global climate change but as a consequence of El Niño events and unsuitable anthropogenic activities. However, since the release of the first volume of the Forth Assessment Report of the "Intergovernmental Panel on Climate Change (ICPP)" on 2nd February 2007 in Paris (ICPP 2007) a worldwide warming of the climate since the second half of the last century must be accepted as true. According to the prognosis of the IPCC-report climate change will exacerbate the water scarcity. Even if emission of greenhouse gases

Fig. 3.10.3. Olive tree overrun by sand dunes due to accelerating desertification, region of Gharabad, Tunesia;
© Clive Shirley/signum/Greenpeace.

would be stabilised today, the increases in temperatures and the associated impacts on human life including those on water availability will continue to come for many, many decades. People in the affected regions have to adapt to the impacts of climate change on water resources. The necessary struggle against drought and water scarcity can only be won if all persons and all countries concerned cooperate, because they have the same fate. The European Water Framework Directive – shortened WFD – (European Union 2000) which entered into force on 22nd December 2000 can offer professional and political solutions to win this challenge.

This contribution has the intention to demonstrate how the concept of the European Water Framework Directive can be transferred to arid and semiarid regions. The author, who was engaged in the successful implementation of the WFD in Hungary and in Poland during the years 2003-2005, wants to clarify that a better protection of the vitally important water resources even in dry regions may not remain a dream.

3.10.2 Climate in the past, today and in the future, and its influence on the water cycle

For understanding the current climate discussion it is of advantage to know how the Earth's climate has developed in the past, especially in the post-glacial epoch of the Quaternary, that means during the last eleven millennia. Earth scientists are able to piece together a picture of the climate in the past by analysing a great number of so-called proxy data, among others resulting from air bubbles trapped in ice cores, thickness of tree rings, glacier lengths, pollen remains, coral growth, chemistry of ocean sediments and rock paintings. The result: the global climate has changed throughout history.

The palaeoclimate during the last Quaternary glacial period in the Middle East and in North Africa was generally cold, sometimes humid and sometimes dry. During the more or less wet episodes, the huge groundwater reserves found in the Nubian sandstones and other deep aquifers were recharged. In the early and mid-Holocene, starting at roughly 11,000 years BP, Middle East and North Africa experienced greatly expanded wet conditions by around 6,000 years BP (Issar 2003). According to palaeoclimate reconstructions and archaeological evidence the Sahara and adjacent Sahel regions were much greener than today (Issar 2003, Neumann 1989). Then, only within one or two centuries, a dramatic desiccation occurred abruptly (Claussen et al. 1999). It is a common hypothesis, that the difference between late and mid-Holocene climate was mainly caused by changes in the Earth's orbit around the sun. This progressive, step-like increase in subtropical African aridity until now is evidenced amongst others in the dust record in the North Atlantic marine sediments. The dust increase in the marine sediments relates directly to changes in vegetation as the Sahara expanded across northern Africa (Issar 2003, de Menocal 1995). In the western parts of the Middle East, especially in the surroundings of the Dead Sea considered by the palaeoclimatologists as climate archive, the more or less wet phase continued by roughly 3,500 years BP. In the last two millennia the climate was rather similar to modern conditions, only interrupted by increased precipitation during the 16th and 17th centuries.

The overwhelming majority of scientific experts believe that today's climate, characterised partly by major heat waves, violent floods, severe droughts, dwindling water resources and extreme weather events, is clearly atypical and that human activity was „very likely“ to be responsible for most of the observed warming in recent decades (IPCC 2007). According to the IPCC climate report, use of fossil energies (Fig. 3.10.4) and changes in land surface are the main drivers behind the increase in carbon dioxide, while agriculture has increased levels of methane and nitrous oxide. High heat-trapping greenhouse gas levels have raised global mean air and ocean surface temperatures with the consequence of widespread melting of snow and ice. Especially the levels of carbon dioxide increased from a pre-industrial level of 280 parts per million (ppm) to 379 ppm in 2005. Most worryingly, the levels have increased more quickly over the past 10 years than they have since 1960 when scientists first began to record the increase. The increase of green-

Fig. 3.10.4. Coal-burning power plant Neurath near Cologne, Germany, emitting carbon dioxide;
© Bernd Arnold/signum/Greenpeace.

house gases in the atmosphere gave rise to the global temperatures. Much of the increase was recorded over the last 50 years, when the temperature increased by an average of 0.13° C per decade – almost twice as fast as over the previous 100 years.

Focused on the Middle East and North Africa, more intense and longer droughts have been seen since the 1970s over wide sub-tropical areas. Deserts warmed up between 1976 and 2000 at an average rate of 0.2 - 0.8° C per decade, much higher than the global mean temperature increase (IPCC 2001, 2007). Since the 1960s the Sahel has lost a roughly 100 km broad belt to the Sahara, rainfall levels have declined by 20 - 40 % and the land has been severely degraded. Over-all in the Sahelian region, the warmer and drier conditions have led to a reduced length of the growth period with detrimental effects on crops. The increase in temperature is considered likely to be linked to global climatic change (and in this connection to the warming of the surface of oceans, predominantly of the Indian Ocean), however, it may also be linked to El Niño southern oscillations. Alarming new results suggest that the westerly jet streams marking the northern boundary of the Tropic of Cancer have moved by 2 degrees latitude or 225 km farther away from the equator since 1979, the year when satellite measurements of troposphere began (Santer et al. 2003). If the tropic moves another 2 to 3 degrees poleward in the 21st century, subtropical deserts might expand into heavily populated mid-latitude regions, threatening to drive the Sahara into southern Europe.

Based on a large number of simulations and models the scientists are able to develop gloomy scenarios what happens next (IPCC 2007). With emissions continuing to rise it is very likely that the temperature will be 0.4° C higher by 2030 than in the year 2000 and that changes in the climate will be greater than those seen in the 20th century. By the end of this century temperatures could be between 1.8°C (with a range of 1.1 to 2.9° C) and 4° C (with a range of 2.4° C to 6.4° C) higher than in 1999. The worst-case scenario with an average warming of 4° C would be the result of rapid economic growth, a global population that peaks in the middle of the century and the rapid introduction of new technologies, but continued reliance on fossil energies. A significant switch to non-fossil energies (water, wind, sun, biomass, geothermal power) would instantly cut the predicted temperature rise to 2.4° C. The EU has defined any rise over 2° C as „dangerous“.

Warming of just this level could be achieved only by moving rapidly towards CO_2-free technologies, but this is unrealistic. Because carbon dioxide and other anthropogenic greenhouse gases, once emitted into the atmosphere, are long-lived, they stay there for more than a century. This means that the time to reverse the human-induced climate change and the resulting damages would not be years or decades, but centuries, even if all emissions of green gases were terminated, which is clearly not feasible.

The therefore long-lasting climate change will severely influence some variables of the water cycle. Due to a higher rate of evaporation an increase in global mean precipitation is predicted, concentrated in fewer bursts of rain and more in winter. However, not all regions will experience an increase in precipitation, and derived from that an increase in run-off or groundwater recharge. In general, countries around the Mediterranean Sea will see little difference in winter rainfall, but they are likely to be much drier in the summer. Because summer temperatures could go up as much as 5 °C in the next 50 years, the small increase in winter rainfalls is likely to be countered by increased evaporation.

With regard to the deserts and semi-deserts in Middle East and North Africa countries climate change has the potential to worsen an already critical situation. In the 21st century drier subtropical regions will warm more than the moister tropics and the global mean. The simulated rise in annual mean warming varies from 3 to 4° C, in Sahara sub-regions the mean temperature increase will be more than 4° C (IPCC 2007). Annual rainfall is very likely to decrease in the northern Sahara. It is unclear how rainfall in the southern Sahara and in Sahel will evolve. Some climate models prolong the partial amelioration of the Sahel droughts in the 1990s in the 21st century. However, the projection for a modest increase in Sahel rainfall is to be seen with caution, most scientists expect a tendency for greater drying. The results of late 2005 climate change modelling studies project that the Sahel will face a period of a dramatic reduction of precipitation of about 25 - 30 % compared with the 20th century situation, if greenhouse gas emissions are not checked. Moreover, global climate change will increase year-to-year variations in desert rainfall, including drought spells increasing in length and frequency. Increasing water stress is expected due not only to a smaller rate of precipitation and enhanced evaporation, but also caused by the growing risk of having several years of summer drought in succession.

With regard to semi-deserts scientists now have little doubt that human-induced climate change will be a major factor in future decades, but anthropogenic action stressing the very fragile, delicately balanced dryland ecosystem beyond its tolerance limit are additional causes of desertification. The increase of population combined with overgrazing of pastures by livestock, deforestation or collection of firewood, non-sustainable farming practices including over-extraction of (ground)water and not adequate irrigation techniques in the end result in desiccated soils eroded by wind and water.

In all, significantly less rainfall und higher evaporation in the arid and semiarid regions being under consideration will exacerbate the current water scarcity even more. Climate change will also have an impact on water quality in rivers and lakes. High temperatures and low flows provide ideal conditions for the accumulation of pollutants and eutrophication. Rising sea levels, also a consequence of climate change, will affect the water quality, too, because in flat coastal regions the fresh groundwater resources will be reduced due to the landward invasion of salty seawater. Also the rivers are affected, because the sea can enter upcountry, thus increasing the mineral content of the surface waters. For instance, the level of the eastern Mediterranean Sea rose about 15 cm between 1973 and 2000 (Shirman & Melzer 2002), and a further rising can be expected.

In view of the Tigris and Euphrates rivers, the two largest perennial rivers in the Middle East and of significant importance for the water supply in the arid and semiarid parts of Syria and Iraq, much of their discharge results from the glaciers and the melting snow accumulated during the winter in the mountains of southeastern Turkey. The projected dramatic glacial melt at first will give for some decades rise to violent floods for which especially the Tigris is notorious already today, followed by a noticeable reduction in flow as the glaciers disappear.

3.10.3 Transfer of the concepts of the European Water Framework Directive to arid and semiarid regions

The arid and semiarid areas in the Middle East and in North Africa face severe water shortages now and even more in the future, still more aggravated by climate change. Consequences of water scarcity will be economic constraints to develop new infrastructure for providing safe water and adequate sanitation. This suggests growing conflicts with agricultural water users, who currently consume the majority of water used by humans. Therefore, only an integrated and sustainable water (and land use) management offers the potential to reduce the current pressures on water resources and human welfare. Despite of political tensions, mainly in the Middle East region, an integrated water management must be related to a river basin as a whole, even in the case of multinational rivers crossing borders of neighbouring countries and transboundary aquifers. Consequently, not water conflicts are the solution, but trustful cooperation of all countries with shared water resources including exchange of data, knowledge and experience, and the implementation of joint water boards (Toussaint 2001). This form of water management, that could be a catalyst for lasting peace, is the fundamentally new approach of the European Water Framework Directive (WFD) from December 2000. And a further step is necessary, namely to consider the hydraulic interdependence of surface waters and adjacent groundwater, in fact with respect to water quantity and quality. A transfer of the concept and implementation strategies of the WFD adapted to the regional features can help to stop or at least to minimize the deterioration of freshwater resources in the foreseeable future.

General approaches and requirements

The new EU Water Framework Directive is a radical improvement on earlier, piecemeal EU water legislation. It is very broad in its scope and addresses inland surface waters, transitional (estuarine) and coastal waters, and groundwater. That means that the environment must be protected in its entirety. The WFD sets a framework for comprehensive management of water resources, within a common approach and with clear objectives, which must be achieved by specified dates, principles and basic measures. At the latest by 2012 the European Commission has to publish a report on the EU-wide implementation of the WFD.

The fundamental objectives of the WFD aim at maintaining „high status" of waters where it exists, preventing any deterioration in the existing status of waters and achieving at least „good status". Member States will have to ensure that a coordinated approach is adopted for the achievement of the objectives of the WFD and for the implementation of programmes of measures for this purpose. The objectives of the WFD, laid down in Article 4, are:

- to protect and enhance the status of aquatic ecosystems (and terrestrial ecosystems and wetlands directly dependent on water),
- to promote sustainable water use based on long-term protection of available water resources,
- to provide for sufficient supply of good quality surface water and groundwater as need for sustainable, balanced and equitable water use,
- to provide for enhanced protection and improvement of the aquatic environment by reducing / phasing out of discharges, emissions and losses of hazardous substances (e.g. heavy metals or organohalogen compounds),
- to contribute mitigating the effects of floods and droughts,
- to protect territorial and marine waters,
- to establish a register of protected areas (e.g. biological reserve designated for protection of habitats or species, or water recovery area) depending on water.

These environmental objectives of the WFD have to be met within a pre-established schedule by 2015, but an extension of this deadline limited to a maximum of two further updates of the river management plan is possible in exceptional cases.

Furthermore, less stringent environmental objectives can be claimed for water bodies when they are so affected by human activities or their natural condition, that the achievement of the objectives would be infeasible or disproportionately expensive. Additionally, further conditions are met: amongst others no further deterioration in the status of the affected water body (derogation clause), and specific mention of the reasons.

Some of the most important elements of the new and innovative approach to managing Europe's water resources in the WFD are:

- the above ambitious objectives (principle of non-deterioration and achievement of overall good status of surface water and groundwater) and clear deadlines,
- the introduction of River Basin Management on a Europe-wide scale,
- the requirement for cross-border cooperation in water management between countries and all involved parties,
- prevention and control of point and diffuse pollution sources on the basis of the so-called combined approach,
- the monitoring of the status of surface waters, groundwater and protected areas,
- the identification and reversal of any significant and sustained upward trends of pollutants in groundwater,
- the public participation and transparency in water policies, and
- the economic analysis of water use and full recovery of the costs associated with water use.

Following, some key elements of the WFD are defined and explained with more details.

River basin (district)

The WFD utilises the river basin as the natural unit for water management - the natural geographic and hydrological unit instead of according to administrative or political boundaries (Fig. 3.10.5). A river basin is the area of land from which all surface run-off flows through a sequence of streams, rivers and possibly lakes into the sea at a single river mouth, estuary or delta. Coastal waters and groundwater are also elements of a river basin. Member States have to identify all river basins lying within their national territory and assign them to an individual river basin district (area of land and sea, made up of one or more neighbouring river basins together with their associated groundwater and coastal/marine waters up to one nautical mile beyond the baseline from which territorial waters are measured). Each Member State must arrange the coordinated water management in relation to each river basin district lying within its territory.

For international river basins or river basin districts, respectively, the Member States and non-Member States concerned shall together ensure the coordination of all relevant measures necessary for achieving the objectives of the WFD. For this purpose they shall use existing structures stemming from international agreements. At the request of the Member States involved, the Commission shall act to facilitate the establishment of programmes of measures.

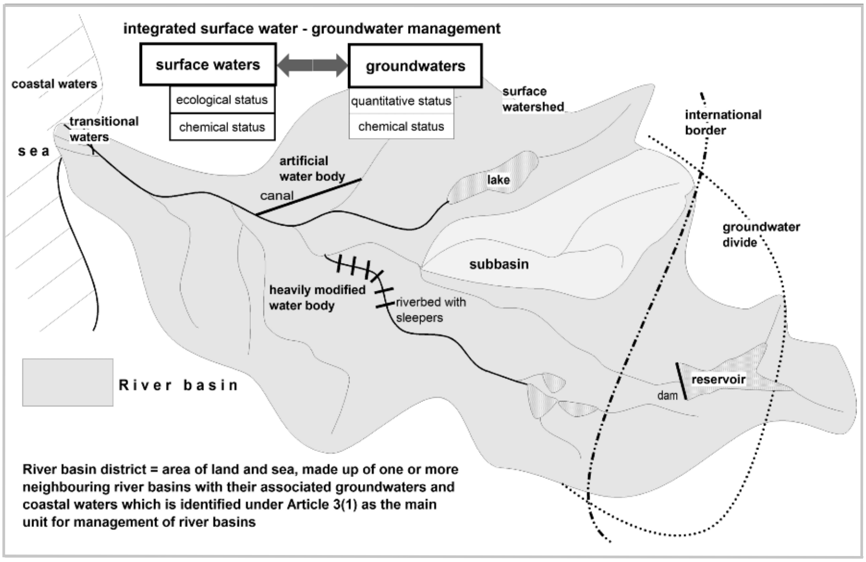


Fig. 3.10.5. Integrated surface water and groundwater management of a river basin (district) crossing an international border. In view of groundwater, the subsurface divide is more or less different from the surface watershed in many cases. The figure shows all WFD-relevant types of waters or water bodies, respectively, within a river basin.

Characterisation of water bodies

For each river basin district – also for those which traverse national frontiers – the relevant characteristics (especially hydrological and geological / hydrogeological conditions, ecological features (only for surface waters), pressures and impacts of human activities on water resources) must be described; moreover, an economic analysis of water use has to be executed. In general, local authorities will have the primary role in promoting, establishing and implementing the relevant activities.

River basin management plan

All the results of the above characteristics of river basins, review of the impact of human activity on the status of waters in the basin, estimation of the effect of existing legislation and the remaining gap to meet these objectives, and a set of measures designed to fill the risk assessment for surface waters and groundwater must be set out in a plan for the river basin. One additional component is the economic analysis of water use within the river basin. This is to enable there a rational discussion on the cost-effectiveness of the various possible measures. The plan is a detailed account of how the objectives set for the river basin (ecological status, quantitative status, chemical status and protected area objectives) can be reached within the timescale required. It is essential that all interested parties are fully involved in this discussion, and indeed in the preparation of the river basin management plan as a whole. The WFD envisages a cyclical process where river basin management plans are prepared, implemented and reviewed every six years. By 2009 the first river basin management plan needs to be produced.

Coordination of measures

The objectives are established for the river basin (district). Then an analysis of human impact is conducted to determine how far from the objective each surface water or groundwater is. At this point, the effect of full implementation of all existing legislation is considered. If the existing legislation solves the problem, the objective of the WFD is attained. However, if it does not, the Member State must identify exactly why, and design whatever additional measures are needed to satisfy all the objectives established. These might include stricter controls on polluting emissions from industry and agriculture, or urban wastewater sources.

Status and protection of aquatic environment

Good status for surface waters and groundwater ensures both quality of life and environmental sustainability and also guarantees the resource.

With regard to surface waters there is a difference between ecological and chemical (qualitative) status to be achieved or at least conserved. Good *ecological status* is defined in Annex V to the WFD, in terms of the quality of the biological community, the hydrological regime, the morphological conditions and the chemical characteristics. The system is somewhat complicated, but this is inevitable with respect to the extent of ecological variability, and the large number of parameters, which must be dealt with. Good c*hemical status* is defined in terms of compliance with all the quality standards established for chemical substances at European level. The WFD also provides a mechanism for renewing these standards and establishing new ones by means of a prioritisation mechanism for hazardous chemicals (European Union 2006 a). This will ensure at least a minimum chemical quality, particularly in relation to very toxic substances, everywhere in the European Community. A set of uses adversely affect the status of surface waters. Examples are flood protection, essential drinking water supply, navigation, and power generation. The problem is dealt with by providing derogations from the requirement to achieve good status for these cases, so long as all appropriate mitigation measures are taken.

In terms of groundwater the case is somewhat different. The presumption in relation to groundwater should broadly be that it should not be polluted at all. For this reason, setting *chemical quality standards* may not be the best approach, as this gives the impression of an allowed level of pollution to which Member States can fill up. A very few such standards have been established at European level for particular issues (nitrates, pesticides and biocides), and these must always be adhered to. Because of the great importance of groundwater protection detailed provisions were tackled separately in a Daughter Directive. This Directive was published on 12th December 2006. It introduces quality objectives, obliging Member States to monitor and assess groundwater quality on the basis of common criteria and to identify and reverse anthropogenically induced upward trends in groundwater pollution (European Union 2006 b). But for general protection, there was taken a precautionary approach. Taken together, these should ensure the protection of groundwater from all contamination, according to the principle of minimum anthropogenic impact.

Quantitative status is also a major issue for groundwater. There is only a certain amount of recharge into a groundwater body each year, and of this recharge some is needed to support connected ecosystems. For good management, only that portion of the overall recharge not needed by the ecology can be abstracted – this is the sustainable resource, and the WFD limits abstraction to that quantity.

Monitoring of surface waters, groundwater, and protected areas

A prerequisite of preventive protection of water resources and of controlling the effectiveness of measures mitigating water damages is the monitoring. One of the innovations of the WFD is that it provides a framework for monitoring of surface waters, groundwater and protected areas for the first time on European level. Monitoring of surface waters and groundwater must be integrative allowing for the fact that there is a hydraulic interconnection between these waters. Annex V to the WFD governs the details of surveillance, operational and investigative monitoring. Additionally, the Groundwater Daughter Directive from December 2006 ensures that groundwater quality is monitored and evaluated across Europe in a harmonised way. By December 2006 Member States have to ensure the establishment of programmes in order to get a coherent and comprehensive overview of water status within each river basin district. At the latest beginning with the year 2007 these programmes should be operational.

For surface waters such programmes cover the volume and level or rate of flow in the extent relevant for ecological and chemical status and ecological potential, and the ecological and chemical status and ecological potential. For the groundwater, such programmes cover monitoring of the chemical and quantitative status. In the scientific literature it is emphasized that especially groundwater monitoring programmes have to be clearly adapted to the partly complex hydrogeological features and to the fate of the pollutants in the underground, and therefore may not be bought off the peg, but should be tailor-made (e.g. Ottens et al. 2000; Toussaint 2002, 2003, 2004). For protected areas (e.g. safeguard zones around drinking water production wells or springs) the above programmes are supplemented by those specifications contained in Community legislation under which the individual protected areas have been established.

Combined approach

The Member States shall ensure that all discharges into surface waters are controlled according to the so-called combined approach. On the source side, it requires that as part of the basic measures to be taken in the river basin, all existing technology-driven source-based controls must be implemented as a first step. But over and above this, it also sets out a framework for developing further such controls. The framework comprises the development of a list of priority substances for action at EU level, prioritised on the basis of risk. On the effects side, it coordinates all the environmental objectives in existing legislation, provides a new overall objective of good status for all waters, and requires additional measures when preceding activities taken on the source side are not sufficient to achieve these objectives.

Public participation

There are two main reasons for an extension of public participation. The first one is that the decisions on the most appropriate measures to achieve the objectives in the river basin management plan will involve balancing the interests of various groups. The economic analysis requirement is intended to provide a rational basis for this, but it is essential that the process is open to the scrutiny of those who will be affected. The second reason concerns enforceability. The greater the transparency in the establishment of objectives, the imposition of measures, and the reporting of standards, the greater the care Member States will take to implement the legislation in good faith, and the greater the power of the citizens to influence the direction of environmental protection, whether through consultation or, if disagreement persists, through the complaints procedures and the courts.

Economic analysis of water use

The need to conserve adequate supplies of a resource for which demand is continuously increasing is also one of the drivers behind what is arguably one of the most important innovations of the WFD – the introduction of pricing. Adequate water pricing acts as an incentive for the sustainable use of water resources and thus helps to achieve the environmental objectives under the WFD. By 2010, Member States will be required to ensure that the price charged to water consumers – such as for the abstraction and distribution of fresh water and the collection and treatment of wastewater – reflects the true costs. Whereas this principle has a long tradition in some countries, this is currently not the case in others. This cost recovery rule is expected to impact particularly irrigated agriculture, where users have not paid the full cost of water supply.

WFD-related measures for mitigating water deterioration

The major concern in many Middle East and North Africa countries is that the scarce renewable water resources are over-exploited and do not yet cover the permanently increasing demands. Additionally to their waste and inadequate management, the water resources are being threatened and polluted by anthropogenic agricultural, industrial and domestic activities. Therefore, an integrated and participatory approach is necessary to balance out the different water needs and demands with the available resources.

A „silver bullet" for solving the resulting water scarcity, rapidly becoming a major concern in most countries being under consideration seems not to be existent, but the EU Water Framework Directive may give aid to mitigate at least the most severe water problems. Because the natural and man-made water scarcity is cross-national, it is of greatest importance that the WFD requires not only a coordination of all countries sharing a surface water catchment area or an aquifer, but a truthful and substantial cooperation, and a common river basin management plan. Apart from this approach fundamentally important in a world region with latent or open political tensions all other individual objectives and resulting requirements of the WFD are helpful and may be transferred to Middle East and North Africa countries. In table 1, WFD articles with relevant concern (left side) are related to the main threats to water resources in the dry regions being under consideration (right side), resulting in an deterioration of surface waters and groundwater. It should be stressed, that certain water-related problems in the MENA countries sometimes are expressed too drastic, but the general statements are true and justified, even though somewhat undifferentiated. For instance, in view of sufficient environment-related legislation there exist more or less significant variations from one country to another: some countries have already achieved substantial progress, but others not. Another example: shortcomings concerning water metering are more or less usual in many countries, in others not. But in all cases an integrated and sustainable water resources management required by the WFD is missing, and this approach takes account not only of economic and social, but also of ecological needs (various ecosystems are depending on water).

The author proposes that analogue to the WFD-requirements for the EU-territory each country in the Middle East and in North Africa should ensure the establishment of a programme of measures for each river basin (respectively basin district). The measures should start with taking account of the results of a gap analysis (showing differences between reality and the environment objectives) and a risk assessment (identification of the anthropogenic pressures on surface waters and groundwater and estimation of the degree of vulnerability of aquifers and ecosystems depending on water) under consideration of existing data, thus allowing a comprehensive view of the water resources and uses as a whole.

Table 3.10.1. Possible transfer of WFD objectives and requirements (left side) to arid and semiarid regions to mitigate water deterioration due to natural conditions and anthropogenic activities (right side)

Important objectives and requirements of the Directive 2000/60/EC (WFD)	Human-made problems and impacts on waters in arid / semiarid regions in the Middle East and in North Africa
Coordination of administrative arrangements within river basin districts (Art. 3) Environmental objectives (Art. 4) Characteristics of a river basin district, review of the environmental impact of human activity and economic analysis of water use (Art. 5), in accordance with Annexes II and III Register of protected areas (Art. 6), in acc. with Annex IV Waters used for abstraction of drinking water (Art. 7), in acc. with Annex V Monitoring of surface water status, groundwater status and protected areas (Art. 8), in acc. with Annex V Recovery of costs for water services (Art. 9) Combined approach for point and diffuse sources (Art. 10) Programme of measures (Art. 11), in acc. with Annex VI River basin management plans (Art. 13), in acc. with Annex VII Strategies against pollution of water (Art. 16), in acc. with Annexes VIII - X, and Directive 2006/11/EC Strategies to prevent and control pollution of groundwater (Art. 17), in acc. with Annexes II and V, and Directive 2006/118/EC	**1) Water quantity** Partly unsufficient environment legislation and inadequate water mangement (Art. 3, 4, 9, 11) Deficits concerning water rights (Art. 4, 5, 7) Partly unsufficient inventories concerning supply, distribution, losses and demand of water (Art. 3, 4, 5, 11) Shortcomings concerning maintenance, repair, and operation of water systems (Art. 4, 5, 9, 11) Water waste in general (Art. 4, 5, 10, 11) Partly missing water meters, readings not always regularly done (Art. 4, 5, 9, 11) Inadequate water distribution methods and irrigation techniques (Art. 4, 5, 9, 11) Subsidy of agricultural irrigation (Art. 9) Cultivation of water-wasting field crops (Art. 4, 5, 10, 11) Over-extraction of groundwater (Art. 4, 5, 7, 8) Missing or too few water protection areas, unadequately protected water catchments (Art. 6, 11) Unorganized urban planning (Art. 4, 5, 10, 11)
	2) Water quality and ecology Unorganized urban planning (Art. 4, 5, 10, 11, 17) Systematically artificial groundwater recharge by injection of more or less treated sewage (Art. 4, 5, 10, 11, 17) Disposal or reinjection of oil field brines (Art. 4, 5, 10, 11, 17) Irrigation with more or less treated sewage (Art. 4, 5, 10, 11, 17) Discharge of sewage into rivers or aquifers (Art. 4, 5, 10, 11, 17) Excessive application of fertilizers and pesticides (Art. 4, 5, 10, 11, 17) Absence of sewage collection and treatment facilities (Art. 4, 5, 10, 11, 17) at many places septic tanks, cesspits, leaking sewer pipes (Art. 4, 5, 10, 11, 17) Municipal and industrial landfills with inappropriate design, illegal dumping sites (Art. 4, 5, 10, 11, 17) Inappropriate storage of fuels and chemicals, and handling with hazardous substances, transport accidents (Art. 4, 5, 10, 11, 17) Abandoned polluted industrial sites (Art. 4, 5, 10, 11, 17)
All facts 1) - 3) result in quantitative and/or qualitative deterioration of waters and/or destruction of ecological potential (Art. 4, 5, 7, 8, 10, 11, 16, 17)	**3) Policy, water management in general** Border-crossing rivers (Art. 3, 5, 7, 8, 11, 13) and transboundary aquifers (Art. 3, 5, 7, 8, 11, 13, 17) Missing or unsufficient transborder exchange of data and information (Art. 3, 13) Population growth above average

These key activities are necessary to provide policymakers and water managers with a sound information basis and a better understanding of the impacts on the hydrological budget of a river catchment area and the influences on the qualitative and quantitative status of surface waters and groundwater in detail. Each programme of measures which should be periodically reviewed should include basic measures, which are to be understood as minimum requirements to be fulfilled, and, where necessary, supplementary measures.

The following basic measures should comprise especially:

- measures to avoid point emissions based on best available techniques (e.g. substitution of latrines by modern sanitation systems), combined with the establishment of relevant emission limit values or with a total prohibition on the entry of pollutants in the environment,
- measures to reduce or avoid emissions from diffuse pollution sources based on best environmental practices and educational programmes for farmers, and combined with regular controls,
- measures to save water especially in the agricultural sector combined with water-pricing policies,
- measures to promote a sustainable abstraction of water resources (water harvesting instead of water mining) including controls of the abstraction of fresh water and impoundment of rivers, and establishment of relevant registers,
- measures to establish protected areas around productive drinking water wells or springs, combined with regular controls of the chemical compounds in the raw and drinking water,
- measures to safeguard water quality in order to reduce the level of purification treatment required for the delivery of drinking water,
- measures to prepare legislation and administration instruments for authorisation of artificial recharge of aquifers by surface water and to control the recharge activities periodically,
- measures to prepare legislative and administrative instruments for the authorisation of a direct discharge of pollutants in special / extraordinary cases (e.g. injection of water containing pollutions into geological formations which for natural reasons are permanently unsuitable for other uses, injection of natural gas or liquefied petroleum gas in the underground, reinjection of pumped groundwater from mines and quarries, or associated with the construction or maintenance of civil engineering works),
- measures to eliminate pollution of surface waters by those substances specified as priority substances (but such a list first has to be established and become legally binding),
- measures to prevent significant chronic losses of pollutants from technical installations und to prevent / reduce the impact of accidental pollution by means of early warning-systems,
- measures to install monitoring networks covering surface waters and groundwater and to establish the monitoring programmes, chemical and/or biological

works in the laboratory, and GIS-based processing, interpreting, mapping and reporting of the data as useful tools in building up knowledge on water situation,

- measures to assess the qualitative groundwater status and to identify significant and sustained upward trends of groundwater pollutants and to reverse this trend when the concentration of the pollutants reaches 75 % of the parametric values of the relevant groundwater quality standards (50 mg/l NO_3, or 0,1 µg/l individual pesticides respectively 0,5 µg/l sum of individual pesticides) or of other threshold values; an earlier starting point for trend reversals is required mainly to prevent cost-effective detrimental changes in groundwater quality (European Union 2000, 2006 b).

Supplementary measures may be adopted in order to provide additional protection or improvement of surface waters or groundwater. Such measures may be amongst others economic or financial instruments, negotiated environmental agreements (e.g. between water managers and agriculture), code of good practice, demand management measures, promotion of adapted agricultural production such as low water requiring crops in areas affected by droughts, efficiency and reuse measures, promotion of water-efficient technologies in industry and water irrigation techniques, construction of desalination plants, execution of soil and/or groundwater remediation projects (in the case of degradable hazardous compounds bioremediation may be indicated), artificial recharge of aquifers, or educational projects. Furthermore, the government should prepare the regulatory procedures and the legislative instruments, so that the regional / local authorities (water boards or environment agencies) are able to order and to supervise mitigation measures such as groundwater remediation measures.

The WFD attaches great importance to clear and comprehensive information and participation of the public, because without strong public pressure political will to solve the water crisis remains weak. A further intention is to induce a dialogue between citizens, local administration and service providers to help bridging gaps between promises and action and to provide simple, sustainable and accessible solutions thus empowering civil society groups to develop a better understanding of their severe situation and to give instructions for self-help.

Where monitoring or other data indicate that objectives of the WFD are unlikely to be achieved by the basic measures, the competent administration should ensure, that the causes of the possible failure are investigated. Relevant programmes may have to be reviewed and adjusted, and appropriate additional measures may have to be performed. This can also include the establishment of stricter environmental standards (but in the case of exceptional and reasonably not foreseen circumstances, e.g. prolonged droughts, the administration may determine that additional measures are not applicable).

Following the author takes the agricultural sector as a very representative example to illustrate what is meant in detail and what can be done to escape from the cycle of poverty and disease due to water scarcity in arid and semiarid regions being under consideration.

WFD related measures to improve water quality in the agricultural sector

Many rivers, lakes and a lot of groundwater resources are under pressure from diffuse pollution, not only affecting water quality, but also changing the characteristics of aquatic ecosystems including fish. Agriculture is not solely responsible for all these pressures, but it is a large contributor especially due to the excessive use of chemical fertilizers leaching much nitrogen into the groundwater, the application of pesticides and the release of olive oil-mill wastes. Hot spots of nitrogen leakage from agriculture are areas with high water demand crops and shallow groundwater mainly in intensively irrigated areas. In many arid and semiarid regions wastewater is used to irrigate non-food crops, or even food crops in the rapidly expanding agricultural areas. Another reason of water pollution is the irrigation return flow resulting in an ongoing increase in the salinity of groundwater, affecting its further use for irrigation and endangering drinking water quality because of residues of fertilizers and pesticides. The requirements of the WFD are especially relevant for the protection of groundwater resources used for the abstraction of drinking water with the aim of avoiding deterioration in their quality in order to reduce the level of purification treatment required in the production of drinking water.

The WFD requires remedial actions when the concentration of pollutants exceeds the relevant quality standards and a trend reversal. By means of raising the awareness of farmers of the severe situation in the framework of education projects, organised by well experienced agrarian experts, people may change their traditional behaviour and learn to adopt environmental friendly methods, e.g. the application of fertilizers in appropriate amounts, considering also the content of mineralised nitrogen in the soil at the beginning of the vegetation period. Furthermore, irrigation by poorly treated sewage must be strictly prohibited. Only sufficiently treated wastewater, regularly controlled in view of its cleanliness, may be allowed to use. An improvement of the qualitative water status arises inherently from putting an end to the traditional water wasting irrigated agriculture as fast as possible by switching to low water-demand crops.

WFD related measures to improve water quantity in the agricultural sector

The traditional irrigated agriculture is by far the most important water user (actually using roughly 80 % of total fresh water) and also probably the least efficient sector in water use. Such low efficiencies in agricultural water use and the unsatisfactory features of irrigated agriculture are undoubtedly the result of the mismanagement of the water resources. In fact the irrigated areas have more than quadrupled since the end of the 20th century (PNUE 2004), but irrigation and drainage have undergone little technological change over the decades. Most irrigation systems are performing far below their potential mainly due to inadequate techno-

a) b)

Fig. 3.10.6. a) Water saving drip irrigation (Prof. P.-J. Paschold, Geisenheim Research Center/Germany).
b) Water wasting sprinkler irrigation in South Jordan Desert near Ram (U.S Geological Survey 1998).

logies, management practices and policies. Average losses of irrigation water are extremely high (55 to 65 %, subdivided into farm distribution, field application and irrigation system), only 35 to 45 % of water diverted or extracted for irrigation actually reaches the crops (PNUE 2004, UNEP 2006).

Modern irrigation techniques and changes in cropping practices significantly improve the water situation on the demand side and decrease the risk of water scarcity. Studies in India, Israel, Jordan or Spain have shown, that drip irrigation, pioneered by Israeli farmers, delivering water drop by drop at or near the root zone of plants (Fig. 3.10.6 a) cuts water use by between 30 and 70 % and increases crop yield by between 20 and 90 %, compared with traditional irrigation, e.g. surface irrigation such as furrow or border strip irrigation, or overhead sprinkler irrigation (Fig. 3.10.6 b). Properly managed drip irrigation is the most water-efficient method of irrigation because evaporation and run-off are minimized thus the formerly high leaching fraction is diminished. In certain intervals of the soil is necessary for avoiding or at least reducing salinisation. Drip irrigation should be combined with computer-controlled delivery of fertilizers (so-called fertigation). This successful technique economizes on water and fertilizer use, and combined with a backflow prevention device it limits soil salinization and groundwater pollution.

Because a number of countries rely heavily on the production of high water-demand crops, switching to low water demanding cereals and fruits and importing products which require a lot of water for their production help conserve water, too. For example, to produce 1 kilogram of wheat about 1,000 litres of water are needed. For meat, about 5 to 10 times more water is needed. Importing „virtual water“ (water embedded in food or other products needed for their production) allows real water savings reducing the pressure on the water resources or making water available for other purposes. But while this strategy of saving virtual water makes economic and hydrological sense, countries often argue that it is a matter of national pride to produce their own crops or not to become dependent on other countries. Egypt is one of the few countries in the Middle East and in North Africa which has reacted on the water scarcity. It imports more than half of its food because it has not enough water to grow it domestically.

Strategies for managing water demand include also reallocating water away from agriculture, having part in the gross domestic product (GDP) of less than 20% at best (PNUE 2004) and toward the domestic and industrial sectors. Such policies can satisfy the needs of a growing urban population, but they can also threaten food security and the livelihood of farmers. Because of this fact, water reallocation may be a controversial way to adjust to water scarcity.

Countries facing both, the pressure from limited water resources availability and rapidly increasing water demand should implement a national water-saving strategy for irrigation. The package of measures should include systematic metering, pricing aimed at progressive cost recovery (which is not the case in most countries being under consideration and therefore an essential requirement of the WFD), targeted financial instruments for water-efficient farming equipment (e.g. leakage detection methods which are applied on water distribution piping, real-time monitoring and telemetric control to optimise the operation and maintenance of the water supply system), major education and awareness campaigns (e.g. integration into school curricula or in connection with the Water Day on 22nd March), and support of revenues of farmers especially in longer drought periods. Especially metering and charging may encourage more efficient and sustainable water use. Also the application of a quota system for the allocation of irrigated water in combination with penalty charges for over-consumption should be discussed. Sometimes imposing restrictions may be necessary and meaningful, e.g. prohibition of car washing during drought periods. Well prepared and together with good arguments these restrictions are accepted by the public. Another possibility to decrease significantly the large gap between water supply and water demand in the arid and semiarid regions may be the creation of water user associations in combination with a concentration of food production on more intensively managed land. This strategy would lead to greater reliability in food production and counteract pressures arising from extreme climate events.

On the supply side, boreholes could be drilled in regions where the amount of renewable groundwater is not yet utilized. However, a minimum flow in rivers must be guaranteed for the survival of species required by the WFD. Furthermore, the recycling of properly treated domestic effluent for irrigation purposes and artificial groundwater recharge should be pursued systematically. Another possibility to make more water resources available for agricultural irrigation is the impoundment of uncontrolled and unused runoff water by (small earthen) dams on wadis. Traditional methods such as rainwater harvesting or collection of water from roofs in cisterns for agricultural use should be encouraged. However, with regard to uncovered reservoirs such as ponds and water-delivery systems, significant water losses have to be taken into account due to high evaporation. Because desalinisation costs have been significantly reduced, the use of fresh water produced in this way might be discussed also for irrigation purposes, but is relevant only in coastal regions and not in the nearer future.

Because on the supply side the renewable water resources can only minimally be augmented and the excessively abstracted fossil groundwater reserves will be exhausted in the nearer future, it's high time to begin to target better demand management. Within a context of worsening water scarcity and in view of the uncertainties brought about by climate change, the message of the European Water Framework Directive highlights the absolute need to envisage a new water policy that is more integrated and participatory, making the players more accountable, i.e. equitable sharing between user sectors, inter-regional water sharing even between countries, and between society and nature. The current supply-based policies, focussed on extending supply and pursuing water abstraction may be inverted through demand-based policies. An intelligent water demand management would make it possible to save at least 25 % of water demand (UNEP 2006).

References

Al-Zubari, W.K. (2002): Guidelines on groundwater protection in West Asia.- Regional training workshop on the application of groundwater rehabilitation techniques under different hydrogeological environments in the ESCWA region, organised by ESCWA and BGR (Beirut, 18 - 22 March 2002); Beirut; BGR-CD.

Claussen, M., Kubatzki, C., Brovkin, V., Ganopolski, A., Holzmann, P. & PACHUR, H.-P. (1999): Simulation of an abrupt change in Sahara vegetation in the mid-Holocene.- Geophys. Res. Letters, 26(14): 2037-2040; Washington D.C.

de Menocal, P.B. (1995): Plio-Pleistocene climate.- Science, 270: 53-59; Washington D.C.

European Union (2000): Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.- Official Journal of the European Communities, L 327, pp. 1-72; Brussels.

European Union (2006 a): Directive 2000/11/EC of the European Parliament and of the Council of 15 February 2006 on pollution caused by certain dangerous substances discharged into the aquatic environment of the Community.- Official Journal of the European Communities, L64, pp. 52-59; Brussels.

European Union (2006 b): Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration.- Official Journal of the European Communities, L 372, pp. 19-31; Brussels.

Gleick, P.H. (1996): Water resources.- In: SCHNEIDER, S.H.: Encyclopedia of climate and weather, vol. 2, pp. 817-823; New York (Oxford University Press).

Gleick, P.H. (2004): The world's water 2004 - 2005. The biennial report on freshwater resources.- 362 pages; Washington D.C. (Island Press).

Helvetas-Wasser-Factsheets (2005): Globale Verteilung der Süsswasserressourcen; http://www.helvetas.ch/wDeutsch/topic_themes/wasser/fakten.asp?navid=35.

International Atomic Energy Agency (IAEA) (2007): Water resources programme, Water sites: Nubian sandstone system project; htpp://www.iaea.org/water.

International Panel of Climate Change (2001): Third assessment report 2001: Working Group I: The Scientific Basis; http://www.grida.no/climate/ipcc_tar/wg1/index.htm.

International Panel of Climate Change (2007): Forth assessment report 2007; WG I from 2 February 2007: The physical science basis, final report, and WG II from 6 April 2007: Impacts, adaptation and vulnerability, summary for policymakers; Geneva; http://www.ipcc.ch.

Issar, A.S. (2003): Climate changes during the Holocene and their impact on hydrological systems.- International Hydrology Series, 143 p.; Cambridge (Cambridge University Press).

Murakami, M. (1995): Managing water for peace in the Middle East: Alternative strategies.- 319 pages; Tokyo, New York, Paris (United Nations University Press).

Neumann, K. (1989): Holocene vegetation of the Eastern Sahara: charcoal from prehistoric sites.- African Archaeological Review, 7(1): 97-116; Dordrecht.

Ottens, J.J., Arnold, G.E., Buzás, Z., Chilton, J., Enderlein, R., Havas-Sziláyi, E., Rouak, P., Tarasova, O., Timmerman, J.G., Toussaint, B. & Varela, M. (2000): Guidelines on Monitoring and Assessment of Transboundary Groundwaters.- UN/ECE Task Force on Monitoring & Assessment, 64 pages; Lelystad/The Netherlands.

PNUE, PAM, Plan Blue (2004): L'eau des Méditeranéens: situation et perspectives, MAP technical report series No. 156, 366 pages; Athènes; http://www.planbleu.org/publications/eau.html.

Roudi-Fahimi, F., Creel, L. & De Souza, R.-M. (2002): Finding the balance: Population and water scarcity in the Middle East and North Africa; http://www.prb.org/Publications/PolicyBriefs/FindingtheBalancePopulationandWaterScarcityintheMiddleEastandNorthAfrica.aspx.

Santer, B.D., Wehner, M.F., Wigley, T.M.C., Sausen, R., Meehl, G.A., Taylor, K.E., Ammann, C., Arblaster, J., Washington, W.M., Boyle, J.S. & Brüggemann, W. (2003): Contributions of anthropogenic and natural forcing to recent tropopause height changes.- Science, 301: 479-483; Washington D.C.

Shirman, B. & Melzer, J. (2002): Mediterranean Sea level changes over the period 1961 – 2000; www.fig.net/pub/fig_2002/Ts4-6/TS4_6shirman_melzer.pdf.

Toussaint, B. (2001): Wasser als Konfliktstoff am Beispiel Jordan-Becken.- Europäische Sicherheit, 5/2001: 7-13; Bonn.

Toussaint, B. (2002): Groundwater monitoring.- Regional training workshop on the application of groundwater rehabilitation techniques under different hydrogeological environments in the ESCWA region, organised by ESCWA and BGR (Beirut, 18 - 22 March 2002); Beirut; BGR-CD.

Toussaint, B. (2003): Grundwasser-Monitoring und EU-Wasserrahmenrichtlinie – Messnetzkonzeption aus hydrogeologischer Sicht.- Geol. Jb. Hessen, 130: 21-35; Wiesbaden.

Toussaint, B. (2004): Überwachung von Grundwasserleitern – Grundwassermonitoring.- In: LANGGUTH H.-R. & VOIGT, R.: Hydrogeologische Methoden, 2. überarb. Und erw. Aufl., pp. 667-777; Berlin, Heidelberg, New York.

UNEP, MAP, Plan Bleu (2006): Blue Plan Notes: n° 4 Facing water stress and shortage in the Mediterranean; http://www.planbleu.org/publications/notesDuPlanBleuUk.html.

U.S. Geological Survey (1998): Overview on Middle East water resources; http://exact-me.org/overview/index.htm.

Worldwater (2007): Total renewable freshwater supply by country; Pacific Institute; Oakland, California: http://www.worldwater.org/data.html.

3.11 Seal Formation Effects on Soil Infiltration and Runoff in Arid and Semiarid Regions under Rainfall and Sprinkler Irrigation Conditions

Meni Ben-Hur
Institute of Soil, Water and Environmental Sciences, ARO, Volcani Center, Bet-Dagan, Israel; meni@volcani.agri.gov.il

List of abbreviations: CV, coefficients of variation; DW, deionized water; EC, electrical conductivity; ESP, exchangeable Na percentage; IR, infiltration rate; MSIS, moving sprinkler irrigation system; MWD, mean weight diameter; OM, organic matter**;** SAR, sodium adsorption ratio; SW, saline water.

3.11.1 Introduction

A major part of the Middle East and North Africa comprises arid and semiarid regions, which are characterized by lack of fresh water sources and highly variable precipitation. In addition, the fresh water resources in these regions are expected to decrease as a result of global warming (Alpert, 2004), while the population continues to grow and the demand for this water increases. This situation has led to two trends with regard to the water resources in these regions: (i) diminishing availability of fresh water; (ii) increasing use of marginal water (saline water and treated sewage water) for irrigation, in order to maintain agriculture to meet the increasing demands for food, and to combat desertification. Therefore, the strategy for management of water resources in arid and semiarid regions should be designed to maximize or optimize crop production, while conserving water and avoiding damage to the environment.

Soils in arid and semiarid regions are characterized by relatively low organic matter (OM) content, high levels of salinity and sodicity, high percentages of expandable clay minerals, and low vegetative cover; all which decrease the stability of the soil structure. Consequently, accelerated surface runoff and soil erosion in arid and semiarid regions present a serious problem in terms of water loss, soil degradation and environmental pollution. Surface runoff could cause flooding downstream, and water for crop production may be lost. Moreover, local runoff within agricultural fields leads to poor water distribution in the fields, and could decrease the crop yield per millimeter of water (Letey et al., 1984; Ben-Hur et al., 1995). Erosion of the upper soil layer and removal of fertilizers and pesticides from cultivated lands with the surface runoff could decrease the field fertility and increase environmental pollution.

In recent years, the moving sprinkler irrigation system (MSIS) has become increasingly popular in irrigation of field crops in modern agriculture (Anonymous, 1993). The advantages of MSIS that make it so popular are automation, large areal coverage, and ability to operate on relatively rough terrain. However, as an MSIS is designed to apply controlled amounts of water within relatively short periods, the instantaneous rate of water application (application rate) of these systems is high. The water application rate of an MSIS with spray nozzle emitters can be >100 mm h^{-1}, compared with ~10 mm h^{-1} or less for fixed micro-sprinkler or impact sprinkler heads. This high application rate of the MSIS could cause high runoff during the irrigation.

Quality of water is determined mainly by the concentration and composition of the solutes in the water, when the major ions present in water are, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}. The concentrations of HCO_3^- and CO_3^{2-} depend on pH and CO_2 partial pressure (P_{CO2}), and their relatively high concentrations in the water tend to precipitate Ca and Mg as carbonates. The total salt concentration in water is commonly determined as the electrical conductivity (EC) of the water. In general, the EC increases linearly with increasing electrolyte concentration (C) in the water, and the approximate relationship between EC (dS m^{-1}) and C (mmolc l^{-1}) in water is:

$$C = 10 \times EC \qquad \textbf{(3.11.1.)}$$

The water sodicity is determined by the sodium adsorption ratio (SAR), as defined in Eq. [3.11.2]

$$SAR = \frac{(Na^+)}{(Ca^{2+} + Mg^{2+})^{0.5}} \qquad \textbf{(3.11.2.)}$$

where the concentrations of the ions Na^+, Ca^{2+}, and Mg^{2+} are measured in mmol l^{-1}.

In Israel, for example, the EC and SAR values of fresh water are commonly ~1 dS m^{-1} and ~2.5 (mmol l^{-1})$^{-0.5}$, respectively, and those of saline water are ~5 dS m^{-1} and ~20 (mmol l^{-1})$^{-0.5}$, respectively.

Raw sewage comprises 0.1 % suspended or dissolved organic and inorganic compounds and 99.9 % water (Feigin et al., 1991). To prevent adverse effects on soil, crop and water resources, raw sewage water intended for irrigation usually, undergoes secondary (biological) treatment. However, this treatment does not decrease the concentrations of the major salts, and does not completely eliminate organic matter from the treated sewage water (effluent) (Ben-Hur, 2004). Long-term irrigation with saline water or effluent could lead to changes in the chemical and physicochemical properties of the irrigated soils, such as increasing their salinity and sodicity. This, in turn, could impair the soil hydraulic properties (Balks et al., 1998; Mamedov et al., 2001; Agassi et al., 2003; Ben-Hur, 2004). Consequently, the amount of surface runoff and soil loss during the rainy season and under irrigation with an MSIS could increase. The present chapter reviews and discusses the factors and the mechanisms that lead to the increase of the surface runoff

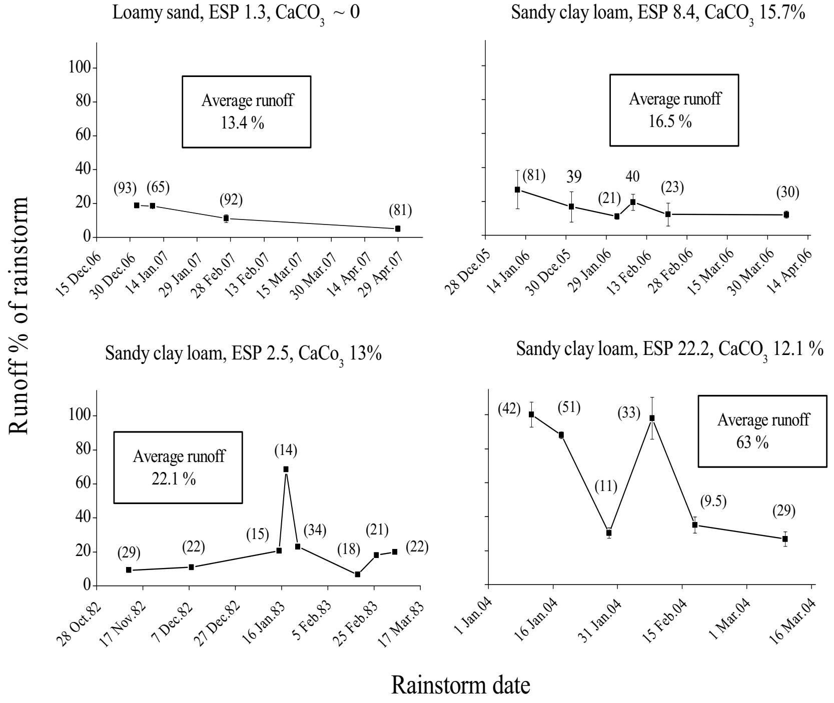


Fig. 3.11.1. Runoff percentages of representative rainstorms, from soils various properties, as measured by means of field runoff plots of <25 m^2 in size under natural rainfall. Verticals bars represent SE, and the numbers above the symbols indicate the rainstorm amount in mm (unpublished data).

under rainfall and sprinkler irrigation in arid and semiarid regions, in light of the changing physical and chemical properties of the water resources and soils in these regions.

3.11.2 Effects of seal formation on soil infiltration and surface runoff

Surface runoff is relatively high under rainfall (Fig. 3.11.1) and MSIS irrigation (Fig. 3.11.2) in arid and semiarid regions in the Middle East and North Africa. The runoff is affected by soil properties: seasonal average values reached 13.4 % in non-calcareous, loamy sand with exchangeable sodium percentage (ESP) of 1.3 %, and 63 % in calcareous sandy clay loam with ESP 22.2 % (Fig. 3.11.1). The amount of runoff could also be affected by the seed bed type and the crop canopy

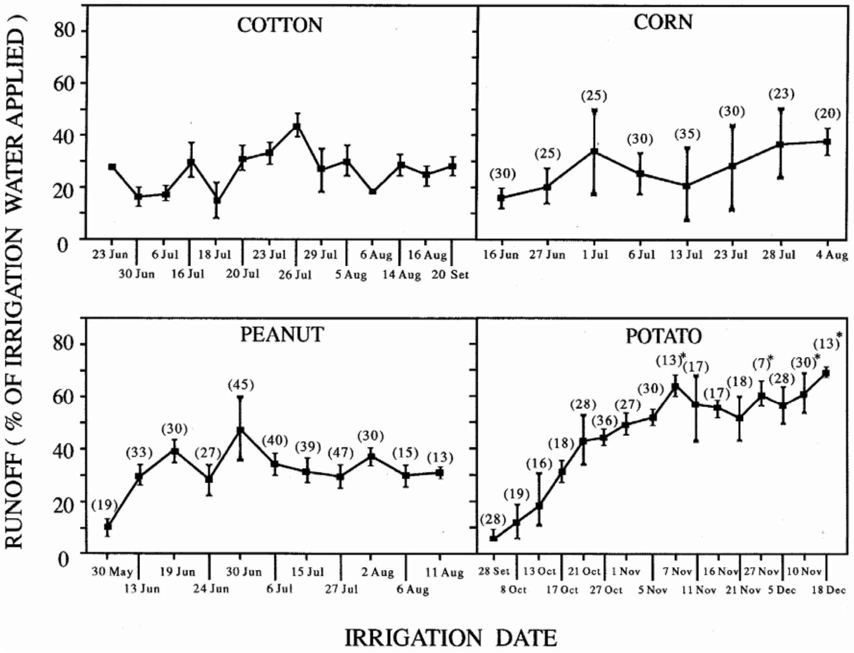


Fig. 3.11.2. Runoff percentages of representative irrigation events and rainstorms, from four different crops, as measured by means of field runoff plots <4.5 m^2 in size. Verticals bars and * represent SD and natural rainstorm, respectively, and the numbers above the symbols indicate the irrigation or rainstorm amount in mm (from Ben-Hur, 1994).

(Fig. 3.11.2): as a percentage of the irrigation amount, runoff reached ~40 % from cotton growing in beds and ~65 % from potatoes growing in ridges (Fig. 3.11.2).

Infiltration is the entry of rain or irrigation water into the soil. It is a dynamic process, and is one of the most important processes in the soil phase of the hydrologic cycle, since infiltration determines the amount of runoff as well as the supply of water to the soil profile. Several factors can reduce the infiltration rate (IR) of the soil during a rainfall or irrigation event. For dry soils with good and stable structures, that do not deteriorate during the wetting process, the initial IR is high because of the combined gravitational and matric potential gradients, which draw water into the soil. As the wetting front advances deeper, the matric potential gradient decreases, and the hydraulic gradient value tends to 1. At this point, the IR approaches a steady-state value, which is approximately equal to the saturated hydraulic conductivity (K_s) of the soil profile (Hillel, 1980).

Since the cohesion of particles in soil aggregates decreases during their wetting and leaching (Ghezzehei and Or, 2000), soil structure seldom remains completely stable during rainfall or irrigation events. During soil wetting, and in the absence of raindrop impact and external compaction, aggregate slaking and clay swelling and dispersion in the soil profile are the three major mechanisms that could cause reduction in the total volume of the conducting pores in the soil. This reduction, in turn, decreases the hydraulic conductivity (*K*) of the soil profile (Shainberg and Letey, 1984; Abo-Sharar, 1987; Lado et al., 2004a), and consequently reduces the IR. In contrast, when the soil surface is exposed to water drop impact under rainfall or sprinkler irrigation conditions, a seal could develop at the soil surface. This seal is relatively thin, and is characterized by greater density, higher strength, finer pores, and lower K_S than the underlying soil (McIntyre, 1958; Chen et al., 1980; Gal et al., 1984; Onofiok and Singer, 1984; West et al., 1992; Wakindiki and Ben-Hur, 2002), and could leading to a drastic decrease of IR during its formation (Morin et al., 1981; Ben-Hur, et al., 1985; Assouline and Mualem, 1997; Assouline, 2004).

According to their mode of formation, seals are classified as structural or depositional (Chen et al., 1980; Tarchitzky et al., 1984; Southard et al., 1988). Structural seal formation is due mainly to the impact energy of the raindrops. In contrast, depositional seals are formed by settling of detached particles transported across the soil surface by runoff, when the sediment load exceeds the runoff transport capacity. The present chapter is focused entirely on structural seals.

Agassi et al. (1981) suggested that the formation of structural seal involves two main mechanisms: (i) physical disintegration of soil aggregates, caused by raindrop impact, and (ii) dispersion of clay particles and their movement into regions of reduced porosity, where they become lodged and plug the conducting pores. The relative importance of these two mechanisms depends on the impact energy of the raindrops, the EC of the applied water, and the ESP of the soil. As the EC of the applied water decreases and the ESP of the soil increases, seal formation is enhanced and the IR decreases (Kazman et al., 1983).

Formation of seal at the soil surface resulted in a two-layer system, with different *K* values for water flow. The effective hydraulic conductivity (K_c) of this two-layer system is related to the *K* and the thickness (*L*) values of the individual layers according to Eq. [3.11.3]

$$K_c = \frac{L_1 + L_2}{\left(\frac{L_1}{K_1} + \frac{L_2}{K_2}\right)} \qquad \textbf{(3.11.3.)}$$

where, the subscripts 1 and 2 refer to seal and the underlying layer, respectively.

The *K* of soil with no seal at the surface and the K_c of soil with seal can be affected differently by various environmental conditions, such as salinity and sodicity, which, in turn, can have differing effects on the steady-state IRs of the soils with and without seal as shown in Fig. 3.11.3. This figure depicts the results of sub-

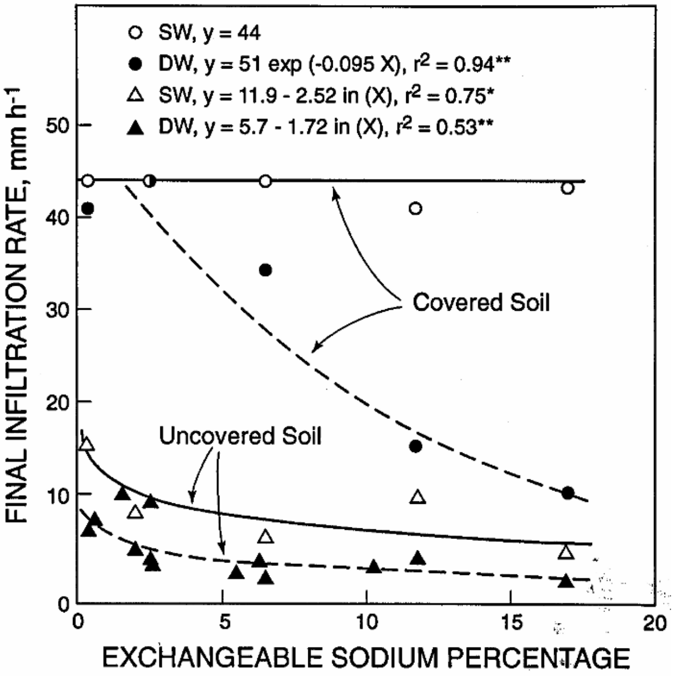


Fig. 3.11.3. Final infiltration rates as functions of exchangeable Na percentage for covered and uncovered vertisol subjected to simulated, deionized water (DW) and saline water (SW) rainfall (from Ben-Hur et al., 1998).

jecting disturbed samples of vertisol with differing ESP values to simulated rainstorms with kinetic energy delivery rates of 18.1 J mm^{-1} m^{-2} (uncovered soil) and 0 (covered soil), in the laboratory. Two waters were used: deionized water (DW), and saline water (SW) that contained NaCl + $CaCl_2$ at a total concentration equivalent to an EC of 5 dS m^{-1} and SAR corresponding to the soil ESP. The final IR was determined as the IR at the end of the rainstorm, and was close to the steady-state IR. The soil covering prevented the breakdown of the aggregates at the soil surface by the raindrop impact, and consequently, a seal was not formed in this treatment (Morin et al., 1981). In contrast, the surface of the uncovered soil was exposed to the impact energy of the raindrops and a seal was formed. The final IRs of the covered soils subjected to SW rainfall (Fig. 3.11.3) were higher than the rainfall intensity (44 mm h^{-1}), therefore, the effect of ESP on IR could not be determined in this case. The final IRs of the uncovered soils subjected to DW and SW rainfall and of the covered soil subjected to DW rainfall were significantly correlated with the ESP values (Fig. 3.11.3). The relationship between FIR and ESP for the uncovered soils is presented in Eq. [3.11.4].

$$Y = a - b \cdot \ln(X) \qquad \textbf{(3.11.4.)}$$

where, Y is the final IR, X is the ESP, and a and b are empirical coefficients.

In contrast, for covered soil subjected to DW rainstorm, Eq. [3.11.5] describes the relationship between FIR and ESP values.

$$Y = a \cdot \exp(-bX) \qquad \textbf{(3.11.5.)}$$

The values of the coefficients a and b for the various treatments are presented in Fig. 3.11.3.

The final IRs of the covered soils, which were mainly dependent on the K_s of the soil layer, were higher than those of the uncovered soils at any ESP in the range from 0 to 17 % (Fig. 3.11.3). This indicates that over a wide range of ESP values, in bare soil subjected to rainstorm, the low K_s of the seal that formed during the rainstorm was a predominant factor controlling the steady-state IR. The final IR of the bare soil was affected by K_c mainly in the ESP range <5 %, whereas the effective ESP range was much greater for the covered soil (Fig. 3.11.3). This indicates that the difference between the steady-state IRs of soils with and without seal decreased as the ESP increased (Fig. 3.11.3).

The effects of seal formation on steady-state IR under field conditions were studied by Ben-Hur et al. (1987) in a 1-ha fallow field in an arid region in the south of Israel. The IR of the soil was measured in 30 randomly selected sites, by two methods in each site: (i) a portable rainfall simulator (Morin and Benyamini, 1977) with rainfall intensity of 40 mm h^{-1} and energy rate of 21 J mm^{-1} m^{-2}; (ii) a double-ring infiltrometer under flooding conditions. The measurements with the rainfall simulator and the double-ring infiltrometer determined the steady-state IRs of soils with and without seal, respectively. The mean values and coefficients of variation (CV, mean/standard deviation) of the steady-state IRs that were measured by the rainfall simulator and the double-rings infiltrometer, and the skew values of their frequency distribution are presented in Table 3.11.1. The absolute skew value represents the degree of asymmetry of the frequency distribution of the steady-state IRs; the higher the absolute skew value, the greater the asymmetry of the distribution. A positive skew value indicates a distribution with a deviation (tail) to the right, and a negative value a deviation to the left.

Table 3.11.1. Mean, coefficient of variation (CV) and skew values of steady-state infiltration rates (Ben-Hur et al., 1987).

Double-ring infiltrometer			Rainfall simulator		
Mean mm h^{-1}	CV %	Skew	Mean mm h^{-1}	CV %	Skew
57.9	41.8	-0.11	8.6	14.7	1.11

The mean steady-state IR measured by the double-ring infiltrometer was 57.9 mm h^{-1}, whereas that measured by the rainfall simulator was 8.6 mm h^{-1} (Table 3.11.1). This low steady-state IR of the soil under rainfall conditions was most likely a result of the very low K_S of the seal that was formed at the soil surface by the raindrop impact (Morin et al., 1981). Formation of the seal also affected the variability of the steady-state IRs (Table 3.11.1). The CV of the steady-state IRs obtained in soil without seal was relatively high – 41.8 % – whereas that in the soil with seal was low – 14.7 % (Table 3.11.1). Because the seal consists of a very dense and compacted layer of very small particles (McIntyre, 1958; Wakindiki and Ben-Hur, 2002), the spatial variability of its structure is probably lower than of the soil profile without seal. Consequently, development of a seal decreased the spatial variability of the steady-state IR (Table 3.11.1). Moreover, the frequency distributions of the steady-state IR of the soils without and with seal were different (Table 3.11.1): that of the soil without a seal had a small deviation to the left (negative skew), and of the soil with seal had a large deviation to the right (positive skew,

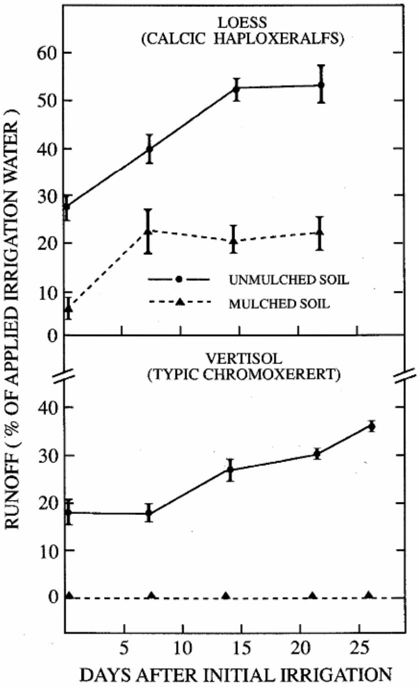


Fig. 3.11.4. Runoff percentage of weekly 50 mm irrigations, from two soils as measured by means of field runoff plots of area 3 m^2. The verticals lines represent SD (from Ben-Hur et al., 1989).

Table 3.11.1). Thus, the development of a surface seal not only caused reductions in the mean value and CV of the steady-state IRs; it could also change their distribution.

The effects of seal formation on surface runoff during irrigation with an MSIS are presented in Fig. 3.11.4. The runoff was measured from 2 × 1.5 m plots that were constructed in two fields with loess (silt loam) and vertisol (clay loam) in the southern part of Israel. The fields were ploughed, disked, and leveled with a roller, but not seeded, and were irrigated once a week with 50 mm of fresh water, by means of a lateral MSIS with Nelson spray nozzles that provided an average water application rate of ~100 mm h^{-1}. Two treatments were studied: (i) bare soil, with its surface exposed to the impact of the water drops during the irrigation events; (ii) mulched soil, of which the surface was fully covered with wheat straw. Surface runoff from the mulched loess was low, ~5 %, in the first irrigation event, and it increased in subsequent irrigation events to a final value of ~22 %, whereas no runoff was obtained from the mulched vertisol (Fig. 3.11.4). Under mulching, no seal was formed, and the IR was determined mainly by the K of the soil profile and the hydraulic gradient. Consequently, the runoff in this treatment was relatively low. In all irrigation events and in both soils, the runoff percentages from the bare soil were higher than those from the mulched soil (Fig. 3.11.4). These greater runoff percentages were due mainly to seal formation at the soil surface, which decreased the IR of the soils.

3.11.3 Effects of soil properties on seal formation

Some soil properties, such as soil texture and mineralogy and organic matter and lime content can affect the stability of the soil structure (Kay and Angers, 1999). Soils with high aggregate stability are less sensitive to aggregate breakdown by water drop impact and therefore are less subject to seal formation, which, in turn, enables them to maintain relatively high IR and low surface runoff under rainfall and sprinkler irrigation.

Soil texture and lime content

In general, an increase in the clay content in the soil increased the aggregate stability (Kemper and Koch, 1966; Larson et al., 1980; Rasiah et al., 1992; Kay and Angers, 1999). This was attributed to the cementing effect of clay particles that hold the soil materials in the aggregates together. The silt content of the soil could also affect the aggregate stability, since soils with high silt content usually have low aggregate stability (Wischmeier and Mannering, 1969; Cary and Evans, 1974). Similar results were obtained by Moldenhaure and Long (1964), who found a good positive correlation between silt content in the soil and the rate of seal formation. The presence of $CaCO_3$ in soil is known to improve the structure of sodic soils. Three different mechanisms for this have been suggested (Rimmer and Greenland,

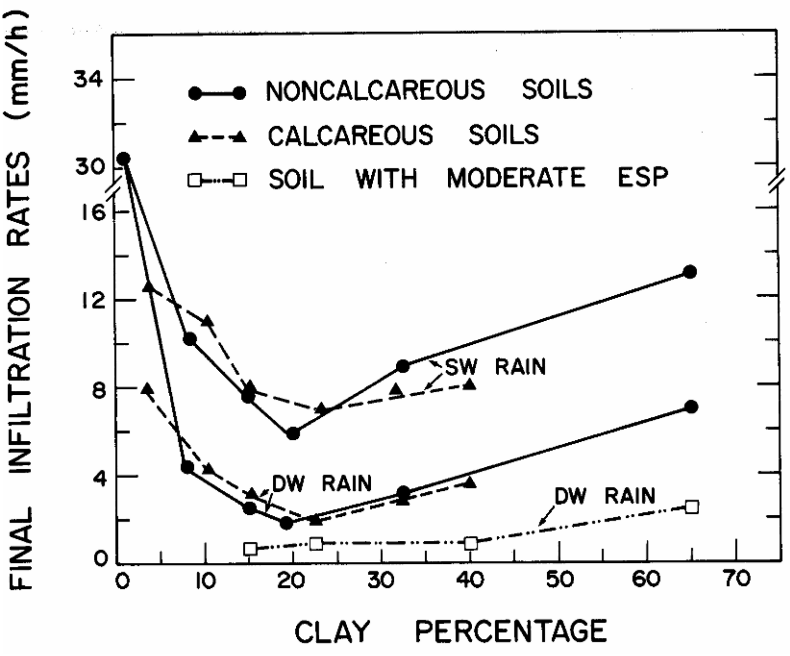


Fig. 3.11.5. Final infiltration rates of calcareous and noncalcareous soils with low (<2.5 %) and of calcareous soils with moderate (~4.6 %) exchangeable Na percentage (ESP), subjected to simulated, deionized water (DW) and saline water (SW) rainfall, as functions of soil clay contents (from Ben-Hur et al., 1985).

1976; Shainberg et al., 1981a; 1981b): (i) the $CaCO_3$ may act as a cementing agent that stabilizes the soil aggregates and prevents their disintegration; (ii) $CaCO_3$ dissolution could maintain the concentration of the soil solution above the flocculation value of the clay particles, thus preventing their dispersion; and (iii) decrease of soil ESP by displacement of adsorbed Na by the Ca released from the $CaCO_3$ during its dissolution.

The effects of soil texture and $CaCO_3$ content on seal formation and steady-state IR under various salinity and sodicity conditions can be studied from Fig. 3.11.5, in which the final IR values (close to steady-state IR) of soils that were exposed to 50 mm of a simulated rainstorm with energy of 21 J mm^{-1} m^{-2} are presented as functions of the soil clay content. The soils were: calcareous and non-calcareous soils with low ESP (<2.5) and calcareous soil with moderate ESP (~4.6 %). For clay content in the soil in the range from 7.8 to 65.2 %, the final IRs obtained with DW rainfall were lower than with SW rainfall for both soil groups (calcareous and non-calcareous) with the low ESP (Fig. 3.11.5). The high electrolyte concentration of the SW rainfall is very likely to have prevented the clay dispersion and the development of the washed-in zone in the seal, and thereby maintained a relatively high K_s in the seal layer and a high steady-state IR (Agassi et al., 1981).

For the soils with low ESP, loamy soil with 20 % clay was the most susceptible to seal formation, and had the lowest final IR when subjected to either DW or SW rainfall (Fig. 3.11.5). In the soils with clay content <20 %, the stabilizing effect of the clay was minor because of its low content; however, increasing the clay content in these soils to 20 % increased the amount of dispersed clay particles at the soil surface during the rainstorm. These clay particles clogged the pores in the seal layer (Wakindiki and Ben-Hur, 2002), which, in turn, led to decreasing seal K_s and decreasing final IR with increasing soil clay content (Fig. 3.11.5). In contrast, an increase of the clay content in the soil above 20 % increased the cementing action of the clay and thereby stabilized the aggregates at the soil surface against the impact energy of the raindrops, and thus diminished the seal formation. Therefore, the final IRs of the two soil types with low ESP increased as the clay content increased above 20 % (Fig. 3.11.5).

The stabilizing effects of the clay, as manifested in diminished seal and runoff formation, were also demonstrated in a field under MSIS irrigation (Fig. 3.11.4). The runoff percentage in the field experiment was higher in the unmulched loess soil with 22 % clay than in the unmulched vertisol with 40 % clay content (Fig. 3.11.4): in the former, 53 % runoff was obtained in the third irrigation event, whereas in the latter, 39 % runoff was obtained only in the fifth irrigation event (Fig. 3.11.4). This difference between the runoff percentages of the two soils could be attributed to the difference between their aggregate stability. The higher clay content in the vertisol than in the loess led to higher aggregate stability and development of a seal with higher K_s in the former than in the latter soil. Consequently, the runoff percentage in the loess was higher than that in the vertisol (Fig. 3.11.4). Similar results were found by Fox and le Bissonnais (1998): soils with higher clay contents had less sealing.

The silt content in the soils did not affect seal formation and final IR (Fig. 3.11.5). The silt/clay ratio in the calcareous soil was 0.82-1.47, compared with 0.13-0.35 in the non-calcareous soils, but the final IRs of two soil groups were similar at any given clay content (Fig. 3.11.5). These results conflict with the findings of Cary and Evans (1974), who suggested that the soils with high silt content had low aggregate stability and were more susceptible to seal formation.

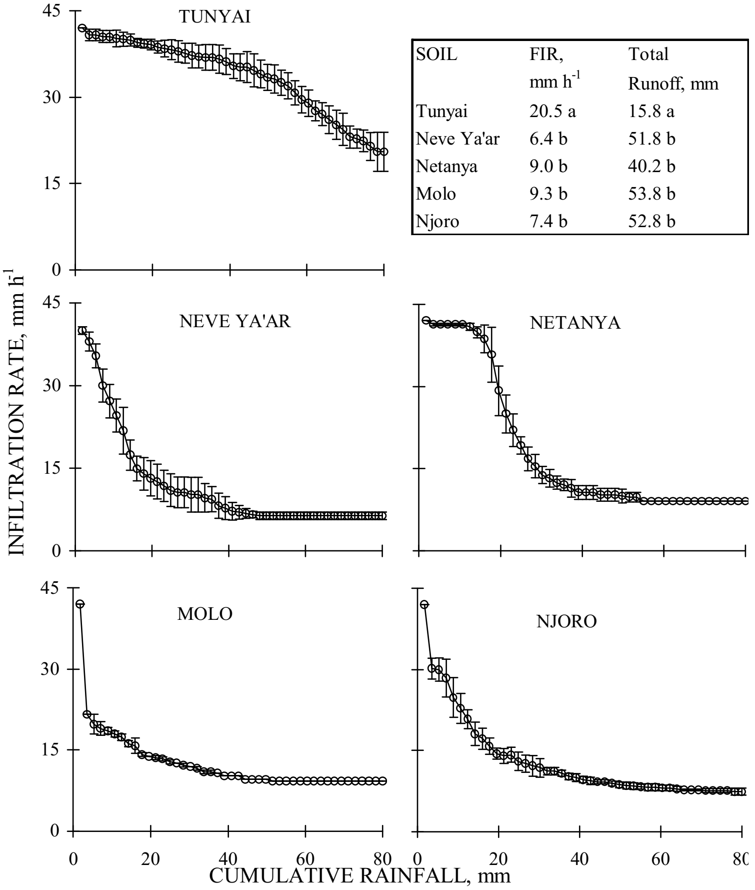
The final IRs of the calcareous and non-calcareous soils with low ESP were similar at any given clay content for both the DW and SW rainfall, (Fig. 3.11.5). These results indicate that $CaCO_3$ content had minor effects on seal formation and final IR. Similar results were obtained by Kazman et al. (1983), who studied the effect of soil sodicity on seal formation in sandy loam and silty loam soils. In contrast, Felhendler et al. (1974), Shainberg et al. (1981b), Shainberg and Gal (1982), and Keren and Ben-Hur (2003) found that the presence of $CaCO_3$ in soil limited the decline of K_s in sodic soils that were leached with DW. It was hypothesized in these studies that while the soil was being leached with DW, the $CaCO_3$ released sufficient electrolytes into the soil solution to prevent clay dispersion and the resulting clogging of the pores. However, with regard to seal formation, in the uppermost 0- to 0.5-cm layer at the soil surface, where the seal could be formed, the soil electrolyte concentration is determined mainly by that of the rainwater. This is because of the relatively fast and intensive leaching of this thin layer during the rainstorm. Therefore, clay dispersion can take place at the soil surface during rainstorms, even in calcareous soils, and a seal could be formed.

The final IRs of the soils with moderate ESP (~4.5 %) under DW rainfall were lower than those in the soils with low ESP (<2.5 %) at any given clay content (Fig. 3.11.5). It is most likely that the increase of the ESP weakened the binding forces within the aggregates, and thereby increased the tendency of the clay to disperse. In this case, the stabilizing effect of the clay diminished and, consequently, the seal formation and reduction of the final IR occurred even in soils with high clay content (Fig. 3.11.5).

Soil mineralogy

Soils can be divided into two main groups on the basis of their mineralogy (Neaman et al., 2000): (i) phyllosilicate soils, which consist mainly of phyllosilicate minerals, of which kaolinite, illite and montmorillonite are the most abundant clays (Allen and Hajek, 1989); (ii) nonphyllosilicate soils that consist of clay-sized minerals, such as quartz and feldspar. Soil mineralogy has been found to play a key role in aggregate stability and clay dispersion (Singer, 1994; Kay and Angers, 1999). Singer (1994) reviewed the effects of clay mineralogy on soil dispersivity, and found that smectitic soils were the most dispersive, kaolinitic soils the least dispersive, and illitic soils exhibited intermediate dispersivity. Other studies with reference clays and with clays extracted from soils (e.g., Arora and Coleman, 1979; Goldberg and Forster, 1990; Chorom and Rengasamy, 1995) also demonstrated that 2:1 clays were more dispersive than 1:1 clays. Rengasamy et al. (1984) found that, in soils with >30 % clay content, the physical properties of the soils depended on the type of clay. Because seal formation is strongly connected to the stability of the soil aggregates, the above results indicate that soil mineralogy should have effects on seal formation and surface runoff, but, in spite of this, the effects of soil mineralogy on these phenomena have received much less attention in the literature than other soil properties.

The effects of soil mineralogy on IR and runoff for five different soils are presented in Fig. 3.11.6: the soils were exposed to DW rainstorm with intensity of 43 mm h^{-1} and kinetic energy of 18.1 J mm^{-1} m^{-2}. For all the soils, the IR decreased with increasing cumulative rainfall until a final IR was reached (Fig. 3.11.6). This decrease of the IR was mainly a result of seal formation at the soil surface (Wakindiki and Ben-Hur, 2002). On the basis of final IR values and total runoff obtained during the entire rainstorm (Fig. 3.11.6), the five studied soils were separated into two groups: in the first, comprising only the kaolinitic Tunyai soil, the IR decreased gradually, the final IR was high (20.5 mm h^{-1}), and the total runoff was



SOIL	FIR, mm h^{-1}	Total Runoff, mm
Tunyai	20.5 a	15.8 a
Neve Ya'ar	6.4 b	51.8 b
Netanya	9.0 b	40.2 b
Molo	9.3 b	53.8 b
Njoro	7.4 b	52.8 b

Fig. 3.11.6. Infiltration rates, as functions of cumulative, simulated rainfall, for various soils. Verticals bars represent SD, and different letters preceding the final infiltration rates (FIR) and total runoff amounts indicate significant ($p < 0.05$) differences between the soils for each parameters (from Wakindiki and Ben-Hur, 2002).

15.8 mm; in the second group, comprising the rest of the soils, the IR decreased sharply, the final IR was low (≤9.3 mm h^{-1}), and the total runoff was high (>40.2 mm). The effects of soil mineralogy on seal formation and IR were also studied by Romkens et al. (1995), with a laboratory rainfall simulator. In this study, the presence of highly expansive smectite clay in loess soils caused a rapid reduction of IR and high an increase of runoff to >50 mm after 82 mm of simulated rainfall despite

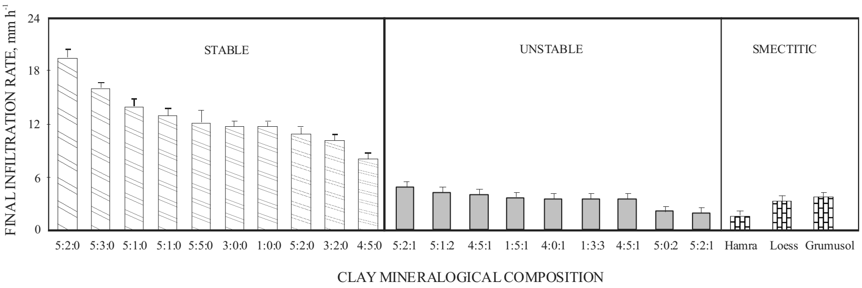


Fig. 3.11.7. Final infiltration rates for stable, unstable, and smectitic soils subjected to simulated, deionized water rainfall. The numbers below the columns represent the relative contents of kaolinite, illite, and smectite, respectively. Verticals bars represent SD (after Stern et al., 1991).

the high OM content and the coarse texture of these soils. In contrast, in a soil in which the clay fraction was dominated by vermiculite, mica and kaolinite, no runoff was observed after 82 mm of simulated rainfall.

In order to generalize the effects of soil mineralogy on seal formation and IR, Stern et al. (1991) determined the IR of 22 phyllosilicate soils – 19 from South Africa and three from Israel – that were exposed to DW rainfall with kinetic energy of 18.1 J mm^{-1} m^{-2} (Fig. 3.11.7). The dominant clay type in these soils was kaolinite, illite, or smectite. In Fig. 3.11.7, the soils from South Africa are arranged in descending order of their final IR, from 19.1 mm h^{-1} to 2.4 mm h^{-1}. The three numbers below each column in Fig. 3.11.7 represent the relative amounts of kaolinite, illite and smectite, respectively, in the soil; 0 indicating undetectable amounts, and 5 indicating the highest amount.

It is evident from Fig. 3.11.7 that the soils from South Africa can be divided into two main groups: stable soils, with final IR values >8.0 mm h^{-1}; and unstable soils, with final IRs < 4.5 mm h^{-1}. The final IRs of the unstable soils were similar to those of the smectitic soils from Israel. Examination of the properties of the studied soils indicated that the differences in texture, ESP, OM content and pH of the various soils did not account for the differences in the final IRs, between the stable and the unstable soil groups (Stern et al., 1991). In contrast, according to the mineralogy of the soils from South Africa, it is evident that kaolinite was the dominant clay in most of the soils, and illite in the remaining ones. However, it was noted that only the unstable soils contained smectite; the stable soils did not. Therefore, it was suggested that kaolinitic and illitic soils that did not contain smectite, or in which the smectite level was below the detection threshold, would be stable soils, and, conversely, that only soils which contained detected amount of smectite (>5 %) would be unstable, and as susceptible to seal formation as the smectitic soils.

Small amounts of smectite may promote kaolinite dispersion by the following mechanisms. In kaolinite, the attraction between the positive charges on the edges of the particles and the negative charges on the planar surfaces of other particles was regarded as the cause of the flocculation of this clay, which occurred even in the absence of salt (Schofield and Samson, 1954). However, a rapid and large increase in the flocculation value of kaolinite was observed with increasing amounts of smectite (Schofield and Samson, 1954; Arora and Coleman, 1979). This significant effect was attributed to the adsorption of smectite platelets on the positively charged edges of the kaolinite particles, which prevented the edge-to-face flocculation that occurs in pure kaolinite. A similar phenomenon was reported by Frenkel et al. (1978), who found that the K_s of kaolinitic soils from North Carolina was not affected by 20 % Na in the exchange complex, but that when the soil was mixed with 2 % montmorillonite it became very susceptible to dispersion. Thus, the presence of smectite in the soils, even in small quantities, increased the clay dispersion significantly. This mechanism could explain the greater decrease in IR in the soils that contained smectite than in those that did not (Fig. 3.11.7).

The role of illite in seal formation is not completely clear from Fig. 3.11.7, and it requires further study. It is known, however, that illite is as dispersive as smectite (Oster et al., 1980). However, it is evident from Fig. 3.11.7 that the dispersive effect of illite on kaolinite was less pronounced than the effect of smectite. The inefficiency of illite in dispersing kaolinite may be attributed to the terraced shape of the illite particles (Quirk, 1978), which probably led to poor contact between the kaolinite edges and the illite planar surfaces. This led to inefficient screening of the kaolinite edges by the illite particles and, consequently, to less dispersion. In the soils that contained smectite (i.e., the unstable soils), the illite and kaolinite had no consistent effect on the final IR (Fig. 3.11.7). In contrast, in the stable soils, the four soils that exhibited the highest final IRs were dominated by kaolinite. Thus, in the absence of smectite, the stabilizing effect of kaolinite in reducing seal formation was enhanced.

Soil organic matter and aggregate size

Organic matter content has been found to be one of the main factors controlling the stability of aggregates of soils with low ESP (Emerson, 1977; Elliot, 1986; Golchin et al., 1995). Soil OM compounds bind the primary particles in the aggregate, physically and chemically, and this, in turn, increases the stability of the aggregates and limits their breakdown during wetting. Chaney and Swift (1984) used the wet sieving method to measure the aggregate stability of 26 agricultural soils with differing properties, and they found a high positive correlation between aggregate stability and OM content, suggesting that OM is an important controlling factor. Benito and Diaz-Fierros (1992) studied the effects of various cropping systems on the structural stability of soils with various OM contents, and found that soil structural stability diminished with decreasing OM content.

Emerson (1977) suggested that OM stabilized the aggregates mainly by forming and strengthening bonds between the particles within them. Tisdall and Oades (1982) classified these organic binding agents into: (i) transient – mainly polysaccharides; (ii) temporary – roots and fungal hyphae; and (iii) persistent – resistant aromatic components associated with polyvalent metal cations, and strongly sorbed polymers. Tisdall and Oades (1982) concluded that macroaggregates (>0.25 μm in diameter) were weaker than microaggregates (<0.25 μm in diameter) because the former were stabilized by transient binding, such as roots, hyphae and polysaccharides, whereas the latter were bound by persistent aromatic humic material associated with amorphous iron and aluminum compounds. Oades and Waters (1991) also considered that there was an aggregate hierarchy, in which microaggregates were associated by the binding action of hydrous oxides of iron and aluminum and by OM, to form macroaggregates.

Although many studies have addressed the effects of OM content on aggregate stability and on the mechanical properties of soil (e.g., Ekwe, 1991; Guerra, 1994; Zhang and Hartge, 1995; le Bissonnais and Arrouays, 1997; Paz, 2000; Castro Filho et al., 2002), few have investigated the effects of OM content on soil K_S and IR under seal-formation conditions. Black and Abdul-Hakim (1985) found that 2 years of wheat growing, with the consequent decrease of soil OM content, reduced the soil permeability significantly more than pasture growing in the same type of soil. Mbagwu and Auerswald (1999) measured the percolation stability (the amount of water percolating through soil samples packed in tubes, during 10 min) of soils under various crops, and found that in soils with OM content ranging from 0.12 to 5.0 %, the percolation stability of the soils was positively correlated with OM content. Auerswald (1995) showed that percolation stability increased as OM increased, and attributed this to the effect of OM in preventing aggregate disintegration caused by the pressure of air entrapped during the wetting process. Le Bissonnais and Arrouays (1997) found that reduction of the organic carbon content of a loamy soil below 1.5-2.0 % decreased the aggregate stability and the soil IR under rainfall simulator conditions.

Table 3.11.2. Mean weight diameter values for soils with low (23 g kg^{-1}) and high (35 g kg^{-1}) organic matter content, and different aggregate sizes. Number followed by different letters indicate significant (p <0.05) differences between the soils for each aggregate size (Lado et al., 2004a).

Organic matter content in soil	Aggregate size, mm		
	<2	2-4	4-6
g kg^{-1}	mm		
23	0.32a*	1.01a	1.37
35	0.72b	3.31b	5.17b

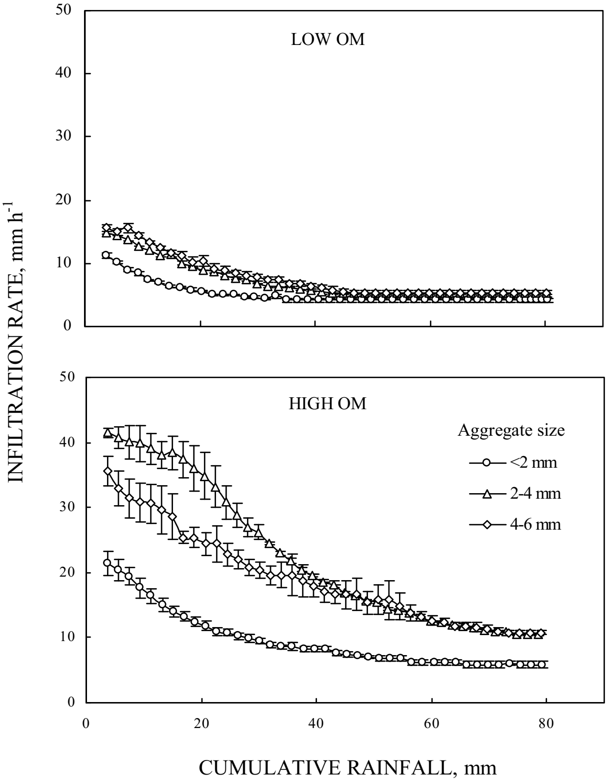


Fig. 3.11.8. Infiltration rate as a function of cumulative, simulated deionized water rainfall, for two soils, characterized by different organic matter (OM) content and three different aggregate sizes. Bars indicate SD (from Lado et al., 2004b).

The initial size of aggregates in the soil is also an important factor in seal formation, IR and runoff (e.g., Moldenhauer and Kemper, 1969; Ekwe, 1991; Freebairn et al., 1991; Shainberg et al., 1997). Moldenhauer and Kemper (1969) and Freebairn et al. (1991) found that, as the initial aggregate size of the soil increased, the IR during a rainstorm dropped more gradually, because seal formation proceeded more slowly. However, the final IR of the studied soils was independent of the initial aggregate size. Lado et al. (2004b) hypothesized that the interactions between aggregate size, OM content and aggregate stability could affect the seal formation, the IR, and the runoff amount.

Soil dispersibility under rainfall conditions could be expressed as a dispersion index, calculated by dividing the percentage of clay in the runoff sediments by that in the original soil (Stern et al., 1991). A dispersion index value of 1 indicates that no significant clay dispersion occurred at the soil surface during the rainstorm. In

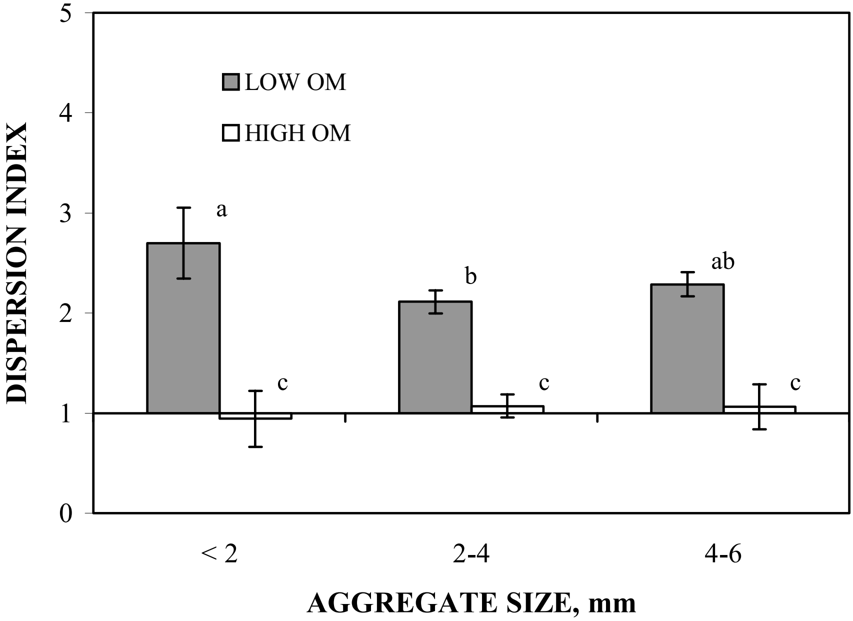


Fig. 3.11.9. Dispersion index (DI) of two soil samples with differing organic matter (OM) contents and three different aggregate sizes. Bars indicate SD, and different letters above the columns indicate significant differences (p <0.05) among the treatments (from Lado et al., 2004b).

contrast, when the clay fraction at the soil surface is dispersed, the clay percentage in the sediments should be higher than that in the original soil, because the clay particles are more easily transported by the surface runoff than the bigger silt and sand particles. In that case, the dispersion index would be greater than 1: the higher the dispersion index, the more dispersive is the soil.

The effects of OM content, aggregate size, and their interaction on seal formation can be seen in Figs. 3.11.8 and 3.11.9 and Table 3.11.2. The IRs of sandy loam with two OM contents, 2.3 % and 3.5 %, and three different aggregates sizes, subjected to DW rainstorm with intensity of 42 mm h^{-1} and kinetic energy of 18.1 Jm^{-2}, are presented in Fig. 3.11.8. Because the IR measurements (Fig. 3.11.8) were conducted mainly under saturation conditions, the decrease of the IR during the rainstorm was mainly a result of increasing destruction of the soil surface structure by the impact of the raindrops and seal formation. The mean weight diameter (MWD) values presented in Table 3.11.2 were determined after fast wetting of aggregates of the sandy loam soil according to le Bissonnais (1996). These MWD values indicate the soil aggregate stability: the larger the MWD, the more stable the aggregates.

An increase of OM content from 2.3 to 3.5 % limited the aggregate breakdown (Table 3.11.2), soil dispersivity (Fig. 3.11.9), and seal formation (Fig. 3.11.8) at the soil surface under raindrop impact conditions. It was suggested that the final IR values were lower in the low- than in the high-OM soil because: (i) there was more extensive breakdown and dispersion of the aggregates, with formation of a more continuous seal at the surface of the former than at that of the latter; (ii) the morphology of the seals in the various treatments (Lado et al., 2004b) indicated that the rearrangement of the detached and dispersed particles in the seal differed between the two soils, so that a thicker, higher-density seal (in some case with a „washed-in“ zone) was formed on the low- than on the high-OM soil.

There was an interaction between OM content and aggregate size in seal formation and IR. Because of the low aggregate stability (Table 3.11.2) and the high dispersivity (Fig. 3.11.9) of the low-OM soil, the breakdown and dispersion of the aggregates at the surface of this soil, under raindrop impact, were extensive even for the large aggregate size. Consequently, a well developed seal was formed on the low-OM soil for all aggregate sizes, and the effect of the initial aggregate size on the IR was negligible. In contrast, the higher aggregate stability (Table 3.11.2) and the lower dispersivity (Fig. 3.11.9) of the high-OM soil limited the breakdown and dispersion of the aggregates at its surface. Therefore, the differences in IR under raindrop impact caused by the presence of large or small initial aggregates were relatively great in the high-OM soil (Fig. 3.11.8).

There is a practical aspect of this interaction between OM content and aggregate size. Cultivation of a soil with high OM content will be effective because in such a soil, the large aggregates will remain stable during the rainy season and thus maintain a relatively high IR. In contrast, in a soil with low OM, the cultivation will have only a short-lived effect, because in such a soil, most of the large aggregates will be broken down and dispersed at the beginning of the rainy season.

3.11.4 Summary and conclusions

The situation regarding the water resources in arid and semiarid regions in the Middle East and North Africa has led to two trends: (i) diminishing availability of fresh water; and (ii) increasing use of marginal water for irrigation, in order to maintain agriculture to meet the increasing demands for food, and to combat desertification. Therefore, the strategy for management of water resources in these regions should be designed to maximize or optimize crop production while conserving water and avoiding damage to the environment.

Soils in arid and semiarid regions are characterized by relatively low OM content, high levels of salinity and sodicity, high percentages of expandable clay minerals, and low vegetative cover; all of which decrease the stability of the soil structure. When these soils are exposed to water drop impact under rainfall or sprinkler irrigation conditions, a seal is developed at the soil surface. This seal is relatively thin and is characterized by greater density, higher strength, finer pores, and lower K_S than the underlying soil**,** and its formation decreases the soil IR. As a result, increased surface runoff and soil erosion in arid and semiarid regions present a serious problem in terms of water loss, soil degradation and environmental pollution. Formation of a seal also decreases the variability of the steady-state IRs and affects their distribution.

Some soil properties can affect the stability of the soil structure. Soils with higher aggregate stability are less subject to seal formation under rainfall and sprinkler irrigation. For soils with ESP <2.5, increasing the clay content in the soil up to ~20 % enhances seal formation during the rainstorm and decreases the final IR. In contrast, an increase of the clay content in the soil above 20 % increases the cementing action of the clay, thereby stabilizing the aggregates at the soil surface against the impact energy of the raindrops, and thus diminishing seal formation and the IR decrease. Therefore, loamy soil with ~20 % clay is the most susceptible to seal formation and has the lowest final IR when subjected to rainfall. The final IRs of soils with moderate ESP (~4.5 %), under rainfall, are lower than those in the soils with low ESP (<2.5 %) for any given clay content up to 65 %. It is most likely that the increase of the ESP weakens the binding forces within the aggregates, and thereby increases the tendency of the clay to disperse. In this case, the stabilizing effect of the clay is diminished and, consequently, seal formation and reduced final IR occur even in soils with high clay content.

Soils from arid and semiarid regions can be divided into two main groups regarding their mineralogy, stable soils with high final IRs and unstable soils with low final IRs when subjected to rainstorms. It is suggested that kaolinitic and illitic soils which do not contain smectite, or in which the smectite level is below the detection threshold, would be stable soils, and, conversely, that only soils which contained detected amount of smectite (>5 %) would be unstable soils.

Soil OM content has been found to be one of the main factors controlling the aggregate stability. The OM compounds bind the primary particles in the aggregate, both physically and chemically, and this, in turn, limits the aggregate breakdown, soil dispersivity, and seal formation under raindrop impact conditions. There is an interaction between OM content and aggregate size in seal formation and IR. Due to the low aggregate stability of low-OM soil, a well developed seal is formed over this soil for all aggregate sizes, and the effect of the initial aggregate size on IR is negligible. In contrast, the high aggregate stability of high-OM soil limits the seal formation and, therefore, the differences in IRs under raindrop impact, caused by the presence of either initially large or small aggregates, are relatively great in this soil. There is a practical aspect of this interaction between OM content and aggregate size. Cultivation of a soil with high OM content will be effective because, in such a soil, the large aggregates will remain stable throughout the rainy season and thus will maintain a relatively high IR. In contrast, in a soil with low

OM, cultivation will only have a short-lived effect because, in such a soil, most of the large aggregates will be broken down and dispersed at the beginning of the rainy season.

References

Abu-Sharar, T.M., F.T. Bingham, and J.D. Thoades. 1987. Reduction in hydraulic conductivity in relation to clay dispersion and disaggregation. Soil Sci. Soc. Am. J. 51: 342-346.

Agassi, M., I. Shainberg, and J. Morin. 1981. Effect of electrolyte concentration and soil sodicity on the infiltration rate and crust formation. Soil Sci. Soc. Am. J. 45: 848-851.

Agassi, M., J. Tarchitzky, R. Keren, Y. Chen, D. Goldstein, and E. Fizik. 2003. Effects of prolonged irrigation with treated municipal effluent on runoff rate. J. Environ. Qual. 32: 1053-1057.

Allen, B.L., and B.F. Hajek. 1989. Mineral occurrence in soil environments. In: J.B. Dixon, S.B. Weed (eds.). Minerals in Soil Environments. Soil Sci. Soc. Am., Madison, pp. 199-239.

Alpert, P., 2004. The water crisis in E. Mediterranean – and relation to global warming. In: F. Zereini and W. Jaeschke (eds.). Water in the Middle East and in North Africa. Springer, Berlin. pp. 55-61.

Anonymous. 1993. Irrigation survey. Irrig. J. Jan.-Feb. Issue: 19-34.

Arora, H.S., and N.T. Coleman. 1979. The influence of electrolyte concentration on flocculation of clay suspensions. Soil Sci. 127: 134-139.

Assouline, S. 2004. Rainfall-induced soil surface sealing: a critical review of observations, conceptual models and solutions. Vadose Zone J. 3: 570-591.

Assouline, S., and Y. Mualem. 1997. Modeling the dynamics of seal formation and its effect on infiltration as related to soil and rainfall characteristics. Water Resour. Res. 33: 1527-1536.

Auerswald, K. 1995. Percolation stability of aggregates from arable topsoils. Soil Sci. 159: 142-148.

Balks, M.R., W.J. Bond, and C.J. Smith. 1998. Effects of sodium accumulation on soil physical properties under an effluent-irrigated plantation. Aust. J. Soil Res. 36: 821-830.

Ben-Hur, M. 1994. Runoff, erosion, and polymer application in moving-sprinkler irrigation. Soil Sci. 158: 283-290.

Ben-Hur, M. 2004. Sewage water treatments and reuse in Israel. In: F. Zereini and W. Jaeschke (eds.). Water in the Middle East and in North Africa. Springer, Berlin. pp. 167-180.

Ben-Hur, M., I. Shainberg, D. Bakker, and R. Keren. 1985. Effect of soil texture and $CaCO_3$ content on water infiltration in crusted soil as related to water salinity. Irrig. Sci. 6: 281-294.

Ben-Hur, M., I. Shainberg, and J. Morin. 1987. Variability of infiltration in a field with surface-sealed soil. Soil Sci. Soc. Am. J. 51: 1299-1302.

Ben-Hur, M., Z. Plaut, I. Shainberg, A. Meiri, and M. Agassi. 1989. Cotton canopy and drying effects on runoff during irrigation with moving sprinkler systems. Agron. J. 81: 751-757.

Ben-Hur, M., Z. Plaut, G.J. Levy, M. Agassi, and I. Shainberg. 1995. Surface runoff, uniformity of water distribution and yield of peanut irrigated with a moving sprinkler system. Agron. J. 87: 609-613.

Ben-Hur, M., M. Agassi, R. Keren, and J. Zhang. 1998. Compaction, aging, and raindrop-impact effects on hydraulic properties of saline and sodic Vertisols. Soil Sci. Soc. Am. J. 62: 1377-1383.

Benito, E., and F. Diaz-Fierros. 1992. Effects of cropping on the structural stability of soils rich in organic matter. Soil Till. Res. 23: 153-161.

Black, A.S., and B.M.S. Abdul-Hakim. 1985. Effect of pasture or wheat cropping on the permeability of a weakly weathered soil to sodic solutions. New Zealand J. Agric. Res. 28: 275-278.

Cary, J., and D.D. Evans. 1974. Soil crust. Tech. Bull No. 214. University of Arizona. Tucson.

Castro Filho, C., A. Lourenço, M. de F. Guimaraes, and I.C.B. Fonseca. 2002. Aggregate stability under different soil management systems in a red latosol in the state of Parana, Brazil. Soil Till. Res. 65: 45-51.

Chaney, K., and R.S. Swift. 1984. The influence of organic matter on aggregate stability in some British soils. J. Soil Sci. 35: 223-230.

Chen, Y., J. Tarchitzky, J. Brower, J. Morin, and A. Banin. 1980. Scanning electron microscope observations on soil crusts and their formation. Soil Sci. 130: 49-55.

Chorom, M., and P. Rengasamy. 1995. Dispersion and zeta potential of pure clays as related to net particle charge under varying pH, electrolyte concentration and cation type. Eur. J. Soil Sci. 46: 657-665.

Ekwe, E.I. 1991. The effects of soil organic matter content, rainfall duration and aggregates size on soil detachment. Soil Tech. 4: 197-207.

Elliot, E.T. 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50: 627-633.

Emerson, W.W. 1977. Physical properties and structure. In: J.S. Russell and E.L. Greacen (eds). Soil Factors in Crop Production in a Semi-Arid Environment. University of Queensland Press, St. Lucia. pp. 78-104.

Feigin, A., I. Ravina, and J. Shalhevet. 1991. Irrigation with treated sewage effluent. Management for environmental protection. Adv. Ser. Agric. Sci., Vol. 17. Springer-Verlag, Berlin.

Felhendler, R., I. Shainberg, and H. Frenkel. 1974. Dispersion and hydraulic conductivity of soils in mixed solution. In: Trans. 10th Int. Cong. Soil Sci. 1: 103-112. Moscow: Nauka Pub. House

Fox, D.M., and Y. le Bissonnais. 1998. Process-based analysis of aggregate stability effects on sealing, infiltration, and interrill erosion. Soil Sci. Soc. Am. J. 62: 717-724.

Freebairn, D.M., S.C. Gupta, and W.J. Rawls. 1991. Influence of aggregate size and microrelief on development of surface soil crusts. Soil Sci. Soc. Am. J. 55: 188-195.

Frenkel, H., J.O. Goertzen, and J.D. Oades. 1978. Effects of clay type and content, exchangeable sodium percentage, and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Sci. Soc. Am. J. 42: 32-39.

Gal, M., L. Arcon, I. Shainberg, and R. Keren. 1984. The effect of exchangeable Na and phosphogypsum on the structure of soil crust – SEM observation. Soil Sci. Soc. Am. J. 48: 872-878.

Ghezzehei, T.A., and D. Or. 2000. Dynamics of soil aggregate coalescence governed by capillary and rheological processes. Water Resour. Res. 36: 367-379.

Golchin, A., P. Clarke, J.M. Oades, and J.O. Skjemstad. 1995. The effects of cultivation on the composition of organic matter and structural stability of soils. Aust. J. Soil Res. 33: 975-993.

Goldberg, S., and H.S. Forster. 1990. Flocculation of reference clays and arid-zone soil clays. Soil Sci. Soc. Am. J. 54: 714-718.

Guerra, A. 1994. The effect of organic matter content on soil erosion in simulated rainfall experiments in W. Sussex, UK. Soil Use Manage. 10: 60-64.

Hillel, D. 1980. Applications of Soil Physics. Academic Press, New York.

Kay, B.P., and D.A. Angers. 1999. Soil structure. In: M.E. Sumner (ed.). Handbook of Soil Science. CRC Press, New York, pp. A-229A-269.

Kazman, Z., I. Shainberg, and M. Gal. 1983. Effect of low levels of exchangeable Na and applied phosphogypsum on the infiltration rate of various soils. Soil Sci. 135: 184-192.

Kemper, W.D., and E.K. Koch. 1966. Aggregate stability of soils from western United States and Canada. Colorado Agric. Exp. Stn. Bull. No. 1355: 1-52.

Keren, R., and M. Ben-Hur. 2003. Interaction effects of clay swelling and dispersion and $CaCO_3$ content on saturated hydraulic conductivity. Aust. J. Soil Res. 41: 979-989.

Lado, M., A. Paz, and M. Ben-Hur. 2004a. Organic matter and aggregates size interaction in saturated hydraulic conductivity. Soil Sci. Soc. Am. J. 68: 234-242.

Lado, M., M. Ben-Hur, and I. Shainberg. 2004b. Soil wetting and texture effects on aggregate stability, seal formation and erosion. Soil Sci. Soc. Am. J. 68: 1992-1999.

Larson, W.E., S.C. Gupta, and R.A. Useche. 1980. Compression of soils from eight soil orders. Soil Sci. Soc. Am. J. 44: 450-457.

le Bissonnais, Y. 1996. Aggregate stability and assessment of soil crusting and erodibility: 1. Theory and methodology. Eur. J. Soil Sci. 47: 425-437.

le Bissonnais, Y., and D. Arrouays. 1997. Aggregate stability and assessment of soil crustability and erodibility: II. Application to humic loamy soils with various organic carbon contents. Eur. J. Soil Sci. 48: 39-48.

Letey, J., H.J. Vaux, Jr., and E. Feinerman. 1984. Optimum crop water application as affected by uniformity of water infiltration. Agron. J. 76: 435-441.

Mamedov, A.I., I. Shainberg, and G.J. Levy. 2001. Irrigation with effluents: effects of prewetting rate and clay content on runoff and soil loss. J. Environ. Qual. 30: 2149-2156.

Mbagwu, J.S.C., and K. Auerswald. 1999. Relationship of percolation stability of soil aggregates to land use, selected properties, structural indices and simulated rainfall erosion. Soil. Till. Res. 50: 197-206.

McIntyre, D.S. 1958. Permeability measurements of soil crust formed by raindrop impact. Soil Sci. 85: 158-189.

Moldenhauer, W.C., and W.D. Kemper. 1969. Interdependence of water drop energy and clod size on infiltration and clod stability. Soil Sci. Soc. Am. Proc. 33: 297-301.

Moldenhauer, W.C., and D.C. Long. 1964. Influence of rainfall energy on soil loess and infiltration rates. I. Effect over range of texture. Soil Sci. Soc. Am. Proc. 28: 812.

Morin, J., and Y. Benyamini. 1977. Rainfall infiltration into bare soils. Water Resour. Res. 14: 813-837.

Morin, J., Y. Benyamini, and A. Michaeli. 1981. The effect of raindrop impact on the dynamics of soil surface crusting and water movement in the profile. J. Hydrol. 52: 321-335.

Neaman, A., A. Singer, and K. Stahr. 2000. Dispersion and migration of particles in two palygorskite containing soils of the Jordan Valley. J. Plant Nutr. Soil Sci. 163: 537-547.

Oades, J.M., and A.G. Waters. 1991. Aggregate hierarchy in soils. Aust. J. Soil Res. 29: 815-828.

Onofiok, O., and M.J. Singer. 1984. Scanning electron microscopy studies of surface crust formed by simulated rainfall. Soil Sci. Soc. Am. J. 48: 1137-1143.

Oster, J.D., I. Shainberg, and J.D. Wood. 1980. Flocculation value and gel structure of sodium/calcium montmorillonite and illite suspensions. Soil Sci. Soc. Am. J., 44: 955-959.

Paz, A. 2000. Influence of long-term cultivation on soil physical properties and compaction of an umbric horizon. In: M. Pagliai and R. Jones (eds.) Sustainable land management - environmental protection: a soil physical approach. Advances in Geoecology 35. Catena Verlag, Reiskirchen. pp. 387-396.

Quirk, J.P. 1978. Some physico-chemical aspects of soil structural stability: a review. In: W.W. Emerson, R.D. Bond, A.R. Dexter (Eds.), Modification of Soil Structure. John Wiley and Sons, New York, pp. 3-16.

Rasiah, V., B.D. Kay, and T. Martin. 1992. Variation of structural stability with water content: Influence of selected properties. Soil Sci. Soc. Am. J. 56: 1604-1609.

Rengasamy, P., R.S.B. Greene, and G.W. Ford. 1984. The role of clay fraction in the particle arrangement and stability of soil aggregates: A review. Clay Res. 3: 53-67.

Rimmer, D.I., and D.J. Greenland. 1976. Effects of $CaCO_3$ on swelling behavior of a soil clay. J. Soil Sci. 27: 129-139.

Romkens, M.J.M., S.H. Luk, J.W.A. Poesen, and A.R Mermut. 1995. Rainfall infiltration into loess soils from different geographic regions. Catena 25: 21-32.

Schofield, R.K., and H.R. Samson. 1954. Flocculation of kaolinite due to the attraction of oppositely charged crystal faces. Faraday Discuss. Chem. Soc. 18: 135-145.

Shainberg, I., and M. Gal. 1982. The effect of lime on the response of soils to sodic conditions. J. Soil Sci. 33: 489-498.

Shainberg, I., and J. Letey. 1984. Response of soils to sodic and saline conditions. Hilgardia 52: 1-57.

Shainberg, I., Rhoades, L.D. and Prather, R.J., 1981a. Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil. Soil Sci. Soc. Am. J. 45: 273-277.

Shainberg, I., L.D. Rhoades, and R.J. Prather. 1981b. Effect of mineral weathering on clay dispersion and hydraulic conductivity of a sodic soil. Soil Sci. Soc. Am. J. 45: 287-291.

Shainberg, I., G.J. Levy, J. Levin, and D. Goldstein. 1997. Aggregate size and seal properties. Soil Sci. 162: 470-478.

Singer, A. 1994. Clay mineralogy as affecting dispersivity and crust formation in Aridisols. In: J.D. Etchevers (ed.). Trans. 15th World Cong. of Soil Science. Acapulco, Mexico. Vol. 8a. Int. Soc. Soil Sci., and Mexican Soc. Soil Sci., Acapulco, Mexico.

Southard, R.J., I. Shainberg, and M. Singer. 1988. Influence of electrolyte concentration on the micromorphology of artificial depositional crust. Soil Sci. 145: 278-288.

Stern, R., M. Ben-Hur, and I. Shainberg. 1991. Clay mineralogy effect on rain infiltration, seal formation and soil losses. Soil Sci. 152: 455-462.

Tarchitzky, H., A. Banin, H. Morin, and Y. Chen. 1984. Nature, formation and effects of soil crusts formed by water drop impact. Geoderma 33: 135-155.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33: 141-163.

Wakindiki, I.I.C., and M. Ben-Hur. 2002. Soil mineralogy and texture effects on crust micromorphology, infiltration and erosion. Soil Sci. Soc. Am. J. 66: 897-905.

West, L.T., S.C. Chiang, and L.D. Norton. 1992. The morphology of surface crusts. In M.E. Sumner and B.A. Stewart (eds.) Soil Crusting: Chemical and Physical Processes. Adv. Soil Sci., Lewis Publishers, Boca Raton. pp. 73-92.

Wischmeier, W.H., and J.V. Mannering. 1969. Relation of soil properties to its erodibility. Soil Sci. Soc. Am. Proc. 33: 131-137.

Zhang, H.Q., and K.H. Hartge. 1995. Mechanical properties of soils as influenced by the incorporation of organic matter. In: K.H. Hartge, B.A. Stewart (eds.). Advances in Soil Science: Soil Structure, its Development and Function. CRC Press, Boca Raton. pp. 93-108.

3.12 Restoring the Shrinking Dead Sea — The Environmental Imperative —

Elias Salameh and Hazim El-Naser

Elias Salameh, Amman 11942, University of Jordan; <salameli@ju.edu.jo>
Hazim El-Naser, Amman; <hazim.el-naser@osd.com.jo>

3.12.1 Introduction

The Dead Sea is a part of the Jordan Rift Valley (JRV) which extends for more than 400 km from Lake Tiberias in the north to the Gulf of Aqaba in the south and includes the Jordan River Valley, the Dead Sea (DS) and Wadi Araba. Its unique climatic conditions, its good soils, availability of water and irrigation form a major potential for Jordan for the production of fruits and vegetables and for tourism and industry.

The JRV is a deep depression in the Earth's Crust. Within its deepest parts the DS, with a recent water level of around 419 mbsl (Potash Co.) and a bottom of around 750 mbsl has formed (Fig. 3.12.1). The topography to the east and west of the DS rises sharply to around 1000 masl within a distance of 15 to 20 km. The catchment area measures around 43000 km^2 (USGS 1998).

The JRV which has the (DS) in its middle part consists of four different topographic zones formed as a result of major tectonic events along the valley from the Red Sea to Lake Tiberias. The topographic zones include the highland area, the escarpment, the foot hills and the Rift Valley. The elevation of the highland area along the eastern boundaries of the rift ranges between 800-1000 meters above sea level.

The climate of the area is subtropical to arid where annual rainfall averages between 400 mm at Lake Tiberias to approxiametly 250 mm at Wadi Yabis north of the JRV. In the wadi Araba area, average rainfall does not exceed 50 mm. The average temperature in the summer is about 40 degrees centigrade and in winter about 15 degrees centigrade (DoM 2006). The average winter humidity is about 65%. The annual potential evapotranspiration rate is approximately 2000 mm in the northern part of the valley increasing to more than 3000 mm in the area of Wadi Araba area which exceeds the annual amount of rainfall by sixty folds.

The major natural resource is the Dead Sea’s minerals and rocks. The estimated reserve of salts in the Deas Sea is about 43 billion tons (Neev and Emery 1967). The utilization of Dead Sea minerals on the Jordanian side is confined to the production of Potassium Chloride at a current capacity of about 1.5 million tons per year, almost all of which is exported to world markets. The Arab Potash Company has started in the last few years to produce other products like Bromine and Magnesium.

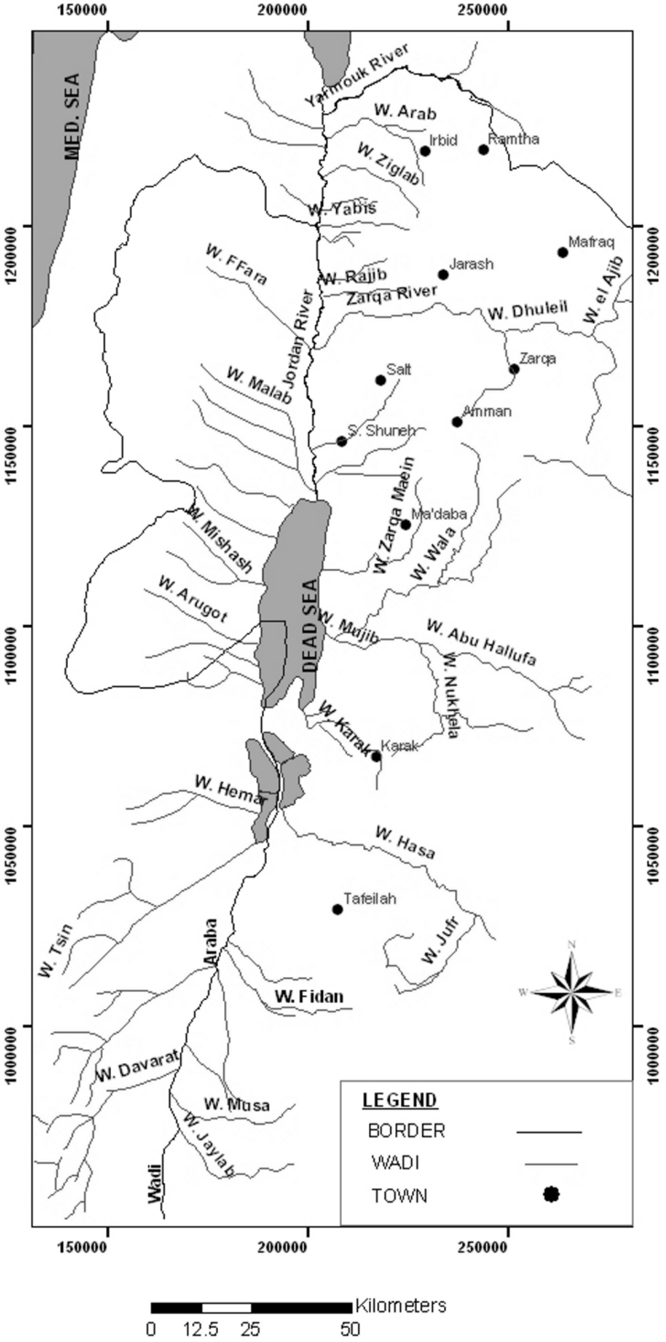


Fig. 3.12.1. Location map of the Dead Sea and its catchment area.

Irrigated agriculture is the largest user of water in the Jordan Valley. Water consumption in the JRV is about 250 Million Cubic Meter (MCM)/yr of various qualities. Currently, the cultivated land in the JRV is about 300 thousand donums (1 domum = 1000 m^3) more than 60 % of which is planted with vegetables and the rest fruits and field crops (JVA).

The unique geomorphological and climatological conditions prevailing in the Jordan valley, characterized by relatively warm weather during winter season, have created an attractive area for tourism. The JRV is endowed with numerous archeological and historical sites covering ancient periods such as Pella village and the archelogical sites at Um Qais. The valley also includes many sites of religious significance which attract large numbers of visitors and pilgrims such as the Baptism site.

3.12.2 The Challenge Facing the Dead Sea

Despite its unique features the rich diversity, the DS ecological and environmental status is being degraded and seriously threatened by the drop in the sea level. This drop is alarming, with a current decline rate of 1m in depth per year. Over the past four decades the water level has fallen by approximately 25 m (Fig. 3.12.2 and 3.12.3). This has led to a reduction in the sea length (north to south) from 75 km earlier in the last century, to 55 km at present, consequently, causing land deterioration (sink holes) along the shoreline as well as the destruction of ecologically sensitive habitats of flora and fauna, due to the imbalance in the hydrological system. Fig. 3.12.4 shows the terraces formed due to the drop in the level of the DS.

3.12.3 The Need to Protect the Dead Sea

Due to the fact that less water is coming to the DS these days than the historical flow, the DS and its unique environment are vanishing. The water level has been droping at an alarming rate for decades which if continues will jeopradize the many unique characteristics of the DS such as:

- Lowest place on Earth with a sea level persently at around 420mbsl.
- Saltiest water body on Earth
- Cradle of human culture
- Unique wildlife
- Unique spectacular landscape
- Unique medical and health resources
- The unique mineral and chemical production
- Huge tourism potential

Fig. 3.12.2. Land sat image of the Dead Sea and surroundings showing the retreat of the Dead Sea from the southern basin.

The environmental consequences associated with the dropping DS level can be summarized as follows

- **Loss of the historic Dead Sea.** Continued decline will result in a loss of a unique international geographic feature as it historically existed. All of the religious, archaeological and historical value will be jeopardized. This would be an immense loss to the international community.
- **Loss of valuable water resources.** Virtually the entire surface and subsurface drainage of the Jordan Rift Valley is into the DS. A high DS level creates a terrestrial groundwater/hypersaline groundwater interface that limits the quantity of groundwater that drains into the DS. Lowering of the D S level increases the groundwater flow into the DS itself (Salameh and Naser 1999). Over a planning horizon of about 50 years, the increase in groundwater flow to the D S could be about 400 million cubic meters per year of which fully

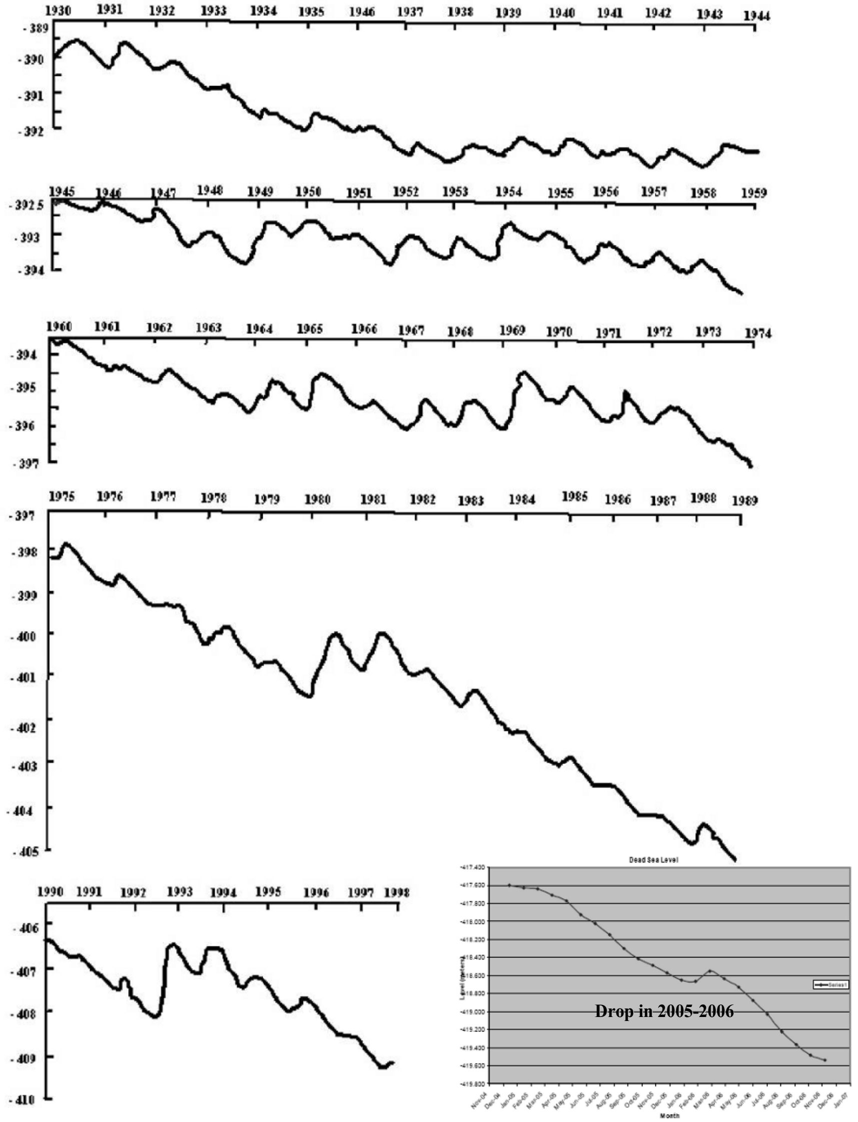


Fig. 3.12.3. Drop in the level of the Dead Sea in the periods 1930 - 1998 and 2005-2006.

one-half is fresh water. This represents a serious loss in the precious fresh water resource of the region.

- **Hydrologic systems out of balance.** As the DS goes down, so does the fresh water level in the area. As the fresh water hits salty layers in the underground, they dissolve, causing underground cavities (Salameh and Naser 2001). Signs of distress are already apparent. In the last years, large sinkholes have begun to appear on the shore. The development of sinkholes could jeopardize the stability of the pond dikes at the Dead Sea Chemical Works and cause other problems.

- **Loss of tourism development.** The constraints to tourism development that relate to the level of the DS are the ugly mudflats that will continue to be increasingly exposed as the level declines and, on the Jordan shore, the very steep drops that will exist as the level decreases. Tourism revenues, which could increase up to more than $ 200 million/year over the planning horizon, as well as initial investments on the order of $ 1 billion, are endangered by the current and future decline in the DS water level.
- **Ecological risk in the basin.** The rich ecosystem in the surroundings of the Dead Sea is at risk due to the geophysical changes that unbalance of the Basin Environment.

3.12.4 The Surrounding Water Resources and The Dead Sea Level

During the last five decades, the water resources within the DS drainage basin were notoriously developed. This development was driven by by two factors, namely:

- Increasing demand for water within the drainage basin.
- Anxiety of the different riparians of the DS that the other riparians will develop the water resources feeding the DS faster and hence deprive them from that water.

That fast development of the water resources deprived the DS of the major portions of water inflows. The ultimate result was a drop in its level. Whereas it was in the fifties and beginning of the sixties at 392 mbsl, it dropped to 419 mbsl in 2006. The question remains, however, whether the drop of 27 m in the level of the DS really reflects the additional uses of the waters, which formerly fed the DS, or are there other mechanisms acting together with the increasing water use, which play a role in determining the DS level?

This article tries to identify the effects of depriving the DS of waters which used to feed it on its level and also to identify the other geo-hazards, which are affecting the DS area and the surroundings.

3.12.5 Predevelopment Water Balance of the DS

Since the Dead Sea is an enclosed basin without an outlet, the only losses from its water are due to evaporation. The predevelopment water inflows to the DS are given in Table 3.12.1 (Salameh and El-Naser 1999) and average 1980 MCM/yr, which are were lost by evaporation from a surface area of 984 km^2. The evaporation rate is calculated accordingly to equal 2013 mm/yr, when the DS level was at equilibrium. Worth mentioning in this context is that the amounts of groundwater

Table 3.12.1. Summarization of water amounts, which used to flow into the DS prior to the development of the water resources within its catchment area (Salameh and El-Naser 1999).

Source	Amount (MCM/a)
I. Surface Water	
- Lake Tiberias (outflows)	542
- East Side Wadis	607
- West Side Wadis	58
- Dead Sea Eastern Catchment	219
- Wadi Araba Basin	
Eastern Side	31
Western Side	50
Subtotal Surface Water	1670
II. Groundwater	
- Eastern Side	90
- Western Side	100
- Northern & Southern Basins	30
Subtotal Groundwater	220
III. Precipitation	
Subtotal ppt over the Dead Sea	90
Total	1980

discharges given in Table 3.12.1 can be higher or lower than than the actual discharges, but that will only affect the predevelopment water balance of the Dead Sea by a few percentage.

3.12.6 Present day water balance

Since about 45 years, large projects to utilize the surface and groundwater resources within the catchment area of the DS have been implemented. The diverted waters have caused during the last 45 years continuous drop in the level of the DS. The present amounts of water flowing into the DS can be summarized in Table 3.12.2 (updated to account for the additional extractions from the feeding sources of the Dead Sea by the different riparians after Salameh and El-Naser 1999). The total quantity of inflows to the DS at present sum up to 363 MCM/yr. It

Table 3.12.2. Present Days Water Balance (some figures are estimates).

Source	Amount (MCM/a)
Average outflow from Lake Tiberias	20
Average surface runoff of the Western Jordan River Catchments	10
Average discharge of the Yarmouk River	10
Eastern Side of the Jordan River	15
Eastern Side of the DS. (Surface)	30
Eastern side of the DS. (ground)	50
Western side of the DS. (surface)	13
Western side of the DS. (ground)	50
Western Wadi Araba	10
Eastern Wadi Araba	10
Irrigation return flows + Subsurface flows and salt water diversions into the JR	85
Precipitation over the DS. (660 km^2)	60
Total Inflows	363

is worth mentioning that some of the given quantities are estimates. But the predevelopment- era contributions of the estimated sources are small. Therefore, even if the estimated figures of these minor water sources were afflicted with an error of 20 %, no major effects will be imposed on the fact that the inflows to the DS declined dramatically from 1980 to 363 MCM/yr

3.12.7 Present day water losses from the DS

Formerly only evaporation losses balanced the incoming amounts of water to the DS. But since the establishment of the DS Works (operated in 1931, then named Palestine Potash Company) and Arab Potash Co. (founded in 1956 and operated in 1985) on both sides of the Sea, water has been extracted and exposed to evaporation in salt pans to extract the different valuable salts. This process is presently consuming an average of 300 Mio m^3/a (pumping minus return flows). The net amount of water reaching the DS at present equals therefore (363-300) Mio m^3/a = 63 Mio m^3/a. Evaporation from the DS at present (660 km^2) amounts to 1320 Mio m^3/a (Salameh and El-Naser 1999).

Evaporation minus net inflows incomes gives around 1260 Mio m^3/a. Divided by the DS area of 660 km^2, excluding the evaporation pans areas results in a DS level decline of 190 cm/a. But, the actual drop in DS level during the last decade averaged only 120 cm/a.

Comment: The 120 cm/yr represent the total drop in the level of the DS, which do not include the inflows. Accordingly, the net drop during the last decade averaged 70 cm/ yr as already mentioned in the Text.

The difference of 70 cm/a water height is surely compensated for by additional outflows of groundwater from the DS surrounding groundwater bodies, due to inclining groundwater gradient and seaward interface migration in order to reach at a hydrodynamic equilibrium state with the dropping DS level (Fig. 3.12.2). The additional quantity of groundwater discharge into the DS to achieve a new equilibrium state amounts to (70 cm/a 660 km^2) = 462 Mio m^3/a during the last decade.

This fact means that the riparian countries of the DS are at present sacrifying 462 Mio m^3/a of freshwater to the saltwater regimes in their undergrounds to compensate for the evaporation losses and consequently to alleviate the drop in the level of the DS.

Table 3.12.3 shows also that the DS has since the early sixties been deprived of around 47.170 $*10^9$ m^3 of water by developing the water sources , which formerly flew into the DS. This means by an average sea surface area of 820 km^2 a drop of

Fig. 3.12.4. Terraces indicating the drop in the level of the Dead Sea. Each terrace shows one year cycle.

Table 3.12.3. Project areas, yearly consumption quantities, period of consumption, total consumed quantities per project area, and the grand total consumption in the D. S. catchment area of the water amounts which used to flow into the DS (Different sources and own estimates).

Project, Area, and Period			Average Quantity Mio m^3/a	Period of Consumption a	Total Mio m^3
National Water Carrier and other extractions from Lake Tiberias and the Upper Jordan River, Israel (1964-2006) (Mekorot, 1995)			500	42	21000
Yarmouk					
	Isr.	67- 87	50	20	1000
		87- 97	100	10	1000
		97-2006	50	9	450
	Syr.	67- 88	90	21	1890
		88- 97	180	9	1620
		97-2006	200	9	1800
	Jor.	64- 97	110	33	3730
		97-2006	60	9	540
Wadi Arab Dam (Jor)			20	23 20	400
Small Dams (Jor) (Ziqlab, Shueib, Kafrein)			8	30-35	250
Jordan Wadis (West)			Gradual Development		1000
West of the DS (Surface)			Gradual Development		1550
East of the DS (Surface)			Gradual Development		1280
East of the DS (Ground)			Gradual Development		450
West of the DS (Ground)			Gradual Development		1400
Wadi Araba (East)			Gradual Development		500
Wadi Araba (West)			Gradual Development		250
Sub Total					40170
Net Uses of the Potash Works					7000
				Grand Total	47110

level of 57.5 m but the actual drop has been only 27 m. The difference has been componsated for by inflows of fresh groundwater into the DS. This means by an average DS area of 820 km^2 groundwater outflows of 25 Bill. m^3 during the last 42 years or an average of 595 Mio m^3/a. Compared with the average rate of the last decade of 462 Mio m^3/a it can be stated that the yearly losses are declining, which can be explained as a result of the shrinking area of the DS.

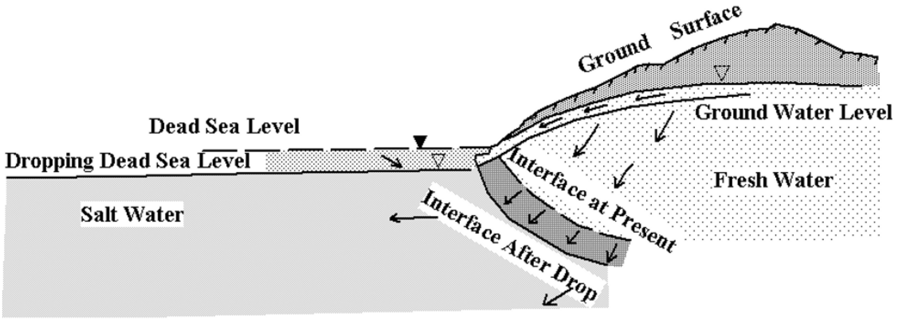


Fig. 3.12.5. Schematic pattern showing the displacement (arrows) of the interface due to dropping Dead Sea level.

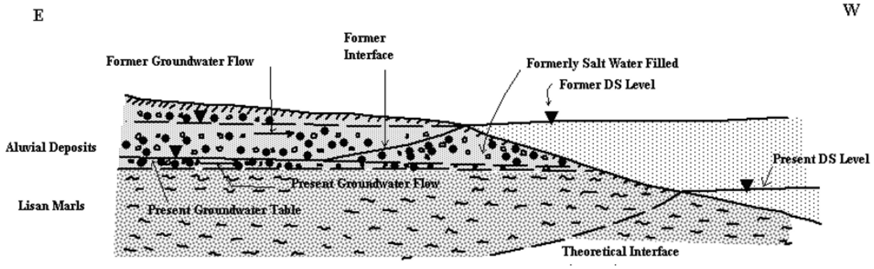


Fig. 3.12.6. Dead Sea level - groundwater level relationship and the effects dropping groundwater level on salt dissolution and particle erosion of the gravel / Lisan Marl interface.

The hydrodynamic dis-equilibrium brought about by the dropping DS level must result in a seaward migration of the salt/freshwater interface, and the discharge of saltwater into the DS. The fresh groundwater must accordingly fill the space which becomes free of saltwater due to the interface seaward migration. The substituting fresh groundwater hence becomes salinized (Fig. 3.12.5).

3.12.8 Other Impacts of the Declining Dead Sea Level

Damage to coastal areas

The coastal rocks of the DS are saturated with DS water (below the interface (Fig. 3.12.6) and are somehow cemented by salts deposited from the oversaturated DS water (Neev and Emery (1967). Lowering the DS level allows fresh- or brackish water to percolate through these rocks, which causes the dissolution of the salts in the underground of the coastal areas (especially the salty Lisan Formation), creat-

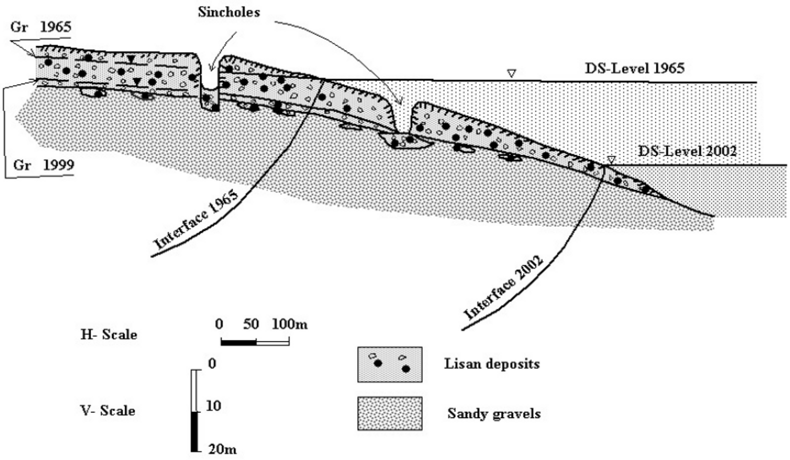


Fig. 3.12.7. Collapses of cavity roofs forming as a result of underground erosion and dissolution processes.

ing herewith underground cavities (Fig. 3.12.7). This in turn results in ground collapses, which have been taking place in the Lisan Peninsula during the last few years, where tens of sinkholes up to 30 m in diameter and 25 m in depth were formed within a few hours (Fig. 3.12.8).

Also at the beginning of September 1999 a huge collapse developed at the northern shore at the Dead Sea by the same dissolution, cavity-building and formation of collapses.

Dam Failure

The failure of one of the Jordanian Potash Works' dams with a capacity of 65 Mio m^3 (Potash Co.) is also considered as an indirect result of the deterioration of coastal areas due to the drop in the level of the DS. The dam was built on the semi-consolidated, salty Lisan Marl Formation very close to the shore of the DS. The drop in the level of the DS was a quasi removing of the foot support of the dam body, which caused its failure and damage.

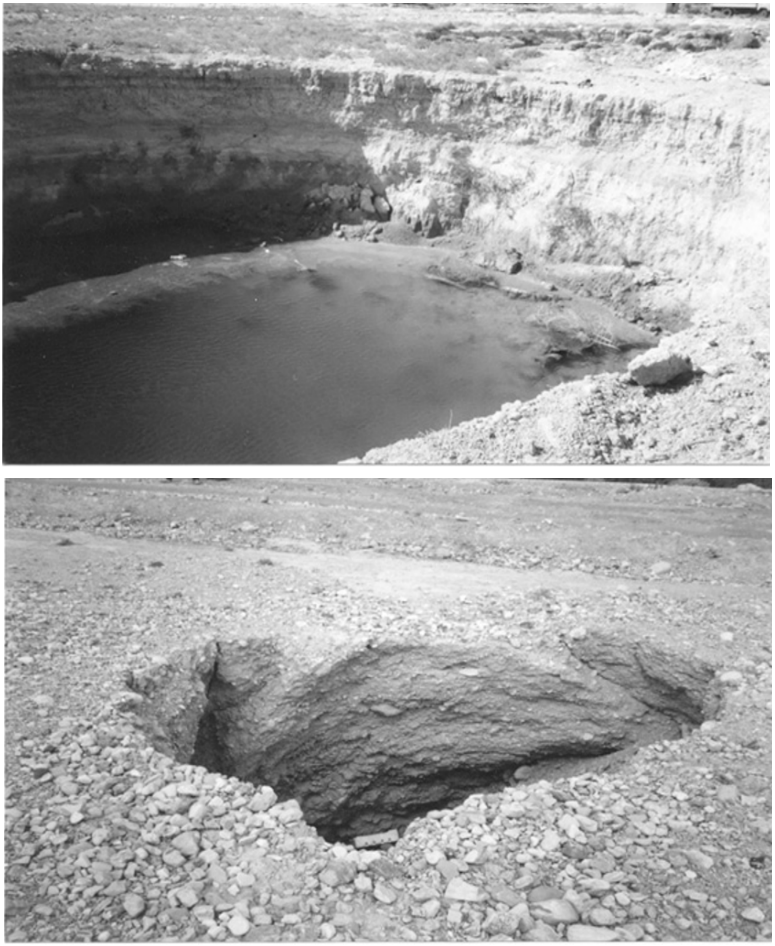


Fig. 3.12.8. Sink holes along the shores of the Dead Sea in Ghor Hadithaa area.

Spring discharges

As explained above, the drop in the level of the DS has been accompanied with simultaneous drops of the levels of the groundwater bodies in the surroundings of the DS. This has caused reduction in the discharge of springs, which are in direct relation with the level of the DS through the salt/fresh interface configuration. Some springs even ceased to discharge.

The reduced discharges of spring are observed along the eastern shores of the Dead Sea, which discharge from the deep aquifers which have not yet been affected by overexploitation of the groundwater resources of the country.

Thermal mineralised springs in Jordan located at the eastern escarpment of the DS are showing increasing salinities and decreasing discharges. Also these deteriorations are related to the dropping DS level and corresponding drops in the surroundings groundwater levels.

Curative projects costing tens of million dollars were established on these mineralized thermal springs both in Jordan and Israel. Ceasing of springs may result in loss of unique spas with health values and investment.

Pumping cost for the Potash Works

Any drop in the DS level means higher pumping cost to the Potash Works in order to lift the water to their evaporation pools lying at the older shores of the DS.

Decreasing humidity

When the area of the DS was about 950 km^2 the evaporation amount from the lake was equal to the incoming water of 1980 Mio m^3/a or 2084 mm/yr equivalent to 63 m^3/s. Presently, with an area of 660 km^2, the evaporation amount does not exceed 40 m^3/s, mostly taking place during the dry summer months. This of course means lower air humidity in the DS further surroundings which may affect human, animal and plant life negatively.

Unloading of the DS bottom

The drop in the DS level of 27 m has during the last 4 decades caused a release in the pressure on the underground rocks by about 3.3 kg/cm^2**.**

Considering the huge area of the DS, such a release may cause seismic activities, especially in a tectonically active area like that of the Jordan Rift Valley.

Climatic Change

In this article climatic changes have not been considering Decreasing precipitation, increasing temperature or decreasing atmospheric relative humidity will cause additional drops in the Dead Sea level enhancing all the above mentioned consequences.

There is an Available Environmental Solution

Since there is no fresh water within the catchment area of the DS or its further surroundings which can be made available to restore the DS, a solution to save the DS was thought of since ages. It has been called The Red Dead Canal Project because it should convey water from the Red Sea to the Dead Sea. The project is bold and visionary. It needs to be bold in order to solve the enormous DS situation. It consists of a water conveyance (a combination of tunnel and canal sections) to convey almost 1.8 billion cubic meters per year of sea water some 180 kilometers from the Red Sea near Aqaba to the vicinity of the DS (MWI). The project in and of itself would reverse the decline in the DS and gradually promote an increase in the level back to historic levels. The cost of the project is about $ 1 billion. The project will require and promote international cooperation.

The project is not an unfounded dream and has a sound technical foundation to support its viability. Several studies have been conducted on the project over the last two decades. The most serious of these was the World Bank funded Jordan Rift Valley Integrated Development Plan (JRV Plan) performed in the mid 1990's. That project was conducted by an international team of consultants led by Baker and Harza Engineering Company (1955).

The findings of that plan concluded that the Red Sea to Dead Sea route was most technically viable. In other words, serious engineers, after a serious investigation, concluded that the conduit that has now come to be known as the Red Dead Canal Project was the best alternative and that it could be built efficiently.

The implementation of the Red Dead Canal Project will accomplish two enormous objectives:

- **Save the Dead Sea.** Save the Dead Sea from environmental disaster and allow the economic benefits of a restored Dead Sea to flourish.
- **Water and Power Development.** Enable the self- sustaining development of very large quantities of renewable power and fresh water.

The Dead Sea has the lowest surface elevation on earth; approximately 419 meters below the surface of the Red Sea. This geographic fact offers the opportunity to generate an enormous amount of power.

The most precious commodity in the region is fresh water. Because of its scarcity, water is a key to development and survival, but water can also become a source of conflict in the region.

The project implementation unlocks the ability to develop the follow-on power/ desalination project. The 1.8 billion cubic meters per year of seawater brought from the Red Sea will utilize the 400 meter elevation difference to generate a renewable source of power. That power will be used to operate reverse osmosis units that will transform seawater to fresh water.

There will be two enormous products from the fully realized project:

- A portion of the water will be directed to the Dead Sea **and will be sufficient to reverse the decline of the Dead Sea levels and restore it at an ecologically prudent rate.**
- A great quantity of fresh water (850 million cubic meters per year) will be produced and directed to satisfy the fresh water demands in Jordan, Israel and Palestine. **The quantity would be sufficient to meet the region's needs for fresh water for the foreseeable future.**

In addition, the project will stop the collapses and rehabilitate the coast of the DS, increases the air humidity in its surroundings and allow springs to reappear or resumes their original discharges. The Potash Works will save in pumping cost and reduce environmental pollution by saving fuel burning.

Although the Red Dead Canal project will have tremendous advantages it might have also some negative impacts, which has to be studied in details in order to work out the necessary measures to avoid these impacts. Such impacts may arise from the mixing of different water qualities and accompanying precepitation/ dissolution of minerals, the environmental hazards the intake and the route of the Canal will be exposed to and what happens to the Canal in case of earthquakes or floods? Such questions are still open and deserve detailed studies before going ahed with the project.

As scientists we are intersested in restoring the Dead Sea. The Red Dead Canal represent one option to do that. The Med Dead Canal may proof to be technically and economically feasible, but it has also to fulfill other requirements such as enhancing peace and cooperation among the riparians of the Dead Sea. Reversing development in the catchment area to allow water to flow back to the Dead Sea is in our opinion irrealistic and not feasable.

References

DoM: Department of Meteorology, Open Files, Amman Jordan, 2006

Baker Inc. and Harza Eng. Co.: Yarmouk Jordan Valley Project, Master Plan Report, Chicago, Illinois1955

JVA: Jordan Valley Authority, Open Files, Amman, Jordan 2006.

Mekorot: Israel National Water Co.: Israel National Water Carrier, 1995.

MWI: Ministry of Water and Irrigation: Protecting the Dead Sea, Amman Jordan, 2001

Neev, D., Emery, K.O.: The Dead Sea depositional processes and environments of evaporites. Ministry of Development, Geol. Survey of Israel, Jerusalem, 1967, pp. 147.

Salameh, E., El-Naser, H.: Does the Actual Drop in Dead Sea level Reflect the Development of Water Sources within its Drainage Basin? Acta Hydrochim. Hydrobiol. *27,* 5-11 (1999).

Salameh, E., El-Naser, H.: Changes in the Dead Sea Level and their Impacts on the Surrounding Groundwater Bodies. Acta Hydrochim. Hydrobiol. *28*, 24-33 (2000).

Potash Company, Jordan, Open Fiels. Amman, Jordan, 2006.

USGS: United States Geological Survey: Overview of the Middle East water resources, Middle East water data banks,EXACT USGS,ISBN 0-607-91785-7

3.13 Groundwater in the Shallow Aquifer of the Jericho Area, Jordan Valley – Noble Gas Evidence for Different Sources of Salinization

Torsten Lange[1]*†, Konrad Hammerschmidt[2], Hans Friedrichsen[2], Amer Marei[3], Stephan M. Weise[1]

(1) Department of Isotope Hydrology, UFZ Centre for Environmental Research, Leipzig-Halle, Germany
(2) Institute for Geological Sciences, Freie Universität Berlin, Germany
(3) Department of Applied Earth and Environmental Sciences, Al Quds University, East Jerusalem, Palestine
* Present adress: Geoscientific Centre of the University of Göttingen, Department of Applied Geology, Goldschmidtstrasse 3, 37077 Göttingen, Germany;
† Author to whom correspondence should be adressed (tlange@gwdg.de)

Abstract

Arid to semi-arid conditions that generally promote water scarcity are common in many regions in the Near East. Moreover, various places in that geographic domain are affected by groundwater salinization. This challenge is also shared by the Jericho area, located on the western side of the lower Jordan Valley, about ten kilometres NW of the Dead Sea. Due to a unique hydrogeological situation in this area, the discrimination of the hydrochemical signatures of the possible sources of salinization are fuzzy. Part of the potentially salt bearing aquifer material was deposited by the high saline Pleistocene precursor of the Dead Sea, the Lake Lisan, and thus resembles the signature of known residual brines of the former lake. Brine occurrences at other locations in the area usually are connected to the western boundary fault, which is a structural element of the Dead Sea Transform system. From the study of the helium and neon noble gas isotope composition of samples from saline wells and springs at the northwestern Dead Sea shore as well as from six Jericho agricultural wells there is evidence that admixing brines are supposedly not the only source of salinization in the study area. Indeed it is shown that the highest helium excess concentrations are related to the vicinity of the border fault, where moderate salinities are already present. Wells not too far in the E of the study area but in close vicinity to Wadi Qilt produce groundwater with a noble gas composition typical for air-equilibrated surface water. This reflects significant volumes of infiltration in the rainy season due to the mountain discharge, that is mainly derived from springs in the upstream area of Wadi Qilt as well as run off. An intermediate position between the first two groups is demonstrated by the most saline groundwaters, which are found remote from the border fault in the E of the study area. This is interpreted as evidence for additional non-brine salinization input probably from the surrounding sediments of the Lisan Formation.

3.13.1 Introduction

General

Phenomena related to groundwater salinization are common in arid to semi-arid environments, for example in agricultural areas, as a consequence of the high evaporative flux or due to infiltrating effluents. If admixing brines or salt bearing sediment formations come into play, like in the highly agriculturally used Jericho area, the implementation of a reasonable water management policy is crucial to maintain on the one hand the economic viability of the local agriculture and industry and on the other hand the quality of groundwater as a common property that is intrinsically worthy to protect. The location of the study area (Fig. 3.13.1 and Fig. 3.13.2) is limited (1) by the easternmost wells, (2) in the W by a fault which separates a Cretaceous limestone and dolomite aquifer from the Quaternary basin fill of the Jordan Valley as well as (3) to the N and S by Wadi Nueima and Wadi Qilt, respectively. There are some wells located on the southern side of Wadi Qilt, however. Except for the local springs that discharge the Cretaceous Judea Group aquifer (in the following referred to as Mountain aquifer) W of the Jordan Valley the utilised groundwaters in the Jericho area are pumped from the Plio-Pleistocene to Holocene Samra and Lisan Formations. This section usually is referred to as the Shallow aquifer. The climate in general is hot and dry and the potential evaporation flux exceeds the amount of precipitation (150 mm/yr) by manifold. Jericho is located at about -250 m asl, some 10 km NW of the Dead Sea and about 30 km E of Jerusalem.

A socio-economic perspective

Due to the favourable conditions in the rain shadow of the mountains, which are provided by several springs of all-season yield of freshwater like Ein Sultan, the site of Jericho has been intermittently settled since the Pre-Pottery Neolithic A, around 10000 B.P. (Bar-Yosef, 1989). It is located along with other similar early settlements in the Dead Sea rift valley. The latter is an element of the Dead Sea Transform system extending from the Red Sea to the compressional plate boundary of the Alpine orogenic belt in Turkey and represents a natural route for N-S movement since ancient history. Agriculture has been practiced in the area since then. The historical open canal system to transfer spring water to remote plots in the Jericho area has been extended and improved by concrete open canals starting in the 1920's under the British Mandate. To further encourage agricultural production in the Jordan Valley, the Hashemite Kingdom of Jordan initiated various well drilling programs, e.g. around Jericho. Between the 1950's and 1967 around 80 wells have been drilled into the Shallow Pleistocene-Holocene aquifer of the Jericho area causing a remarkable improvement of the long traditional mode of agriculture while extending the area of cultivated land. On the other hand the cultivation of

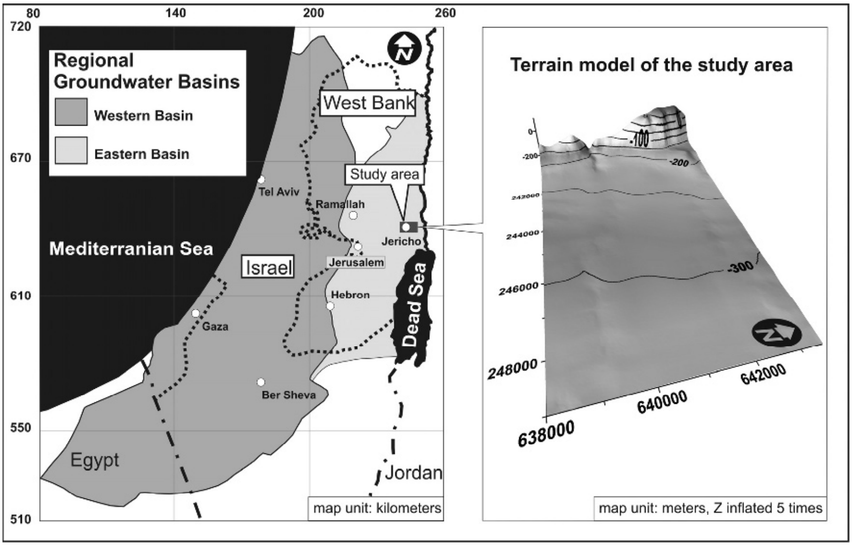


Fig. 3.13.1. Regional outline map and terrain model of the study area.

vegetables and fruits with high water demand like bananas and citrus fruits was made feasible on a much larger scale - even for export. These crops consumed much of the additional water now provided by groundwater wells.

While groundwater levels were decreasing, a general increase in the groundwater salinity of the Shallow aquifer, especially during the last decades, now endangers the agri-economic development of the Jericho area. At the easternmost agricultural plots salt tolerable plants like maize are the only crops, which can be utilized. High levels of nitrate and locally an increase in bacterial counts endanger health of consumers. The town of Jericho experienced an increase in the population number from an estimated 12,000 in 1980 to an estimated 25,000 people in 2003. Without any appropriate wastewater treatment facilities it relies solely on cesspits and a private sector controlled disposal, which has to be seen in the light of the difficult political situation in the area. This publication continues recent efforts, e.g. by Marei & Vengosh (2001) and Khayat et al. (2006) to understand the processes that lead to the deterioration of the Shallow aquifer groundwaters.

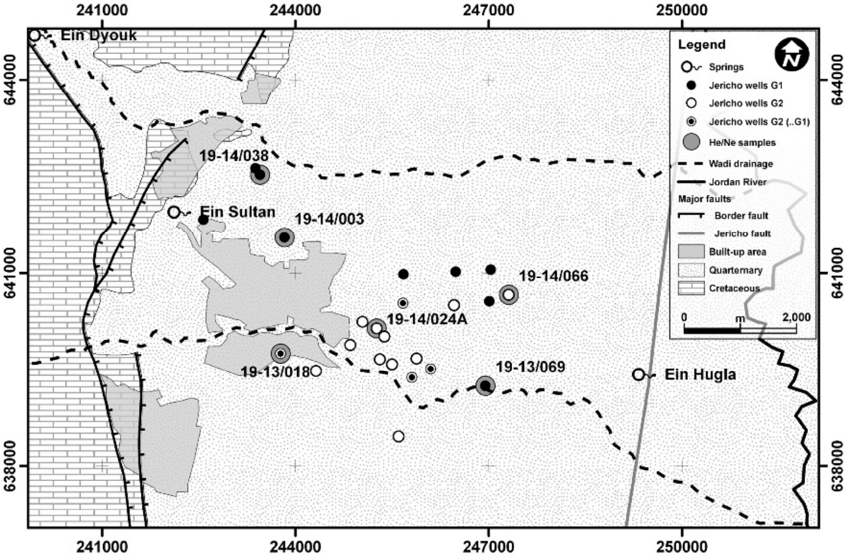


Fig. 3.13.2. Outline map of the study area around Jericho including well locations.

3.13.2 Hydrogeological and geochemical background

Geological setting

Of local importance as aquifers are the Plio-Pleistocene Samra and Lisan Formations that belong to the Dead Sea Group, the Miocene to recent sedimentary fill of a subdivided system of graben basins within the Dead Sea – Jordan Valley that are related to the Dead Sea Transform system. The Jericho fault (Fig. 3.13.2) is one active local branch of that transform fault system. Samra and Lisan Formations have been extensively described e.g. by Begin (1974) and Begin et al. (1975). In the W of the study area these sediments are separated from the high conductive Cretaceous limestone and dolomite formations and the confining Senonian chalks that all build up the Hebron and Ramallah Mountains (Judea and Samaria Mountains). In the crestal zone of the Hebron (Judea) Mountains the outcropping Mountain aquifer limestone and dolomite strata represent the most important recharge area for both, Israel and the West Bank. Simultaneously the crestal zone is the surface and groundwater divide between the Western and the Eastern Groundwater Basins (Fig. 3.13.1). The age of the top of the Lisan Formation is determined to be between 18,000 to 15,000 B.P. (e.g. Kaufman 1971; Stein, 2001; Landmann, 2002). With the retreat of the saline Lake Lisan, the precursor of the current Dead Sea, the local hydrography reshaped to its present state due to the development of the erosive Jordan River and the incision of Wadi Qilt and Wadi Nueima into their

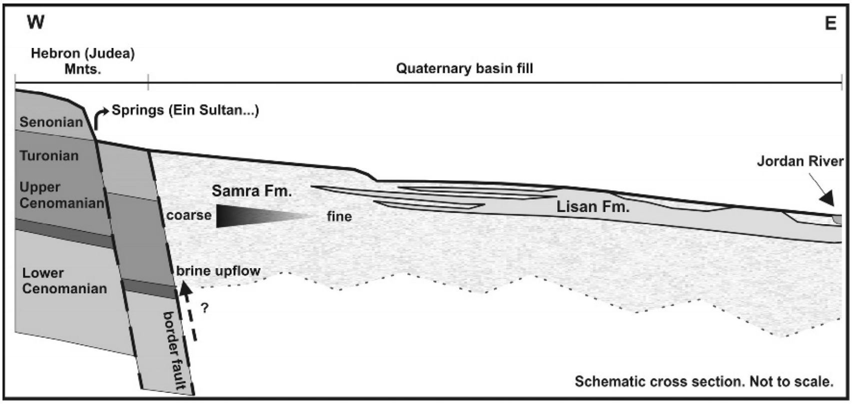


Fig. 3.13.3. Schematic W-E cross section of the Jericho area. Note, that this cross section is not scaled.

own fan deposits as well as into the Lisan and Samra Formations. The local record of Samra Formation comprises calcitic lutites, arenites, and conglomerates partly showing cross bedding and ripple marks. The sequence was deposited in an interfacing fluviatile-lacustrine environment (Begin, 1975). With closer distances to the border fault W of Jericho, which separates the basin fill from the consolidated Cretaceous rocks of the Hebron (Judea) Mountains, fan deposits gain in importance. Whereas more to the E of the Jordan Valley Lisan Formation overlays Samra Formation, a „Samra-like“ lithofacies prevails even through Lisan times where the wadis cross the border fault and continued to build up sedimentary fans and flood plains according to the lake level fluctuations. Similar sedimentation modes proceeded in Holocene times. Such fan and floodplain layers are the source of the rich arid Brown Soils of Jericho (Begin, 1975; Applied Research Institute Jerusalem, 1995). However, the Lisan lake level had been relatively stable for much time of its existence around -290 to -270 m asl (Stein, 2001), which is the ground level range for about half of the Jericho agricultural wells. Depending on the basin geometry of Lake Lisan in the Jericho area, the thickness of Lake Lisan sediments therefore may vary broadly. Particularly in marginal areas of the former lake, calciclastics with varying particle sizes, beach ridges, and channels occasionally intercalate. A schematic geological cross section is provided in Fig. 3.13.3. Because of its importance as a potential contributor to groundwater salinization, the geology and geochemistry of the Lisan Formation sediments will be shortly described in the next paragraph.

Geochemistry of Lisan Formation

It already has been mentioned that the salinity of Lake Lisan was high. However, it was much lower than that of the current Dead Sea. Laminated authigenic white aragonitic chalk, dark detrital layers and gypsum layers constitute main parts of the Lisan Formation. The aragonite layers are authigenic chemical precipitates whereas the non-calcic silt and clay fraction is imported from remote areas by wind as it is described also for the current Dead Sea detritus (Singer et al., 2003). However, it is generally observed that microorganisms can mediate the formation of calcium carbonate seed crystals (e.g. Kolodny et al., 2005; Rivadeneyra et al., 1998; Kawaguchi & Decho, 2002; Pérez et al., 2002), which would be in agreement with the fact that Lake Lisan aragonite has been precipitated directly from the surface water of Lake Lisan (Stein et al., 1997). Generally Mg/Ca ratios > 3.5 favour aragonite precipitation (Lippmann, 1973), ratios < 2 promote the formation of Mg-calcites or calcites. After the final decline of the lake level, the aragonite was preserved owing to the arid conditions in the Jordan Valley and the high Mg/Ca ratio of interstitial soluble salts, which were precipitated from the pore water (Katz et al., 1977). Indeed aragonite would recrystallize or transform in any solution having low salinity and low Mg concentrations as has been demonstrated by Katz et al. (1977) and Katz & Kolodny (1989). Because compared to calcite, aragonite is able to incorporate relative high amounts of Sr, the transformation of aragonite to calcite in turn should release relevant amounts of Sr. From Lisan sections in the Perazim Valley SE of the Dead Sea, Stein et al. (1997) derived two precipitation mechanisms for gypsum, which at this location forms distinct layers of up to 70 cm, thin laminae or authigenic crystals, which are to be found disseminated mainly in the detrital laminae but also in the aragonite laminae throughout the Lisan Formation. Landmann et al. (2002) showed that those authigenic crystals are of secondary nature since they penetrate the original lamination starting to grow from the detrital laminae into the aragonitic laminae. They also observed that organic matter is associated with the crystals. Torfstein et al. (2005) analysed $\delta^{34}S$ for the two groups of gypsum revealing values between 18 to 28 ‰ for the distinct bulky gypsum layers and -26 to -1 ‰ for laminated and disseminated gypsum. This is indicative for the oxidation of sulfidic compounds as has also been suggested by the latter authors who related those processes to the final recession of Lake Lisan. This process is believed to have caused the oxidation of the reduced pore water and solid matter, respectively. Indeed they could not find any sulfide minerals nor have such been described anywhere. The high $\delta^{34}S$ values prevailing in the bulky gypsum layers can be explained by the divergent path that is responsible for their deposition. These layers have been precipitated due to overturns of Lake Lisan, which are generally associated with a dropping level, i.e. limited freshwater input. Just these overturn events enabled the precipitation of such gypsum layers and bulky beds since the sulfate ions were locked in the less saline surface water layer, which continuously lost all Ca through the precipitation of aragonite. On the other hand the deep brine water layer was anoxic and hosted a major calcium pool owing its existence to a previous development starting with the desiccation of the Sedom lagoon and the exchange of sodium against calcium in the Cretaceous limestones (Starinsky, 1974). However, interestingly Stein et al. (1997) mentioned that considering the sulfate balance, the amount of gypsum found as layers and bulky beds is three times less than expected based on the estimated sulfate input. This information is helpful for the understanding of the sulfur isotope signature of the later discussed groundwater samples.

Water sources

The groundwater regime in the study area is highly unsteady, since groundwater level decrease has been a general trend throughout the last decades. Salinization phenomena might be attributed to brine supply, and according to Wolfer (1998) seasonal variations in pressure head can reach about 20 m when the amount of rain was very high as in 1991/1992. Infiltration by precipitation is assumed to steadily equal zero. For the area of Deir Alla, in the middle part of the Jordan Valley with comparable overall conditions but a higher average annual precipitation of ~250 mm, Zagana et al. (2007) determined infiltration rates below 1 mm/y. The known freshwater sources in and around the Jericho area are derived from springs NW of Jericho (Ein Dyouk, Ein Nueima, Ein Sultan - average annual discharge ~13.5 Mm^3), springs in the upper Wadi Qilt (Ein Fara, Al Fawwar, Ein Qilt - average annual discharge ~5 Mm^3) as well as surface runoff from Wadi Qilt and Wadi Nueima accompanying heavy rain events in their mountainous catchments during the rainy season (Beinhorn et al., 2004). Most of the mentioned springs are connected to a more or less developed karstic network; some localities are related to permeability barriers caused by faults. All of them discharge the Cenomanian-Turonian section of the Mountain aquifer. Although mountain runoff is assumed to represent a very significant amount of the total annual recharge, estimates of its long-term annual proportion are very uncertain, because the timing of runoff generation in the mountains can not be predicted and thus hardly be measured on time when it enters the Jordan Valley. Beinhorn et al. (2004) and Khayat (2005) estimated ~2 and ~9 Mm^3 per year, respectively. Only recently efforts have been undertaken in that direction. But up to now the main obstacle to record real runoff data is that flash-floods can be very powerful and thus can damage gauging installations, not even spoken at this point about measuring infiltration rates anyway. However, the main contribution for domestic and irrigation purposes in the actual study area is derived from Ein Sultan spring (also known as Elisha). Until early 2006 the spring water was distributed through a concrete and earth embankment supported open canal system directly to the water right holding farmers. Because water allocation was controlled by an inflexible scheme of opening and closing of water gates, most of the farmers used open pools or ponds to buffer momentary inapplicable amounts of their share as well as pumped groundwater, making the water vulnerable to the high potential evaporation but to greater extent to seepage. It may be noted, that the individual water shares were determined based on time durations of flow through the water gates, specifically at an hourly basis. Consequently that kind of distribution procedure failed to be reproducible since the water shares did not necessarily coincide with a specific volume. The flow rate considerably dropped along the canal branches from the spring outlet in the NW downstream to the E. The reasons were as would be expected the sequentially organised water diversion but also seepage losses from the canal (Al-Jayyousi, 1999). Different numbers exist about the total amount of spring water lost before application. A probably resonable estimate of the loss, based on calculations by the latter author and on findings of the International Fund for Agricultural Development (IFAD, 2007), which mentions a survey conducted by the Palestinian Water Authority (PWA), sums up to about 30%, whereas the annual discharge of Ein Sultan is about 5 Mm^3. Approximately 1.4 Mm^3 are diverted for domestic purposes annually. With respect to the groundwater balance a major part of the above-mentioned seepage might be accounted rather to be a gain then a total loss. But also the Jericho municipal tap water network is heavily affected by leakage. According to Applied Research Institute Jerusalem (2001) losses amount to ~65 %. Yet it is not known to the authors how much water annually passes the system in total. The real amount of irrigation return flow remains speculative and is assumed to be considerably below 10%, perhaps as low as about 2 % of the applied water (Khayat, 2005). In 2006 the old canal system was completely replaced by a pressurised pipe system that was funded by the IFAD. This turned the water allocation scheme from time to volume based. Thus the farmers are not dependent on their storage facilities anymore. However it has to be seen whether this „re-setting“ will rather complicate or enlighten the understanding of the Jericho shallow groundwater system in future. Possible fluxes of fresh groundwater (e.g. Laronne, 2003; Guttman, 2000) and of trapped ancient brines from W to E across the border fault have always been a matter of debate. Brines were discovered in the 1970’s in groundwater wells on the western side of the border fault across from Jericho. In general the border fault W of Jericho is considered to be impervious (Golani, 1972), because the Senonian impermeable chalks were down-faulted against the high permeable Cenomanian-Turonian section of the Mountain aquifer. On the other hand Yechieli et al. (1995) showed that under similar geological conditions seeping along the Dead Sea is likely to occur.

Methodology

One part of the hydrochemical data were taken from Khayat et al. (2006). The other part was analysed at the Environmental Laboratory at Al Quds University, Jerusalem by flame photometer, titration and ion chromatography - depending on the ion. Stable isotopes except for noble gases were measured at the laboratories of the Isotope Hydrology Department of the Helmholtz Centre for Environmental Research – UFZ – in Halle, Germany. $\delta^{18}O$ and $\delta^{2}H$ in water were determined by isotope ratio mass spectrometry (IRMS) after equilibration with CO_2 and H_2, respectively. Samples for analysis of the $\delta^{34}S(SO_4)$ signature were flushed through

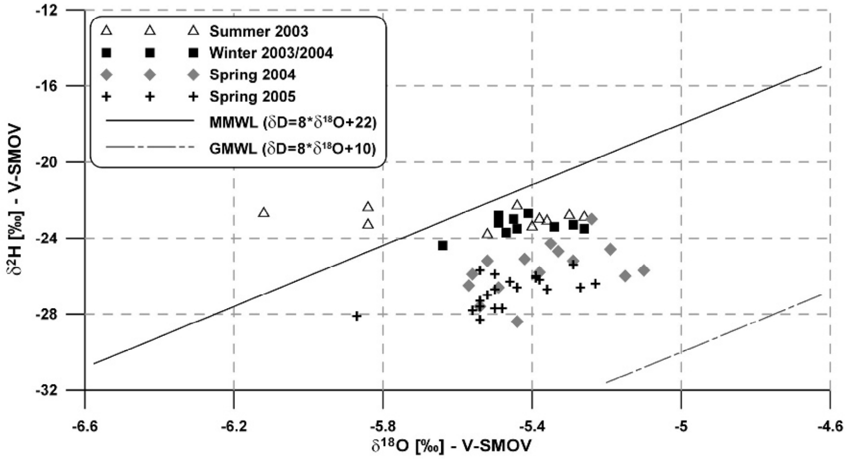


Fig. 3.13.4. δ^{18}O and δ^{2}H distribution of groundwater from the Shallow Aquifer, Jericho area (MMWL – Mediterranian Meteoric Water Line, GMWL – Global Meteoric Water Line). Groundwater from wells in the Eastern Basin of the Mountain aquifer range between -5.9 and -5.6 ‰ in δ^{18}O and -22.5 and -28 ‰ in δ^{2}H.

resin columns to adsorb the dissolved sulfate. After eluting and precipitating sulfate as $BaSO_4$ it was converted to to SO_2 gas. δ^{34}S signatures weres determined by IRMS. Noble gas analysis for the Jericho samples was performed at the Institute of Environmental Physics and Oceanography, Bremen University. A description of the analytical procedure can be found in Sültenfuß et al. (2007). The remaining noble gas samples were measured at Freie Universität Berlin.

Table 3.13.1. Hydrochemistry of the samples. The sources are: (1) - our samples, (2) - data from Khayat, S. (2005, 2006). Since in (2) the sampling dates were given as ’October to November, 2003’ the date format '10./11.2003' was used in the table.

Object	East	North	Source	Date	Na	K	Ca	Mg	Sr	Cl	Br	SO_4	HCO_3	NO_3	B	SO_4/Cl	Na/Cl	Br/Cl	B/Cl	$\delta^{34}S$	Group
					meq/L											meq ratio					
Ein Dyouk	240050	644660	2	10./11.2003	1.01	0.06	4.00	2.45	0.003	0.98	0.006	0.35	4.84	0.47	0.0043	0.351	1.023	0.0064	0.0044	6	spring
Ein Sultan	242200	641950	2	10./11.2003	0.99	0.06	3.88	2.47	0.003	0.97	0.013	0.36	4.71	0.68	0.0043	0.367	1.023	0.0129	0.0044	8.7	spring
19-14/026A	242573	641834	2	10./11.2003	2.81	0.16	5.78	5.28	0.012	3.41	0.021	0.47	7.17	0.26	0.1032	0.138	0.823	0.0063	0.0302	10	well, G1
19-14/038	243450	642530	2	10./11.2003	7.66	0.50	6.28	8.40	0.027	15.45	0.077	0.82	6.23	0.12	0.2448	0.053	0.495	0.0050	0.0158	5.9	well, G1
19-14/038	243450	642530	1	12.09.2003	7.22	0.49	6.00	8.00		14.00		1.10	7.50	0.15			0.516				well, G1
19-14/062	243380	642630	2	10./11.2003	10.00	0.62	6.90	9.04	0.027	20.56	0.109	0.85	5.97	0.08	0.2456	0.041	0.486	0.0053	0.0119	6.7	well, G1
19-13/069	246950	639250	2	10./11.2003	20.01	2.04	5.72	11.52	0.045	33.09	0.137	2.16	6.86	0.40	0.6810	0.065	0.605	0.0041	0.0206	3.8	well, G1
19-14/052	245680	640980	2	10./11.2003	13.06	0.92	5.98	10.23	0.065	23.44	0.091	1.50	6.23	0.55	0.4125	0.064	0.557	0.0039	0.0176	12.5	well, G1
19-14/067	247010	640560	2	10./11.2003	27.79	2.66	8.20	18.17	0.065	52.52	0.176	3.82	6.01	0.63	1.0990	0.073	0.529	0.0034	0.0209	-2.2	well, G1
19-14/073	247030	641050	2	10./11.2003	15.63	2.04	6.29	13.54	0.042	31.73	0.096	2.00	6.65	0.65	0.8101	0.063	0.492	0.0030	0.0255	6	well, G1
19-14/067	247010	640560	1	01.12.2004	40.81	2.99	8.68	20.51		68.37		3.96	7.40	0.89		0.058	0.597				well, G1
19-14/020	246490	641020	1	01.12.2004	17.67	2.34	6.36	14.87		42.01		3.24	8.00	0.99		0.077	0.421				well, G1
19-14/003	243830	641550	1	07.06.2003	12.35	0.87	7.96	9.43		23.78		1.08	6.80	0.15			0.519				well, G1
19-14/073	247030	641050	1	01.12.2004	20.64	2.14	6.56	13.31		38.03		2.97	7.60	0.88		0.078	0.543				well, G1
19-13/069	246950	639250	1	01.12.2004	26.89	2.18	5.19	11.72		29.33		2.25	8.30	0.44		0.077	0.917				well, G1
19-13/015	246100	639510	2	10./11.2003	9.33	0.98	4.88	8.34	0.040	15.63	0.067	1.27	6.21	0.54	0.3963	0.081	0.597	0.0043	0.0254	9.7	well, G2
19-13/015	246100	639510	1	01.12.2004	11.57	0.85	2.79	6.84		13.91		1.13	7.40	0.53		0.081	0.832				well, G2
19-13/050A	245810	639380	1	01.12.2004	9.54	0.85	2.63	6.72		12.76		1.78	7.30	0.66		0.139	0.747				well, G2
19-14/015	245670	640530	1	01.12.2004	10.32	0.47	6.05	10.52		15.64		1.46	9.50	0.93		0.093	0.660				well, G2
19-13/006	245500	639580	2	10./11.2003	6.90	0.20	8.50	7.69	0.081	12.68	0.031	2.45	6.17	1.17	0.2596	0.193	0.544	0.0025	0.0205	3.5	well, G2
19-13/020	244320	639480	2	10./11.2003	6.45	0.44	4.51	6.04	0.037	7.82	0.031	2.29	5.73	0.80	0.3426	0.293	0.825	0.0040	0.0438	3.6	well, G2
19-13/020	244320	639480	1	07.06.2003	4.22	0.63	3.89	5.03		7.29		2.10	5.60	0.38		0.288	0.579				well, G2
19-13/047	244850	639880	2	10./11.2003	5.06	0.32	4.59	5.48	0.049	6.53	0.028	1.61	5.70	0.71	0.2224	0.246	0.775	0.0042	0.0341	6.9	well, G2
19-13/048	245310	639660	2	10./11.2003	4.94	0.39	4.49	5.75	0.046	6.95	0.031	1.46	5.82	0.67	0.2136	0.210	0.711	0.0045	0.0307	5.7	well, G2
19-13/052	245880	639670	2	10./11.2003	9.02	0.72	6.26	9.37	0.082	16.65	0.052	3.46	6.05	0.75	0.4126	0.208	0.542	0.0031	0.0248	-5.9	well, G2
19-14/012	245380	640010	2	10./11.2003	4.01	0.29	4.33	5.21	0.043	5.26	0.024	1.23	6.85	0.65	0.1734	0.234	0.763	0.0045	0.0330	4.6	well, G2
19-13/006	245500	639580	1	01.12.2004	11.57	0.20	10.02	6.80		18.21		3.89	7.20	1.22		0.213	0.635				well, G2
19-13/026A	245600	638456	1	01.12.2004	17.83	0.97	6.37	8.48		21.39		4.69	7.40	0.92		0.219	0.833				well, G2
19-14/023	245040	640240	1	01.12.2004	6.10	0.36	5.03	5.88		7.66		1.07	8.50	1.41		0.139	0.796				well, G2
19-14/066	247310	640660	2	10./11.2003	25.10	2.11	9.12	17.58	0.081	45.53	0.197	6.27	7.20	0.48	0.8975	0.138	0.551	0.0043	0.0197	-9.7	well, G2
19-13/052	245880	639670	1	01.12.2004	17.67	0.85	8.96	14.15		28.93		6.48	6.50	0.99		0.224	0.611				well, G2
19-14/019	246460	640500	1	01.12.2004	17.04	1.45	11.30	15.87		27.61		7.66	8.00	1.15		0.278	0.617			-7.2	well, G2
19-14/066	247310	640660	1	01.12.2004	34.87	2.30	9.16	15.51		47.72		7.99	9.70	0.72		0.167	0.731				well, G2
19-13/026A	245600	638456	2	10./11.2003	4.56	0.43	6.37	8.03	0.092	12.44	0.031	1.86	4.25	1.13	0.0639	0.150	0.366	0.0025	0.0051	-5.1	well, G2

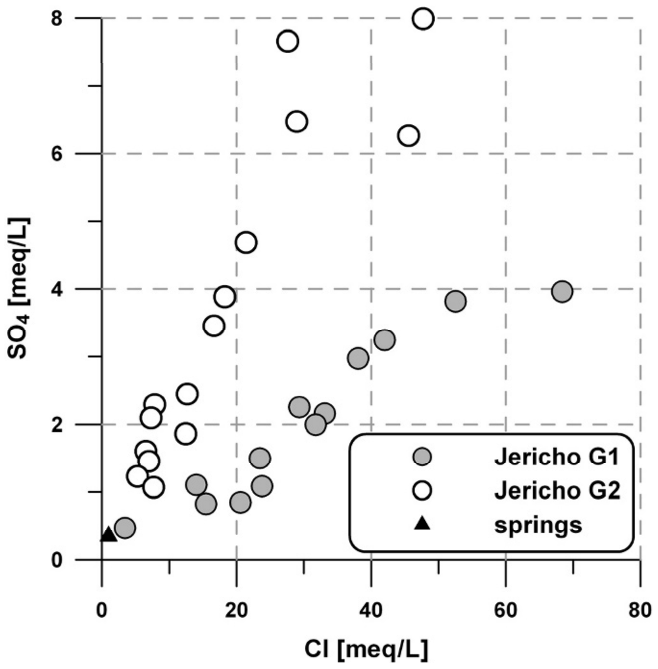


Fig. 3.13.5. Scatter plot showing the distribution of SO_4 and Cl in samples from group 1 and group 2 (G1, G2) as well as from the local springs.

3.13.3 Results and Discussion

This paragraph will essentially focus on characteristic hydrochemical and isotopic indicators for different sources of salinity based on the data available to this study. A general assumption for the Shallow aquifer groundwater of Jericho claims that the high salinities especially in the eastern part of Jericho are almost entirely a result of upflow of brines as a result of heavy groundwater abstraction. The latter is claimed to cause skimming of the freshwater pillow on top of a deeper seated salt water body, which in turn leads to a relevant pressure release and thereby upconing of brines. In the following we will discuss, how salinization by Water-rock interaction can be distinguished from brine admixture, and which arguments speak in favour for or would modify the above assumption.

Water stable isotope distribution

The $\delta^2H/\delta^{18}O$ (H_2O) isotope pattern in the Jericho area resembles the groundwater signature of the Mountain aquifer (Fig. 3.13.4). The relative high excess in deuterium in the Eastern Mediterranean region compared to the global isotope pattern in precipitation is related to the Mediterranean Sea itself, since it is a rather closed marine basin with elevated temperatures and lower humidity in the air compared to the open ocean. This causes enhanced kinetic fractionation during evaporation. However, the two isotopes are not suited to prove or disprove mixing with CaCl brines. Kolodny et al. (2005) estimated, that for instance the $\delta^{18}O$ signature of Lake Lisan reached maximal values of approximately 7 ‰. Model mixing of Lisan brine (Cl 120000 mg/L) with fresh mountain water (Cl 30 mg/L, $\delta^{18}O$ 5.8 ‰) to reach the salinity level of well 19-14/067 (Cl = 1862 mg/L) requires a mixing ratio of 0.015 : 0.985 and would yield a $\delta^{18}O$ value of -5.6 ‰. Indeed the samples with the highest Cl concentrations do not distinctly differ from the less saline samples. On the contrary, evaporation is expected to have a stronger effect on groundwater $\delta^{18}O$ if we for instance consider wadi runoff or contribution of seepage water from the numerous water storage pools and the open canal system in the valley.

Hydrochemical tracing of salinization

All hydrochemical data are presented in Table 3.13.1 except for a few data from sources that are not located inside the study area. For them the literature sources are given instead. As a first assumption, the hydrochemistry in the Shallow aquifer system of Jericho may be characterised and controlled by the freshwaters originating from the Mountain aquifer, by waste water of different quality, by rising brines as well as by Water-rock interaction in Samra and Lisan Formations. Lisan Formation emodies an important potential supplier of sulfate and other water soluble salts. For instance Katz & Kolodny (1989) found that at the Massada site, some fifty kilometres S of Jericho, the Lisan aragonite layers contain about 50 mg TSS/g (milligram of total (water-) soluble salts per gram of soil) and the detrital layers about 140 mg TSS/g (Lower Lisan). Since those water soluble salts except for sulfate obey a similar elemental signature like CaCl brines found in the greater vicinity of the Dead Sea, a clear discrimination of both end members is hampered. On the other hand SO_4/Cl ratios of CaCl brines in general are very low and mountain derived groundwaters have a comparatively low salinity. So the SO_4/Cl ratio provides a first approach to group the samples, since gypsum is an abundant mineral phase in the Shallow aquifer especially in the Lisan Formation. Thus gypsum solution should interfere the carbonate dominated hydrochemistry of the infiltrating mountain waters whereas brine admixture should be identifiable by low SO_4/Cl ratios. Thus saline groundwater exhibiting high SO_4/Cl ratios may be the result of two processes: (1) mixing of fresh and brine water as well as dissolution of sufate from the Lisan Formation or (2) at least part of the salt load is derived directly from the Lisan Formation. Fig. 3.13.5 shows how SO_4 and Cl are distributed in the samples. A distinction of two sample groups (G1, G2) according to their SO_4/Cl ratios seems appropriate. The means of G1 and G2 are 0.065 and 0.213, respectively. Samples from an intermediate range of the SO_4/Cl ratio (0.08 to 3.134) were not used for the calculation. Even so, these samples are assigned to G2, and are marked on the map of Fig. 3.13.2 as G2(...G1). They are limited to lower SO_4 levels of up

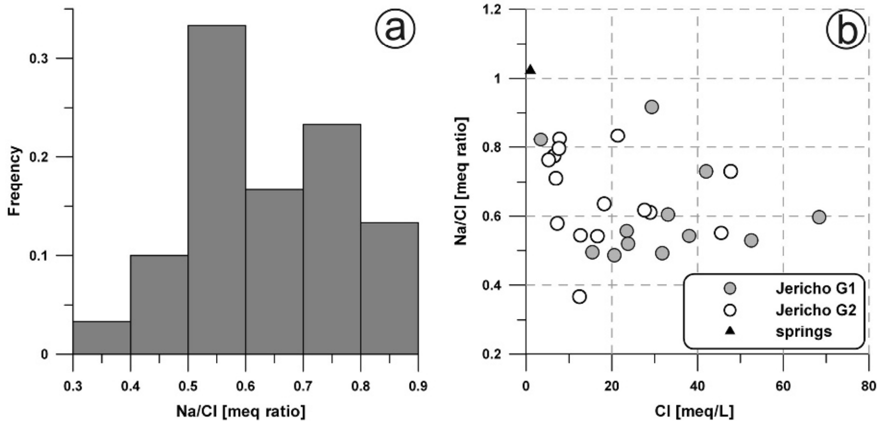


Fig. 3.13.6. **a:** Frequency distribution of the Na/Cl ratio.
b: Na/Cl – Cl scatter plot.

to 1.78 meq/L and Cl concentrations < 16 meq/L. The locations of the sampled wells according to their grouping are given in Fig. 3.13.2 showing that their distribution is not randomly. Wolfer (1998) showed, that the main difference in pressure head between autumn 1991 and 1992 was observed in wells in the vicinity of Wadi Qilt. With respect to the grouping of the wells it becomes obvious that wells from G2 cluster in the vicinity of Wadi Qilt (Fig. 3.13.2), where during the rainy season infiltration from wadi runoff is expected. It is further probable that along the course of Wadi Qilt higher hydraulic conductivities prevail. Note that all geographic coordinates used in this publication belong to the New Israeli Grid (NIG).

The Na/Cl distribution reveals an apparent bimodality (Fig. 3.13.6). Less saline water samples fall onto the peak with high Na/Cl ratios. With increasing Cl contents the ratio tends to converge against 0.5 to 0.6, for which two possible explanations apply: (1) Mixture of high Na/Cl water (fresh/sewage sources) with a small fraction of CaCl brine, because such brines have Na/Cl ratios below 0.5; (2) The mentioned range of 0.5...0.6 also mimics the usual ratio of Lisan Formation porewater (Arkin & Starinsky, 1981; Katz & Kolodny, 1989, Salameh, 2001).

Salinization might also be promoted by anthropogenic activities like infiltration of waste water effluents, dissolution of soil precipitates and leaching of sediments in the unsaturated zone. Since the Jericho area is intensively agriculturally used, nitrate is a good indicator for percolation water reaching the saturated zone. The samples generally are characterized by high nitrate levels of up to 80 mg/L and a mean of 41.9 mg/L (data set available to the study). One case of waste water disposal by tank trucks has been observed during the sampling. Because, as mentioned above, Jericho lacks appropriate waste water treatment facilities, this should be considered as a probable, common practice rather than an individual case. In

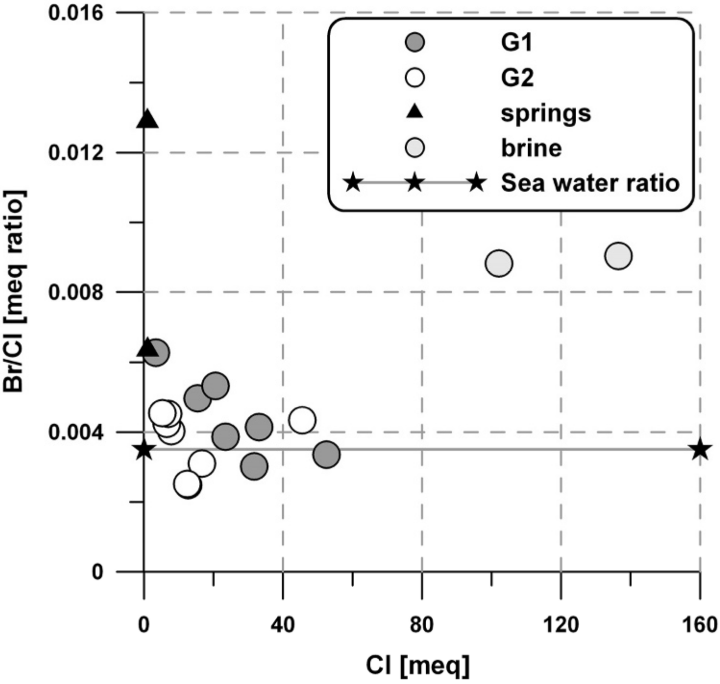


Fig. 3.13.7. Scatter plot showing the distribution of the Br/Cl ratio with respect to Cl concentrations.

this sense Jericho is not an exception for an urgent problem in many places of the West Bank. A main nitrate contribution nowadays comes from the major springs itself. For example concentrations in Ein Sultan since the 1980's have risen by a rate of ~1.36 mg/L per year, in 2004 reaching the preventive action limit of 50 mg/L defined by World Health Organisation. Because nitrate concentrations drop after the rainy season by about 1/4th to 1/3rd it is very likely that nitrate is derived through rapid infiltration of contaminated surface water upstream in the wadis and rapid transport through karst networks to the springs. The expected sources are dumping of waste water into wadis by tank trucks, more or less continuous waste water streams and related deposits as well as infiltration from waste water irrigated soils. Indeed the springs especially in the wet season discharge very young groundwater components (Kroitoru, L. et al., 1985). However, since nitrate contents in the samples often exceed 50 mg/L and the vadose water needs some time to infiltrate, nitrate must be introduced in considerable amounts by other sources, such as local cesspits, etc. Whatever the souce may be, this proves that water percolates through the unsaturated zone and in part it is highly corrosive, if we consider waste water infiltration. Thus infiltration is a potential driving mechanism for groundwater salinization, because it may transport water soluble salts from the soil into the groundwater and it may leach Lisan sediments as well. In order to better understand the processes occurring in the groundwater and soil, trace elements have been analyzed and interpreted.

Trace elements, sulfur isotopes

Usually NO_3 is introduced in agricultural areas by mineral and organic fertilizers, as well as manure and waste water. The only parameters obviously correlating to NO_3 at the study site are Sr ($r_{NO3,Sr} = 0.71$), Sr/Ca, Sr/Mg, as wells as Br/Cl ($r_{NO3,Br/Cl} = 0.78$). Br/Cl is a good indicator for different sources of salinity when it diverges from the ratio of sea water (~ 1.5...1.7 ‰ – equivalent ratio). Both, the high Br/Cl ratio and the high NO_3 concentrations in the springs exhibit contribution from effluents upstream in the Wadis as has been described earlier. Some bromide contribution from Senonian Br-rich bituminous layers or phosphorites cannot be outruled, since the groundwater passes the border fault zone, where Senonian is down-faulted against the Cenomanian-Turonian aquifer. A limiting factor, however, is the transit time of the groundwater within the border fault zone until it reaches the spring outlets. This time is assumed to be low for reasons that were mentioned before in this publication. The distribution of the sample groups in Fig. 3.13.7 indicates a three component mixing between spring water, groundwater that is increasingly subjected to Water-rock interaction as well as a brine end member. Water-rock interaction may lower the Br/Cl ratio as a result of halite dissolution in the Lisan Formation. But since Br/Cl has a good correlation with NO_3, flushing of soil precipitates by agricultural return flow could have an additional effect. In Fig. 3.13.8a Sr/Ca is plotted against Br/Cl. The sample with the highest Br/Cl and Sr/Ca ratios together with a high NO_3 load, and the lowest Na/Cl ratio of all samples (0.37) at well 19-13/026A could be related to a small iron factory, where according to Khayat (2005) high amounts of $NaNO_3$ are used for steel hardening - a process that could be related to steel nitridation. But without analyses of such effluents the authors can not rate this source. Samples with the highest Sr/Ca ratios are assumed, however, to represent enhanced impact from anthropogenic effluents regarding the positive correlation to NO_3

For Jericho there exist several potential Sr sources:

1. The distribution of Sr is a valid candidate for tracing Water-rock interaction by means of dissolution where percolation waters or groundwaters pass the Lisan Formation. Just considering the process of dissolution of Lisan aragonites it should be reflected by increasing Sr/Ca ratios since they contain up to 7700 ppm Sr (Katz, 1977; Stein, 1997).
2. Also transformation of aragonite to calcite could be responsible for a relevant Sr release (e.g. Kahle, 1965; Yoshioka et al., 1986).
3. A third potential Sr source of relevance may be provided through the application of mineral - especially phosphorous fertilizers where it can be an important part of the impurities (Mortvedt & Beaton, 1995; Böhlke, 2002). Unfortunately

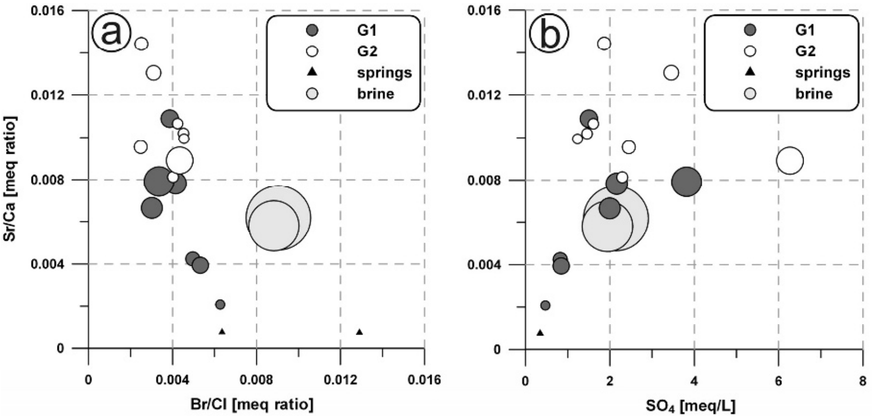


Fig. 3.13.8. **a:** Sr/Ca vs. Br/Cl in samples of groups G1 and G2, the local springs, and brines. The symbol size indicates relative Cl concentration. Brine data were obtained from Klein-BenDavid (2004).
b: Sr/Ca vs. SO_4 in samples of groups G1 and G2, the local springs, and brines. The symbol size indicates relative Cl concentration. Brine data were obtained from Klein-BenDavid (2004).

phosphate as a cross check is unavailable because it gets fixed in calcareous dominated soils.

Fig. 3.13.8a and 3.13.8b compare Sr/Ca ratios with Br/Cl ratios as well as with sulfate concentrations, respectively. Both diagrams include typical CaCl brine samples from springs NW of the Dead Sea (Klein-BenDavid et al., 2004). Whereas in Fig. 3.13.8a the degree of anthropogenic deterioration is depicted, Fig. 3.13.8b exposes how this process is related to the sulfate content of the samples. Relative Cl concentrations are indicated by the size of the symbols. What can be taken from the figures is that the Sr/Ca ratio ranges between less then 0.001 in the springs and 0.014, whereas samples with the highest salinities cluster around a ratio of about 0.008. By comparing the latter with the two plotted CaCl brine samples it is shown, that the ratios of the CaCl brines plot around 0.006, and a ratio of 0.008 is likely to be related to Water-rock interaction, very probably in connection with Lisan Formation. Both CaCl brine samples also have a significant lower SO_4/Cl ratio than the Jericho samples with the highest salinities. Additionally, the previously made assumption is supported that the SO_4/Cl ratio could be a good indicator for admixture of CaCl brines, even though it is not sufficient. It is obvious, however, that the difference of both, the CaCl brine ratios and the suggested ratio from Water-rock interaction is not very large and therefor insufficient to value the individual impacts of the two processes on salinization. It has to be noted that the Sr/Ca ratio of the CaCl brine samples already represents a mixture between pure brine and

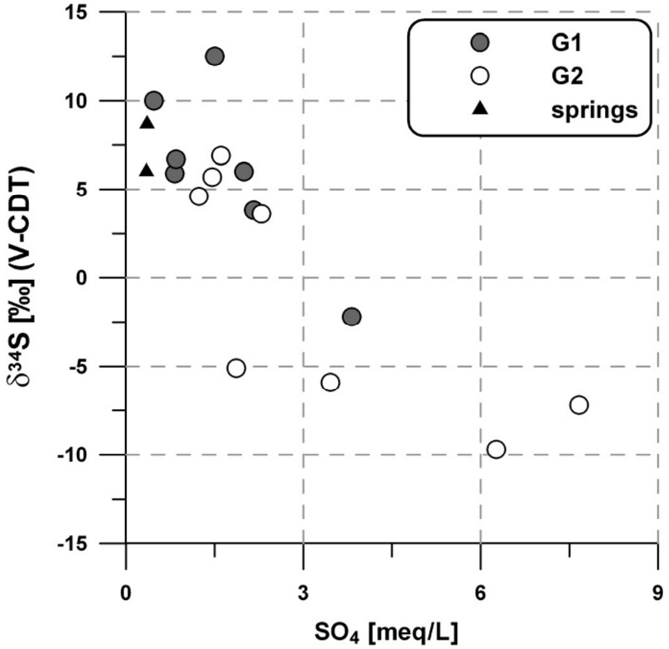


Fig. 3.13.9. $\delta^{34}S(SO_4)$ vs. SO_4 in samples of groups G1 and G2 as well as the springs.

freshwater from the Mountain aquifer. With increasing salinity these brines would also adopt a Sr/Ca ratio of about 0.008. However, groundwater in the Shallow aquifer is far from being saline.

If one consideres the surplus in sulfate especially in the G2 samples to be controlled to a great extend by Water-rock interaction in the Lisan Formation, then this should be reflected by the $\delta^{34}S$ (SO_4) signature. All samples are undersaturated with respect to gypsum ($SI_{gypsum} < -1.0$) The sulfur isotopic pattern of sulfate clearly indicates that the dominant source is considerably depleted in ^{34}S (SO_4) as shown in Fig. 3.13.9. A similar trend seems also valid for the G1 samples. But whereas for G2 the depleation of ^{34}S (SO_4) clearly conicides with an increase in Cl concentrations this can not be shown for G1. Only the sample from well 19-14/067, which is situated in the E of the study area, has both, the highest salinity as well as the lowest $\delta^{34}S$ (SO_4) signature of G1. These observations support the possibility that Lisan Formation significantly contributes to salinity, which would be more pronounced in the easternmost wells. They further rule out CaCl brines as the sulfate source, because all known brines in the area exhibit a strongly enriched signature (Gavrieli et al., 2001). As has been stated earlier in this paper, disseminated gypsum from Lisan Formation is the only verified depleted source in the Lisan Formation. However, although metal sulfides in Lisan sediments have not been found

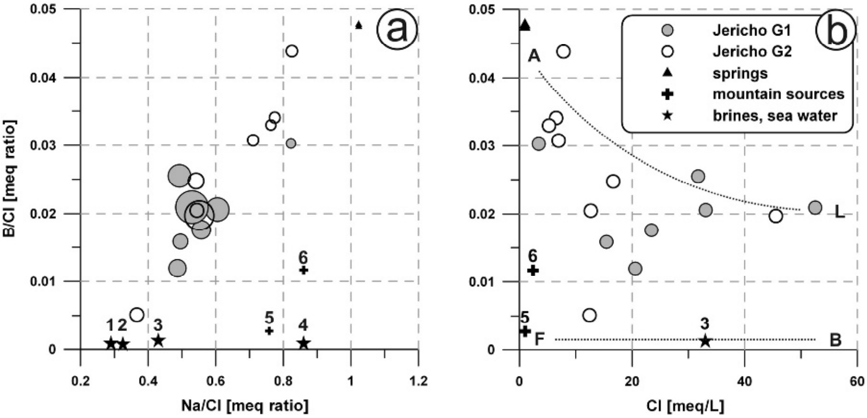


Fig. 3.13.10. **a:** B/Cl – Na/Cl scatter plot including wells from the Shallow aquifer, the local springs, as well as other sources in the area (1 - Dead Sea, 2 - Hamme Mazor (hot spring), 3 - Ein Feshka, 4 - sea water, 5 - Modi'in 4 (deep freshwater well, Mountain aquifer), 6 - Ein David (freshwater spring W of the Dead Sea). Data from these other sources in the area were obtained from Vengosh, A. (1991).
b: B/Cl –Cl scatter plot including the Jericho Shallow aquifer wells, the local springs, as well as other sources: Modi'in 4 (deep freshwater well, Mountain aquifer), 6 - Ein David (freshwater spring W of the Dead Sea). Data from the other sources in the area were obtained from Vengosh, A. (1991). End members assigned to the letter index: A – anthropogenically affected (e.g. by effluents), L – Lisan Formation signature, F – anthropogenically unaffected freshwater, B – brine signature.

in accessible outcrops they are supposedly preserved in presence of interstitial porewater. Both, dissolution of authigenic secondary gypsum and pyrite oxidation result in decreasing $\delta^{34}S$ values. Unfortunately it is impossible to verify the latter process since measured Fe_{tot} concentrations in solution in the Shallow aquifer groundwaters are very low (Khayat, 2005), probably because of the carbonate buffered soil (pH ~7). Beside gypsum dissolution and pyrite oxidation a third process of H_2S generation by microorganisms from sulfate and organic matter and its transformation back to SO_4 under oxic conditions could be possible as well. It is also uncertain, how the described individual processes would modify the Sr/Ca ratio. However, the main conclusion that was reached with the help of the sulfur isotope signatur of sulfate was, that salinization by Water-rock interaction is not implausible. It becomes even more likely in the easternmost wells of the Jericho area.

The assumption that leaching could represent a major source at least for the eastward increasing sulfate load is supported by boron concentrations since both parameter strongly correlate in G1 as well as G2. Vengosh et al. (1991) showed that the boron adsorption onto the detrital clay fracture of sediments in hypersaline

Table 3.13.2. Measurement values of the noble gases.

Source	Date	^{22}Ne * 10^{-5}	^{20}Ne * 10^{-4}	^{4}He * 10^{-5}	^{3}He/^{4}He * 10^{-6}	R_{sample}/R_a
		mL STP/kg	mL STP/kg	mL STP/kg		
19-13/018	27.04.2005	2.570	2.513	7.499	1.399	1.016
19-13/018	27.04.2005	2.575	2.519	7.592	1.399	1.015
19-14/024A	26.04.2005	3.201	3.131	9.059	1.400	1.022
19-13/069	26.04.2005	5.395	5.278	20.564	1.394	1.016
19-14/003	27.04.2005	2.116	2.074	29.030	1.354	0.977
19-14/003	27.04.2005	3.541	3.477	34.907	1.317	0.943
19-14/038	27.04.2005	2.065	2.021	14.815	1.411	1.021
19-14/038	27.04.2005	2.051	2.007	14.789	1.414	1.023
19-14/066	26.04.2005	2.484	2.431	10.374	1.390	1.005
19-14/066	26.04.2005	2.502	2.452	10.423	1.390	1.005
Ein Feshka	24.03.1995	NA	0.932	26.000	1.453	1.050
En Zukim	03.01.1997	NA	5.116	220.000	1.024	0.740
Rn-1 15	05.09.1996	NA	3.061	120.000	1.060	0.766
Rn-1 25	05.09.1996	NA	1.250	170.000	1.070	0.773
Rn-1 45	05.09.1996	NA	0.829	400.000	1.050	0.759
Rn-1 54	05.09.1996	NA	0.865	300.000	1.005	0.726
Rn-2 15	05.09.1996	NA	0.868	79.000	1.121	0.810
Rn-2 23	05.09.1996	NA	1.001	68.000	1.118	0.808

environments indeed can be very effective. In Fig. 3.13.10a the B/Cl - Na/Cl scatter plot compares samples from this study with brine and mountainous freshwater sources. Less saline water samples from this study having relevant nitrate concentrations are associated with high Na/Cl and B/Cl ratios. On the other hand samples from wells located near the border fault and remote to Wadi Qilt, i.e. in the NW of the study area, reveal moderate salinities (TDS between 1000 and 2000 mg/L) but significantly low B/Cl and Na/Cl ratios. It becomes very likely that these wells produce water, which represents a mixture of a major fresh and a minor brine component. This fact supports the general assumption that brines, which occur elsewhere along the western border fault, contribute to a certain amount to the groundwater of the Jericho Shallow aquifer. The sample that was taken in October/November of 2003 from well 19-13/026A has an odd position in the B/Cl - Na/Cl scatter plot. If this position would represent mixing with the charted potential brine end members a much higher salinity would be expected. Therefore this sample again should be handled with care because the hydrochemistry is assumed to be affected by effluents from the iron factory site, but boron on the other hand is also a trace supplement of inorganic fertilizers. Well 19-13/026A however is situated next to Wadi Qilt, an area potentially highly susceptible to surface infiltration. By reverting to the other samples the question arises whether brine supply might be limited to the border fault zone, because the initial B/Cl – Na/Cl and B/Cl – Cl pattern becomes completely masked to the E by the infiltration waters as well as probably by the Lisan signature as indicated in Fig. 3.13.10b.

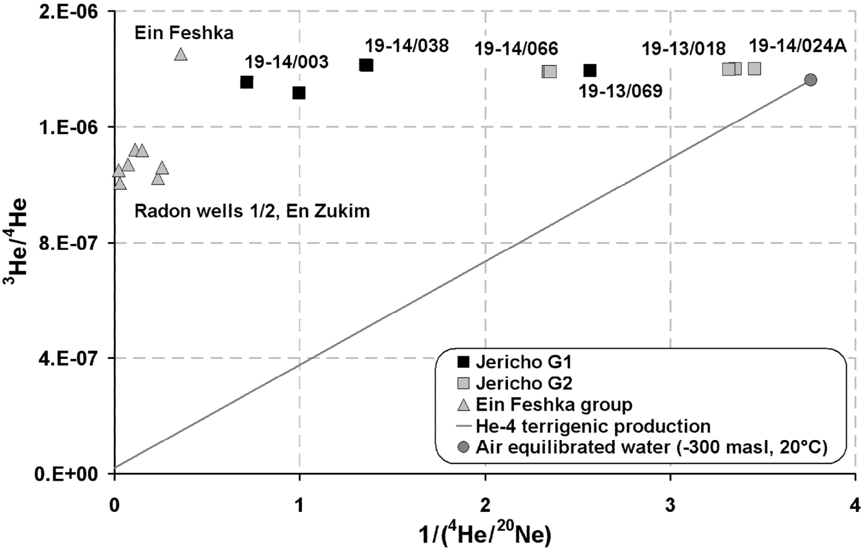


Fig. 3.13.11. $^3He/^4He$ ratio plotted versus $1/(^4He/^{20}Ne)$. Whereas the $^3He/^4He$ ratio reflects the He source, the abscissa indicates the amount of ^4He that was added to the groundwater. The starting point for a water system is usually represented by water, which is in equilibrium with air. Thus a data point will be shifted left if ^4He increases. If the ^4He accumulation is related to radiogenic in situ production or/and a continental, crustal flux component a data point would be shifted along the ^4He terrigenic production line. Mantle contribution would shift a data point away from the ^4He terrigenic production line to a higher $^3He/^4He$ ratio.

Noble gases

A generally promising and complemental approach to balance difficulties related to cases of ambiguous hydrogeochemical patterns, which also has been unfolded during the course of this study, is the application of noble gas analysis regarding their chemical inertness. Mazor (1972), who was the first to sample springs and wells along the Jordan Valley for noble gases with the intention of using them as climate proxy in terms of paleotemperatures found in contrast to the other analysed noble gases Ne, Ar, Kr, and Xe remarkable helium excesses at many locations. Because our present study was limited to helium isotopes, some introductory remarks focus on these isotopes. Determination of air excess helium that is more or less common to many natural water sources was provided by ^{20}Ne and ^{22}Ne. The initial noble gas concentrations of usual groundwaters are set by effectively equilibrium conditions between surface water and atmosphere which is essentially also valid for the specific isotopic ratios (atmospheric ratio of $^3He/^4He$: R_a = 1.384 x

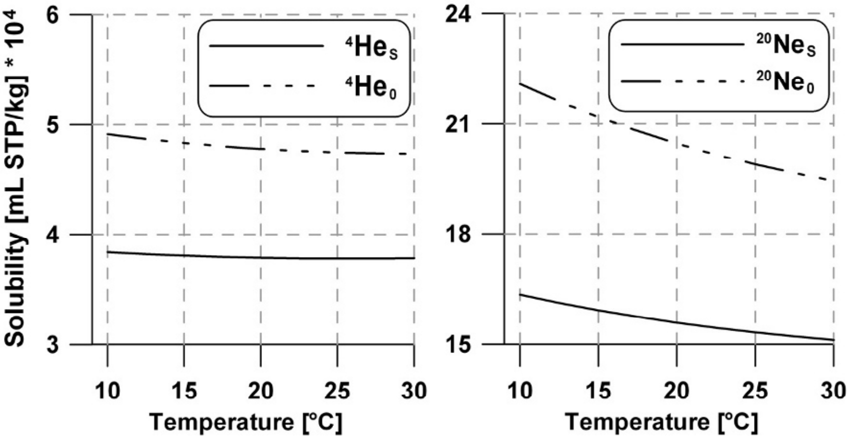


Fig. 3.13.12. ^4He and ^{20}Ne solubilities vs. temperature in pure water and 1 molar NaCl solution referring to indices 0 and S, respectively.

10^{-6}; Clarke et al., 1976). Deviations from the initial atmospheric signature in particular affects the helium isotope distribution because ^4He and ^3He concentrations are modified by in situ radiogenic production and by flushing He from continental crust and old lithosphere as well as by more or less steady fluxes originating in certain geochemical domains from the upper mantle. Whereas continental, crustal fluxes as well as in situ radiogenic production lower the $^3He/^4He$ ratio (continental, crustal signature: $R_c \sim 2 \times 10^{-8}$; Mamyrin & Tolstikhin, 1984), it is raised in the presence of mantle derived helium ($R_m \sim 1 \times 10^{-5}$; Ozima & Podosek, 2002). However, helium from subcontinental lithospheric mantle domains may be associated with ratios considerably lower then R_m (e.g. Dodson, 1998). In case of in situ production and/or continental, crustal fluxes helium accumulates in the groundwater as it passes the aquifer from the area of infiltration to the area of discharge thus providing valuable information about the residence time of the groundwater. Mantle helium contribution in groundwater sources along the Jordan Valley border faults is not unexpected and has been published for instance by Bergelson et al. (1989, 1999) for the western side of the Sea of Galilee ($R_{sample}/R_a \sim 1.4$).

Samples from six Jericho wells were compared with additional data from characteristic brines at the northwestern Dead Sea shore, close to Jericho (Starinsky & Friedrichsen, 1997). The measurement results (Table 3.13.2) suggest a mantle helium component probably accompanied by a radiogenic and continental, crustal signature. The situation in the Jericho area therefore resembles the regional pattern indicating that brines have been passing through or at least have been in contact with the border fault. All Jericho samples fall along a mixing line between the Ein Feshka, Ein Zukim, and Radon wells end member on one hand and water in equilibration with atmosphere on the other, although Ein Feshka itself is already a mixture between a high saline end member and fresh groundwater derived from the Mountain aquifer (Fig. 3.13.11). A significantly lower $^3He/^4He$ ratio is found in the Radon wells and can be interpreted as a result of high Radium activities of up to 400 dpm/L depending on sampling depth, which is responsible for additional radiogenic ^4He production. The ^{20}Ne concentrations of the Radon wells and Ein Feshka samples are considerably lower as would be expected from an air equilibrated originally freshwater source. This could be a strong hint that the brine end member of the Radon wells and Ein Feshka infiltrated the surrounding aquifers as already high saline surface water in past, maybe Lisan times. In turn it would have been saturated rather with respect to air-equilibrated brine. ^{20}Ne in groundwater is not modified by radiogenic processes and therefore usually represents the initial condition at infiltration. However, correction for salinity according to Smith & Kennedy (1983) can not fully explain the low ^{20}Ne values in all samples. The effect of water salinity on the noble gas concentration can be taken from Fig. 3.13.12 and is expressed by the Setchenow equation (Eqn. 1), where $\beta_{i,S=0}(T)$ and $\beta_i(T, S)$ are the Bunsen solubility coefficients for gas i in freshwater and brine, respectively, C_M is NaCl molarity, and $K_i(T)$ the empirical salting coefficient.

$$\ln\left(\frac{\beta_{i,\,S\,=\,0}(T)}{\beta_i(T,S)}\right) = C_M K_i(T) \qquad \textbf{(3.13.1.)}$$

Weiss & Price (1989) showed that differences in the ionic ratios like between ocean and Dead Sea water have only a moderate impact on K_i and thus can be calculated using the existing Setchenow relation by substituting an equivalent sea water salinity in the form of $f{*}C_M{*}K_i$ (e.g. f_{He}~1.08). Applying this modified correction to our data does also not explain the low ^{20}Ne values, which involves partly degassing responsible for the loss in Ne of at least the Ein Feshka, Rn-1 45/54 and Rn-2 15/23 samples. But it can be assumed that the other Radon well samples might be affected as well by partial loss of the dissolved gases. It is interesting, however, that the most saline waters, which are found in the E of the Jericho area do not coincide with the highest ^4He excess concentrations. Indeed this applies to the wells of G1 in the northwestern vicinity of the border fault (19-14/003, 19-14/038) where already moderate salinities prevail. The G2 wells close to Wadi Qilt (19-13/018, 19-14/024A) show an atmospheric-like helium signature, which is in agreement with regard to the local high infiltration rates expected from the wadi bed in the rainy season. The two easternmost wells that were sampled are also the most saline wells and belong to G1 (19-13/069) as well as G2 (19-14/066). Both sample signatures lie between the atmospheric-equilibrated and the 19-14/003 and 19-14/038 wells signatures, which consequently supports (1) mixing between these two groups and (2) adding of soluble salts from the surrounding sediments rather than exclusive brine admixture. In turn there is noble gas evidence for different sources of salinization specifically in the eastern Jericho area. Hence the availability of a thick column of Lisan Formation is self-suggesting to have high potential as a contributor to salinization.

3.13.4 Conclusions

The investigations performed on the groundwater of the Shallow aquifer of Jericho focused on possible salinization mechanisms that are observed since several decades. A clear discrimination of possible salt pools, which are expected to contribute to the overall salinization is hampered due to the unique situation that upwelling brines as well as leaching of sediments like the Lisan Formation are charcterized by a very similar hydrochemical fingerprint. This is caused by the tight genetic relation, which is characteristic for the brines and the Lisan Formation, because they represent the brine and the precipitated solid remnants of Lake Lisan, respectively. Lake Lisan was the Pleistocene precursor of the Dead Sea.

It has been described that the highly unsteady conditions in the Jericho area, its limited lateral extension and the great uncertainty concerning the estimated infiltration volumes, rates and mechanisms further impede the understanding of the Shallow aquifer system. For instance estimates of the annual recharge through Wadi Qilt and Wadi Nueima range between 2 and 9 Mm^3/yr. For the investigated area this difference accounts for a huge amount of water, either passing the system or not. In turn this would have dramatic implications for the interpretation of the system, like how susceptible the freshwater layer is for brine upwelling or how much irrigation return flow is to be expected. A self-evident obstacle for the correct interpretation of the hydrochemical pattern of the samples is its potential dependence on the timing of sampling.

By using a broad variety of hydrochemical and isotope data from this study and from different literature sources it was possible to shed some light on the mechanisms that are responsible for groundwater salinization. Two general groups of groundwaters were identified by their SO_4/Cl ratios, where high ratios (G1) reflect SO_4 contribution from the sedimentary column itself (e.g. Lisan formation) and by sewage or soil precipitates due to surface infiltration. The processes that control the addition of SO_4 and that may modify the Sr/Ca ratio cannot be specified, because due to the carbonate buffered environment important trace elements like Fe can hardly be detected in solution. Samples with low SO_4/Cl ratios (G2) are assumed to be affected to a lower degree by possible leaching from the sedimentary section than the previous group. In turn a possible brine signature is less overprinted, since brines and Lisan formation leachates potentially have the same hydrochemical fingerprint, except for their sulfate signature as well as some trace elements like boron.

The hydrochemical analogy between brines and Lisan Formation end members is supported by parameters like the Na/Cl and Sr/Ca ratios. B/Cl ratios on the other hand gave initial strong indication for brine admixture in two samples of G1 that are assigned to two wells in the NW of the study area, but remote from Wadi Qilt.

Noble gas analyses by means of He and Ne isotopes support and harden this initial indication. The noble gas isotope signature thereby is fitting perfectly in the regional context, where R_{sample}/R_a ratios are between ~1 (northwestern Dead Sea shore) and 1.4 (in a well at the western side of Lake Galilee). All Jericho samples fall along a mixing line between air-equilibrated water and brines from the northwestern Dead Sea shore. The two samples of G1 with the lowest B/Cl and Na/Cl ratios also show the highest ^{4}He excess, whereas the samples with a He signature close to air-equilibrated conditions are assigned to wells in the close vicinity of Wadi Qilt but not too far in the E of the study area. An intermediate position between the two groups is adopted by the most saline and eastern wells, which provides evidence for salt contribution from sources other than upwelling brines.

The findings of this study can provide helpful information concerning the implementation of water management schemes in the Jericho area. An important suggestion resulting from the high uncertainty and complexity of the ascertainment of the annual recharge rate and the various recharge paths is a reasonable monitoring system focusing on these two topics. Furthermore, a comprehensive GIS database which should include continuously collected data about sewage storage in tanks and disposal in cesspits would improve knowledge about the distribution of these practices especially in context of possible occurrences of contaminations, which also applies to former and actual stockyards for hazardous materials. The implementation of an environmental record system would effectively support future investigations and a possible realization of an advanced groundwater management scheme for that highly susceptible Shallow aquifer system.

Acknowledgements

The study was part of the GAPI-Project (*G*roundwater *A*vailability and the *F*ate of *P*esticide *I*nput), which was funded by German Federal Ministry of Education and Research. Noble gas analyses from the northwestern Dead Sea shore were obtained from the record of the GIF-Project (Radioactivity and Noble Gases in Waters along the Dead Sea Rift, Israel), financed by the GIF (German-Israeli Foundation for Scientific Research and Development).

References

Al-Jayyousi, O. R. (1999): Rehabilitation of Irrigation Distribution Systems: The Case of Jericho City. – Water Resources Management, 13, pp. 117-132.

Applied Research Institute Jerusalem (2001): Localizing Agenda 21 in Palestine. – http://www.arij.org/Agenda-21/l_o_c_a_l_i_z_i_n_g.htm

Applied Research Institute Jerusalem (1995): Environmental Profile for the West Bank Volume 2: The Jericho District. - http://www.arij.org/pub/Jericho-Profile.pdf, pp. 97.

Arkin, Y. & Starinsky, A. (1981): Lisan sediment porosity and porewater as indicators of original Lake Lisan composition. – GSI Current Research, 1981, pp. 83-84.

Bar-Yosef, O. (1989): The PPNA in the Levant – an overview. – Paléorient, 15, pp. 57-63.

Begin, Z.B.; Ehrlich, A. & Nathan, Y. (1974): Lake Lisan – the Pleistocene precursor of the Dead Sea. – Geol. Surv. Isr. Bull., 63, 30 pp.

Begin, Z. B. (1975): The Geology of the Jericho Sheet. – Geol. Surv. Israel Bull., 67, 35 pp.

Beinhorn, M.; Guttman, J. & Kolditz, O. (2004): Groundwater flow and transport model of the Jericho area. – Technical report, Nr. 2004-30, Center for Applied Geosciences, University of Tübingen, 9 pp.

Bergelson G., Nativ R. & Bein A. (1999): Assessment of hydraulic parameters of the aquifers around the Sea of Galilee. – Ground Water, 36, pp. 409-417.

Bergelson G., Nativ R. & Bein A. (1998): Salinization and dilution history of ground water discharging into the Sea of Galilee, the Dead Sea Transform, Israel. – Applied Geochemistry, 14, pp. 91-118.

Böhlke, J.K. (2002): Groundwater recharge and agricultural contamination. – Hydrogeology Journal, 10, pp. 153-179.

Clarke, W.B.; Jenkins, W.J. & Top, Z. (1967): Determination of tritium by mass spectrometric measurement of ^{3}He. – The International Journal of Applied Radiation and Isotopes, 27, pp. 515-522.

Dodson, A.; J., D.; DePaolo & Kennedy, B.M. (1998): Helium isotopes in lithospheric mantle: evidence from tertiary basalts of the western USA. – Geochimica et Cosmochimica Acta, 62, pp. 3775-3787.

Gavrieli, I.; Yechieli, Y.; Halicz, L.; Spiro, B.; Bein, A. & Efron, D. (2001): The sulfur system in anoxic subsurface brines and its implication in brine evolutionary pathways: the Ca-chloride brines in the Dead Sea area. – Earth and Planetary Science Letters, 186, pp. 199-213.

Golani, A. (1972): Water resources in the Jericho area. – Report HR/72/016, Tahal Consulting Engineers Ltd., Tel Aviv, Israel, in Hebrew.

Guttman, J. (2000): Multi-Lateral Project - Project 02WT9719 within the framework of the German-Israeli-Jordanian-Palestinian Joint Research Program for the Sustainable Utilization of Aquifer Systems, Final Report 1997-2000, Sub Project B: Hydrogeology of the Eastern Aquifer in the Judea Hills and Jordan Valley. – Mekorot report – Mekorot Israel National Water Co., 468, 36 pp., unpublished report.

IFAD (2007): Modernizing an ancient oasis - Jericho's Ain Al-Sultan spring project. – http://www.ruralpovertyportal.org/english/regions/asia/pse/voices/oasis.htm.

Kahle, C.F. (1965): Strontium in oolitic limestones. – Journal of Sedimentary Research, 35, pp. 846-856.

Katz, A.; Kolodny, Y. & Nissenbaum, A. (1977): The geochemical evolution of the Pleistocene Lake Lisan-Dead Sea system. – Geochimica et Cosmochimica Acta, 41, pp. 1609-1611.

Katz, A. & Kolodny, N. (1989): Hypersaline diagenesis and evolution in the Dead Sea-Lake Lisan system (Israel). – Geochimica et Cosmochimica Acta, 53, pp. 59-67.

Kaufman, A. (1971): U-series dating of the Dead Sea Basin carbonates. – Geochimica et Cosmochimica Acta, 35, pp. 1269-1281.

Kawaguchi, T. & Decho, A.W. (2002): A laboratory investigation of cyanobacterial extracellular polymeric secretions (EPS) in influencing $CaCO_3$ polymorphism. – Journal of Crystal Growth, 240, pp. 230–235.

Khayat, S.K. (2005): Hydrochemistry and Isotope Hydrogeology in the Jericho Area/ Palestine. – Ph.D. Thesis, University of Karlsruhe, Germany, 141 pp.

Khayat, S.; Hötzl, H.; Geyer, S. & Ali, W. (2006): Hydrochemical investigation of water from the Pleistocene wells and springs, Jericho area, Palestine. – Hydrogeology Journal, 14, pp. 192-202.

Khayat, S.; Hötzl, H.; Geyer, S., Knöller, K. & Strauch, G. (2006): Sulphur and oxygen isotopic characters of dissolved sulphate in groundwater from the Pleistocene aquifer in the southern Jordan Valley (Jericho area, Palestine). – Isotopes in Environmental and Health Studies, 42, pp. 289-302.

Klein-BenDavid, O.; Sass, E. & Katz, A. (2004): The evolution of marine evaporitic brines in inland basins: The Jordan-Dead Sea Rift valley. – Geochimica et Cosmochimica Acta, 68, pp. 1763-1775.

Kolodny, Y.; Stein, M. & Machlus, M. (2005): Sea-rain-lake relation in the Last Glacial East Mediterranean revealed by ^{18}O-^{13}C in Lake Lisan aragonites. – Geochimica et Cosmochimica Acta, 69, pp. 4045-4060.

Kroitoru, L.; Mazor, E. & Gilad, D. (1985): Hydrological characteristics of the Wadi Kelt and Elisha springs. *In:* IAHS (ed.): Scientific Basis for Water Resources Management. – Proceedings of the Jerusalem IAHS Symposium, September 1985, IAHS Publications, 153, pp. 207-218.

Landmann, G.; Abu Qudaira, G.M.; Shawabkeh, K.; Wrede, V. & Kempe, S. (2002): Geochemistry of the Lisan and Damya Formations in Jordan, and implications for paleoclimate. – Quaternary International, 89, pp. 45-57.

Laronne, L. (2003): Groundwater flow modeling in the Eastern Judea Group Aquifer, Israel. – M.Sc. Thesis, Hebrew University Jerusalem, Israel, 87 pp.

Lippmann, F. (1973): Sedimentary carbonate minerals. – Monograph Series Theoretical and Experimental Studies, Vol. 6, Springer, Berlin, pp. 228.

Mamyrin, B.A. & Tolstikhin, I.N. (1984): Helium Isotopes in Nature. – Fyfe, W. S. *(ed.)* Developments in Geochemistry, Vol. 3, Elsevier, Amsterdam, pp. 273.

Marei, A. & Vengosh, A. (2001): Sources of Salinity in Ground water from Jericho Area, Jordan Valley. – Ground Water, 39, pp. 240-249.

Mazor, E. (1972): Paleotemperatures and other hydrological parameters deduced from noble gases dissolved in groundwaters; Jordan Valley, Israel. – Geochimica et Cosmochimica Acta, 36, pp. 1321-1336.

Möller, P.; Geyer, S.; Salameh, E. & Dulski, P. (2006): Sources of mineralization and salinization of thermal groundwater of Jordan. – Acta hydrochimica et hydrobiologica, 34, pp. 86-100.

Nicholson, R.V., Gillham, R.W., Reardon, E.J. (1988): Pyrite oxidation in carbonate-buffered solution: 1. Experimental kinetics. – Geochimica et Cosmochimica Acta, 52, pp. 1077-1085.

Ozima, M. & Podosek, F. (2002): Noble gas geochemistry. – Cambridge University Press, Cambridge, pp. 286.

Pérez, A.; Luzón, A.; Roc, A.C.; Soria, A.R.; Mayayo, M.J. & Sánchez, J.A. (2002): Sedimentary facies distribution and genesis of a recent carbonate-rich saline lake: Gallocanta Lake, Iberian Chain, NE Spain. – Sedimentary Geology, 148, pp. 185-202.

Rivadeneyra, M.A.; Delgado, G.; Ramos-Cormenzana, A. & Delgado, R. (1998): Biomineralization of carbonates by Halomonas eurihalina in solid and liquid media with different salinities: crystal formation sequence. – Research in Microbiology, 149, pp. 277-287.

Salameh, E. (2001): Sources of Water Salinities in the Jordan Valley Area/Jordan. – Acta hydrochimica et hydrobiologica, 29, pp. 329-362.

Singer, A.; Ganor, E.; Dultz, S. & Fischer, W. (2003): Dust deposition over the Dead Sea. – Journal of Arid Environments, 53, pp. 41-59.

Smith, S.P. & Kennedy, B.M. (1983): The solubility of noble gases in water and in NaCl brine. – Geochimica et Cosmochimica Acta, 47, pp. 503-515.

Starinsky, A. (1974): Relationship between Ca-chloride brines and sedimentary rocks in Israel. – Ph.D. Thesis, Hebrew University Jerusalem.

Starinsky, A. & Friedrichsen, H. (1997): Radioactivity and noble gases along the Dead Sea rift. – Unpublished report to the German Israeli Foundation.

Stein, M.; Starinsky, A.; Katz, A.; Goldstein, S.L.; Machlus, M. & Schramm, A. (1997): Strontium isotopic, chemical, and sedimentological evidence for the evolution of Lake Lisan and the Dead. – Geochimica et Cosmochimica Acta, 61, pp. 3975-3992.

Stein, M. (2001): The sedimentary and geochemical record of Neogene-Quaternary water bodies in the Dead Sea Basin – inferences for the regional paleoclimatic history. – Journal of Paleolimnology, 26, pp. 271-282.

Sültenfuß, J.; Rhein, M. & Roether, W. (2007): The Bremen Mass Spectrometric Facility for the measurement of helium isotopes, neon, and tritium in water. – IAEA Proceedings, IAEA-CN 119-7, in press.

Torfstein, A.; Gavrieli, I. & Stein, M. (2005): The sources and evolution of sulfur in the hypersaline Lake Lisan (paleo-Dead Sea). – Earth and Planetary Science Letters, 263, pp. 61-77.

Vengosh, A.; Starinsky, A.; Kolodny, Y. & Chivas, A.R. (1991): Boron isotope geochemistry as a tracer for the evolution of brines and associated hot springs from the Dead Sea, Israel. – Geochimica et Cosmochimica Acta, 55, pp. 1689-1695.

Weiss, R.A. & Price, B.A. (1989): Dead Sea gas solubilities. – Earth and Planetary Science Letters, 92, pp. 7-10.

Wolfer, J. (1998): Hydrogeological investigatios along the Jerusalem – Jericho Transect (Wadi el Qilt) Israel/West Bank. – Diploma Thesis, Universität Karlsruhe, 106 pp.

Yechieli, Y.; Ronen, D.; Berkowitz, B. & Dershowitz, A. (1995): Aquifer characteristics derived from the interaction between water levels of a terminal lake (Dead Sea) and an adjacent aquifer. – Water Resources Research, 31, pp. 893-909.

Yoshioka, S.; Ohde, S.; Kitano, Y. & Kanamori, N. (1986): Behaviour of magnesium and strontium during the transformation of coral aragonite to calcite in aquatic environments. – Marine Chemistry, 18, pp. 35-48.

Zagana, E.; Obeidat, M.; Kuells, C. & Udluft, P. (2007): Chloride, hydrochemical and isotope methods of groundwater recharge estimation in eastern Mediterranean areas: a case study in Jordan. – Hydrological Processes, in press.

3.14 The Interaction of Population Dynamics and Transformations in Water Supply Systems in the Jordan River Basin

Diana Hummel
Institut für sozial-ökologische Forschung (ISOE), Frankfurt/Main

Key Words

Demography, Jordan River Basin, Israel, Jordan, Palestine, demographic change, population dynamics, supply systems, re-allocation strategies, virtual water trade, water demand, water conflicts

Abstract

Israel, Jordan and Palestine are partners in the geography and hydrology of the Jordan River Basin. At the same time the demographic development of the countries is closely interlinked. The paper examines the interdependence between demographic developments, water scarcity and resource conflicts in the Jordan River Basin. One major issue of conflicts is emphasized: growing competition between different users and sectors, in particular between agriculture, on the one hand, and municipal/ domestic water supply, on the other, as a result of the heterogeneous population growth in the region. The potential of re-allocation-strategies to cope with increasing demand for drinking water is discussed, focusing on the concept of virtual water trade.

3.14.1 Introduction

With water resources of less than 500 m^3 per capita the Jordan River Basin is one of the most water-challenged areas in the world, poorly endowed with fresh surface and groundwater resources. A rising imbalance between limited availability and increasing consumption of freshwater is the basic cause of the water crisis in the region. Climate change and demographic change represent major drivers for increasing pressure on the region's freshwater resources. Temperatures are projected to increase in all seasons, and extreme weather events such as droughts are predicted to be more frequent. As a result, demand for water increases, while less water is available and its timing becomes more erratic. With respect to the socio-economic implications of climate change impacts on water resources it is estimated that GDP could be reduced by 1-2 percent in Israel and Jordan, and 2-5 percent in West Bank and Gaza, depending on the agricultural activity of the country. In Jordan and Palestine, the impact of unequal water resources distribution is expected to be the most severe, since they have large rural populations that rely on agricultural production and on small-scale water management networks (World Bank 2007; El-Fadel/Bou-Zeid 2001). At the same time, decreasing availability of freshwater resources interacts with high population growth and -density in the region. As a vital resource, the water has a security dimension and is being considered as a strategic resource in the region (Renger 1998). But evidence shows that despite many water-related tensions *between* the different conflict parties in the Jordan River Basin, there has been no violent conflict explicitly fought over water resources[1]. Instead, as many authors state, concern over the availability of freshwater can serve as a catalyst to negotiated agreements and joint management in international relations (Lonergan 1997; Yoffe/Wolf/Giordano 2003; El-Fadel/ el Fadl 2005). However, with growing water stress conflicts *within* nations are predicted to increase: among provinces, between rural and urban populations, among different ethnic groups, and among water users in different economic sectors. This is particularly true in the case of societies characterized by weak social institutions, and ethnic and political conflicts.

In this context, *demographic developments* gain importance: Population growth results in increasing consumption of drinking water and can aggravate disputes over the allocation, distribution and utilization of the vital resource. With respect to these interlinkages, the situation in the Jordan River Basin represents a specific accumulation of interconnected geopolitical, demographic, and environmental conflicts. Since the 1970s, the region has begun to „run out of water“ (Allan 2001). Over the same period considerable demographic changes can be observed.

This paper seeks to shed some light, from a social-ecological point of view, on this complex issue, focussing on the interaction of population dynamics and transformations in water supply systems. These transformations are characterized by fundamental changes in distribution and allocation, supply and demand management of water resources. It will be argued that rising water demand due to population dynamics results in growing *intersectoral competition*, in particular between agriculture on the one hand and municipal/ domestic water supply on the other. However, as will be illustrated, a simple carrying-capacity point of view, i.e. the notion of a linear, causal relationship between population numbers and use of water resources will contribute little to an adequate analysis of the problems in the Jordan River Basin.

In what follows, the demographic phenomena in the region and their implications for water supply systems are examined first. Then, new emerging water conflicts in the region are discussed, focussing on the significance of growing competition among users and economic sectors. The final section addresses chal-

---

1. Whether not only the strife for land and security, but also for water directly or indirectly motivated the Six-Day-War 1967 between Israel and its Arab neighbours is contentious among experts. In fact, the war consolidated Israel's control over the water resources in the West Bank (Pearce 2006: 168; Johannsen 2003: 347; Dombrowsky 2003: 732).

lenges for water management, focussing on re-allocation of water resources in the context of demand-side management. In this context, the potential of virtual water trade is discussed.

3.14.2 Demographic Patterns and their Implications for Water Supply

In the following, the region's most important demographic characteristics are examined. First of all, however, the problem of data must be dealt with. Estimates and forecasts about population dynamics, as well as about freshwater supply and demand, are extremely disparate and often contradictory. For example, demographic figures in official Israeli projections make no distinction between Jewish residents of Israel and those living in settlements on Palestinian territory. With respect to water resources and their use, there is no generally accepted, publicly accessible database. As a result, the general sociological argument that scientific knowledge is socially constructed and influenced by the cultural and institutional conditions of its production assumes particular importance here (Chenoweth/Wehrmeyer 2006: 252f. Coubrage 2000: 2; Martin 1999: 2). Figures and forecasts are dependent on expert's beliefs and their situated knowledge. Therefore, data are always subject to bias and are, hence, contestable. As such, they are already politicized in the scientific and official discourse.

Notwithstanding these fundamental constraints, it is a fact that the region has experienced enormous demographic changes during the last decades. Population growth rates in the countries are still considerably high. According to estimates of the United Nations Population Division (medium variant), the average population growth rate for the period 1975-2005 was for Israel 2.3 percent, for Palestine 3.7 and for Jordan 3.5 percent (United Nations Population Division 2007). However, in all countries, population growth has decelerated, and fertility rates have started to decline, as a result of a drop in infant and child mortality rates, urbanization, improvements in female education and employment opportunities, as well as increasing family planning activities. Furthermore, the populations have experienced a sharp decline of mortality and a considerable increase in life expectancy. This shift from high to low mortality and from high to low fertility is a common feature of the overall 'demographic transition' in the region (Winckler 2005). However, demographic trends and patterns[2] in Israel, Palestine and Jordan vary extensively, as they are results of different socio-cultural, political and economic background (see Table 3.14.1).

---

[2] Unless indicated otherwise, the date presented refer to the year 2006 (main sources for the latest revision are United Nations Population Division 2007; Population Reference Bureau 2006; Central Intelligence Agency 2007).

Table 3.14.1. Demographic trends and patterns in Israel, Palestine and Jordan.

Country	Population 2006 (millions) (1)	Births per 1.000 pop. (1)	Life expectancy at birth (1)	Rate of natural pop. increase (1)	Projected population (millions) 2025 (1)	Projected population (millions) 2050 (1)	Percent urban 2005 (2)	Population density per square km 2005 (2)
Israel	7.2	21	80	1.5%	9.3	11.0	91.7%	302
Palestine	3.9	37	72	3.3%	7.1	11.2	71.9%	625
Jordan	5.6	29	72	2.4%	7.9	9.9	79.3%	62

(Source: (1) Population Reference Bureau 2006; (2) United Nations Population Division 2007).

Agriculture is by far the largest water user in the Jordan River Basin. The second most important aspect of water use is the number of inhabitants in a certain area. Therefore, the future demographic development in each country is crucial for an estimation of future water demand and water policies.

Demographic trends in Israel, Palestine and Jordan

The current population in Israel amounts to some 7.2 million inhabitants, with a population growth rate of 1.5 percent. The Jewish population rose from 717,000 in 1948 to 5.1 million in 2000 as the result of a growth rate of 3,8 per year, of which 40 percent was a result of net immigration. In 1948, after the exodus, Palestinian citizens of Israel (Israeli Arabs) numbered only 158,000; by 2000 the number had risen to nearly a million. Today, demographic growth of Jewish and Arab Israeli population is almost equal, excluding immigration (Courbage 2000). Currently, Israel has a total fertility rate (TFR)[3] of 2.8 children, the lowest fertility rate compared to the other two countries, but in contrast to most Western industrial countries it is still considerably high[4]. Moreover, demographic patterns, in particular fertility, are a major result of the heterogeneity of Israel's entire population. The number of children per family differs considerably among the different ethnic and religious groups, as well as with regard to socio-economic structures. There are significant differences in fertility among Jews, Moslem Arabs, Christian Arabs and Druze Arabs, but also among a Jewish majority consisting of different ethnic backgrounds, i.e. of European-American, Middle Eastern and North African origins. Within the Jewish population, the fertility rate is relatively low among the non-reli-

---

[3] Total fertility rate (TFR) is the average number of live births per woman of reproductive age (15-49 years).

[4] For example, in Germany and Italy TFR is 1,3 and in France 1,9.

gious population of European and American origins and higher among the religious population of Asian and African origins. The highest fertility rates are to be found within ultra orthodox Jews. The Christian Arab minority which consists mainly of urban dwellers has reached a current level of fertility equal to the level of fertility of the Jewish majority. The fertility rate of the larger Muslim group of Israeli citizens is much higher. For the period 1995-2000, when Israel's overall TFR was 2.9, the Jewish non-religious segment, which was 67-70 per cent of the Israeli population, had a total fertility rate of 2.2, the Arab Christian population (2 percent) a TFR of 2.6, Arab Moslems and Druze (16 percent) a TFR of 4.0. The highest TFR of 6.0-7.0 children born per woman was among the Jewish ultra-orthodox and National Orthodox, which had a percentage of 12-15 (Friedlander 2002: 443). At the end of the 20th century population growth in Israel was strongly influenced by immigration. Around 1 million immigrants arrived between 1990 and 2000, particularly after the collapse of the Soviet Union. Since that time, immigration numbers have decreased significantly (DellaPergola 2003).

The Palestinian Territories (Gaza Strip and West Bank) display the highest population growth rates in the region, and birth rates are also still among the highest in the world. Extending over an area of 360 sq kilometres, Gaza Strip had in mid-2006 a population of approximately 1,429.000 people and ranks among the most densely populated areas in the world. The total fertility rate in Gaza Strip is currently at around 5.78 children per woman, and the natural population growth rate is 3.71 percent. The West Bank, extending over an area of 5,860 sq km, has a population of nearly 2,460,000 people. Furthermore, there are about 187,000 Israeli settlers in the West Bank and around 177,000 Jewish Israeli inhabitants in East Jerusalem. The total fertility rate in the West Bank is 4.28 children born per woman, and the rate of natural increase is 3.06 percent (CIA 2007).

Apart from population growth as result of high fertility rates, future demographic development in Palestine as well as in Israel will significantly depend on the movement of Palestinian refugees. In June 2007 there were more than 1.6 Million Palestinian refugees in the West Bank and Gaza Strip registered by the United Nations Relief and Works Agency for Palestine in the Near East. A further 2.6 million Palestinian refugees are not living in Israel or Palestine, but in Syria, Lebanon or Jordan (UNRWA 2007)[5]. The population growth rate among these communities is also high. In the event of a peace settlement between Israel and Palestine it is possible that some of the Palestinian refugees living abroad may return either to Israel or to Palestine (Chenoweth/Wehrmeyer 2006: 247).

---

5. According to DellaPergola (2003: 17); in the year 2000, about half of the whole Palestinian people – 4.3 million (49%) – lived on the territory of historic Palestine, either in the State of Israel (13%), or in the West Bank and Gaza Strip (36%). Another estimated 4.1 million (46%) were living in neighbouring Muslim countries in the Middle East and North Africa, over 60% of them in Jordan.

Particularly in Jordan the demographic profile has been heavily affected by the geopolitical developments in the Middle East (Salemeh/Haddadin 2006; Winckler 1997). In 2006, Jordan had a population of some 5.6 million inhabitants and a rate of natural increase of 2.4 percent. The total fertility rate in 2006 is 3.7 children born per woman. As health improves, death rates are declining. Combined with the decline in fertility rates this development will lead to a slowing of population growth. However, the young age structure will sustain population growth in the country, in a manner similar to Palestine.

The population growth in the country is a result of both natural increase, on the one hand, and the consequences of heavy immigration, on the other. Jordan is a major receiver of migrants, and the country has hosted several waves of refugees, displaced persons and returnees as a result of the Middle East conflict, as well as the Gulf war. This has significantly contributed to an unprecedented population growth, particularly to urban growth. The population of Jordan consists to a large extent of people of Palestinian origin who arrived after the Israeli occupation of the West Bank and the wars 1948 and 1967, together with their offspring, and who live in the country as foreigners. Precise figures on the percentage of Palestinians of the total Jordanian population are unknown. According to Winckler (2005: 24) the population of Palestinian origin in Jordan constituted at least 58% of the Kingdom's total population. In 2003, more than 1.7 million people were registered as refugees in Jordan (DellaPergola 2003: 16).

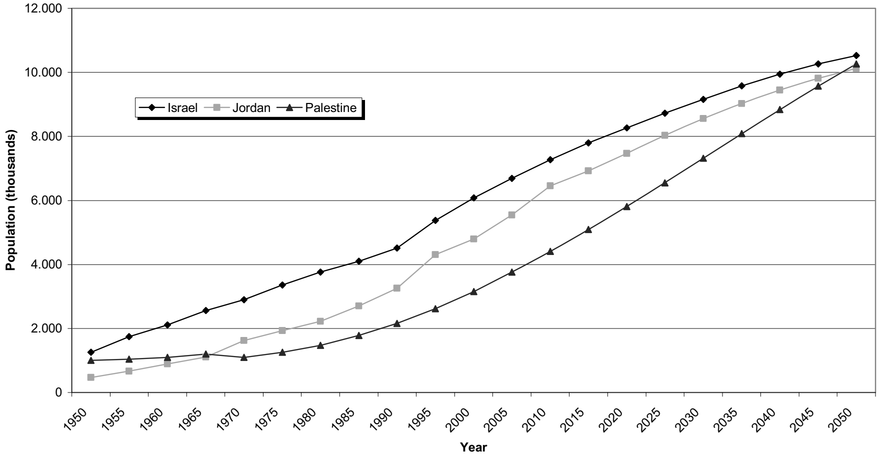
A particular feature of the country is high urban growth. The annual urban growth rate is expected to be 3.1 percent 2000-2015, compared to 1 percent in the rural areas (Tropp 2006: 16). Population growth due to immigration is especially prominent in the case of the capital of the country, Amman: In 1921, when Amman was chosen as the capital of the newly established Emirate of Transjordan (later renamed the Hashemite Kingdom of Jordan), the city had a population of 5,000 people. Since that time, the city has experienced extraordinary growth, which can be partly attributed to natural population growth and to urban migration by rural people. However, the growth of Amman has also been greatly determined by the waves of refugees, displaced persons, and returnees as well, as an influx of foreign labourers from Egypt, Iraq, and Syria. At the beginning of the 1948 Arab-Israeli conflict Amman's population was estimated at 60.000 people. Within two decades some 240,000 Palestinian refugees settled in Amman and the surrounding areas. An additional 180,000 refugees are estimated to have settled in Amman as a direct consequence of the 1987 Arab-Israeli war. Furthermore, some 350,000 Jordan citizens, including Palestinians who had obtained Jordanian citizenship, relocated to Amman from Kuwait and Saudi Arabia as a result of the 1990-91 Gulf war, due to the refusal of King Hussain to support the US-led anti-Iraqi coalition. The UN refugee agency UNHCR estimates that there are around 750,000 Iraqi refugees in Jordan, although exact numbers are not easy to obtain (ESCWA 2005; Winckler 2005; Daoud et al. 2006). These refugee and migration waves did not only affect the socio-economic composition of the city, but also the water supply systems.

Political Demography

In sum, the demographic situation in Israel, Palestine and Jordan reflects the persistent geopolitical conflict in the Jordan River Basin. It is a complicated mosaic of changing reproductive behaviour, migration outcomes, ethnic and religious majority areas in a contested territory, which together builds „a complex and often bloody arena of human interaction and political clash, whose demographic implications constitute one of the most sensitive issues in the region“ (DellaPergola 2003: 19). The changes in ethnic compositions due to demographic development, in particular development of birth rates and migration are combined with very differing interests which potentially aggravate the disputes over water resources. Regardless of political borders, in the geographical region of the Jordan River basin there will soon be a rough numerical balance between the two peoples, Israeli Jews and Arabic Palestinians (Coubrage 2000: 4). According to recent projections, the Jewish majority in the State of Israel, at 78% in 2000, will have fallen to 69% by 2050 due to the higher fertility of Israeli Arab citizens. With respect to Israel plus the Palestinian Territories, there is now a bare Jewish majority of 53%. According to the medium projections, this majority will disappear before 2010. By 2050, the share of the Jewish population will have diminished to 35-37 percent (DellaPergola 2003: 42f.). Against the background of these scenarios, the demographic argument has gained in importance and the rhetoric of a „demographic threat“ has surfaced repeatedly in Israeli politics in recent times. It is argued that, over time, the geopolitical conflict may be simply decided by demographic changes.

On the one hand, the imperative to maintain the Zionist ideal of a Jewish majority in a sovereign state may end up powering a search for a resolution to the conflict (Fargues 2000; Orenstein 2004). On the other hand, the „demographic competition“, i.e. the policy of gaining or keeping a demographic majority within the territory of historical Palestine can be conceived, by the Israelis as well as by the Palestinians, as a means to enforce their own political claims on territory and resources. This results in pro-natalist population policies and the promotion of immigration, which in turn may intensify conflicts on resources.

As Libiszewski (2005) has illustrated, demographic patterns in the Jordan River Basin are intimately connected with the political roots of the conflict between Arabs and Israelis. „In competing over land, Arabs and Jews always saw the demographic balance between each other in terms of national security and existence (…) These circumstances complicate the discussion of demographic issues from a pure environmental carrying capacity view“ (Libiszewski 1995: 68). Obviously, a political settlement fixing Israel’s definite borders and giving the Palestinians their own independent state is a prerequisite for a constructive and rational discussion of population dynamics. On the other hand, a peace settlement may also lead to population growth in the region, but it is unclear how many of the millions of registered Palestinian refugees are allowed to resettle, and how many of them will do so (ibd.). Owing to these political factors and conditions, there is considerable uncertainty concerning future population dynamics in the Jordan River Basin.



Source: United Nations Population Division 2007.

Fig. 3.14.1. Population development in Israel, Palestine, Jordan (medium variant).

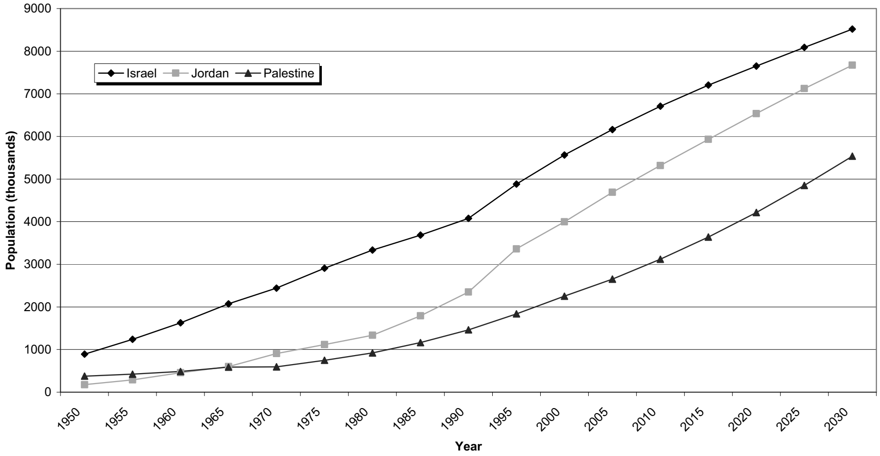
Implications of population dynamics for water supply systems

From the demographic perspective, population growth in the region is a result of two different demographic phenomena: natural increase and migration. Although demographers forecast slower population growth, the region's population is expected to more than double by 2050, reaching some 33 million individuals (see Fig. 3.14.1).

Population density as well as population concentration is high, and the countries have experienced rapid urbanization, especially in Israel, with an urban population of 91 percent, and Jordan, where 79 percent of the population live in urban areas, among them more than 2 million urban dwellers in Amman.

Fertility decline will cause a shift in the age structure leading to a higher proportion of the population in older age groups and a decrease in household sizes. Average household sizes differ considerably among the countries. Israel has, with 3.4 persons on average, the smallest household size compared to its neighbours. In the other countries, average household sizes are much higher: Jordan has an average household size of 5.4 persons, while in West Bank and Gaza Strip it is 6.1 persons on average (CBS 2006; DOS 2005; PCBS 2005).

Household size and household numbers have great impacts on domestic water consumption, which has increased in all countries in recent years. According to Martin (1999) population growth rates account for approximately two-thirds of the growth rate of domestic water use in Jordan, Israel and Palestine. A probable increase in household numbers and a decrease in household size in the coming decades will significantly affect future domestic water demand in the region, both due to household-related economies of scale and to more effective water-saving technology. A household consisting of six members will use less than twice the amount of water



Source: United Nations Population Division 2005; United Nations Population Division 2006.

Fig. 3.14.2. Urban population in Israel, Palestine and Jordan (medium variant).

for cooking, laundry, dish washing, house cleaning, car washing etc. than a three-person household. Decreasing household sizes will also reduce the effectiveness of investments into technical water saving measures such as water-saving appliances, toilets and shower heads (ibd.). An increase in household numbers has also indirect effects on water supply and quality, as it requires more household units, increasing area covered by housing and materials needed for construction[6].

In sum, urbanization, changing lifestyles, consumption patterns, age structures and household compositions are socio-demographic causes for an increasing domestic water demand and consumption for the future.

It is therefore important to take into consideration not only quantitative demographic aspects but also qualitative factors. Obviously, the number of people who have to be supplied strongly influences water use, quantitatively formulated as per-capita-use. The pressure imposed on the resource base as a result of population growth might aggravate water supply problems. However, the relationship between water use and population size is non-linear because different individuals and populations use water resources in different ways. As the heterogeneous demographic patterns in the Jordan River Basin indicate, migration and urbanization in particular have to be considered. Migration is a relevant factor for water supply because it changes population distribution and density. Regional population movements and

---

[6] Unfortunately, there is no detailed data available about domestic water use in the region, analyzed according to behaviour, endowment of appliance (dishwasher, washing mashine etc.) and sanitary. These data would be necessary for estimating the potential for water saving on the level of households as a basis for target group oriented regulation of domestic water demand.

settlement patterns are crucial factors, especially for infrastructure and supply systems. Urbanization also has great impact on water supply, as it is linked to changing population size, distribution and density, which impact on location, infrastructure, and administration of water supply systems. On the other hand, urbanization, particularly when based on rural-to-urban migration, is associated with rising incomes and standards of living, changing lifestyles and consumption patterns. The common view is that the general increase in the living standard accompanying further development is linked to an increase in per capita water demand. These demographic changes, combined with economic development, increase water demand, leading in particular to an even greater pressure on the cities and their infrastructure, public services, housing and jobs, as well as increased claims on water presently being used for irrigated agriculture.

3.14.3 Water supply - New emerging conflicts in the wake of population pressure

Even though the Jordan river's role for the region's water supply is marginal, it can be regarded as „the epicentre for the geo-strategic risks linked to water access in the region“ (Collomb 2003: 785). The Jordan River Basin is a complex system of watersheds, geopolitically fragmented. Almost all significant water resources are transboundary, i.e. they cross international borders, and are found in areas over which political control is disputed. Problems of water supply in the region are characterized, on the environmental side, by aridity, water scarcity and a growing diminishment of water quality while on the societal side, there is an expanding gap between supply and demand, and a lack of sustainable management policies (Libszewski 1995; Dombrowski 2003; Allan 2001).

Water availability and demand

In the following, the water supply and allocation situation in the different countries in the area are sketched:

Israel's water supply is estimated to be about 2,100 million cubic metres/ year. 80 percent of the water supply is to be found north of the river Yarkon in an area that presents only 30 percent of the state's territory. The mountain aquifers of the West Bank cover more than 22 percent of the Israeli demand for water, the Golan Heights about 7 percent. Israel is working on several plans to increase the water supply and reduce its consumption, in particular in agriculture. By the year 2000 the agricultural water consumption had been reduced from 1,000 million cubic metres/ year to 740 million cubic metres/ year (Sabbagh 2003: 312). The country is meeting half of its water demand with water resources located outside its internationally recognized borders (Renger 1998: 48). The water supply situation in Israel is complicated by the fact that the country currently draws between one quarter and one-third of its total fresh water supplies, and 50% of its drinking water, from sources that originate in the West Bank. At 80 per cent of West Bank ground water, Israel utilizes the lion's share. As many experts note, the country would face immediate water shortages, and significant curtailment of its economic development, if it lost control of the West Bank water resource supplies in a sudden or disruptive manner. The West Bank has thus become a critical source of water for Israel (Bosnjakovic 2003: 724; Lonergan 1995; Johannsen 2004: 349). Today, the country maintains a modern water infrastructure, which guarantees domestic and industrial water requirements. It has witnessed a transition from an agricultural to a post-industrial society and the contribution of agriculture to GDP is now marginal. But agriculture is still the largest consumer of water (Dombrowsky 2003).

Groundwater extracted from aquifers is the primary water source in Palestine. There are considerable differences in the water resources of the two areas due to their different geographical location. The worst situation is to be found in *Gaza Strip*. The entire water resources are gained from a 10 to 15 meter deep aquifer with an estimated renewable storage capacity of about 60 million m^3/yr. However, the present water demand in Gaza is estimated at around 110 million cubic metres; for the year 2010 the demand for water is estimated to be around 180 million cubic metres, of which only about 19 percent is intended to be used in households. (Sabbagh 2004: 313). The large withdrawal and over-pumping leads to an annual fall of the groundwater level, leading to salt and seawater intrusion. Water quality is far below drinking water standards (Dombrowsky 2003: 733). For the West Bank, the water resources are estimated at 600 – 650 million cubic metres. Groundwater and springs, supplied by three aquifers (Western, Northeastern and Eastern Aquifer) presently provide essentially all of the water consumed. It is estimated that 90 percent of the total recharge of the aquifer basins originate in the West Bank, while the present Palestinian share of well abstraction is only 13 percent (Yayyousi 2003). The State of Israel restricts the utilization of water by the Palestinians, resulting in an extremely asymmetrical allocation of water and per capita consumption. Several West Bank communities are connected to the Israeli water supply system provided by the Israeli water company, Mekorot. However, water from the Israeli system was supplied at full costs. On the other hand, many communities are without access to a public water supply and depend on local springs or on harvesting cisterns, providing water which is usually not suitable for drinking (Dombrowsky 2003: 733; Haddad 2005: 183) Thus, water scarcity in not only due to climatic, geographic and hydrological conditions, but largely a problem of unequal distribution of water resources.

Jordan's situation regarding supply and distribution of water is considered the most alarming in the region, next to Palestine. Per capita water consumption is rising twice as fast as the population. An example given by the Ministry of Water and Irrigation is worth mentioning: A child born in the year 1960 entered a country where the annual fresh water availability was around 530 m^3/cap/yr. By the time that person reaches the age of 65, i.e. in the year 2025, the amount of fresh water available will have declined by 80 percent to around 91 m^3/cap/yr (The Hashemite Kingdom of Jordan – Ministry of Water and Irrigation 2002: 6). The shortage of water resources in Jordan was first widely recognized in the early 1970s. Since then, many strategies and measures have been proposed to alleviate and overcome it, including supply augmentation measures involving the construction of various hydraulic structures and the development of groundwater. Jordan has also been exploiting non-renewable fossil water since the late 1980ies. The consumption of this water is today estimated at about 210 million cubic metres per year (Sabbagh 2003: 315)[7].

Table 3.14.2. Water Availability in Israel, Jordan and Palestine.

Country	Total internal renewable water resources (km^3/ year)	Groundwater produced internally (km^3/ year)	Surface water produced internally (km^3/ year)	Total renewable water resources per capita (m^3/cap/yr) 2000	Total renewable water resources per capita (m^3/cap/yr 2005	Total water use (%)
Israel	075	0,50	0,25	276	250	122
Jordan	0,68	0,50	0,40	179	160	115
Palestine	0,05	0,05	0,00	52	41	-

Source: World Water Development Report 2006; FAO 2007; Tropp 2006

Projected water requirements for the year 2020 are 2000 million cubic metres (MCM) annually for Israel – this is approximately 130% of current renewable supplies, 1000 MCM for Jordan (120% of current supplies) and 310 MCM for the Westbank and Gaza Strip, which is around 150% of current supply (Wolf 2000; GTZ 1998)[8]. Assuming the projected water requirements are approximately, water resource development in the region seems to have exceeded its limits. As a rule of thumb, people require about three litres drinking water per capita and day or one cubic metre per capita and year, they need about 50 to 100 m^3/c/yr for other

---

[7] For example, in the Disi area in southern Jordan, agrobusiness is conducted on a large scale with highest-quality fossil aquifer water for the cultivation of water-intensive crops such as grain, melons, potatoes. Huge computer-directed irrigation systems sprinkle the fields in the desert area. As a result, a considerable amount of this water is lost due to evaporation.

[8] Projections about future water availability have to be interpreted carefully since they are based on past trends for water supply. For the most part they do not incorporate possible changes in water use efficiency. Another limitation of estimates of future demand is that they are largely based on extrapolations from demographic trends. Given the political current political situation, there is great uncertainty as to future population development.

domestic purposes, and over 1000 m^3/c/yr of soil water, either naturally occurring in soil profiles, or transported by irrigation systems, for food production (Allan 2001: 6). Shuval (2004) estimated for arid areas in the Middle East a „minimum water requirement" of around 125m^3/capita/ year to meet all hygienic, social and economic requirements for domestic, urban, commercial, industrial and tourist uses at a reasonably high standard of urban living. This assumes little fresh water for agriculture and import of most food. As the figures in Table 3.14.2 indicate, Israel and Jordan are (still) above that level, while Palestine is already far below the level. In 2005, the total area of Israel, Palestine and Jordan had an average per capita availability of some 117 cubic metres per capita and year. This quantity might be enough for households and other municipal water demand, as well as for the demand of industry. But the countries could never be self-sufficient in agricultural production based on indigenous water resources.

Competition between users and sectors

Demographic changes, in particular urbanization, can lead to growing tensions within the countries, e.g. between urban and rural settlements. The interaction between transformations in water supply systems and demographic changes can be illustrated by looking at Jordan, where the urbanization of rural poor has led to increased competition for scarce natural resources in the expanding urban communities. Access to water supply and sanitation is unequally distributed throughout the country. In rural areas 16 percent of the population lack access to clean water and 2 percent to adequate sanitation, while in the cities the access to water supply and sanitation seem to be relatively well secured. But already by 1992 Amman had been withdrawing twice the 'safe' extraction volume from the underground aquifer at Azraq Oasis, which supplies the city with almost all of its water. The over-extraction of the aquifer water to supply the urban populations of Amman and the country's second largest city, Zarqa, has led to reduced availability of water to local farmers and the draining of surrounding wetlands. As a result of the scarcity of water resources poor rural farmers abandon agriculture and livestock as their main source of income (Tropp 2006; Daoud et al. 2006). Increasing settlements also lead to competition between water management for the settlers and for irrigated agriculture. Moreover, urban growth is at the expense of good agricultural land, which also serves as reservoirs for soil water. The acquisition by urbanization of 400 ha of agricultural land translates into the loss of the equivalent of around 1 million cubic m^3 of irrigation water per year (Haddadin et al. 2006: 82).

In addition, competition increases among the different sectors – i.e. among agriculture, urban households, and industry. At present, around 54-75 percent of the extracted water in the studied area is used for agriculture, while industry has a much lower share of only 3-7 percent. As a result of demographic changes and the rising demand of the industrial sector the situation is becoming critical, especially because agriculture is often regarded as the only sector from which water can be withdrawn. Whether this will diminish its potential to meet the rising demand for food production and economic growth in rural areas is a subject of debate among researchers.

Table 3.14.3. Water use and water productivity in different sectors[9].

Country	Agriculture	Domestic (1)	Industry (1)	Rate Agriculture GDP 2006	Labour force in agriculture 2006
Israel (1997)	54%	39%	7%	2.6 %	1.8 %
Palestine (1999)	63 %	37%	0 %	Gaza Strip 8% West Bank 8%	Gaza Strip 12% West Bank 16%
Jordan (1993)	75 %	22 %	3 %	3.6 %	5 %

Sources: World Resources Institute 2003; Nasser 2004; Central Intelligence Agency 2007.

Estimates of future water demand forecast a change in the allocation of water to different end users within the different countries. Whereas at present the largest portion of water is still used for irrigation in agriculture, the portion used for domestic purposes will substantially increase to 50 or 60 percent by 2040, due to an increase in domestic water demand, related to population growth and a general increase in the standard of living. In Jordan, in 2020, municipal demand will claim 58 percent of the freshwater resources of the country. As a result, competition among different users will most likely intensify. „There has clearly been an increase in intensity of competition over water resources, especially those of drinkable quality with some degree of treatment. The likely victim of any reallocation of water resources will be agriculture, to the advantage of municipal supplies“ (Salameh/ Haddadin 2006: 24).

Water Management Strategies to Cope with Water Scarcity: Re-Allocation of water resources and the role of agriculture

Given the scarcity of water as a resource, there has been much discussion of how to improve the efficiency and equity of water use. The traditional solutions to water shortage has been *supply management*, i.e the deployment of technical and engineering options. Supply management implies measures such as traditional and modern technologies of rainwater harvesting or, for instance, the mining of fossil

---

[9] For Palestine, municipal (domestic) and water use are summarized.

water. Pumping from deep groundwater is one strategy, but at high economic and environmental costs. As many experts stress, desalination of seawater or brackish groundwater will play a major role in the region over the coming decades (Shuval/ Feitelson 2002; Beaumont 2000). However, not all states can afford this technology, albeit the costs of desalinated water are declining. Furthermore, desalinated sea water is considered too expensive for any agricultural use. The re-use of water through waste water recycling is another technique for providing new water. Other strategies aim at technological improvements in irrigation. The water use efficiency in agricultural irrigation is often very low. In many areas 60 to 75% of the water diverted or pumped for irrigation is 'lost' from the system via evaporation, leakage of canals, seepage or inefficient management. Efficient technologies such as drip-irrigation systems, lining of irrigation canals, more efficient sprinklers and better irrigation timing and volume control could lead to savings and contribute to enhanced water availability (Webb/Iskandarani 1998; Haddadin et al. 2006; Tropp 2006). Other possibilites are the use of treated wastewater in irrigated agriculture and the cultivation of crops which are better adapted to local conditions.

Technical solutions that allow usage of alternative sources such as desalination of seawater or multiple re-usage of water do hold some promise, but are not sufficient. In recent times, and in particular under conditions of water scarcity, the *demand management approach* is emphasized, which is more concerned with the efficiency of water use than with the volumes of water available. The underlying idea of the policy is „making better use of existing supplies rather than developing new ones“ (Turton 1999: 12) by employing economic instruments such as water tariffs, water markets, legislation and regulatory systems. Thus, the approach is more governance-oriented. On the one hand, demand management policies are targeted to increase end-user efficiency, e.g. more efficient irrigation technologies („doing more with water/ more crop per drop“). On the other hand, they aim at increasing allocative efficiency („doing better things with water/ more jobs per crop“). This approach focuses on water services and the purpose for which water is used.

Since irrigation agriculture utilizes by far the largest volume of water in the region, the future needs of the agricultural sector and, moreover, the status of agriculture as a whole, will be decisive. Historically, agriculture has been an important pillar of all three societies and the backbone of their economies. But in practice, as the figures in Table 3.14.3 indicate, it is not in the region’s agriculture that the essential economic remedies are to be found, particularly in Israel and Jordan. The main improvements in livelihood generation are to be achieved outside the agricultural sector in industry and services. Given the rising domestic and industrial demands for water, the agricultural sector comes increasingly under pressure, and economic reasoning speaks for a re-allocation of low-value agricultural freshwater uses to higher value-adding uses. Redistribution of water resources among uses and sectors is often regarded as the greatest potential for meeting the growing urban water demand in the Middle Eastern countries, and thus shifting from a supply side management to a more demand side management oriented policy. Conversation strategies focus on optimizing efficiency without questioning the uses of water themselves. In contrast, re-allocation means shifting the water distribution from those uses and sectors which show a low value-added per unit of water consumed to those of primary social need or with higher water productivity. This approach aims at a restructuring of the economy away from heavily irrigated agriculture towards other sectors, in particular domestic consumption as well as industry and commercial uses.

Some recent studies and model scenarios of re-allocation of water in Israel show that water reduction in the agricultural sector would be feasible and would be, economically, relatively low cost. Some experts - hydrologists as well as economists – argue that the water saved could then be used to satisfy domestic and industrial demands. Some propose that agricultural production in Israel, and the water needed for it, should be gradually shifted to the West Bank and Gaza Strip because of a number of objective factoral advantages, above all cheaper labour force (Libiszewski 1996: 65). According to Peter Beaumont, about 24% of total irrigation water needs to be reallocated to urban uses in Israel. „If certain crops were withdrawn from irrigated cultivation the monetary savings would be substantial and the water could then be used to supply urban needs. For Israel it is a case of the politicians needing to convince the people that it is more important to have water for the towns and cities than for agricultural production. If this can be achieved urban water needs can be easily met“ (Beaumont 2002: 327). In fact, the agricultural sector is continually shrinking. However, it still has a high symbolic meaning, owing to the country's history. In the early state years, the agricultural sector was seen as the main state-building organ (Feitelson 2005: 416).

In Jordan, 113 percent of the irrigation use of 1990 would be required by 2025 to meet its predicted urban water demand of 832 million cubic metres. This means that even if the country would reallocate all the irrigation water there would not be sufficient water to meet the expected demand. Long-term-adjustments aimed at gradually reducing irrigated agriculture and promoting water-saving activities are seen as inevitable. Besides a better supply side management and the reallocation of irrigated water, a policy of desalinated water supply, as well as the import of water, are regarded as the only long-term solutions (Beaumont 2002: 331). In Palestine, a resizing of the agrarian sector seems very difficult to realize, due to the high unemployment rate, the lack of job opportunities, and the precarious social, political and economic conditions which worsened considerably since the Al-Aqsa-Intifada in 2000. Thus, improvements in water supply to Palestinian agriculture are considered to be necessary and economically appropriate in the middle term.

Virtual Water Trade as a part of conflict resolution?

In the context of water resource management, and the re-allocation water from the agricultural sector to urban supply, „virtual water trade“ (VWT) may gain importance for the region in the coming decades[10]. The concept is based on the idea that water-poor developing countries are increasingly importing their food from water-rich-countries in order to conserve their own water resources and use them in other, more productive areas where more added value per volume unit of water is generated (Horlemann/Neubert 2007). Economically, the low return of agricultural water use can be replaced by higher returns when allocating water to industry, services and municipal/domestic uses. Usually, the use of water as drinking water has priority over other uses, regardless of the value added that could be achieved. The water saved would thus benefit the drinking water supply. For these reasons many experts argue that it would be more rational to import most high water-consuming food and staples. According to Shuval (2004), Jordan, Israel and Palestine „should accept the reality that priority in utilization of their limited fresh water resources should go to meet the immediate human needs of drinking water, domestic and urban use as well as for high income producing commercial, trade, crafts industrial, tourism use and assuring the quality of life with water allocated to nature and green open space“ (Shuval 2004). Given international trading systems it would be possible to transfer commodities requiring high water inputs from water surplus areas to the water scarce countries of the Middle East. Accompanied by a VWT strategy, enormous quantities of water could be saved on a national and regional level through a reduction in agricultural production.

In Israel, Jordan and Palestine virtual water trade is already a fact. None of the countries is self-sufficient in agricultural production for local needs. Even though Jordan uses 1.45 km^3 of its water resources each year in the production of food for domestic consumption, the country imports about three times as much virtual water (4,37 km^3) in the form of agricultural products, mainly wheat, barley, maize and meat (Magiera in Hummel et al. 2006; Horlemann/Neubert 2007: 35). In the year 2000, Israel imported 80 percent of the national calorie intake of food from abroad in the form of virtual water (Shuval 2004). Palestine imports about 30 times more water than it exports (Nassar 2004). Over the past decades Palestine had a comparative advantage in producing and exporting vegetables, fruits, citrus and olive products, for which Israel and Jordan are the major outlets (Nassar 2004).

Thus, VWT strategy seems to be advantageous for the region, in particular for Jordan and Israel which can be regarded as middle-income and high-income countries, respectively. If virtual water trade would be strategically implemented, it could contribute to the enhanced security of the supply and utilization of water resources. However, there are also some constraints on applying the concept of virtual water as a strategy:

---

10. The concept of virtual water trade was introduced into scientific discussion by Tony A. Allan in the early 1990s. Virtual water is the water embedded in commodities such as grain, fruits, and other food as well as clothing, cars and technical devices. Every trade action implies indirectly a trade with water used for the production of the commodity. Agricultural products take the largest share and account for some 80 percent of all virtually traded water.

VWT presupposes that the paradigm of national food sovereignty is abandoned, which is politically highly sensitive. It thus may increase the economic and political dependency of the importing countries on the exporting countries (Horlemann/ Neubert 2007: 3). Besides these economic and political risks, social impacts of a VWT strategy must be carefully weighed. The discussion of virtual water imports as an option for irrigated agriculture is related in particular to urbanization and growing domestic water demands. Given growing numbers of urban dwellers water resources are coming more and more under pressure. Virtual water trade can be a strategy for coping with water scarcity by re-allocating water away from the irrigated agriculture towards other sectors. However, this strategy might result in a vicious circle. If reliance on virtual water import rises, the number of farmers needing to find other economic livelihood options also increases. On the one hand, a re-allocation strategy, i.e. the transfer from irrigation to urban usage, might intensify the decline of rural areas and increase impoverishment of peasant farmers. On the other hand, it will likely speed up urbanization in the region, as unemployed farmers look for jobs in other economic sectors (Tropp 2006: 7). Thus, virtual water trade as strategy to cope with water scarcity might even end up putting more pressure on urban centres and would thus cause, albeit unintended, the reverse impact.

Considerable potential for social conflicts emerges due to transitions in agriculture. According to El Naser (2005) „in rural societies old farmer families are by tradition politically influential which will prohibit new policies for water allocation. Agriculture and rural life (…) have historically played central roles in the life, economy and culture of those people“ (El Naser 2005: 6, cited in Horlemann/Neubert 2007: 72). The question thus arises concerning the social acceptance of radical changes to local economic structures by shifting from agriculture to industrial production. People must be prepared for these transformations in terms of education and qualification, and new income opportunities must be created in other sectors, not only in the cities, but also in rural areas to avoid marginalization (Horlemann/ Neubert 2007: 71).

Therefore, a narrow focus on hydrological and economic advantages of VWT seems inadequate. Virtual water trade has different social-ecological impacts, and the societies concerned must adapt to changing conditions of production, and to new power balances. Given these prerequisites, VWT could contribute to an adaptation to the demographic changes and an overall strengthening of capabilities for sustainable development in the region. A well directed implementation could complement re-allocating water from the irrigated agriculture towards other sectors. Its potential to mitigate the tensions over transboundary water resources between the neighbouring countries and to facilitate co-operation should be considered.

3.14.4 Conclusion

The demographic changes and transformations in water supply systems in the Jordan River Basin that have been examined represent a problem constellation, whose particularities lie in the close entanglement of environmental, political, economic and societal problems. The conflict is associated with fundamental uncertainties with respect to the temporal and spatial range of effects, as well as to the difficulty of anticipating future developments. Demographic changes will increase water demand in the region, leading in particular to an even greater pressure on the cities and their infrastructure, public services, housing and jobs, as well as an increased demand for water that is presently used for irrigated agriculture. However, according to a recent scenario analysis for 2050 for the Israeli and Palestinian water sector (Chenowth/Wehrmeyer 2006), population dynamics and water scarcity must not be an impediment to peace or economic development in the region. Under conditions of good governance and management, the domestic and industrial water resource needs of the population could indeed be met. Limited water resources are not „by nature“ conflictive. On the other hand, the water crisis is more than a problem of inequitable distribution of water resources. Against the background of demographic changes in the region, not only water availability in terms of quantities, but also the forms of demand and purpose of use of water resources must be considered. Re-allocation of water resources are required, not only for economic, but also for social reasons. However, the discussion still focuses on the role of agriculture, while urban water demand itself is widely neglected. If carefully implemented within strategies for an Integrated Water Resources Management (IWRM), a virtual water trade strategy could contribute to mitigating the impact of growing competition between rural and urban water users, and between the domestic and agricultural sector. At the same time, it could enhance co-operation among the neighbouring countries and thus contribute to a resolution of the geopolitical conflict.

References

Allan, John Anthony (2001): The Middle East Water Question. Hydropolitics and the Global Economy. London/ New York

Beaumont, Peter (2000): The Quest for Water Efficiency – Restructuring of Water Use in the Middle East. In: Water, Air, and Soil Pollution 123, 551-56

Beaumont, Peter (2002): Water Policies for the Middle East in the 21st Century: the New Economic Realities. In: Water Resources Development, Vol. 18, No. 2, 315-334

Beaumont, Peter (2005): Water Institutions in the Middle East. In: Gopalakrishnan, Chennat/ Tortajada, Cecilia/ Biswas, Asit K. (Eds.): Water Institutions: Policies, Performance and Prospects. Berlin/ Heidelberg/ New York: Springer, 131-153

Bosnjakowic, Branko (2003) Shared Groundwater Resource Management and Protection in the Mediterranean – A Joint Approach by United Nations Agencies. In: Brauch, Hans Günter et al. (Eds.): Security and Environment in the Mediterranean. Conceptualising Security and Environmental Conflicts. Berlin/ Heidelberg,: Springer 719-728

CBS – Central Bureau of Statistics (2006): Statistical Abstract. Available at: www1.cbs.gov.il/reader (30 May 2007)

CIA - Central Intelligence Agency (2006): The World Factbook. Available at: www.odci.gov./cia/publications/factbook/index.htmll (06 March 2007)

Chenoweth, Jonathan L./Wehrmeyer, Walter (2006): Scenario Development for 2050 for the Israeli/ Palestinian Water Sector. In: Population & Environment (27), 245-261

Coubrage, Youssef (2000): The future population of Israel and Palestine. Population et Sociétés, 362, November 2000

Daoud, Ra'ed/Naber, Helena/Tarbush, Mai Abu/Quossous, Razan/Salman, Amer/Karablieh, Emad (2006): Environmental Issues of Water Resources. In: Haddadin, Munther (Ed.): Water Resources in Jordan. Evolving Policies for Development, the Environment, and Conflict Resolution. Washington, 88-115

DellaPergola, Sergio (2003): Demographic Trends in Israel and Palestine: Prospects and Policy Implications. American Jewish Yearbook, vol. 103. New York

Dombrowski, Ines (1998): The Jordan River Basin: Prospects for Cooperation Within the Middle East Peace Process? In: Scheumann, Waltina/ Schiffler Manuel (Eds.): Water in the Middle East. Potential for Conflicts and Prospects for Cooperation. Berlin et al., 91-112

Dombrowski, Ines (2003): Water Accords in the Middle East Peace Process: Moving towards Cooperation? In: Brauch, G. et al. (Eds.): Security and Environment in the Mediterranean. Berlin et al., 729-744

DOS – Department of Statistics (2005): Jordan in Figures 2005. Available at: www.dos.gov.jo.dos_home.jorfig/2005/for_f_e.htm (30 May 2007)

El-Fadel, M./El-Fadl, K. (2005): Water in the Middle East revisited: conflict management alternatives. In: Water Policy 7 (2005), 385-412

El-Fadel, Mutasem and Bou-Zeid, Elie R. (2001): „Climate Change and Water Resources in the Middle East: Vulnerability, Socio-Economic Impacts, and Adaptation" (June 2001). FEEM Working Paper No. 46

El Naser (2005): Virtual Water in the MENA region: Expert statement for the research project „Virtual Water Trade – A realistic concept for resolving the water crises?". Paper on behalf of the German Development Institute (DIE), Bonn

ESCWA – Economic and Social Commission for Western Asia (2005): Urbanization and the changing character of the Arab city. New York: United Nations

FAO (2007): Aquastat Database. Available: www.fao.org/landandwater/aglw/aquastat/main/index.stm (30 May 2007)

Fargues, Philippe (2000): Protracted National Conflict and Fertility Change: Palestinians and Israelis in the Twentieth Century. In: Population and Development Review, Vol. 26, No. 3 (Sept. 2000), 441-482

Feitelson, Eran (2005): Political Economy of Groundwater Exploitation: The Israeli Case. In: Water Resources Development, Vol. 21, No.3, 413-423

Friedlander, Dov (2002): Fertility in Israel: Is the Transition to Replacement Level in Sight? In: United Nations Population Division: Completing the Fertility Transition. New York, 440-447

GTZ (1998): Middle East Regional Study on Water Supply and Demand Development. Eschborn

Haddad, Marwan (2005): Future water institutions in Palestine In: Water Policy No. 7 (2005), 181-200

Haddadin, Munther (2001): Diplomacy on the Jordan: International Conflict and Negtiated Resolution. Boston/ Dordrecht: Kluwer Academic Publishers

Haddadin, Munther/Sunna', Sami J./Al Rashid, Hani A. (2006a): Development of Water Resources and Irrigation. In: Haddadin, Munther (Ed.): Water Resources in Jordan. Evolving Policies for Development, the Environment, and Conflict Resolution. Washington, 66-87

Horlemann, Lena/Neubert, Susanne (2007): Virtual Water Trade. A realistic concept for resolving the water crisis? Bonn: DIE

Hummel, Diana/Kluge, Thomas/Liehr, Stefan/Hachelaf, Miriam (2006): Virtual Water Trade: Documentation of an International Expert Workshop. Frankfurt/ Main: ISOE

Johannsen, Margret (2004): Control, Allocation and Consumption of Water Resources in the Jordan Basin: The Struggle over a Scarce and Vital Resource in the Context of the Middle East Conflict. In: Zereini, Fathi/ Jaeschke, Wolfgang (Eds.): Water in the Middle East and in North Africa. Resources, Protection, and Management. Berlin et al.: Springer, 345-351

Libiszewski, Stephan (1995): Water Disputes in the Jordan River Region and their Role in the Resolution of the Arab-Israeli Conflict. ENCOP Occasional Paper No. 13, Zürich

Libiszewski, Stephan (1996): Integrating Political and Technical Approaches: Lessons from the Israeli-Jordanian Water Negotiations. In: Gleditsch, N.P. (Ed.): Conflict and Environment. Dordrecht et al. 386-402

Lonergan, Steve (1997): Water Resources and Conflict: Examples from the Middle East. In: Gleditsch, Nils Ptter (Ed.): Conflict and the Environment. Dordrecht/ Boston/ London: Kluwer Academic Publishers, 375-384

Martin, Nicola (1999): Population, Households and Domestic Water Use in Countries of the Mediterranean Middle East (Jordan, Lebanon, Syria, the West Bank, Gaza and Israel). IIASA-Interim Report IR-99-032. Laxenbourg

Nassar, Yasser H. (2004): Virtual water trade as a policy instrument for achieving water security in Palestine. Paper presented at the 2nd Israeli-Palestinian Conference „Water for Life in the Middle East“, Turkey, 10-14 October 2004

Orenstein, Daniel E. (2004): Population Growth and Environmental Impact: Ideology and Academic Discourse in Israel. In: Population and Environment, Vol. 26, No.1, 41-60

Pearce, Fred (2006): When the Rivers Run Dry. Boston: Beacon Press

PCBS – Palestinian Bureau of Central Statistics (2005): Child Statistics Series No. 1. Available at: www.pcbs.gov.ps (30 May 2007)

Population Reference Bureau (2006): World Population Data Sheet 2006. Washington: PRB

Renger, Jochen (1998): The Middle East Peace Process: Obstacles to Cooperation over Shared Waters. In: Scheumann, Waltina/ Schiffler Manuel (Eds.): Water in the Middle East. Potential for Conflicts and Prospects for Cooperation. Berlin et al., 47-55

Sabbagh, Jamill (2004): Water Conflict and Water Management in the Middle East. In: Zereini, Fathi/ Jaeschke, Wolfgang (Eds.): Water in the Middle East and in North Africa. Resources, Protection, and Management. Berlin et al., 309-318

Salameh, Elia/Haddadin, Munther (2006): The Population-Water Resources Equation. In: Haddadin, Munther (Ed.): Water Resources in Jordan. Evolving Policies for Development, the Environment, and Conflict Resolution. Washington, 7-27

Shuval, Hillel (2004): The Role of „Virtual Water in the Water Resources Management of the Arid Middle East. Paper presented at the 2nd Israeli-Palestinian Conference “Water for Life in the Middle East“, Turkey, 10-14 October 2004

Shuval, Hillel I./Feitelson, Eran (2002): Is Peaceful Co-operation on the Jordan River Basin Possible? In: Al Baz, I. et al. (Eds.): Co-operation on transboundary rivers. Baden-Baden, 167-188

The Hashemite Kingdom of Jordan – Ministry of Water and Irrigation (2002): Water Sector Planning & Associated Investment Program 2002 – 2011. Amman

Tropp, Hakan (2006): Water Scarcity Challenges in the Middle East and North Africa (MENA). Thematic paper for Human Development Report 2006, Stockholm: Stockholm Water Institute (SIWI), Final Draft, 26/10/2006

Turton, Anthony R. (1999): Water scarcity and social adaptive capacity: Towards an understanding of the social dynamics of water demand management in developing countries. MEWREW Occasional Paper No. 9. London: SOAS

United Nations Population Division (2007): World Population Prospects: The 2006 Revision Database. Available at: http://esa.un.org/unpp, (30 Mai 2007)

United Nations Population Division (2006): World Urbanization Prospects: The 2005 Revision. Available at: http://esa.un.org/unup (07 June 2007)

United Nations Population Division (2005): World Population Prospects. The 2004 Revision. New York

United Nations Relief and Works Agency for Palestine Refugees in the Near East (UNRWA) (2007): Available at: http://www.un.org/unrwa/ (5 June 2007)

Webb, Patrick/Iskandarani, Maria (1998): Water Inscecurity and the Poor: Issues and Research Needs. ZEF-Discussion Papers on Development Policy, No. 2. Bonn

Winckler, Onn (2005): Arab Political Demography. Volume One: Population Growth and Natalist Policies. Brighton/ Portland: Sussex Academic Press

Winckler, Onn (1997): Population Growth and Migration in Jordan, 1950-1994. Brighton/ Portland: Sussex Academic Press

Wolf, Aaron T. (2000): Trends in Transboundary Water Resources: Lessons for Cooperative Projects in the Middle East. In: Water Security for Multinational Water Systems – Opportunity for Development. SIWI-Report 8. Stockholm, 94-108

World Bank (2007): Making the Most of Scarcity. Accountability for Better Water Management Results in the Middle East and North Africa. MENA Development Report. Washington D.C.: World Bank

World Resources Institute (2003): Earth Trends 2003. Available at: http://earthtrends.wri.org (5 June 2007)

World Water Development Report (2006): Water – a shared responsibility. Paris/ New York: UNESCO

Yayyousi, Anan (2003): Water Supply and Demand Development in Palestine: Current Status and Future Prospects. In: Daibes, Fadia (Ed.): Water in Palestine. Problems – Politics – Prospects. Jerusalem: PASSIA

Yoffe, Shira/Wolf, Aaron T./Giordano, Mark (2003): Conflict and cooperation over international freshwater resources: indicators for basins at risk. In: Journal of the American Water Resources Assoication, Vol. 39, No. 5, 1109-1126

Author Index

Subject Index