Springer Hydrogeology

Abhijit Mukherjee *Editor*

Groundwater of South Asia

Springer

Springer Hydrogeology

More information about this series at http://www.springer.com/series/10174

Abhijit Mukherjee
Editor

Groundwater of South Asia

Springer

Editor
Abhijit Mukherjee
Department of Geology and Geophysics
Indian Institute of Technology Kharagpur
Kharagpur, West Bengal
India

and

School of Environmental Science
and Engineering
Indian Institute of Technology Kharagpur
Kharagpur, West Bengal
India

ISSN 2364-6454 ISSN 2364-6462 (electronic)
Springer Hydrogeology
ISBN 978-981-10-3888-4 ISBN 978-981-10-3889-1 (eBook)
https://doi.org/10.1007/978-981-10-3889-1

Library of Congress Control Number: 2017963981

© Springer Nature Singapore Pte Ltd. 2018
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
part of Springer Nature
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

डॉ अमरजीत सिंह
Dr. AMARJIT SINGH
सचिव
SECRETARY
Tl. : 23710305
Fax : 23731553
E-mail : secy-mowr@nic.in

सत्यमेव जयते

भारत सरकार
जल संसाधन, नदी विकास और
गंगा संरक्षण मंत्रालय
श्रम शक्ति भवन,
रफी मार्ग, नई दिल्ली-110 001
GOVERNMENT OF INDIA
MINISTRY OF WATER RESOURCES,
RIVER DEVELOPMENT &
GANGA REJUVENATION
SHRAM SHAKTI BHAWAN,
RAFI MARG, NEW DELHI-110 001
http://www.wrmin.nic.in

Groundwater is now the engine of growth in South Asia. It plays a primary role in meeting the water needs of various user sectors in India and also in its neighboring countries in South Asia. However, it does not receive the importance and emphasis that it should be receiving as an extremely important natural resource, which is under tremendous stress, worldwide and specifically in highly populated areas of South Asia. With growing awareness, the role of groundwater as a sustainable resource needs to be emphasized for our present and future generations. This effort is not possible singly, either by the academicians or by consumers, managers or decision makers, but there needs to be a concerted effort from all the stakeholders. Therefore, there was an urgent need to bring various aspects of groundwater of South Asia under one cover.

The strength of this book on groundwater of South Asia is in making a robust case of linking up the complex technical aspects of groundwater quantity and quality, with health and management, and its interplay with climate change, business, and societal parameters. An important part of the study of groundwater is defining the context of the problem being managed, i.e., geological, physical, chemical, and epidemiological, which, till now, has not been studied through a unified framework in this extremely important geographical area. I believe this book will bridge this gap, and all readers, whatever their expertise is in practicing or learning the groundwater scenarios in this densely populated part of the world, would find some interesting nuggets from this work, either new or comprehensive overview of existing literature. The other interesting aspect is that it is not limited to academic, theoretical studies, but also integrates the practical knowledge derived from the field.

The book has been very effectively organized in thematic sections, covering groundwater exploration, recharge, and availability, groundwater quality and pollution, management and resilience to climate change and economics. Because of the geographical extent of thousands of kilometers of coastal areas, a special emphasis has also been laid on coastal groundwater studies and adaptation options from the local to subcontinental scale. The role of sustainable development in modulating those risks has been lucidly brought out through insights from specific case studies.

I appreciate the efforts made by Dr. Abhijit Mukherjee and his team in compiling scientifically the experience from India and her neighboring countries.

9/06/17
(Amarjit Singh)

New Delhi
June 9, 2017

Dr. Amarjit Singh
Secretary, Ministry of Water Resources
River Development and Ganga Rejuvenation
Government of India

Preface

Groundwater, being the largest liquid freshwater resource to humankind, plays a crucial role in sustenance and global food security by groundwater-fed irrigation. Dependency on groundwater as human-usable water source is rapidly increasing worldwide. In addition to human consumption for domestic, large volume of groundwater is required for industrial and irrigational purposes. Groundwater resource dynamics is sensitive to recharge, through variability in spatiotemporal precipitation patterns and intensification of extreme climate events. The South Asia, which comprises only ~4% of the terrestrial area, hosts about 24% of the global population and more than 30% of global irrigated land. The region, which consumes largest volume of global groundwater resource, is facing an acute shortage of usable waters, as it is witnessing rapid rise in population, urbanization, and change in societal water use, cropping pattern, and lifestyle. It acts as a global paradigm for interaction of society, human strategies, nature and groundwater resources in a changing world with new sociopolitical alignments at present and near future.

The study region in parts of South Asia, comprising Afghanistan, Bangladesh, Bhutan, India, Pakistan, Nepal, Myanmar, and Sri Lanka, has the densest world population and also the highest global user of groundwater. The area is drained by some of the largest and most important transboundary river systems of the world, like the Indus–Ganges–Brahmaputra–Meghna (IGBM) system, Kabul River system, Irrawady River system. However, availability of groundwater within the region is extremely heterogeneous, with aquifers ranging from high-yielding unconsolidated sedimentary formations to low-yielding crystalline bedrocks. Further, because of monsoon-dependent precipitation-based aquifer recharge is spatially (monsoonal path dependent) and temporally (>75% precipitation during monsoon months) variable, thereby influencing the formation of climate zones that range from extremely arid to some of the wettest places on earth. Moreover, the available groundwater is profusely abstracted, which is more than a quarter of the global groundwater extraction, thereby characterizing much of the region as very high water-stressed area. Hence, groundwater storage and availability in the study region is largely based on dynamic equilibrium between hydraulic quality of the aquifers, precipitation distribution and intensity, and human interventions by abstraction or replenishment. However, recent estimates show that groundwater pollution may pose larger constraints even to the available groundwater, in terms of geogenic and anthropogenic contaminants. Therefore, strategies for groundwater management and policy possibly need to scale and is condition-dependent. While large similarities exist among the fluvial basin aquifers, they are widely distinct from the hard-rock aquifers. However, on a local scale, arsenic pollution in Bengal Basin in India would need a different strategy than that in Bangladesh, and possibly Brahmaputra River basin aquifers. Similarly, groundwater salinity in the aquifers of lower reaches of Indus River requires a different management strategy to Middle Indus Basin and Beas River doab aquifers. There are also growing threats of the anthropogenic pollution through improper sanitation and industrial discharge. Hence, the subcontinental to very local-scale challenges highlight the need of knowledge base for integrated scientific and technological advances, as well as building policy and management capacities in order to adapt and evolve for the present-day groundwater needs and potential groundwater demand for future generations.

In this book, I attempt to integrate the knowledge base that exists from various studies on groundwater across the South Asia, extending from the extensively and intricately studied aquifers of Bangladesh to rarely studied regions of Afghanistan. Authored by leading experts across the world, the studies compiled in this book range from high-resolution, field-scale studies to subcontinental-scale gross estimates, thereby attempting to bridge the gap of the scale of observation. I have arranged the chapters following logical, thematic thrust areas, such that the readers can easily find out their subject of interest. Besides the obvious thrust areas of groundwater availability and groundwater quality, I have also tried to integrate emerging topics like effect of climate change on groundwater resources. Considering the existence of extensive, highly populated coasts in the region, I have also designated a theme to coastal groundwater. Being a rapidly depleting natural resource, no book on groundwater can be completed in today's time, without including the societal aspects. A dedicated thematic section is provided for groundwater sustainability, management, and governance. Groundwater, like any other natural phenomena and resources, exists as transboundary resources. However, since it is regarded as national resource for any country, the studies, provided as contributed chapters, are arranged according to country names, alphabetically, for each of the themes.

I hope the book provides the first step for integration of ideas and knowledge for this invaluable resource for this immensely populous and diplomatically important area of the world, with one of the fastest growing global economies. I envisage that we would be able to effectively manage and preserve the water security for our future generations.

Kharagpur, India
March 2018

Dr. Abhijit Mukherjee
Indian Institute of Technology (IIT)—Kharagpur

Acknowledgements

This work would not have been possible without constant inspiration from my students, lessons from my teachers, enthusiasm from my colleagues and collaborators, and support from my family.

I am indebted to Ms. Oindrila Bose for her diligent editorial assistance.

The book is dedicated to the residents of South Asia.

In Memory

In fond memory of late ***Dr. Palash Debnath*** *(1987–2017), one of the finest upcoming hydrogeogeologist of India, my former doctoral scholar and lead author of one of the chapters of this book (Chap. 28). He prematurely left us during the final stage of publication of this book. May his soul rest in peace.*

Disclaimer

The authors of individual chapters are solely responsible for ideas, views, data, figures, and geographical boundaries presented in the respective chapters of this book, and these have not been endorsed, in any form, by the publisher, the editor, and the authors of forewords preambles or other chapters. The political boundaries between the different countries of South Asia are presented for illustration purpose only, and no other inference should be drawn from them.

Contents

Part I Groundwater Systems of South Asia

Part II Groundwater Availability: Exploration, Recharge and Storage

Part III Groundwater Quality and Pollution

Part IV Coastal Groundwater

Part V Groundwater and Climate Change

Part VI Groundwater Sustainability: Management and Governance

Preamble

a) Groundwater Quantity of South Asia

South Asia is itself a world macrocosm that fully represents all natural and human conditions. South Asia is now among the fastest growing economic world regions, and this progress is expected to continue. Other regions that previously experienced fast development and increasing populations have sadly come to only partial accommodation with the stresses and changes that such growth imposes on the earth and society. Water supply can be one of the main stresses on a society, and the need for and accessibility of water will always be local, requiring local organization and management.

In areas where population, agriculture, and industry are concentrated, these human infrastructures strongly impact the surface and subsurface environments, spoiling long-standing natural earth balances. In such areas, special care is required to maintain access to sufficient surface water and groundwater of good quality and to maintain good conditions on the earth's surface. However, water management can be a contentious issue. Because there are so many competing users of water, effective care must come in the form of agreements between the various land resource and water users. Good agreements allow for sustainability of the most valued types of water uses. If agreements are not reached and implemented, vital water supplies and their dependent systems may collapse.

Agreements are most easily reached when all users can understand the impacts of their and others' interaction on the balances within their local hydrogeologic system. Hydrogeologic science, as expounded in this volume, can provide support to a vital part of the necessary discussions that South Asian countries must undertake in striving for sustainable development. Hydrogeologists are valuable in providing support to society in terms of 'how things related to water work'—knowledge that focuses on the natural and human-impacted water systems. This knowledge is clearly a key factor that informs development discussions and resulting agreements and management strategies.

South Asia is also a water macrocosm, wherein water comes in all possible types and in all possible natural settings. The groundwater of South Asia occurs in the total variety of natural hydrogeologic environments that exist on earth, considering the geologic fabric of its aquifers, the sources and amounts of groundwater replenishment, and the interaction of groundwater with the surface environment. The noteworthy collection of reports in this volume focuses on these topics and will serve as part of the needed hydrogeologic basis for water development and management discussions in the region. The chapters express the results of significant work underway. Valuable findings are reported regarding how particular South Asian aquifer systems function, how much water is available, and how particular types of natural and anthropogenic contamination occur at both inland and coastal locations. In addition, remaining and new questions are identified by authors regarding aquifer functioning and response to human impacts and to possible future changes in climate. These questions will be vital to explaining what new knowledge is needed to improve understanding and management of water in South Asia. Further, high-level strategies presented in some chapters concern mitigation options, which are, in effect, engineering approaches to improving the quantity and quality of stressed groundwater resources. Widespread implementation of such engineering efforts may be needed as a counterbalance to the often deleterious impacts of the necessary and unavoidable uses of groundwater and earth systems for human habitation, food supply, and industry. Thus, this volume will serve as a reference point and basic resource on South Asian groundwater for years to come.

Dr. Clifford I. Voss
Senior Scientist, U.S. Geological Survey
and
Executive Editor, Hydrogeology Journal
International Association of Hydrogeologists

b) Groundwater Exploration of South Asia

A constant supply of freshwater is vital to life on land. The atmosphere delivers huge amounts of freshwater to the land as rain and snowfall, but they are unevenly distributed in space and time. For example, South Asia encompasses deserts and rain forests, monsoon regions, and regions of relatively consistent precipitation across the seasons. Hence, the ability of the land to store water as snowpack, surface water, soil moisture, and groundwater is just as important as the precipitation itself. Of these stocks of freshwater, groundwater is by far the most enduring—it can persist in aquifers under the hottest, driest deserts for hundreds of thousands of years, long beyond when every bit of near-surface moisture has been stripped away. A large, porous aquifer also can store enough water to support irrigated agriculture for generations. For those reasons, groundwater is the key to human survival in parts of the world where precipitation is scarce or inconsistent.

Unfortunately, groundwater is often not managed to ensure its long-term availability. Irrigated agriculture is by far the biggest consumer, yet most governments emplace no restrictions on the amount of groundwater that can be withdrawn, and some even provide incentives, such as free electricity, for pumping more water. Their motivation is an abundant food supply and a happy, healthy populace. Long-term considerations, beyond a politician's lifetime or term in office, are de-emphasized. Without adequate controls, competition for a shared, limited resource like groundwater will only multiply.

Breaking this cycle before it enters the crisis stage requires information, awareness, and forethought. Because groundwater is hidden from view, aquifer depletion and impurity are harder to measure and their significance is more difficult to convey than for a shrinking or polluted surface reservoir. Further, monitoring wells are expensive to install, they only represent water levels and quality in one portion of an aquifer, and where they do exist the data are rarely made available to the public. Thus, innovative monitoring approaches are needed. For example, the NASA/DLR Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry mission (2002–2017) proved to be essential for quantifying regional-scale groundwater variability and identifying areas of rapid, sustained depletion. The GRACE Follow-On mission, scheduled for launch in the spring of 2018, will extend GRACE's observational record. Other information that is valuable for assessing groundwater threats and trends includes groundwater withdrawal and consumption surveys, recharge assessments, aquifer properties, irrigation maps, groundwater age dating, water budget analyses, and numerical model output. This book represents the first compilation of South Asian groundwater studies which make use of all of these. We hope it will raise awareness and thereby encourage the forethought necessary to ensure that groundwater will be clean and plentiful in South Asia for generations to come.

Dr. Matthew Rodell
Chief, Hydrological Sciences Laboratory
NASA Goddard Space Flight Center
USA

c) Groundwater Quality of South Asia

During the last two decades, global awareness of water resource issues in South Asia has grown, but compilations encompassing the scope of groundwater-related topics in the region have been lacking. This volume is thus a welcome addition to the literature. South Asia, perhaps the most densely populated region on earth, faces a variety of water-quality challenges. Undoubtedly, the best known is the widespread occurrence of elevated arsenic in Bengal Basin groundwater. However, there are instances of contamination by arsenic elsewhere in the region, as well as other geogenic pollutants (particularly chloride and fluoride) and anthropogenic pollutants (e.g., nutrients, pathogens, and synthetic organic compounds). There is increasing recognition of the need not only to provide sufficient water for humans but to limit environmental degradation.

Collectively, the chapters in this volume provide a conceptual framework for understanding many of the processes controlling groundwater quality in South Asia. Because of the monsoonal climate, meteoric recharge is typically seasonal. Solute chemistry tends to reflect weathering of detrital carbonate and/or silicate minerals, ion exchange, and bacterially mediated redox reactions. Lithologic heterogeneity can cause both spatial and temporal variability in solute chemistry. In particular, elevated arsenic in groundwater is commonly associated with reduction of secondary iron oxyhydroxides, which occur in shallow sediments of the floodplains of rivers draining the Himalayas. Spatial patchiness in arsenic and iron reflects the juxtaposition of channel and interfluve deposits, but also differences in source terrains. Beyond contributing anthropogenic contaminants, human activities can exacerbate geogenic contamination. Intensive pumping can perturb groundwater flow, drawing contaminated shallow groundwater to greater depths and inducing salinization of coastal aquifers, which are also at risk from sea-level rise. Application of fertilizers and disposal of human waste can promote anoxic conditions and potentially mobilize weakly bound species such as arsenic from sediments.

This book makes a very valuable contribution by documenting the variety of processes affecting groundwater quality not only in well-studied areas like Bangladesh and India, but also in areas with few previous studies, such as Afghanistan and Myanmar. Moreover, it presents emerging issues in the region, such as the extent of pesticide contamination of groundwater and the potential for nutrient loading to coastal waters via submarine groundwater discharge.

Dr. Alan Fryar
Associate Professor, University of Kentucky, USA

and

Former Chair, Hydrogeology Division
Geological Society of America

d) Groundwater Sustainability of South Asia

In 2002 the UN Committee on Economic, Social and Cultural Rights recognized the human right to water as "..indispensable for leading a life in human dignity." And today this is further reinforced by the UN 2015 sustainable development goals. These require all countries by 2030 to achieve universal and equitable access to safe and affordable drinking water; to improve water quality by reducing pollution and deliver integrated water resources management.

In meeting these goals, an essential part of the water cycle/system is groundwater. Often regarded as an 'invisible' utility, we usually only see its evidence through springs, and wells and even in countries with major surface irrigation schemes, e.g., Pakistan, pumping from this 'hidden resource' is an essential component of supply.

The growth trend in urbanization across the globe and especially in Asia is increasingly demanding access to sustainable water resources to make our cities 'inclusive, safe, resilient, and sustainable.' This coupled with climate change (including changing snowmelt and monsoon conditions) will significantly increase water stress with the potential to lead to water conflict.

Against such a challenging backdrop, this book of research papers focused on South Asia is timely. It provides a modern analysis and summary of research into a wide variety of issues relating to Asian groundwater. The complexity of understanding water resources, impact of over-abstraction, and importance of water quality are highlighted. Coastal cities are singled out as special cases requiring integrated research for planning to manage the causes and impacts of both natural and anthropogenic contamination, especially arsenic and saline ingression.

What is different about this book is the range of research including the application of new and exciting approaches including the application of remote sensing data and geomorphology and the use of artificial intelligence to study aquifer architecture and groundwater depletion. What strikes me is that it succeeds because it draws together a spectrum of water practitioners from across many Asian countries with government, major funders and international experts and academia represented, and provides a useful snapshot of the current groundwater research for future transboundary catchment studies.

As a mapping geologist, I often work with hydrogeologists (and even the occasional water diviner!) including previously on geothermal and carbon capture and storage projects and more recently on modeling the sediments beneath Varanasi in India. Through the latter work, I have come to know Prof. Abhijit Mukherjee and this impressive range of papers is a testament to his editorial energy and enthusiasm for this hydrogeological subject.

Dr. Martin Smith
Science Director, BGS Global Geoscience
British Geological Survey, UK

e) Groundwater Management of South Asia

In the global context, groundwater has received belated attention in comparison with surface water management. In many nations, the constructions of surface water dams and irrigation systems have taken pride of place in the past and have become powerful symbols of national development. Many politicians in many countries have jostled for kudos as they have opened such schemes. Groundwater has taken second place, despite the obvious relationship between it and surface water availability. It has almost been the case of out of sight is out of mind. At a personal level, and to my own embarrassment, in the early 1980s I complained to my research institution when as a social scientist, I was placed in a unit that concentrated entirely on groundwater. I could not see the need. Two years later I was grateful, as I began to appreciate the fundamental need to manage groundwater sustainably for communities everywhere. Fortunately, in the last 30 years the dependence of communities and economies on groundwater has become accepted by all nations as lowering of groundwater tables and the need for conjunctive water management have become obvious problems that need to be addressed.

The significance of the need to manage groundwater is nowhere more evident than in South Asia, probably the most densely populated region of the globe. While there are major river systems, there are many communities that depend on groundwater for irrigation. It is also evident that in many regions groundwater tables are declining and water quality issues exist. Dealing with these issues is not easy, with an understanding of aquifer systems being often hampered by lack of mapping of aquifers and an understanding of the basic hydrological processes. Without at least basic knowledge programs such as watershed development, schemes aimed at sustainability are hard to implement. Basic issues such as the appropriate scale of delivery of such programs are still being resolved, despite recent encouraging initiatives. There are also issues surrounding the effect of land use on water quality and how naturally occurring water quality problems such as arsenic levels can be dealt with.

While progress needs to be made in the traditional areas of hydrology and hydrogeology, these approaches need to be integrated with an understanding of social and economic systems within which groundwater is used. Issues associated with farmer decision making, equity of use between interest groups, the appropriate property rights regime, the necessary legal framework and how institutions can function to maximize livelihoods, are also important if sustainable communities and economies are to be underpinned by the groundwater resource. These issues need the same amount of attention as understanding the resource itself. The major challenge for researchers in particular will be to integrate the findings of all disciplines within programs that can incorporate the key questions of the community, NGOs, and government decision makers. This will be especially challenging in an environment of climate change.

This volume represents an important contribution to achieving such integration. Its six sections carry us on a journey through the issues of availability, quality, climate change, and economics and management. It provides an important benchmark as well as suggestions as to how we can proceed toward sustainable management of this vital resource for South Asia. I commend it to you.

Dr. Geoff Syme
Professor, Edith Cowan University, Australia

and

Editor in Chief, Journal of Hydrology

f) Groundwater Governance of South Asia

In 1947 when India and Pakistan emerged as sovereign nations from the colonial rule, they inherited the world's largest canal irrigation network. For millennia, rural communities on the Indian subcontinent had thrived by husbanding rain and surface water. In the Indo-Gangetic Basin, agriculture flourished with various techniques of overflow irrigation. In peninsular India and Sri Lanka, agriculture prospered around tank irrigation created and overseen by kings, overlords, and temple priests.

Since the mid-1960s, however, this scenario has undergone massive transformation. South Asia has emerged as the world's largest user of groundwater in agriculture and other uses. With emergence of 30 odd millions of small private wells and pumps watering farms, the region ushered in an era of atomistic irrigation. Earlier, irrigation was confined to command areas of large and small reservoirs, with the rest condemned to rainfed farming. This silent groundwater revolution took irrigation to the nook and corner of the subcontinent. Today, the irrigation surplus supported by groundwater irrigation in South Asia may well be of the order of US $ 100 billion/year. Never in the history of humankind has a regional agricultural economy has had to support as vast an agrarian population as South Asian agriculture has during recent times. The resulting agrarian stress would arguably have been far more lethal but for the spread of groundwater irrigation.

Regrettably, even as groundwater has emerged as the mainstay of South Asian agriculture, the region's governments continue showering resources on large-scale canal irrigation projects. They are blind to groundwater, the elephant in the drawing room; their real challenge is of mastering the craft of aquifer storage. Groundwater governance and management is yet to receive policy attention and resource commensurate to the growing significance of this resource. As a result, all manner of externalities are raising their head in response to intensive groundwater development in an unplanned manner. These externalities are now seriously undermining the productivity, equity, and environmental benefits of South Asia's groundwater boom. Vast areas are suffering from secular decline in water levels; equally serious is the deterioration of water quality throughout the subcontinent. South Asian water policy makers, managers, and researchers need to quickly come to grips with the changing nature of the unique water governance challenge facing the region.

This collection of research papers from a galaxy of scientists and researchers working on groundwater in South Asia is, therefore, a very welcome and much-needed contribution. Some of the finest researchers have offered their analyses based on years of scientific research in their perspective fields. The volume has been able to strike a good balance between physical and social, among the hydrogeological subregions of the subcontinent and between science and policy. I have no doubt that this collection will make a priceless addition to our limited but growing stock of knowledge on this extremely important subject.

Dr. Tushaar Shah
Senior Fellow, International Water Management Institute

and

Interim Chairperson, Institute of Rural Management, India

About the Editor

Prof. Abhijit Mukherjee graduated from the University of Kentucky, USA, and completed his postdoctoral work at the University of Texas, Austin, USA. He also served as the Physical Hydrogeologist at the Alberta Geological Survey in Canada. He is currently an Associate Professor at the Department of Geology and Geophysics, and the Research Coordinator of the School of Environmental Science and Engineering at the Indian Institute of Technology Kharagpur (IIT Kharagpur), India. His main research areas are physical, chemical, and isotope hydrogeology, including modeling and contaminant transport, as well as water resource management and the effects of climate change on the hydrosphere. He is a member of the Geological Society of America (GSA), International Association of Hydrogeologists (IAH), and Indian Science Congress Association. He has over 20 years of teaching and research experience. He leads several international groundwater research consortiums and has researched in several countries, with emphasis on basin-scale hydrogeology and groundwater management. He is the convenor of the Applied Policy Advisory to Hydrogeosciences (APAH) group. Among many awards and recognitions, in 2016, he was conferred the National Geoscience Award by the President of India. He has served as Associate Editors of several journals, including the Journal of Hydrology, Applied Geochemistry, Groundwater for Sustainable Development, Frontiers in Environmental Science, and Journal of Earth System Science.

Part I
Groundwater Systems of South Asia

Chapter 1
Overview of the Groundwater of South Asia

Abhijit Mukherjee

Abstract The South Asia, arguably the most densely populated part of this planet, hosts about 24% of the world's population within only ~4% of the total global land area. Although the region encompasses three of the most extensive riverine systems of the world (Indus, Ganges, and Brahmaputra river basins) that host several of the high groundwater-producing aquifers of the globe, the availability of safe and sustainable groundwater in the region is not consistent, and there is a growing concern about the accessibility of safe water in many of these aquifers (e.g., Ganges basin) due to presence of geogenic pollutants. Moreover, the groundwater from these trans-boundary aquifers has become a politically sensitive issue. The region is also the most extensive user of groundwater resources in the globe, leading to severe concern of groundwater availability, even for groundwater affluent aquifers. Several anthropogenic activities, particularly irrigation (accounts for >80% of the groundwater withdrawal), lead to groundwater depletion in most of areas within the region. Varying precipitation rates and subsurface hydraulic condition are providing more challenges to groundwater governance. Widespread occurrences of geogenic groundwater contaminants along with emerging pollutants, increasing food demand associated with growing population, and effects of climate change further complex the scenario toward sustainable groundwater resource management.

A. Mukherjee (✉)
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee
Applied Policy Advisory To Hydrogeosciences (APAH) Group, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_1

Keywords Groundwater · South Asia · Irrigation · Aquifer · Quality

Afghanistan, Bangladesh, Bhutan, India, Myanmar, Nepal, Pakistan, and Sri Lanka, these eight countries of South Asia (SA, Fig. 1.1) occupy only ~4% of the land area of the globe, but hosts almost quarter of the global population (FAO 2013). The region does not only host this large population but also has some of the densest populated part of the world (Mukherjee et al. 2015). Precipitation rate varies spatially and temporally over the region, with country-wise lowest occurrence in northwestern part of Afghanistan and parts of Thar Desert, India, and Pakistan (<200 mm/year; WBA 2015; Scanlon et al. 2010) and highest in eastern part, Bangladesh (2600 mm/year; WBA 2015) (Fig. 1.1). The Indus, Ganges, Brahmaputra, and Meghna river systems (IGBM basin) together form the largest fluvial basin in the globe (Mukherjee et al. 2015), together with Irrawaddy and Kabul river, drains the region (Figs. 1.1 and 1.2), and form some of the highest yielding aquifers of the world (Figs. 1.3 and 1.4) (Mukherjee et al. 2015). Consequently, the aquifers associated with these river basins continue across the geopolitical boundaries of the contiguous SA countries (Mukherjee et al. 2015),

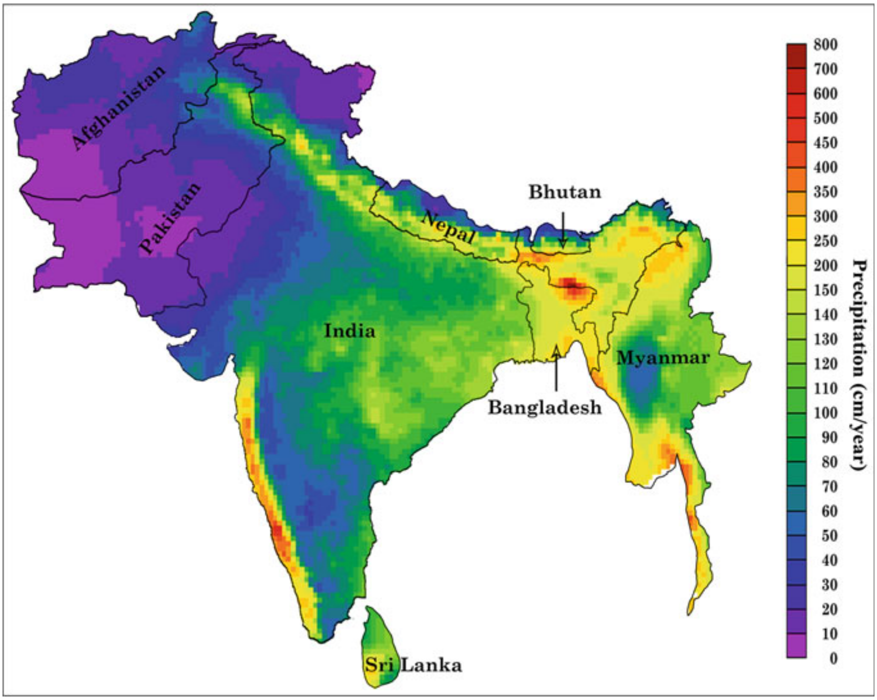


Fig. 1.1 Map of South Asia showing the range of mean annual precipitation distributions (1961–2011). *Source* APHRODITE database. The figure is not to scale, and the country boundaries are for illustrative purpose only

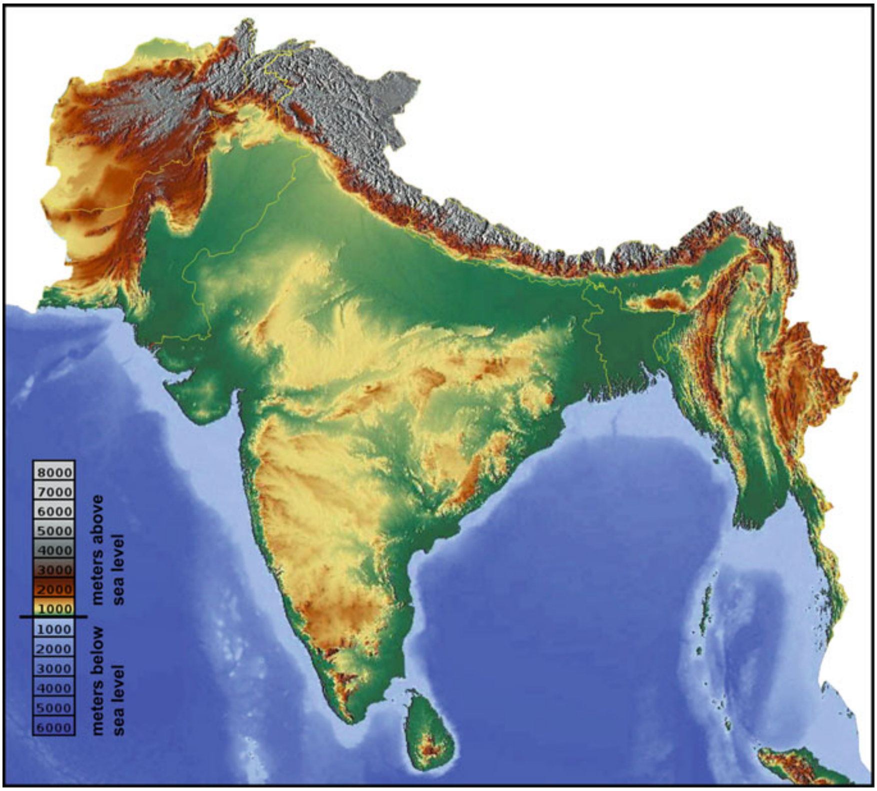


Fig. 1.2 Topographic and geomorphic map of South Asia, demonstrating the major topographic features visible in the area. The figure is not to scale, and the country boundaries are for illustrative purpose only

thus forming prominent and some of the most important trans-boundary aquifers, e.g., Indus basin aquifers (between India and Pakistan), Ganges and Brahmaputra basin aquifers (between Bangladesh and India), Meghna basin (between Bangladesh and India), the aquifers of the tributaries to the Ganges (between Nepal and India), the aquifers of the tributaries to the Brahmaputra (between Bhutan and India and between India and Bangladesh) (UN-IGRAC 2014) (Fig. 1.5).

Almost half of the ~5000 billion m^3 water that enters the SA hydrologic system at the beginning of the hydrologic year dissipates by poorly understood and unquantified processes (Verma and Phansalkar 2007). Further, being the largest user of fresh groundwater resources in the world, the SA is subjected to intense groundwater abstraction activities throughout the year (Siebert et al. 2013) (Table 1.1). The SA faces acute shortage of drinking water and other usable waters, as it is witnessing rapid rise in water demand and change in societal water use pattern because of accelerated urbanization and change in lifestyle (Mukherjee et al. 2015). In many urban, peri-urban, and rural regions of the SA, the surface water channels have been historically used as pathways of sewage and industrial waste (solid and liquid) rendering them unfit for consumption, thus influencing the inhabitants and planning authorities to gradually switch to groundwater sources for their drinking and irrigational water needs (Mukherjee et al. 2011). Presently, 60–80% of the domestic water supplies across SA are met by groundwater (e.g., Bangladesh, India, and Pakistan). Groundwater withdrawal as a function of irrigation exceeds 85% throughout the SA (FAO 2013, 2015). Portions of the north SA aquifers (Fig. 1.5) are acutely depleting (Rodell et al. 2009; Tiwari et al. 2009; Shamsudduha et al. 2012; Bhanja et al. 2014, 2017) with maximum possible groundwater footprint in Ganges aquifers (Gleeson et al. 2012). Moreover, as the usable groundwater in SA is not uniformly distributed, there are concerns about the availability of safe water in many areas (e.g., wide portions of the Ganges–Brahmaputra basin) due to presence of natural contaminants (e.g., As, Fe, F) as well as emerging contaminants (Fig. 1.6). Of these, the widespread presence of elevated concentrations of dissolved arsenic (As), fluoride (F), salinity, etc., have been detected in wide tracts of the SA, varying from alluvial aquifers to crystalline bedrocks. Arsenic contamination of groundwater in the Bengal Basin has been called ‘the largest mass poisoning in human history.’ The extent and effect of other emerging and unidentified groundwater contaminants (e.g., nitrate, pesticides, radiogens, antibiotics) are yet to be largely accounted for (Saha and Alam 2014). Intensive agriculture is associated with generous input of chemical fertilizers, and synthetic pesticides infiltrate into groundwater systems. Consequently, most of SA has been marked as high water-stressed area (water stress indicator: groundwater withdrawal to availability ratio >0.8) (Fig. 1.3) (Bates et al. 2008). Reduction in precipitation trends over the region (analyzed between 1979 and 2005; Bates et al. 2008) projects further decrease in per capita availability of groundwater in the region (Mukherjee et al. 2015). With the present-day rate of exponentially increasing population, the availability of usable groundwater would seriously decline in near future, if not managed properly with immediate attention.

These above-discussed groundwater crises might further aggravate with the predicted, impending climate change and melting of the high-altitude glaciers that feeds the hydrological system of the SA. Glacial lake outburst floods are increasing in recent years, exposing the habitats to become more prone to flash flood hazards in foothills of Himalayas and other high-altitude areas of the area. Higher surface runoff is projected for the last decade of this century (2090–2099) in comparison with that of the last century, as an effect of global warming processes (Bates et al. 2008), enhancing potentiality of flood inundation hazards to approximately a billion people residing at the lower parts of the major river basins. Projections also suggest that the northern parts of SA will experience comparatively lower surface runoff in future time periods, leading to draft-like situation (Bates et al. 2008). While high recharge rates (>300 mm/year; Fig. 1.3) have been observed in the eastern side of SA owing to higher present-day precipitation in the region, much of the western SA barely get any recharge.

Based on the physiographic and hydrogeology of the South Asian region, there are six primary aquifer types (Mukherjee et al. 2015):

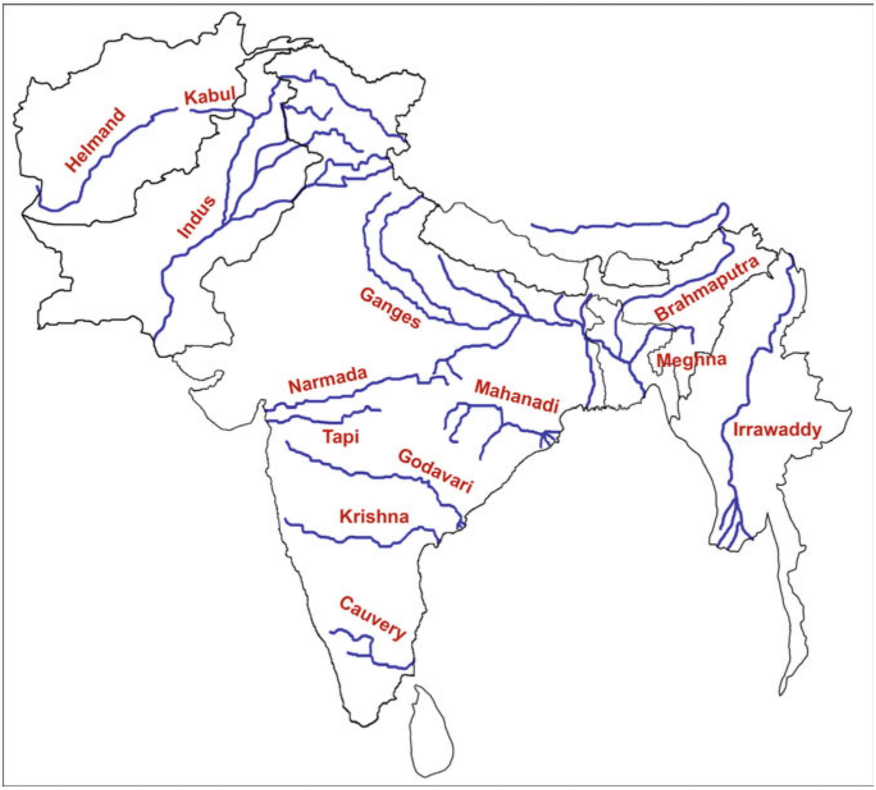


Fig. 1.3 Map of major river systems of South Asia. The figure is not to scale, and the country boundaries are for illustrative purpose only

- The Indus, Ganges, Brahmaputra, Meghna (IGBM) river basin fluvial aquifers, extending from west to east as Pakistan, India, Nepal, and Bangladesh,
- Other alluvial aquifers, e.g., Kabul river in Afghanistan, Mahanadi, Krishna, Godavari rivers in India, Irrawaddy in Myanmar,
- Himalayan and other mountainous aquifers in Afghanistan, Pakistan, India, Nepal, Bhutan, Bangladesh, and Myanmar,
- Crystalline aquifers of cratonic regions of India and Sri Lanka,
- Desertic and other arid zone aquifers of Afghanistan, Pakistan, and India,
- Coastal aquifers of Pakistan, India, Sri Lanka, Bangladesh, and Myanmar.

Of these, the IGBM aquifers are the most groundwater prolific, with some of the highest yielding aquifers in the world. They may be regarded as the ‘bread basket of South Asia.’ However, in recent decades, several studies have stressed on the alarming dwindling of groundwater resources, mostly in northwest India and Pakistan (Rodell et al. 2009) and Ganges basin in India and Bangladesh (Shamsudduha et al. 2011; Bhanja et al. 2017) based on satellite and ground-based

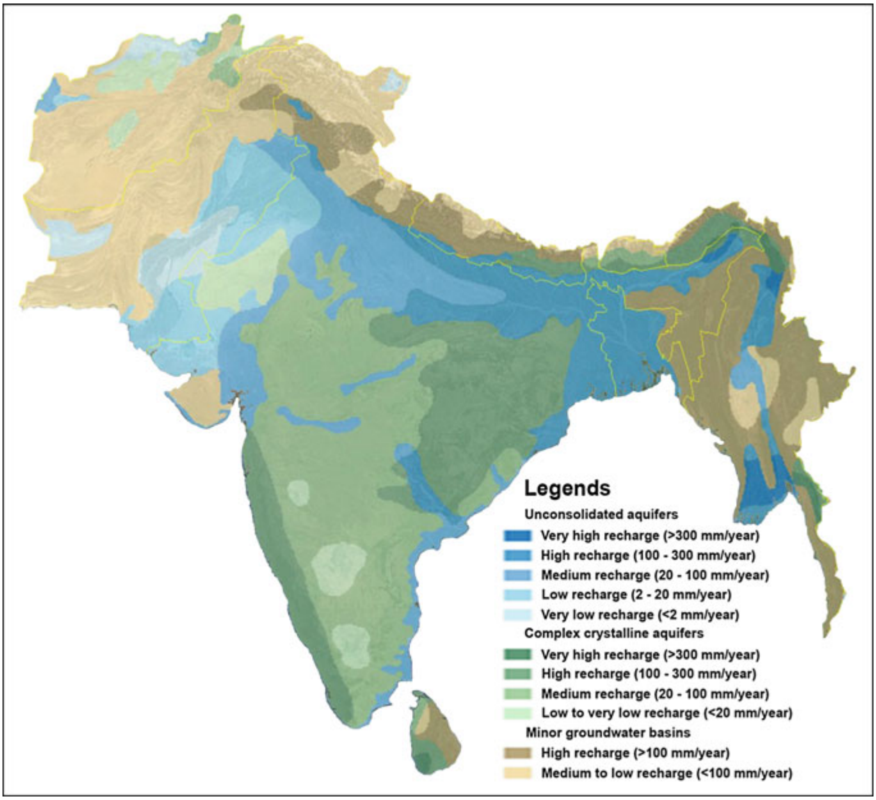


Fig. 1.4 Hydrogeological map of South Asia, showing major river channels and distribution of groundwater recharge rates (modified from WHYMAP database, www.bgr.de). The figure is not to scale, and the country boundaries are for illustrative purpose only

data. Notwithstanding these threats of groundwater quantity stresses, recent estimates show that about quarter of the 300 billion m^3 of IGB basin is extremely saline and about 40% of groundwater contaminated by arsenic, thus making about 60% of the water to be unusable and unsafe (MacDonald et al. 2016). Although the aquifers of basin seem to be composed of uniform porous media, significant variation in aquifer hydraulics actually determines the groundwater availability in these vast aquifers (Bonsor et al. 2017). In the following sections, synopses of country-wise groundwater resources of the eight member countries of the SA are outlined (*in alphabetical order*) as an introduction to the rest of the technical chapters of this book. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

Table 1.1 Summary of land area, population, precipitation, irrigated land area, renewable groundwater resources, groundwater withdrawal, and total water uses in South Asia

Country	Land area estimates (as of 2009)[a]		Population estimates (as of 2011)[a]		Annual precipitation (1962–2011 mean)[b]	Irrigated land[a]	Renewable Groundwater resource (as of 2014)[c]	Groundwater withdrawal (between 2000 and 2010)[d]				Total water uses (year of estimation)[d]
								Total abstraction	A[f]	D[f]	I[f]	
	Million ha	Global %	thousands	Global %	mm/year	thousand ha	bcm/year	bcm/year	(%)	(%)	(%)	bcm/year
Afghanistan	65	0.50	35,320	0.51	327	3199	10.7	7.12	94	6	0	23.12
Bangladesh	13	0.10	150,494	2.16	2666	5100	21.1	30.21	86	13	1	35.87 (2008)
Bhutan	4	0.03	738	0.01	2200	28	8.1	0.04	N.A.	N.A.	N.A.	0.34 (2008)
India	297	2.28	1,241,492	17.80	1083	66,700	432.0	245.00[e]	89	9	2	761.00 (2010)
Myanmar	65	0.50	48,337	0.69	2091	2275	453.7	4.02	N.A.	N.A.	N.A.	33.23
Nepal	14	0.11	30,486	0.44	1500	1168	20.0	2.91	N.A.	N.A.	N.A.	9.79 (2005)
Pakistan	77	0.59	176,745	2.53	494	20,200	55.0	64.82	94	6	0	183.45 (2008)
Sri Lanka	6	0.05	20,869	0.30	1712	570	7.8	1.17	N.A.	N.A.	N.A.	12.95 (2005)
Total	541	4.16	1,704,481	24.44		99,240	1008	350.15				1059.75

[a] Food and Agriculture Organization of the United Nations (FAO) (2013) FAO statistical yearbook 2013: world food and agriculture, 289 pp

[b] World Bank Archive (WBA) (2015). http://data.worldbank.org/indicator/AG.LND.PRCP.MM. Accessed on Jan 20, 2015

[c] Food and Agriculture Organization (FAO) of the United Nations (2015) AQUASTATDFO. AQUASTAT (Database) 2015. (Latest update: Mar 20, 2014) Accessed Jan 20, 2015. http://data.fao.org/ref/75f7d9c5-57ab-4a62-88d3-91e47fb50c45.html?version=1.0

[d] Margat J, Van der Gun J (2013) Groundwater around the world: a geographic synopsis. CRC Press

[e] Central Ground Water Board (CGWB) (2014c) Ministry of Water Resources, G.o.I. Dynamic groundwater resources of India

[f] Percentage contribution to total groundwater withdrawal from: A: Agriculture, D: Domestic, I: Industry

N.A.: Data not available

1.1 Afghanistan

Afghanistan is a mountainous country in South Asia, mostly encompassed by the Hindu Kush Mountains, a westward extension of the Alpine–Himalayan range. This high-altitude terrain separates the Kandahar-Helmand desert region in the south from the fluvial plains of Amu Darya River in northern areas. The climate varies from arid to semiarid (Mack et al. 2013, 2014). The most important groundwater-enriched area in the country is the Kabul river basin aquifers. The basin is structurally controlled, lined by a fault that divides the area into several sedimentary subbasins, namely the aquifers of Paghman/Upper Kabul, Logar, Central Kabul, Deh Sabz, and Shomali (Broshears et al. 2005). Dominant groundwater flow takes place through saturated alluvium and other sediments in the basin in the direction of the surface drainage gradient. The aquifers are mostly recharged by snowmelt runoff from the adjoining mountains, as well as precipitation, mostly in the winter months. In the Central Kabul groundwater area, static water levels range from a minimum of about 2.5 m below land surface. Static water levels have seasonal fluctuations from 0.5 to 3 m. Pumping appears to cause a drawdown of about 8 m. The groundwater is mostly found to be of potable quality, but has been found to be polluted with geogenic salinity, nitrate, and boron, along with coliform in more populated areas (Fig. 1.6). The shallow groundwater is mostly estimated to be of young age (<30 years), suggesting recharge from river bed leakage and snowmelt seepage. Climate change scenarios, with potential receding glacial snows and peaking, can severely impact the groundwater levels in future, with groundwater depletion of several meters and recharge period altering in the hydrological year, rather than late winter–early spring at the present times (Mack et al. 2010).

1.2 Bangladesh

As a country, Bangladesh receives highest rate of precipitation within ISC (Fig. 1.1, Table 1.1). About 80% of the total precipitation occurs in the monsoon months of June to September (FAO 2015). Very high amount of annual precipitation, subdued topography in much of the country, and discharge of regional flow systems result in some of the largest fluvial systems of the world (Figs. 1.2, 1.3, and 1.4). The central and southern part of the country is characterized by world's largest fluvio-deltaic plain formed by three rivers, Ganges, Brahmaputra, and Meghna (GBM) (Mukherjee et al. 2009a; Shamsudduha et al. 2011). Furthermore, the country is drained by a huge number of 230 streams, which are either tributaries or distributaries of the GBM system (FAO 2015). As a result, ~80% of the landmass is comprised of fertile alluvial sediments (FAO 2015). Groundwater in all areas is mostly available within <5 m below ground level (bgl) within the alluvial aquifers (MPO 1987). Agriculture plays a major role in the country's economy, and thus more than 50% of

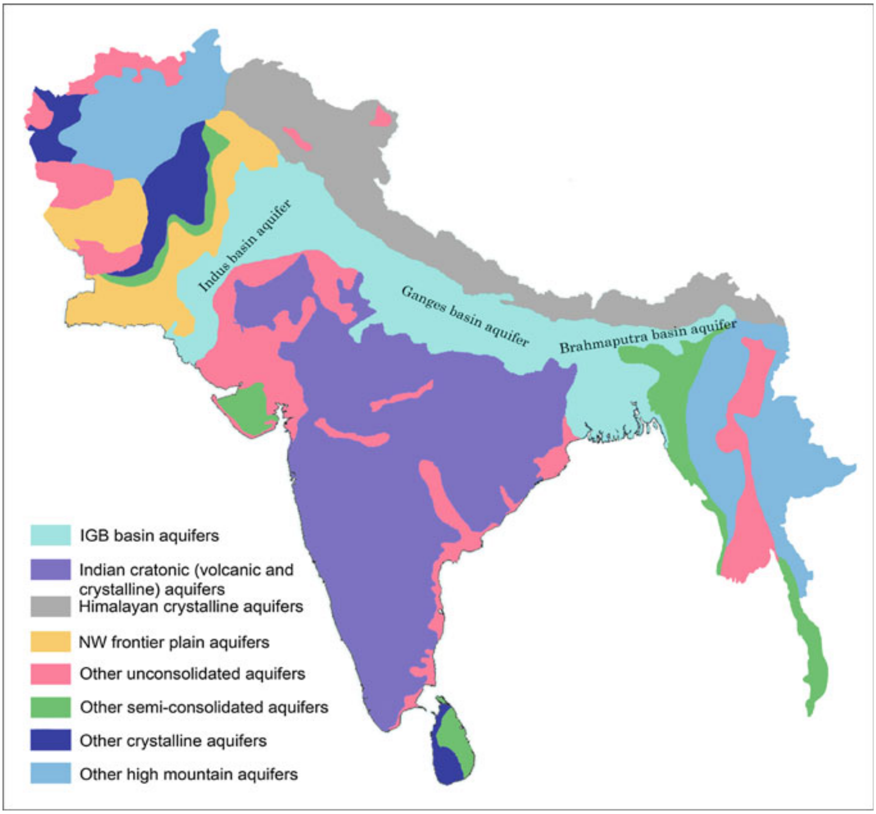


Fig. 1.5 Major aquifer map of South Asia. The map demonstrates the major aquifer types that are found in the area and generally used for groundwater abstraction. The figure is not to scale, and the aquifer and country boundaries are for illustrative purposes only

the cultivable lands are cropped twice or more times (FAO 2015). Intense irrigational activities account for 79% of groundwater withdrawal (FAO 2015), creating immense pressure on groundwater resources leading to rapid depletion of groundwater storage of about −0.44 to −2.04 km^3/year, with accelerating depletion rates in recent years (Shamsudduha et al. 2012). A substantial amount of declination in groundwater level has been observed in the area surrounding the country capital, Dhaka (Ahmed 1994; Alam 2006). In general, the regional-scale flow of groundwater is from northwest to southeast (Ravenscroft et al. 2009) with local-scale variations, based on topography and surface hydrologic units, e.g., the effluent river systems. Modern continuation of such flows is however questionable at shallow level in light of extensive pumping (Harvey et al. 2002). Furthermore, existence of widespread, elevated concentrations of geogenic As in groundwater has caused havoc to the usable groundwater resources of the country (Ahmed et al. 2004) (Fig. 1.6). High concentrations of groundwater arsenic in most of the

Bangladeshi aquifers have also made them probably the most scientifically studied groundwater system in the world. More than 80% of tube wells within shallow aquifers of the major river basins in southern and coastal aquifers have been detected with high arsenic concentrations (Ahmed et al. 2004). The anoxic, shallow aquifers are also prone to microbiological contamination in many parts of the country (BGS 2001a). Waterlogging is a critical issue in the southern areas as most of the areas were flooded during monsoon time (FAO 2015). The coastal areas also suffer from large-scale seawater intrusion resulting in increasing groundwater salinity.

1.3 Bhutan

Bhutan is the smallest country within the SA in terms of population and land area (Table 1.1). The country has three major geomorphic features, the higher Himalayas, the lesser Himalayas, and the southern foothills (FAO 2015). Consequently, the aquifers are all composed of Himalayan fractured, crystalline rocks (Figs. 1.3 and 1.4). Annual precipitation pattern is highly variable throughout the country with minimum value of 477 mm at Gidakhom in Thimphu district and maximum value of 20,761 mm at Dechenling in Samdrup Jongkhar district (FAO 2015) (Fig. 1.2, Table 1.1). Monsoon lasts from June to September with occurrence of 60–90% of the total precipitation and is the main source of recharge. Groundwater availability is much localized and depends on the structural discontinuities of the Himalayan geology. Hence, the yields of the aquifers are extremely variable, and much of the population depends on surface water.

1.4 India

India is the largest country within SA, both in terms of land area and population (Table 1.1). Large parts of India receive precipitation between 750 and 1500 mm/year, with very low precipitation in the western parts of the country (<150 mm/year) and few of the world's highest rainfall receiving places being in the northeastern parts (> 2500 mm/year) (CGWB 2009) (Fig. 1.1, Table 1.1). The major part of the total precipitation is predominantly influenced by the southwest monsoon season that contains the four months between June to September (CGWB 2014). The major aquifers are related to the major river basins that are draining the country (Figs. 1.2, 1.3, and 1.4). The total land of the country can be divided into 22 major river basins (CWC 2010; Bhanja et al. 2016), which may be further aggregated into four groups according to their origin and flow pattern: (i) the Himalayan rivers (Ganges, Brahmaputra, Indus) that originate from the melted high-altitude glaciers and snow, and are perennial throughout the hydrological year; (ii) rivers of Indian craton (Godavari, Krishna, Pennar, Cauvery, Mahanadi, Tapi, and Narmada) are mostly rain-fed and strive on baseflow; (iii) the coastal rivers, mostly non-perennial;

(iv) rivers of the western desert originate within small fluvio-aeolian basins and are rain-fed ephemeral and disconnected from the groundwater systems (FAO 2015). The Ganges river basin system is the most extensive river system in the country, with a catchment area of $\sim$86.1 million ha (CWC 2010). The Indus–Ganges–Brahmaputra (IGB) systems that together drain the northern Indian plains form a huge alluvial aquifer system that is regarded as one of the most affluent aquifers of the world. On the contrary, groundwater is available only within fractured aquifers within the rest two-third of the country (CGWB 2011). While the northern porous aquifers are both of unconsolidated and semi-unconsolidated alluvial sedimentary type, the fractured aquifers are mostly composed of pre-Cenozoic crystalline rocks of the Indian craton (CGWB 2014a, b). Intense irrigational activities are prevalent in the highly fertile IGB basin, which is also the most populous part of the country (Kulkarni et al. 2015). Annual replenishable groundwater resources have been estimated to be $\sim$430 bcm, with annual groundwater draft of $\sim$243 bcm in 2009. Of these, $\sim$221 bcm of groundwater was used for irrigation, and the rest $\sim$22 bcm were used for domestic and industrial purposes (CGWB 2011). Increasing agricultural demand with multiplying population has resulted in fourfold increase in production of crops (50–204 million tones) between 1950s and 2000 (Kumar et al. 2005), thus severely stressing the groundwater resource of the country. Consequently, rapid depletion in groundwater storage has been observed in the intense agricultural regions particularly within Ganges basin (Rodell et al. 2009; Tiwari et al. 2009; Bhanja et al. 2014, 2017) that also links with surface water storage of IGBM rivers (Papa et al. 2015). More than 4 m decline in groundwater levels with respect to decadal mean groundwater level has been observed in several parts of the country (CGWB 2014a). Additionally, similar to its eastern neighbour Bangladesh, groundwater in large parts of the north Indian alluvial aquifers is anoxic and is enriched with elevated As concentrations (Bhattacharya et al. 2011, 2014) (Fig. 1.6). Elevated groundwater As concentrations have been identified in groundwaters of 86 districts in ten Indian states (Mukherjee et la. 2009b; Bhattacharya et al. 2014; CGWB 2015; Mahanta et al. 2015; Verma et al. 2015). The pollution is believed to have further aggravated due to extensive groundwater abstraction (Mukherjee et al. 2011). High concentrations of groundwater fluoride have also been observed, mostly in the crystalline aquifers in parts of 19 states (Maheshwari 2006; CGWB 2015; Hallet et al. 2015). High concentrations of groundwater iron (Fe) and nitrate (NO_3^-) have also been reported from several aquifers of the country (CGWB 2015). Seawater intrusion resulting in aquifer salinization has also been observed in many of the aquifers adjoining the coastal regions of Bay of Bengal and Arabian Sea; however, highly saline groundwater is also prevalent in the inland aquifers of several states (CGWB 2015). Such inland salinization may be linked with mineral dissolution and/or agricultural pollution (MacDonald et al. 2016; Bonsor et al. 2017). Frequent, widespread floods caused by intense precipitation and rejected recharge are common in parts of eastern India.

1.5 Nepal

Nepal is characterized by the Himalayan crystalline aquifers in the north and piedmont alluvial fan and plain aquifer in the south (BGS 2001b). The southern part, called the Terai, is comprised of relatively low topography alluvial deposits formed from recent fluvial sedimentation (Figs. 1.2, 1.3, and 1.4). The Terai region also serves as the sediment and solute provenance for many of the south-flowing rivers to India and Bangladesh. Much of the population of Nepal resides in the fertile Terai region. The unconfined, mostly Quaternary-aged aquifers, which are >250 m thick, are exploited by several hundred thousand tube wells. These wells supply water to about 90% of the residents of the Terai. The fractured basement aquifers are mostly replenished from precipitation during monsoon time (Andermann et al. 2012) (Fig. 1.1, Table 1.1). More than 98% of the groundwater withdrawal is associated with irrigation in the country (FAO 2013). Arsenic contamination in groundwater is a critical health issue in densely populated southern region of the country (Thakur et al. 2010). Most of the aquifers associated with the rivers flowing through the Siwalik Hills in the Himalayan piedmonts are found to be As enriched (Mukherjee et al. 2009b; Diwakar et al. 2015) possibly from baseflow (Fig. 1.6).

1.6 Myanmar

The major aquifers of Myanmar range from Precambrian to Recent age and vary from coastal and north-south trending tectonically controlled basins. The major groundwater recharge is from monsoonal rainfall, which extends from June to September, ranges up to 3050 mm in the deltaic area, 3810 mm in the north, ~2000 mm in the eastern mountainous region, and only 760 mm in the central dry zone. The largest aquifer is the Irrawaddy river basin, which like the IGBM basin is the most prolific aquifer, however, much of the aquifers of the basin have been identified to have groundwater enriched with As (Figs. 1.5 and 1.6). The other aquifers are in the Thanlwin, the Chindwin, and the Sittaung rivers. The total groundwater potential of Myanmar is ~495 km^3/year, respectively. The groundwater use in Myanmar is mostly for agriculture purposes, ranging up to ~90%, the rest ~10% being used in industrial practices and domestic purposes.

1.7 Pakistan

The Indus basin, which includes the Indus river and its five major Himalayan tributaries (Beas, Chenab, Jhelum, Ravi, and Sutlej), forms the major fluvial aquifers of Pakistan, which also hosts the most groundwater-enriched areas of the country (Figs. 1.2, 1.3, and 1.4). The Indus river basin covers ~65% of the land area in the country (FAO 2015). The Indus river aquifers of Punjab and Sindh provinces of

Pakistan are the westward component of the IGBM basin and are similar to the Ganges–Brahmaputra alluvial systems of Bangladesh and India (Van Steenbergen et al. 2015). These aquifer sediments are sourced to the western Himalayas and are transported by the Indus river system. The alluvial deposits are of considerable thickness and mostly form unconfined aquifers with fresh groundwater (Mukherjee et al. 2009b). Two-thirds of the total precipitation occur within three months of July to September. Climate in the country is characterized as semiarid to arid, with low to very low annual precipitation. Annual precipitation ranges from <100 mm to ~750 mm, spread in parts of the Lower Indus basin and Upper Indus basin near the foothills respectively (Fig. 1.1, Table 1.1). More than 20 million ha land area of the country was cultivated in 2009 (FAO 2015). As a result, groundwater withdrawal for irrigation amounts to ~94% of the total water demand (FAO 2013). Rapid agriculture demand requires high amount of groundwater abstraction which is taking place through more than 500,000 tube wells in the country (Kahlown and Majeed 2003). The North-West Frontier Province has been subjected to rapid groundwater level depletion associated with intense withdrawal (Watto and Mugera 2015) and also effected by high groundwater salinity (>3000 mg/L). In similarity to the Ganges–Brahmaputra river aquifers, the Indus aquifers are also relatively toxic (Fig. 1.6). Availability of high amount of nitrate in groundwater facilitates the pathogenic pollution in the groundwater around the cities of Islamabad, Karachi, Lahore, and Rawalpindi (Chilton et al. 2001). Much of the groundwater of the Indus river basin aquifers, mostly in Punjab and Sindh provinces, are as enriched (Fig. 1.6). High amount of dissolved fluoride is also observed in groundwater in Punjab, Sindh, and Baluchistan (Tariq 1981). Groundwater in the recent-aged alluvial aquifers of Indus basin, specifically in Punjab and Sindh regions, has been reported to be widely contaminated with As (Smedley 2005) and salinity (Bonsor et al. 2017).

1.8 Sri Lanka

The country, being an island in the Indian Ocean, is physically disconnected from landmass of any of the other countries of the SA. As a result, the groundwater systems in this country are secluded and it does not have any trans-boundary aquifer. Annual climate and precipitation suggest a humid climate in Sri Lanka. Large amount of precipitation occurs during southwest monsoon season extending from May to September (FAO 2015) (Fig. 1.1, Table 1.1). Sri Lanka is also a river dominant country having 103 distinct river basins, covering 90% of the total land area (FAO 2015). The country has similar geologic formation (and aquifers) like southern parts of India, and ~90% of the subsurface area of the country is composed of crystalline, metamorphic rocks of Precambrian age, and rest of the area is underlain by Miocene limestone and Quaternary sedimentary deposits (Cooray 1984) (Figs. 1.2, 1.3, and 1.4). The weathered sediments, generated from crystalline formations, exist at variable depths (<10–35 m) owing to favorable weathering conditions (Dharmagunewardene 2003). There are six major types of aquifers that are found in the country, e.g., shallow depth karst aquifers, deep confined sandstone and Miocene-aged limestone aquifers, shallow Quaternary-aged coastal sand aquifers, alluvial aquifers of small rivers, confined to semi-confined lateritic aquifers and the shallow depth regolith aquifers (Panabokke 2001). Total cultivated area in the country exceeds 2 million ha (FAO 2015). Intense irrigation practice leads to rapid utilization of groundwater; 87.4% of water withdrawal is associated with irrigation (FAO 2013). Advanced drilling techniques, cheaper pumps, subsidized government schemes, etc., have facilitated large-scale groundwater depletion (Senaratne 2002). Intense groundwater withdrawal leads to seawater intrusion in coastal region resulting in high salinity in groundwater (Rajasooriyar et al. 2002). Fluoride and nitrate contamination of groundwater is also a serious groundwater pollution issue in some of the areas, where proper sanitation system is absent (Villholth and Rajasooriyar 2010) (Fig. 1.6).

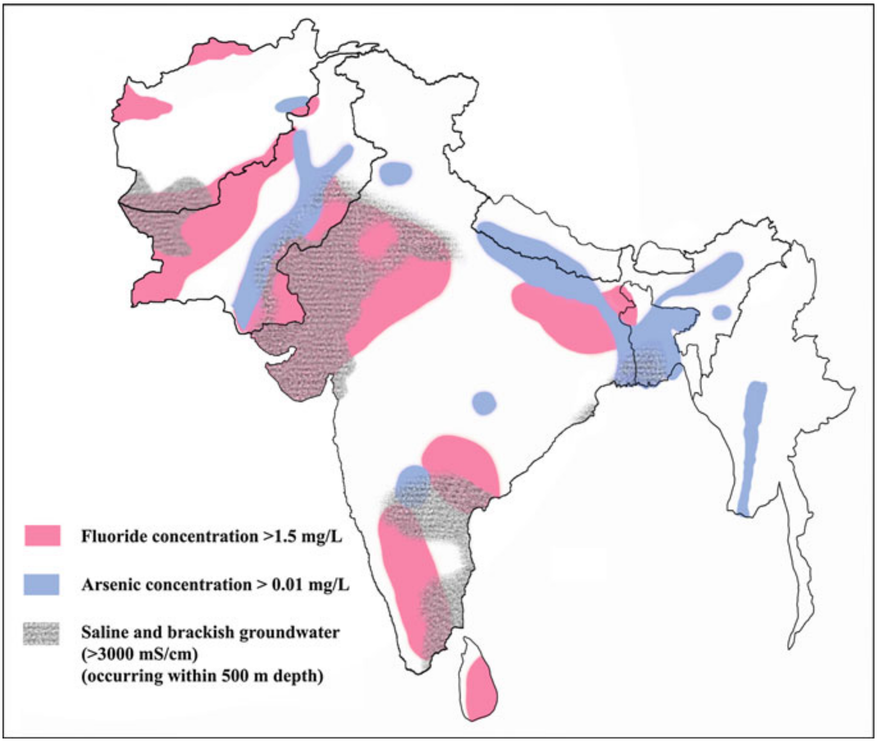


Fig. 1.6 Map of major geogenic groundwater contaminants of South Asia. The figure is not to scale, and the aquifer and country boundaries are for illustrative purposes only

1.9 Conclusion

The eight countries, namely Afghanistan, Bangladesh, Bhutan, India, Myanmar, Nepal, Pakistan, and Sri Lanka, form the South Asian region. The region hosts about $\sim 25\%$ of the world population in an area which is only $\sim 3.7\%$ of the global land area. Hence, the region is the densest populated part of the globe. The Indus, Ganges, Brahmaputra, and Meghna river systems (IGBM basin) form the largest fluvial basins in the globe and form some of the highest yielding aquifers of the world. There are other important river basin aquifers, such as the Irrawaddy and Kabul rivers. The aquifers formed from these fluvial systems continue across the geopolitical boundaries of the contiguous SA countries, forming globally important trans-boundary aquifers. Thus, the groundwater resource in SA becomes a politically sensitive issue. The region is also the largest user of groundwater resources in the globe, leading to severe concern of groundwater availability. Irrigational and other human-induced groundwater demands have resulted in severe groundwater depletion in most of the locations within the region. Further, presence of widely spread, natural groundwater contaminants, e.g., arsenic, fluoride, manganese, salinity, etc., along with emerging contaminant of natural and anthropogenic sources have limited the availability of the safe and usable groundwater in the region. In the backdrop of such groundwater quantity and quality concern for a huge population of inhabitants in SA, this book agglomerates a horde of selected synthesis and case studies from area. The chapters illustrate studies of groundwater exploration and quantity assessment from basin to local scale, highlight the groundwater chemical evolution pathways and various pollutions in the tectonic-controlled, high-yielding fluvial aquifers to crystalline cratonic aquifers, discuss the coastal groundwater dynamics and their susceptibility to climate changes, and ultimately indicate groundwater economics, management and policy development strategies for societal development.

References

Ahmed KM (1994) Hydrogeology of the Dupi Tila aquifer of the Barind Tract, NW Bangladesh. Unpublished Ph.D. thesis, University London, London

Ahmed KM, Bhattacharya P, Hasan MA, Akhter SH, Alam SM, Bhuyian MH, Sracek O (2004) Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview. Appl Geochem 19(2):181–200

Alam A (2006) Groundwater zoning map and its application. A national seminar of Bangladesh agricultural development corporation paper, Dhaka, Sech Bhaban

Andermann C, Longuevergne L, Bonnet S, Crave A, Davy P, Gloaguen R (2012) Impact of transient groundwater storage on the discharge of Himalayan rivers. Nat Geosci 5(2):127–132

Bates BC, Kundzewicz ZW, Wu S, Palutikof J (eds) (2008) Climate change and water. Technical paper of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change Secretariat, Geneva, Switzerland

Bhanja S, Mukherjee A, Rodell M, Velicogna I, Pangaluru K, Famiglietti J (2014) Regional groundwater storage changes in the Indian Sub-Continent: the role of anthropogenic activities. American Geophysical Union. Fall meeting, GC21B-0533

Bhanja SN, Mukherjee A, Saha D, Velicogna I, Famiglietti (2016) Validation of GRACE based groundwater storage anomaly using in-situ groundwater level measurement in India. J Hydrol 543:729–738

Bhanja SN, Rodell M, Li B, Saha D, Mukherjee A (2017) Spatio-temporal variability of groundwater storage in India. J Hydrol 544:428–437

Bhattacharya P, Mukherjee A, Mukherjee AB (2011) Arsenic contaminated groundwater of India. In: Nriagu J (ed) Encyclopedia of environmental health. Elsevier B.V, Netherlands, pp 150–164

Bhattacharya P, Mukherjee A, Mukherjee AB (2014) Groundwater arsenic in India: source, distribution, effects and alternate safe drinking water sources. Reference module in earth systems and environmental sciences, Chapter 09342. Elsevier B.V., Netherlands. http://dx.doi.org/10.1016/B978-0-12-409548-9.09342-8, 19 p

Bonsor H et al (2017) Hydrogeological typologies of the Indo-Gangetic basin alluvial aquifer. Hydrogeol J. https://doi.org/10.1007/s10040-017-1550-z

British Geological Survey (BGS) report (2001a) Groundwater quality: Bangladesh, p 6

British Geological Survey (BGS) report (2001b) Groundwater quality: Nepal, p 4

Broshears RE, Akbari MA, Chornack MP, Mueller DK, Ruddy BC (2005) Inventory of ground-water resources in the Kabul Basin, Afghanistan. U.S. Geological Survey Scientific Investigations Report 2005–5090, 34 pp

Central Ground Water Board (CGWB) (2009) Ministry of Water Resources, G. o. I., Dynamic groundwater resources, 225 pp

Central Ground Water Board (CGWB) (2011) Ministry of Water Resources, G. o. I., Dynamic ground water resources of India

Central Ground Water Board (CGWB) (2014) Ministry of Water Resources, G. o. I., Ground water scenario in India, 50 pp

Central Ground Water Board (CGWB) (2014a) Ministry of Water Resources, G. o. I., A concept note on geogenic contamination of ground water in India with special reference to nitrate, 99 pp

Central Ground Water Board (CGWB) (2014b) Ministry of Water Resources, G. o. I., Groundwater year book 2013–14, 76 pp

Central Ground Water Board (CGWB) (2015) Ministry of Water Resources, G. o. I., Groundwater quality scenario. http://www.cgwb.gov.in/GW_quality.html. Accessed on 16 Feb 2015

Central Water Commission (CWC), Ministry of Water Resources (2010) Water and related statistics, 253 pp

Chilton PJ, Jamieson D, Abid MS, Milne CJ, Ince ME, Aziz JA (2001) Pakistan water quality mapping and management project. Scoping study, LSHTM/WEDC Report to DFID

Cooray PG (1984) The geology of Sri Lanka (Ceylon), 2nd edn. National Museums of Sri Lanka, Colombo, 340 pp

Dharmagunewardene HA (2003) Groundwater quality problems in Sri Lanka. In: National workshop on fresh water related issues, 31 March–2 April 2003. JNU, New Delhi

Diwakar J, Johnston SG, Burton ED, Shrestha S (2015) Arsenic mobilization in an alluvial aquifer of the Terai region, Nepal. J Hydrol Reg Stud

Food and Agriculture Organization (FAO) of the United Nations (2015). AQUASTATDFO. AQUASTAT (Database) 2015. Latest update: 20 Mar 2014. Accessed 20th Jan 2015. http://data.fao.org/ref/75f7d9c5-57ab-4a62-88d3-91e47fb50c45.html?version=1.0

Food and Agriculture Organization of the United Nations (FAO) (2013) FAO statistical yearbook 2013: world food and agriculture, 289 pp

Gleeson T, Wada Y, Bierkens MF, van Beek LP (2012) Water balance of global aquifers revealed by groundwater footprint. Nature 488(7410):197–200

Hallet B, Dharmagunawardhane HA, Atal S, Valsami-Jones E, Ahmed S, Burgess WG (2015) Mineralogical sources of groundwater fluoride in Archaed bedrock/regolith aquifers: mass balances from Southern India and North-Central Sri Lanka. J Hydrol Reg Stud 4:111–130

Harvey CF, Swartz CH, Badruzzaman ABM, Keon-Blute N, Yu W, Ali MA, Ahmed MF (2002) Arsenic mobility and groundwater extraction in Bangladesh. Science 298(5598):1602–1606

Kahlown MA, Majeed A (2003) Water-resources situation in Pakistan: challenges and future strategies. Water Resources in the South: present scenario and future prospects

Kulkarni H, Shah M, Shankar V (2015, this issue) Shaping the contours of groundwater governance in India. J Hydrol Reg Stud 4:172–192

Kumar R, Singh RD, Sharma KD (2005) Water resources of India. Curr Sci 89(5):794–811

MacDonald AM et al (2016) Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. Nat Geosci 9:762–766

Mack TJ, Akbari MA, Ashoor MH, Chornack MP, Coplen TB, Emerson DG, Hubbard BE, Litke DW, Michel RL, Plummer LN, Rezai MT, Senay GB, Verdin JP, Verstraeten IM (2010) Conceptual model of water resources in the Kabul Basin, Afghanistan. U.S. Geological Survey Scientific Investigations Report 2009–5262, 240 pp

Mack TJ, Chornack MP, Taher MR (2013) Water-level trends and sustainable water in the Kabul Basin, Afghanistan. Environ Syst Decisions. https://doi.org/10.1007/s10669-013-9455-4

Mack TJ, Chornack MP, Flanagan SM, Chalmers AT (2014) Hydrogeology and water quality of the Chakari Basin, Afghanistan. U.S. Geological survey scientific investigations report 2014–5113, 35 pp

Mahanta C, Enmark G, Nordborg D, Sracek O, Nath BN, Nickson RT, Herbert R, Jacks G, Ramanathan AL, Mukherjee A, Bhattacharya P (2015) Understanding distribution, hydrogeochemistry and mobilization mechanism of arsenic in groundwater in a low-industrialized homogeneous part of Brahmaputra river floodplain, India. J Hydrol Reg Stud 4:154–171

Maheshwari RC (2006) Fluoride in drinking water and its removal. J Hazard Mater 137(1): 456–463

MPO (Master Plan Organisation) (1987) Groundwater Resources of Bangladesh. Technical report no 5. Master Plan Organization, Dhaka. Hazra, USA; Sir M MacDonald, UK; Meta, USA; EPC, Bangladesh

Mukherjee A (2018) Groundwater of South Asia. Springer, Singapore. ISBN 978-981-10-3888-4

Mukherjee A, Fryar AE, Thomas WA (2009a) Geologic, geomorphic and hydrologic framework and evolution of the Bengal basin, India. J. Asian Earth Sci 34(3):227–244

Mukherjee A, Fryar AE, O'Shea BM (2009b) Major occurrences of elevated arsenic in groundwater and other natural waters. In: Henke KR (ed) Arsenic—environmental chemistry, health threats and waste treatment. Wiley, Chichester, U.K., pp 303–350

Mukherjee A, Fryar AE, Scanlon BR, Bhattacharya P, Bhattacharya A (2011) Elevated arsenic in deeper groundwater of western Bengal basin, India: extents and controls from regional to local-scale. Appl Geochem 26:600–613

Mukherjee A, Saha D, Harvey CF, Taylor RG, Ahmed KM (2015) Groundwater systems of the Indian sub-continent. J Hydrol Reg Stud 4A:1–14

Panabokke CR (2001) Groundwater management in Sri Lanka. Econ Rev 27(8 & 9):19–22

Papa F, Frappart F, Malbeteau Y, Shamsudduha M, Vuruputur V, Sekhar M, Ramillien G, Prigentm C, Aires F, Clamant S (2015, this issue). Satellite-derived surface and sub-surface water storage in the Ganges-Brahmaputra River Basin. J Hydrol Reg Stud, 4:15–35

Rajasooriyar LD, Mathavan V, Dharmagunewardene HA, Nandakumar V (2002) Groundwater quality in the Valigamam region of the Jaffna Peninsula, Sri Lanka. In: Hiscock KM, Rivett MO, Davison RM (eds) Sustainable groundwater development. Special publications 193. Geological Society, London, pp 181–197

Ravenscroft P, Brammer H, Richards K (2009) Arsenic pollution: a global synthesis, vol 28. Wiley

Rodell M, Velicogna I, Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India. Nature 460:999–1002. https://doi.org/10.1038/nature08238

Saha D, Alam F (2014) Groundwater vulnerability assessment using DRASTIC and Pesticide DRASTIC models in intense agriculture area of the Gangetic plains. Environ Moni Assess, India. https://doi.org/10.1007/s10661-014-4041-x

Scanlon BR, Mukherjee A, Gates JB, Reedy RC, Sinha AN (2010) Groundwater recharge in natural dune systems and agricultural ecosystems in the Thar desert region, Rajasthan, India. Hydrogeol J 18(4):959–972

Senaratne A (2002) Groundwater exploration in Sri Lanka—personal experience. In: Proceedings of symposium Use of groundwater for agriculture in Sri Lanka, Peradeniya, Sri Lanka, 30 Sept 2002. Agricultural Engineering Society of Sri Lanka, Peradeniya, pp 23–28

Shamsudduha M, Taylor RG, Ahmed KM, Zahid A (2011) The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. Hydrogeol J 19:901–916

Shamsudduha M, Taylor RG, Longuevergne L (2012) Monitoring groundwater storage changes in the highly seasonal humid tropics: validation of GRACE measurements in the Bengal Basin. Water Resour Res 48:W02508. https://doi.org/10.1029/2011WR010993

Siebert S, Henrich V, Frenken K, Burke J (2013) Update of the digital global map of irrigation areas to version 5

Smedley P (2005) Arsenic occurrence in groundwater in South and East Asia—scale, causes and mitigation. Towards a more effective operational response: arsenic contamination of groundwater in South and East Asian countries, vol II. Technical report, World Bank report no. 31303

Tariq MN (1981) Survey of fluorides and their removal. Public Health Engineer. J. Pak Soc Public Health Eng Lahore

Thakur JK, Thakur RK, Ramanathan AL, Kumar M, Singh SK (2010) Arsenic contamination of groundwater in Nepal—an overview. Water 3(1):1–20

Tiwari VM, Wahr J, Swenson S (2009) Dwindling groundwater resources in northern India, from satellite gravity observations. Geophys Res Lett 36:L18401

UN-IGRAC (2014) Transboundary aquifers of the World. http://www.un-igrac.org/publications/320. Accessed on 20th Feb 2015

Van Steenbergen F, Kaisarani AB, Khan NU, Gohar MS (2015) A case of groundwater depletion in Balochistan: Enter into the void. J Hydrol Reg Stud 4:36–47

Verma S, Phansalkar SJ (2007) India's water future 2050: potential deviations from 'business-as-usual'. Int J Rural Manage 3:149–179

Verma S, Mukherjee A, Chaudhury R, Mahanta C (2015, this issue). Brahmaputra river basin groundwater: solute distribution, chemical evolution and arsenic occurrences in different geomorphic settings. J Hydrol Reg Stud 4:131–153

Villholth KG, Rajasooriyar LD (2010) Groundwater resources and management challenges in Sri Lanka–an Overview. Water Resour Manage 24(8):1489–1513

Watto MA, Mugera AW (2015) Econometric estimation of groundwater irrigation efficiency of cotton cultivation farms in Pakistan. J Hydrol Reg Stud 4:193–211

World Bank archive (WBA) (2015). http://data.worldbank.org/indicator/AG.LND.PRCP.MM. Accessed on 20 Jan 2015

Part II
Groundwater Availability: Exploration, Recharge and Storage

Chapter 2
Groundwater Availability in the Kabul Basin, Afghanistan

Thomas J. Mack

Abstract The Kabul Basin in eastern Afghanistan contains a sedimentary and semi-consolidated rock aquifer that is as much as 1,000 m thick. The city of Kabul is in the southern part of the basin where the population has doubled in the past 15 years to about 4.8 million in 2015, which represents about 15% of the total population of Afghanistan. This rapid population growth, together with potential impacts of climate change, has raised concern for groundwater availability, which is the primary source of drinking water in the basin. Rising groundwater levels indicate that the basin has emerged from the severe drought of the late 1990s and early 2000s that affected much of Afghanistan. However, groundwater level declines of up to 1.5 m/yr in the city of Kabul illustrate the concern for the sustainability of groundwater resources in the face of growing demands for water. Groundwater flow modeling has been used to estimate water resources in the basin, the potential effects of increased groundwater withdrawals, and potential climate-induced changes to recharge in the basin. Simulated increases in groundwater withdrawals will affect areas of the basin with the greatest population growth, while a climate-induced reduction in recharge may have a more widespread impact and may particularly affect areas near the mountain front. In addressing the sustainability of groundwater in the Kabul Basin, there are various options for water resource managers to explore while continued development of groundwater and surface water monitoring networks is needed.

2.1 Introduction

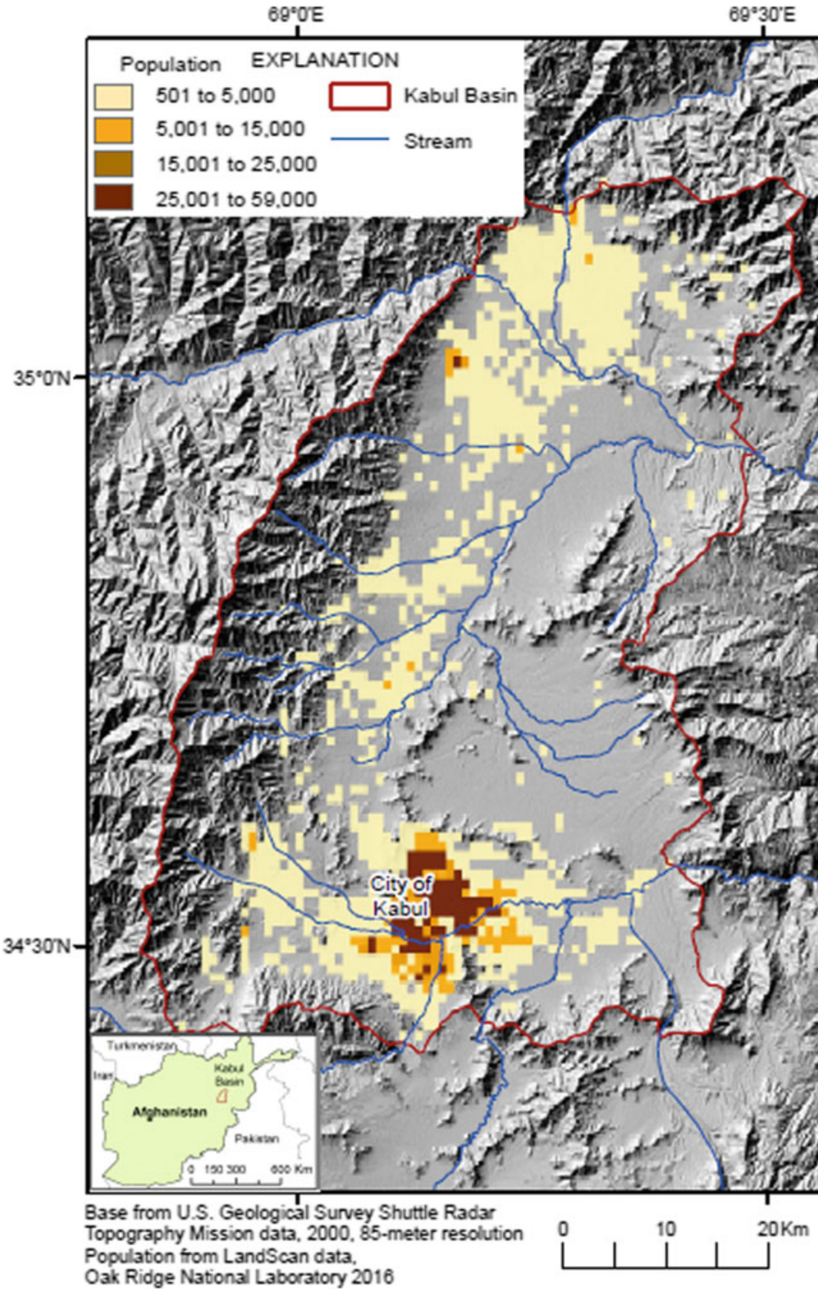
The Kabul Basin (Chap. 1, Fig. 1.3) is a fault block valley in eastern Afghanistan, approximately 80 km long and 10–35 km wide, which contains Afghanistan's capital city of Kabul in the southern part of the basin (Fig. 2.1). Groundwater is the primary source of drinking water supply in the basin and is increasingly being used

---

T. J. Mack (✉)
U.S. Geological Survey, Pembroke, NH, USA
e-mail: tjmack@usgs.gov

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_2



Base from U.S. Geological Survey Shuttle Radar Topography Mission data, 2000, 85-meter resolution
Population from LandScan data, Oak Ridge National Laboratory 2016

Fig. 2.1 Kabul Basin and estimated 2015 population, Afghanistan for agricultural irrigation. Between 2000 and 2015, the population of Kabul grew from 2.4 to 4.8 million (United Nations 2016) as a result of numerous factors including returning refugees, nationwide conflict, and relative security in Kabul, and population migration due to a drought that affected much of Afghanistan in the late 1990s. As of 2015, about 15% of the population of Afghanistan resides in the city of Kabul (Fig 2.1) (Oak Ridge National Laboratory 2016). This is the highest percentage of any one city in South or Central Asia (United Nations 2016). This rapid population growth, and the potential effects of climate change, has raised concern for the groundwater availability for a considerable proportion of Afghanistan's population and particularly those in the Kabul Basin.

Comprehensive investigations of the groundwater resources of the southern sub-basins of the Kabul Basin, immediately surrounding the city of Kabul, include those of Böckh (1971), Houben et al. (2009), Myslil et al. (1982), and Niard (2007). The investigations of Broshears et al. (2005) and Mack et al. (2010) covered the entire Kabul Basin. Niard's (2007) investigation, in the sub-basins of the southern Kabul Basin, includes a numerical groundwater flow model that was valuable for the conceptual understanding of the groundwater flow system. Mack et al. (2010) developed a groundwater flow model of the entire Kabul Basin, also to assess the conceptual understanding of the flow system and to estimate the effects of increasing groundwater withdrawals with population growth and the potential effects of climate change on groundwater availability in the basin. More related information regarding groundwater of South Asia are available in Mukherjee (2018).

2.2 Climate

The Kabul Basin is a semiarid region that receives approximately 330 mm of precipitation annually with the highest precipitation historically occurring during winter months as snow (Mack et al. 2010). Much of Afghanistan was in a drought from about 1998 to 2004, with reports that Kabul received no precipitation during this period (International Water Management Institute 2002). The rate of evapotranspiration in the basin, 1600 mm/yr, is much greater than total precipitation resulting in little if any groundwater recharge by direct precipitation on the land surface. Therefore, the winter snowpack in the mountains adjacent to the Kabul Basin is an important source of recharge in the Kabul Basin (Mack et al. 2010). The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) found that Central Asia, including Afghanistan, was particularly at risk for increasing warming temperatures (Cruz et al. 2007). This assessment has not changed in more recent IPCC analyses (IPCC 2014).

Although a gap of more than 20 years exists in Afghanistan's climate record, preliminary analysis of limited temperature data noted increasing monthly mean temperatures in the city of Kabul (Fig. 2.2). The greatest change in monthly mean temperatures was observed in February (Mack et al. 2010). Warming winter

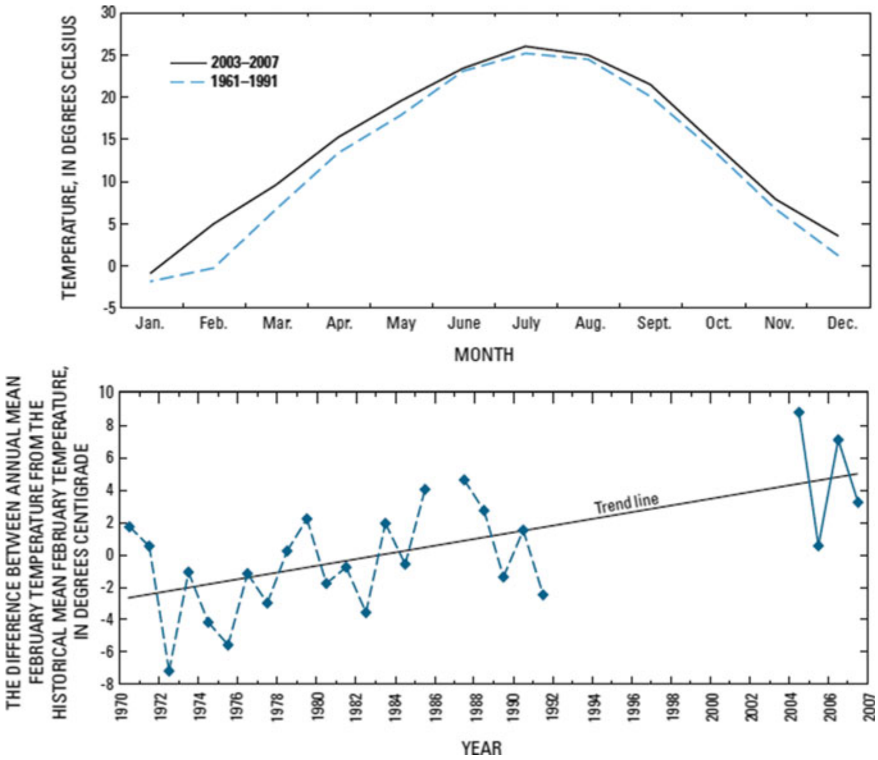


Fig. 2.2 Graphs of monthly mean temperatures for 1961–1991 and 2003–2007, and difference in mean February temperature from historical mean February temperature for 1970–2006, at Kabul, Afghanistan

temperatures may decrease spring recharge and snowmelt may occur earlier in the year, further from the summer growing period when it is most needed. Along this line, the IPCC Working Group 2 ranked the water resources of central and west Asia as “highly vulnerable” to impacts of climate change at a “very high” level of confidence (Cruz et al. 2007).

2.3 Geohydrology

The surficial geology of Afghanistan had been mapped by Soviet and Afghanistan Geological Survey (AGS) efforts prior to 1980. The Soviet-AGS maps were refined by the USGS, and surficial geologic maps of the Kabul Basin are provided by Bohannon (2010a, b). The primary aquifer in the Kabul Basin is a surficial sedimentary aquifer, consisting of alluvium and loess, in the base of a valley formed by eastern and western flanking mountain ranges of various rock types (Fig. 2.3).

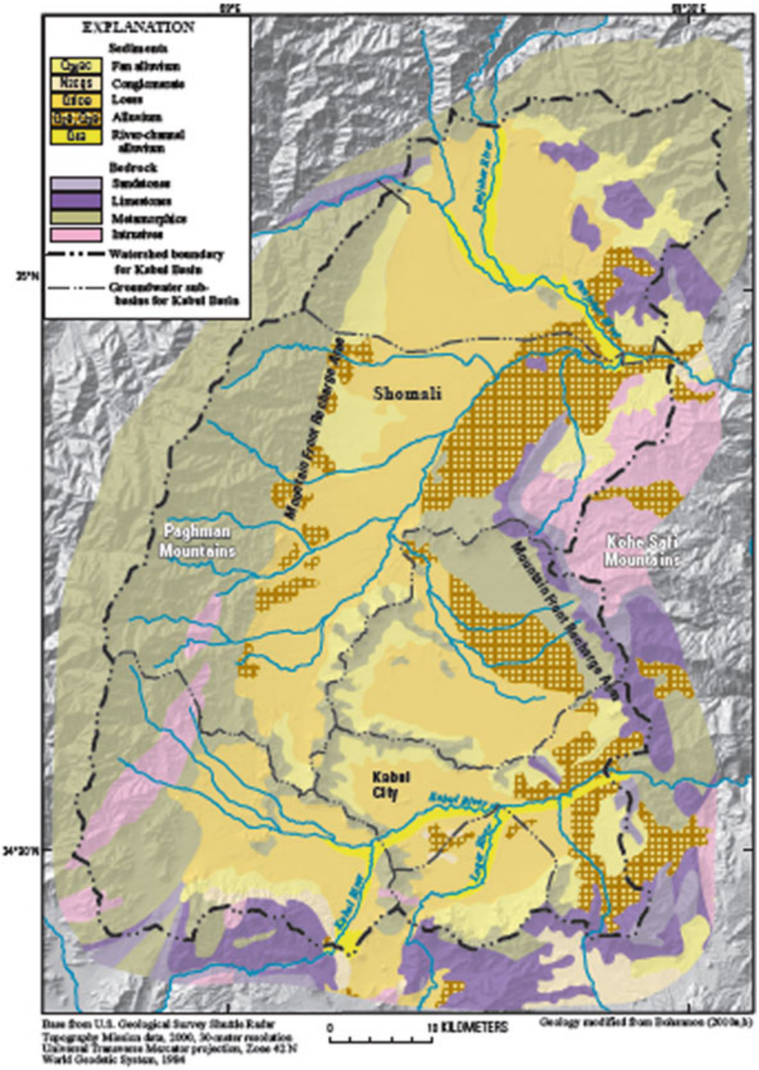


Fig. 2.3 Generalized surficial geology of the Kabul Basin, Afghanistan. Modified from (Mack et al. 2010)

Figure 2.4 presents a generalized schematic diagram of the Kabul Basin (Mack et al. 2010). This conceptualization was used to develop a groundwater flow model for estimation of the effects of increasing groundwater withdrawals and climate change on the basin's groundwater availability. The thickness of the surficial aquifer is generally less than 80 m but may be 200 m or greater in the center of the valley, particularly in the northern Kabul Basin (Böckh 1971). Reworked river channel alluvium along the main river channels in the basin (Fig. 2.3)

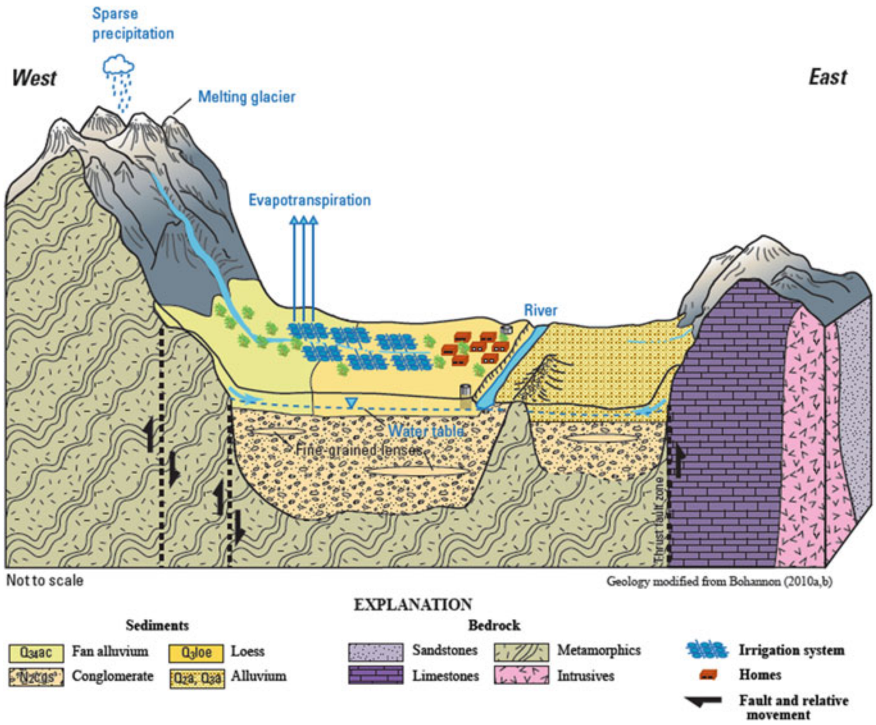


Fig. 2.4 Generalized schematic diagram of the Kabul Basin, Afghanistan. Modified from (Mack et al. 2010)

has been estimated to be highly transmissive (more than 100 m/d, Böckh 1971) which allows for considerable infiltration from the Kabul River and its tributaries. The underlying semi-consolidated Neogene conglomerates are up to 1,000 m thick and represent a lower yielding secondary aquifer system (Homilius 1969; Japan International Cooperation Agency 2007). Sub-basins in the Kabul Basin are formed by interbasin bedrock ridges. The southern part of the Kabul Basin is separated into several sub-basins where the southernmost contain the city of Kabul (Figs. 2.3 and 2.4). The interbasin ridges restrict, or prevent, groundwater flow between sub-basins of the Kabul Basin.

2.4 Recharge

Recharge to the Kabul Basin aquifer system occurs primarily from infiltration leakage from streams and irrigated areas in the basin, and from mountain front recharge at the valley walls adjacent to the basin (Figs. 2.3 and 2.4) (Mack et al. 2010). Very little recharge occurs from precipitation directly on the aquifer.

Direct precipitation recharge is primarily from larger precipitation events, or snowmelt, during the non-growing periods. Chemical and isotopic analysis of groundwater in the basin found that groundwater in the surficial primary aquifer was generally less than 30 years old, becoming older further from recharge areas (Mack et al. 2010). Carbon-14 analysis of groundwater at the top of the lower secondary aquifer was several thousand years old and may be much greater at depth (Mack et al. 2010). Based on analysis of historical streamflows (Olson and Williams-Sether 2010), and chemical and isotopic data, mean annual recharge on the 780 km^2 basin floor area was estimated to be approximately 8.2 Mm^3 from river leakage and 2.8 Mm^3 from irrigation leakage and recharge directly on the land surface (Mack et al. 2010). Streamflow into the northern Kabul Basin was about five times that of the southern basin. The northern Kabul Basin is fed by the Panjsher River and its tributaries (Fig. 2.3) which, as of 2007, contained approximately 66 km^2 of glacier-covered area (Mack et al. 2010). The Kabul River and its tributaries drain lower elevation upland areas with no glaciers. Analysis of historical streamflow data for rivers and tributary streams flowing into the Kabul Basin found an average annual runoff per square kilometer of 0.020 m^3/s for the northern drainages compared to 0.004 m^3/s for the southern drainages (Mack et al. 2010). Additionally, the Panjsher River streamflow, and the other northern drainages, typically peaks in June or July about 2 months later than streamflow in the Kabul River (April) and the southern drainages. The timing of the streamflows in the northern Kabul Basin, particularly the higher flows later in the summer months in the northern part of the basin, is critical for agriculture needs and recharging groundwater during the seasonal high demand.

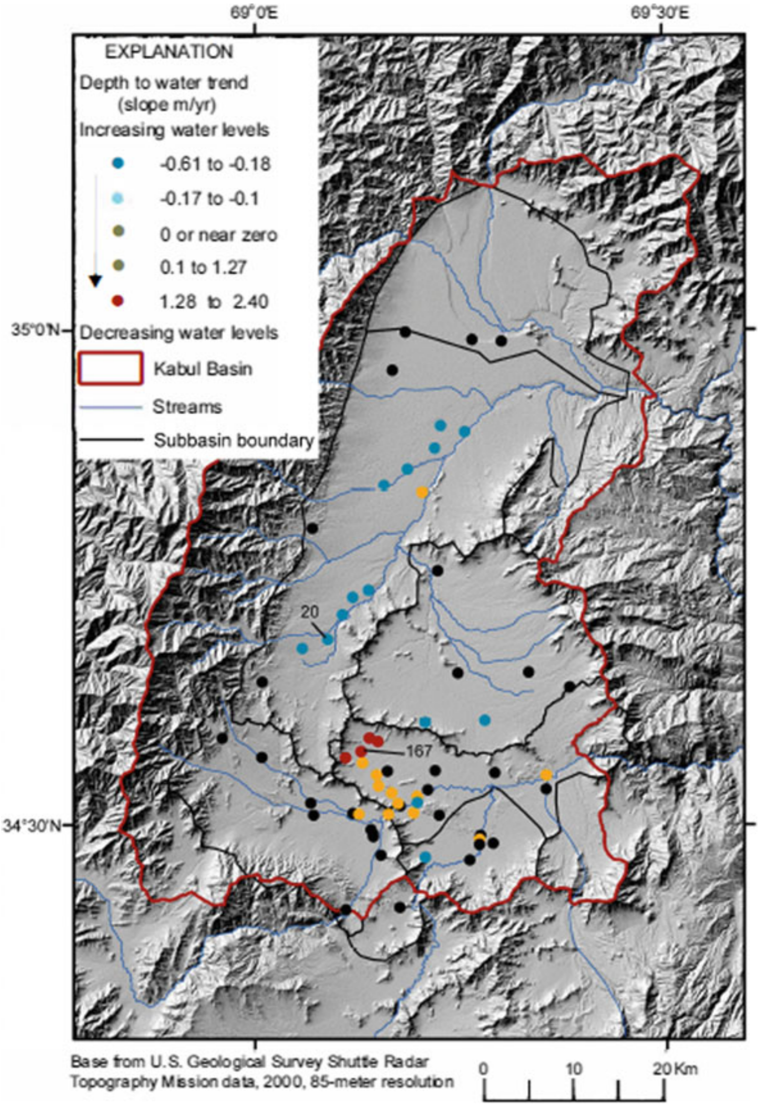
2.5 Groundwater Availability and Future Needs

Historically, drinking water for many areas of the Kabul Basin was supplied by shallow hand dug wells or karezes, a hand dug water conveyance system that skims water from an upgradient water table. The amount of agricultural water use in the basin is unknown but is likely to be an order of magnitude greater than that of domestic use. Historically, this use was supplied by kareze flows and channel diversions from streamflow. However, agricultural use is increasingly being supplied by pumped groundwater, which is leading to kareze failures throughout Afghanistan (Goes et al. 2017). The decline in functional karezes has been documented in the Kabul Basin and in the Chakari Basin, about 20 km southeast of the city of Kabul (Mack et al. 2014a, b). Municipal water use in the Kabul Basin is not metered but was estimated to be about 46,765 mL/yr (128,000 m^3/d) based on a 2002 population of 3.5 million and a per capita use estimate of 25 L/d (Mack et al. 2010). The per capita water use rate and agricultural demands are expected to increase in the future with the rising living standards and population growth. United Nations projections estimate the population in the Kabul Basin to grow to about 9 million by the year 2057 (United Nations 2015). With an expected per capita use rate of 78 L/d, closer to other surrounding countries, the projected drinking water use rate in the basin would increase to about 725,000 m^3/d, a sixfold increase (Mack et al. 2010).

Between 1997 and 2005, non-governmental organizations had installed more than 1500 shallow drinking water supply wells, with a median depth of 22 m, in the Kabul Basin (Safi and Vijselaar 2007). About 25% of those wells in the city of Kabul, and about 20% of those in the larger Kabul Basin, were reported to be dry (Safi and Vijselaar 2007). There also are anecdotal reports of groundwater level declines of up to 10 m in the city in the early 2000s (Uhl 2006). A simulated sixfold increase in groundwater withdrawals was projected to result in groundwater level declines of 0.5 m, at 54% of the basin's wells, and more than 1.0 m at 36% of the wells (Mack et al. 2010). Given that most of the wells in the basin are screened at the water table such groundwater level declines may cause many wells to be seasonally inoperative or dry in the future.

An analysis of groundwater level trends between 2004 and 2012 in the Kabul Basin (Fig. 2.5) was conducted on 70 wells monitored by the AGS and 10 wells monitored by the Danish Committee for Aid to Afghan Refugees (DACAAR). The study found that although groundwater levels in the basin were recovering from the drought of the late 1990s and early 2000s, at rates of up to 0.6 m/yr, there were declines of more than 1.5 m/yr in the city of Kabul (Mack et al. 2013). Monthly groundwater levels between 2004 and 2012, for two AGS network wells in the Kabul Basin, are shown in Fig. 2.6. Well 20 (Fig. 2.6a) located in the Shomali sub-basin (Figs. 2.3 and 2.5) shows a groundwater level rise of about 5 m since the early 2000s while at well 167 (Fig. 2.6b) in the city of Kabul in the Central Kabul sub-basin (Figs. 2.3 and 2.5), groundwater levels have declined more than 15 m in this same period. The areal extent of measured groundwater declines in the city of Kabul, for the September 2008–2012 period with the greatest measured declines (Mack et al. 2013), was in line with groundwater model simulated declines due to projected population growth (Mack et al. 2010) (Fig. 2.7). The sub-basin containing a large part of the city of Kabul is isolated by interbasin ridges from the major sources of recharge in the region such as mountain front recharge and irrigation leakage. The primary source of groundwater recharge to the city of Kabul is leakage from the Kabul River while flow from the river to this area is restricted by ridges with low permeability (Fig. 2.7).

The potential effects of climate change on the water resources of Southeast Asia and Afghanistan's have been examined by numerous investigations including Milly et al. (2005), Vining and Vecchia (2007), and the IPCC (2014). Potential changes identified by these studies include warming temperatures, which could result in earlier spring-melt peak recharge events, and increased rates of evapotranspiration. Groundwater flow simulations of a 10% reduction in recharge, as suggested by Vining and Vecchia (2007), result in even greater, and more widespread, groundwater level declines in the Kabul Basin than were simulated by increasing groundwater withdrawals (Mack et al. 2010). An earlier annual recharge peak, from snow and glacier melt, would greatly reduce the available water in the Kabul Basin and particularly in the northern areas of the basin where this peak typically occurs during the summer growing period.



Base from U.S. Geological Survey Shuttle Radar Topography Mission data, 2000, 85-meter resolution

Fig. 2.5 Groundwater level trends from 2004 to 2012 in the Kabul Basin, Afghanistan. From (Mack et al. 2013)

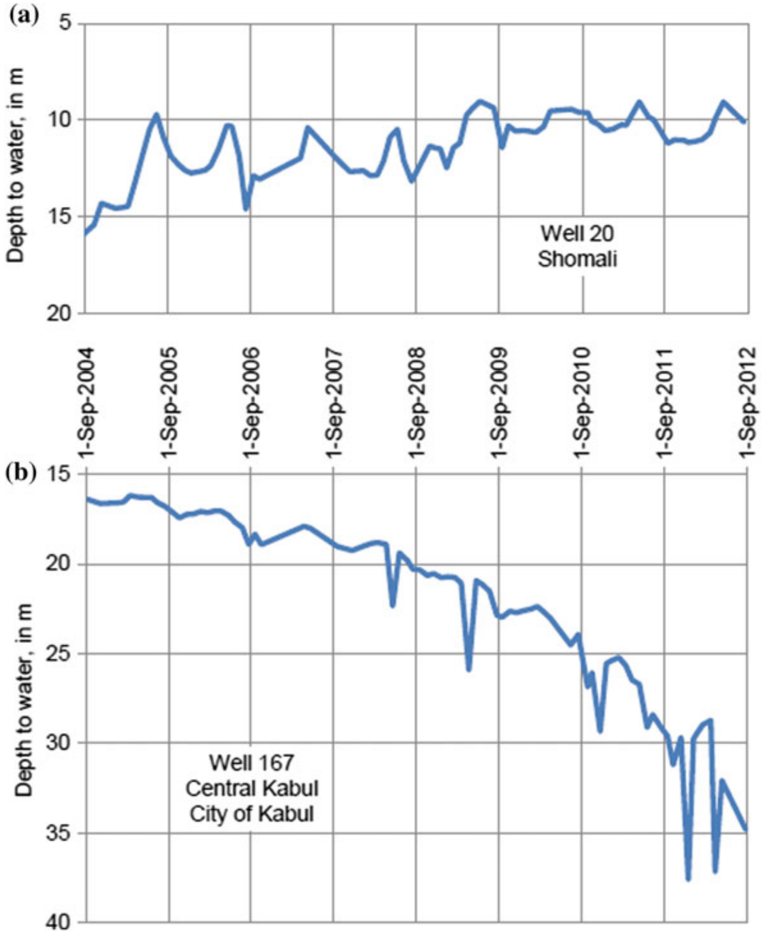
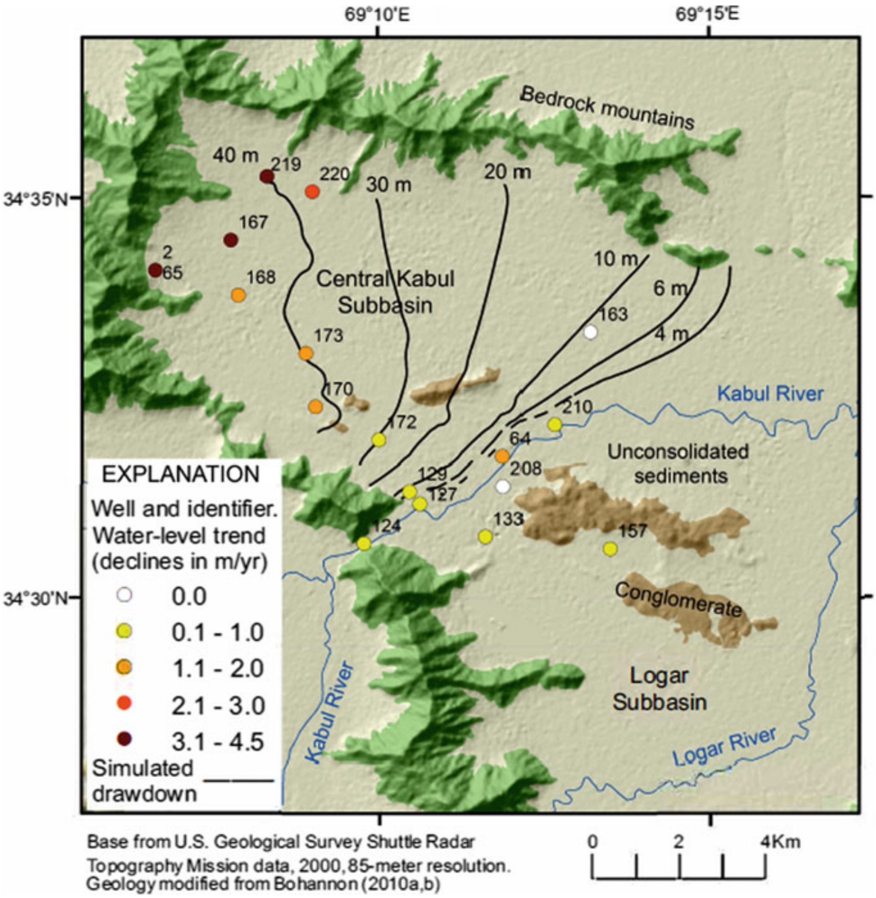


Fig. 2.6 Depth to water at Afghanistan Geological Survey groundwater network wells in Shomali (**a**) and Kabul city (**b**). From (Mack et al. 2013)

2.6 Discussion

The availability of groundwater in the Kabul Basin is challenged by droughts, the growing population's increasing needs for water, and potential changes to the timing or quantity of recharge due to climate change. To help address future water needs water managers may explore several options. The deep, or secondary, semi-consolidated aquifer, underlying the primary surficial aquifer, may represent a relatively unused source of water with considerable storage. However, the deep aquifer has a relatively low permeability and coarse-grained lenses within this aquifer would need to be identified in order to support large groundwater withdrawal rates. Additionally, the age of the groundwater in the deep aquifer is likely



Base from U.S. Geological Survey Shuttle Radar Topography Mission data, 2000, 85-meter resolution. Geology modified from Bohannon (2010a,b)

Fig. 2.7 Groundwater level trends between 2008 and 2012, and simulated drawdown with a projected sixfold population increase, in the city of Kabul, Afghanistan. From (Mack et al. 2013)

to be two or more orders of magnitude greater than that of the surficial aquifer and therefore may have an undesirably high dissolved solids content. Another potential source of water includes capturing more of the spring high flows and designing means to increase the infiltration of that water. Thirdly, the northern Kabul Basin has much greater recharge and groundwater in storage than the southern basin and water systems may be designed to make wider use of water in the northern basin. However, water availability in the northern basin is dependent on snow and glacier melt and the timing of such water may be impacted by climate change. These factors highlight the importance of continued groundwater level and surface water flow monitoring and exploration of comprehensive water management strategies.

References

Böckh EG (1971) Report on the groundwater resources of the city of Kabul, Report for Bundesanstalt fur Geowissenschaften und Rohstoffe [unpublished]. BGR file number: 0021016, 43 pp

Bohannon RG (2010a) Geologic and topographic maps of the Kabul North 30’ x 60’ quadrangle, Afghanistan. U.S. Geological Survey Scientific Investigations Map 3120, 2 map sheets, scale 1:100,000, 34 pp

Bohannon RG (2010b) Geologic and topographic maps of the Kabul South 30′ × 60′ quadrangle, Afghanistan. U.S. Geological Survey Scientific Investigations Map 3137, pamphlet, 2 map sheets, scale 1:100,000, 34 pp

Broshears RE, Akbari MA, Chornack MP, Mueller DK, Ruddy BC (2005) Inventory of ground-water resources in the Kabul Basin, Afghanistan. U.S. Geological Survey Scientific Investigations Report 2005–5090, 34 pp

Cruz RV, Harasawa H, Lal M, Wu S, Anokhin Y, Punsalmaa B, Honda Y, Jafari M, Li C, Huu Ninh N (2007) Asia, climate change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge, U.K., pp 469–506

Goes BJM, Parajuli UN, Haq M, Wardlaw RB (2017) Karez (qanat) irrigation in the Helmand River Basin, Afghanistan: a vanishing indigenous legacy. Hydrogeol J 25:269–286. https://doi.org/10.1007/s10040-016-1490-z

Homilius J (1969) Geoelectrical investigations in east Afghanistan. Geophys Prospect 17(4): 468–487

Houben G, Niard N, Tunnermeier T, Himmelsbach T (2009) Hydrogeology of the Kabul Basin (Afghanistan), part I: aquifer and hydrology. Hydrogeo J 17:665–677

Intergovernmental Panel on Climate Change (2014) Climate change 2014: synthesis report. In: Core writing team, Pachauri RK, Meyer LA (eds) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change, IPCC, Geneva, Switzerland, 151 pp. http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

International Water Management Institute (2002) Current drought situation in Afghanistan. http://www.iwmi.cgiar.org/droughtassessment/files/pdf/Drought2000inAfghanistan.pdf

Japan International Cooperation Agency (2007) Study on groundwater resources potential in Kabul Basin, in the Islamic Republic of Afghanistan. Sanyu Consultants, Kabul, 20 pp

Mack TJ, Akbari MA, Ashoor MH, Chornack MP, Coplen TB, Emerson DG, Hubbard BE, Litke DW, Michel RL, Plummer LN, Rezai MT, Senay GB, Verdin JP, Verstraeten IM (2010) Conceptual model of water resources in the Kabul Basin, Afghanistan. U.S. Geological Survey Scientific Investigations Report 2009–5262, 240 pp. https://pubs.usgs.gov/sir/2009/5262/

Mack TJ, Chornack MP, Taher MR (2013) Water-level trends and sustainable water in the Kabul Basin. Environment, Systems and Decisions, Afghanistan. https://doi.org/10.1007/s10669-013-9455-4

Mack TJ, Chornack MP, Verstraeten IM (2014a) Sustainability of water supply at military installations, Kabul Basin, Afghanistan. In: Sustainable cities and military installations: climate change impact on energy and environmental security, NATO Science for Peace and Security Series: C: Environmental Security. http://link.springer.com/chapter/10.1007/978-94-007-7161-1_11#

Mack TJ, Chornack MP, Flanagan SM, Chalmers AT (2014b) Hydrogeology and water quality of the Chakari Basin, Afghanistan. U.S. Geological Survey Scientific Investigations Report 2014–5113, 35 pp. http://dx.doi.org/10.3133/sir20145113

Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. Nature 438:347–350

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore, ISBN 978-981-10-3888-4

Myslil V, Eqrar MN, Hafisi M (1982) Hydrogeology of Kabul Basin (translated from Russian). Sponsored by the United Nations Children's Fund and the Ministry of Water and Power, Democratic Republic of Afghanistan, p 47

Niard N (2007) Hydrogeology of the Kabul Basin, Part III: Modeling approach, Conceptual and numerical models. Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany, p 103

Oak Ridge National Laboratory (2016) LandScan 2015 worldwide population database. http://web.ornl.gov/sci/landscan/

Olson SA, Williams-Sether T (2010) Streamflow characteristics at streamgages in northern Afghanistan and selected locations. U.S. Geological Survey Data Series 529, 512 pp. https://pubs.usgs.gov/ds/529/

Safi H, Vijselaar L (2007) Groundwater monitoring, evaluation of groundwater data. DACAAR, Kabul, Afghanistan, p 99

Uhl VW (2006) Afghanistan—an overview of groundwater resources and challenges. Ground Water 44(5):626–627

United Nations Department of Economic and Social Affairs, Population Division (2015) World population prospects: the 2015 revision, vol. I: comprehensive tables (ST/ESA/SER.A/379)

United Nations Department of Economic and Social Affairs, Population Division (2016) The world's cities in 2016—data booklet (ST/ESA/SER.A/392)

Vining KC, Vecchia AV (2007) Water-balance simulations of runoff and reservoir storage for the Upper Helmand watershed and Kajakai Reservoir, Central Afghanistan. U.S. Geological Survey Scientific Investigations Report 2007–5148, 17 pp

Chapter 3
Estimating Present-Day Groundwater Recharge Rates in India

Abhijit Mukherjee and Soumendra Nath Bhanja

Abstract Large number of people in the globe depends on groundwater as a major source of freshwater. Here, we provide present-day regional-scale groundwater recharge rates in a major part of the Indian subcontinent. We have used a combination of ground-based observed water level data obtained from an intense network of observational wells, along with satellite and global land-surface model-based outputs to calculate our estimates. Large variations were observed in the spatial groundwater recharge rates over the region based on geology and climate. High groundwater recharge rates (>300 mm/year) are observed over the highly fertile alluvial plains of Indus–Ganges–Brahmaputra (IGB) system. Comparatively higher rate of precipitation, high porosity and permeability of the unconsolidated fluvial deposits and rapid groundwater withdrawal (>90% of groundwater withdrawal are associated with irrigation) synergistically influence high recharge rates. Most of the regions on the central and southern study areas exhibit lower recharge rates (<200 mm/year). Magnitude of estimated recharge rates was quite similar from different approaches of groundwater recharge calculation; however, inconsistency in the output of different approaches over some of the regions is discussed herein.

Keywords Groundwater recharge · Indian subcontinent · Water table fluctuation
Water budget

A. Mukherjee (✉) · S. N. Bhanja
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology, Kharagpur, India

A. Mukherjee
Applied Policy Advisory to Hydrogeosciences Group, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_3

3.1 Introduction

Groundwater is the largest source of freshwater available in the globe. Large number of people solely depends on groundwater to fulfill their requirement of potable water (Bates et al. 2008). The number will increase further as the population continues to increase. However, the balance between global groundwater depletion rates with natural renewal rate is still unclear (Gleeson et al. 2012). Therefore, groundwater resource quantification is a solemn issue in the densely populated regions of the globe, where it is a challenging task to provide adequate amount of water to every citizen of present and future. Thus, as a component of groundwater resource quantification, groundwater recharge estimation became important in recent times. The downward movement of water reaching water table can be termed as groundwater recharge, which ultimately increases the amount of groundwater storage (Healy 2010).

Intense agricultural activities in parts of the densely populated Indian subcontinent are highest in the world in terms of percentage of irrigated land (Siebert et al. 2013). More than 50% of the irrigational water demand has been fulfilled by abstracting groundwater (CGWB 2009). World Bank (1998) and Ministry of Water Resources, Government of India, estimated approximately 9% of India's GDP has come from groundwater. However, so far, only few studies (Goel et al. 1975; Bhandari et al. 1982; Athavale et al. 1992; Rangarajan et al. 1995, 1997, 1998; Athavale et al. 1998; Rangarajan and Athavale 2000; Scanlon et al. 2010) have reported groundwater recharge rates in some sporadic locations (Fig. 3.1). Highest groundwater stress has been indicated on upper Ganges aquifer of India and Pakistan among all the global aquifers (Gleeson et al. 2012). Although, groundwater is an annually renewable resource but the rate and space of renewal are extremely heterogeneous and anisotropic in time and space.

Difficulties in direct measurement of groundwater recharge and its enormous temporal and spatial variation account for the complexity in recharge rate estimation processes (Healy 2010). In absence of availability of high resolution, local-scale datasets for aquifer properties, climatic parameters, and other influencing factors that could be used in a complicated calculation of recharge, a simple method like WTF has been preferably used in many studies because of the minimal assumptions associated with it. Recharge estimation techniques based on observed groundwater data collected below the water table or piezometric surface provide actual recharge rates (Rushton 1997; Scanlon et al. 2002). Out of these, in spite of several limitations, water table fluctuation (WTF) method might be the most widely used technique for estimation of groundwater recharge (Healy and Cook 2002). Moreover, WTF method can be successfully executed over a large area (Healy and Cook 2002), simultaneously.

Recharge can be estimated by balancing all of the hydrological components in the form of input and output of water by water budget method. Scanlon et al. (2002) extensively described balancing techniques between various hydrologic parameters; however, lack of accurate measurement of hydrologic parameters introduces errors

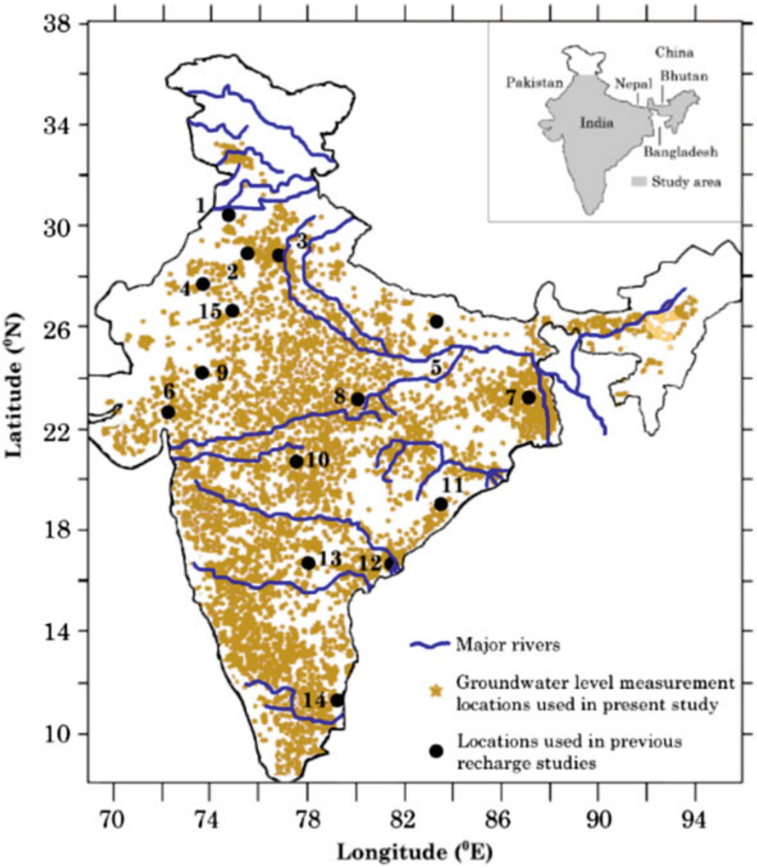


Fig. 3.1 Map of the study area showing locations of groundwater level measurement that are used in this study. Groundwater recharge estimates using chemical tracer method in 15 different locations obtained from previous studies are marked with black filled circles. The numbers beside these locations correspond to serial numbers in Table 3.1

in the recharge estimation through water budget method. As recharge rate is small compared to most of the other influencing parameters, particularly evapotranspiration, small uncertainty in these parameter values can create enormous error in recharge estimation. Therefore, some authors (e.g., Gee and Hillel 1988; Lerner et al. 1990; Hendrickx and Walker 1997) questioned about the usefulness of water budget methods. However, recent advancement in geophysical techniques, remote sensing, and modeling has lowered the magnitude of error; hence, the simplistic water budget method becomes the backbone of most of the hydrological modeling studies (Healy 2010). This recharge process can be termed as direct recharge by meteoric inflow only (Mukherjee et al. 2007), as it deals with the precipitated water and neglects any other type of inflows.

In this study, groundwater recharge is estimated for the present time for a large part of the densely populated India (Chap. 1, Fig. 1.1) from numerous ground-based water level measurements. Direct groundwater recharge by meteoric inflow is also estimated through a combination of satellite and model-based approach. Finally, recharge information from both of the estimation methods is compared over the entire study region to indicate the discrepancies of result of these studies. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

3.2 Methods

3.2.1 Study Area

Groundwater recharge dominantly takes place over the study area from monsoonal rainfall (between June and September), which accounts for most (>74%) of the annual precipitation (Guhathakurta and Rajeevan 2008; Scanlon et al. 2010). Precipitation data were obtained from the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al. 2000), a joint satellite mission between National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), that was designed to observe rainfall in the tropical countries. We have also used long-term (1961–2007) gridded precipitation data from the archives of Asian Precipitation Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE) (Yatagai et al. 2012). The APHRODITE team has archived real-time precipitation measurement data through their own data collection processes and National hydrological and meteorological services (NHMs) under World Meteorological Organization (WMO) agreement (Yatagai et al. 2012). Precipitation data show distinct spatial variation (Chap. 1, Fig. 1.1) resulting to extreme humid to arid climate over the Indian region. Precipitation pattern also suggests the spatial nature of the potentially available meteoric water for groundwater recharge. The entire region is composed of various different hydrogeologic setting (CGWB 2012), varying from highly permeable fluvial sediments in the Indus–Ganges–Brahmaputra (IGB) aquifers to fractured, crystalline rock aquifers in cratonic parts of peninsular India (Chap. 1, Fig. 1.4). As a result, the IGB basin has been subjected to rapid groundwater withdrawal comparing other parts of India (Mukherjee et al. 2015).

3.2.2 Water Table Fluctuation (WTF) Method

The principle of WTF method deals with determination of groundwater recharge rates as an outcome of water level increase in an unconfined aquifer (Healy and

Cook 2002). Ground-based observation data locations ($n > 13{,}000$) were obtained from achieves of Central Groundwater Board (CGWB, Government of India) to calculate annual groundwater level changes (Δh) from 2007 to 2011. Initially, the data were screened to get temporally uniform, continuous dataset over all the selected locations ($n > 5500$, Fig. 3.1) for each year. Annual fluctuation in groundwater level at each observation location was calculated by subtracting the lowest from the highest groundwater depth for each year. In order to get error-free estimates, water level values beyond the range of third quartile (75%) of the selected locations of each year were omitted from the further analyses, resulting to at least ~4500 locations for each year. Values of Δh values were gridded by kriging ($0.1° \times 0.1°$) over the entire study region. Aquifer specific yield (S_y) values were obtained from CGWB and assigned according to aquifer characteristics. Average S_y value ranges between 0.02 and 0.13 within the study area (CGWB 2012). Gridded ($0.1° \times 0.1°$) S_y was created based on the hydrogeological setting of the study area. In each grid cell, annual recharge rate is calculated by multiplying Δh with S_y.

Minimal assumptions in the measurement techniques and lack of influence of preferential flow paths are some major advantages of using WTF method (Healy and Cook 2002). However, Healy and Cook (2002) noted some disadvantages of this method, e.g., WTF method will not be suitable in recharge estimation within confined aquifer; best recharge estimates will be found in regions with shallow water table, which perfectly represent small changes in water level associated with groundwater depletion or replenishment; the point location(s) should be the best possible representative of each grid cells; uncertainty may arise due to improper assumption of S_y. One of the major drawbacks of WTF method is the incapability of removing inter-aquifer flow from recharge calculation. Errors related to lateral flow from large surface water bodies are also debatable issue here.

3.2.3 Water Budget (WB) Method

Water budget method deals with conservation of mass of water components, i.e., total water input equals to the total water output. A simple but effective approach is used here to calculate gridded ($1° \times 1°$) groundwater recharge rate (R) by water budgeting as (Healy 2010)

$$R = P - \mathrm{ET} - \Delta\mathrm{SM} - \mathrm{SR} \tag{3.1}$$

Precipitation (P) data are used from the database of the TRMM. Evapotranspiration (ET), surface runoff (SR), and change in soil moisture storage (ΔSM) data are obtained from the archives of the Community Land Model (CLM) (Dai et al. 2003) which operates as a part of Global Land Data Assimilation System (GLDAS) (Rodell et al. 2004). The model simulates soil moisture up to a depth of 3.4 m below the ground surface; consequently, soil moisture below that depth is not considered in this study. Also, it is not possible to consider rejected recharge because of aquifer full condition, by using WB method. Unavailability of absolute quantification of irrigational groundwater withdrawal and return flow of water volumes from irrigated land restricted us to include agricultural influence in estimating recharge through WB method. The calculated recharge does not take into account the presence of near-surface confining layers, thereby adding errors in the calculation.

3.3 Result and Discussion

3.3.1 Groundwater Recharge Rate Estimates

Groundwater recharge through WTF method demonstrates high spatial variation (Fig. 3.2) for each year within the study period. High recharge rate (>300 mm/year) was observed in most of the regions of IGB basin. Apart from comparatively higher rate of precipitation, high effective porosity and permeability of the unconsolidated sediments, mostly unconfined aquifers in these basins influence higher recharge rate. Furthermore, higher groundwater withdrawal rate caused by intense irrigation over the region (Siebert et al. 2013) accelerates the depletion of water storage and level during pre-monsoon period; thus creating more recharge space, resulting to higher amount of recharge during monsoon period. On the other hand, irrigation increases recharge rate by allowing infiltration of irrigational return flow though the groundwater cultivated lands (Mukherjee et al. 2007). Thus, as a function of agricultural land use pattern, the magnitude of recharge rate is not same everywhere within IGB basin (Chap. 1, Fig. 1.3). Most of the areas on the central and southern parts of study area exhibit lower recharge rates (<200 mm/year). The crystalline rock aquifers in those regions might provide hindrance to direct infiltration of potential recharge water, thus causing an imbalance between available precipitation

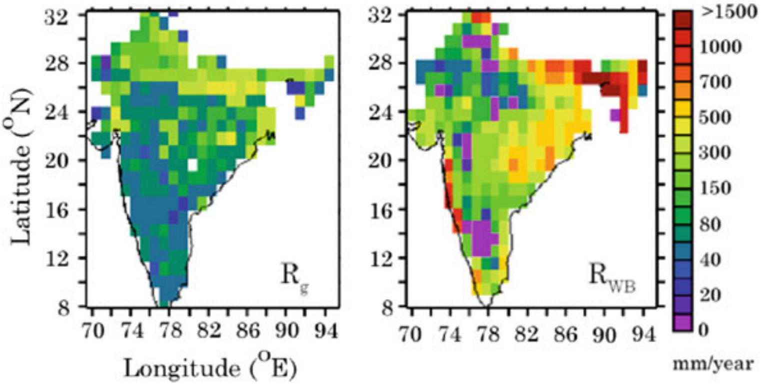


Fig. 3.2 Annual mean values of R_{WB} and R_{g}

water and fluctuation of the water table. Further, relatively lower rates of precipitation (Chap. 1, Fig. 1.1) are also a reason for lower recharge rates observed in parts of the central and southern study region.

The data obtained from this study compare well (Table 3.1) with many previous estimates of groundwater recharge reported from the region. However, recharge rates (WTF method) estimated in this study overestimate the recharge rate reported

Table 3.1 Comparison of groundwater recharge rates over parts of the Indian subcontinent

S. No.	Locations	R_g (mm/year), present study	R_{WB} (mm/year), present study	Recharge rates (mm/year) by chemical tracer methods in previous studies (study year)
1.	Punjab	205.92	207.14	56[a] (1972)
2.	Haryana	224.22	201.19	70[a] (1973)
3.	Western Uttar Pradesh	221.40	46.39	195[a] (1971)
4.	Churu District, Rajasthan	251.70	33.30	62[b] (1994–95)
5.	Nalanda district, Bihar	328.54	10.32	82[c] (1996)
6.	Sabarmati basin, Gujarat	382.50	184.56	107[d] (1973–76)
7.	Bankura district, West Bengal	462.46	549.36	179[e] (1995)
8.	Shahdol district, Madhya Pradesh	79.36	432.34	98[f] (1992)
9.	Upper Hatni watershed, Madhya Pradesh	106.15	134.36	17–275[c] (1993)
10.	Jam basin, Maharashtra	55.82	287.16	131[g] (1988)
11.	Parlijhori watershed, Odisha	51.17	454.74	166[c] (1996)
12.	East Godavari dist, Andhra Pradesh	231.76	250.82	90[c] (1997)
13.	Gaetec watershed, Andhra Pradesh	50.63	213.67	46[h] (1997)
14.	Neyveli basin, Tamil Nadu	59.07	429.68	161[g] (1985)
15.	Jaipur, Rajasthan	264.60	108.15	50–120[i] (2008)

[a]Goel et al. (1975); [b]Athavale et al. (1998); [c]Rangarajan and Athavale (2000); [d]Bhandari et al. (1982); [e]Rangarajan et al. (1997); [f]Rangarajan et al. (1995); [g]Athavale et al. (1992); [h]Rangarajan et al. (1998); [i]Scanlon et al. (2010)

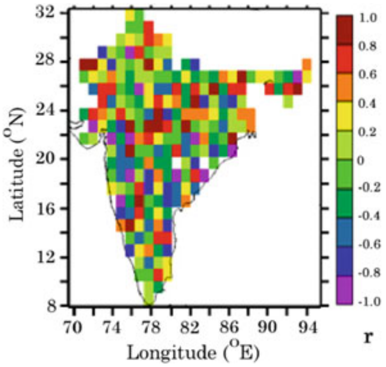
in some other studies (Goel et al. 1975; Bhandari et al. 1982; Rangarajan et al. 1997; Athavale et al. 1998; Scanlon et al. 2010). This is expected as almost all of the tabulated recharge rates (Table 3.1) were calculated for the natural recharge occurring through vadose zone only using chemical tracer approach, which does not consider inter-aquifer flow, base flow and irrigational abstraction, and probably were done during a different land use/land cover pattern than present.

Groundwater recharge estimated through WB method also exhibits spatial variation (Fig. 3.2). Recharge rates show higher (>500 mm/year) values over eastern and east-central coastal regions. On the other hand, recharge rates are found to be lower (<300 mm/year) in the parts of southern region. As only meteoric recharge is considered in WB method, infiltration was solely calculated from precipitation. In WB method, hydrogeologic parameters like porosity, permeability do not influence calculation of recharge rates. Accordingly, recharge rates follow precipitation pattern on most of the grid cells. Recharge rates calculated using WB method on the corresponding grid cell overestimates the recharge rate reported in most of the earlier studies over following locations (Table 3.1).

3.3.2 Comparison Between Recharge Rates Estimated Through WTF and WB Method

Good matches were found in recharge values calculated using WB method with WTF method on the IGB basin. Recharge using WB method overestimates the recharge calculated using WTF method on east-coastal region. Most of the east-coastal region is covered by forest (Bhanja 2017) and hence canopy interception of precipitated water can be a major impediment, which was not considered for calculation owing to unavailability of suitable data. Total amount of precipitated water cannot reach ground surface due to presence of tree canopies. Eventually, the intercepted water evaporates from tree leaves and get lost in the atmosphere. Recharge rates following WB method exhibit higher values in central study region. On the contrary, recharge estimated through WTF method reveals lower value on parts of central and southern region. However, discrepancy in recharge estimates of WTF and WB methods might be arising as a result of the following factors: (i) hydrologic parameters are not used in WB method; (ii) WB method does not consider inter-aquifer flow and base flow components, it only consider diffuse recharge through precipitation only; (iii) recharge associated with irrigation, also termed as return flow, is not considered in the WB method; (iv) soil moisture information was available up to a depth of 3.4 m; hence, vadose zone extending beyond 3.4 m is out of scope in the WB method. Notwithstanding these discrepancies, our results indicate dynamic nature of groundwater recharge as a function of precipitation, land use pattern, and hydrogeologic parameters (Fig. 3.3).

Fig. 3.3 Correlation between R_g and R_{WB}



3.4 Conclusions

In this study, groundwater recharge rates for present time are calculated between 2007 and 2011 over parts of the densely populated Indian subcontinent. On the basis of heterogeneity in geology and climate, noteworthy spatial variations were observed in groundwater recharge rates over the region. Groundwater recharge rates exhibit comparatively higher values (>300 mm/year) over the highly fertile alluvial plains of Indus–Ganges–Brahmaputra (IGB) system. High precipitation rates along with a combination of favorable hydrogeologic properties of the unconsolidated fluvial deposits and rapid groundwater withdrawal influence recharge rates in these regions. Most of the regions on the central and southern study areas are subjected to lower recharge rates (<200 mm/year). Groundwater recharge rates, calculated using WTF and WB method, respectively, match well in the IGB basin. On the other hand, recharge estimates using WB method overestimates the recharge values calculated using WTF method over natural vegetation covered east-coastal region. Reasonably comparable matches were found in calculated groundwater recharge rates using the two applied methods with previous estimates over the parts of the Indian subcontinent.

Acknowledgements SNB acknowledges CSIR (Government of India) for their support for providing the SPM fellowship. We also acknowledge CGWB, India and TRMM satellite mission for providing water level data and precipitation data, respectively. We also acknowledge APHRODITE database for providing precipitation data. The GLDAS data used in this study were acquired as part of the mission of NASA's Earth Science Division and archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC). We thank Pragnaditya Malakar and Charudutta M. Nirmale for their help in data retrieval. SNB thanks Dr. S. Verma for her advice.

References

Athavale RN, Rangarajan R, Muralidharan D (1998) Influx and efflux of moisture in a desert soil during a one year period. Water Resour Res 34(11):2871–2877

Athavale RN, Rangarajan R, Muralidharan D (1992) Measurement of natural recharge in India. J Geol Soc India 39:235–244

Bates BC, Kundzewicz ZW, Wu S, Palutikof J (eds) (2008) Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change Secretariat, Geneva, Switzerland

Bhandari N, Gupta SK, Sharma P, Premsagar, Ayachit V, Desai BI (1982) Hydrogeological investigations in Sabarmati basin and coastal Saurashtra using radioisotope methods. Final scientific report, PRL, Ahemedabad, India, 220 pp

Bhanja SN (2017) Groundwater Recharge and Storage Across Parts of The Indian Sub-Continent By In Situ Measurements, Satellite-Based Observations and Numerical Simulations (PhD Thesis)

Central Ground Water Board (CGWB) (2009) Dynamic groundwater resources. G. o. I. Ministry of Water Resources, 225 pp

Central Ground Water Board (CGWB) (2012) Aquifer systems of India. G. o. I. Ministry of Water Resources, 92 pp

Dai Y et al (2003) The Common Land Model (CLM). Bull Amer Meteor Soc 84:1013–1023

Gee GW, Hillel D (1988) Groundwater recharge in arid regions: review and critique of estimation methods. Hydrol Proc 2:255–266

Gleeson T, Wada Y, Bierkens MF, van Beek LP (2012) Water balance of global aquifers revealed by groundwater footprint. Nature 488(7410):197–200

Goel PS, Datta PS, Rama Sanghal SP, Kumar H, Bahadur P, Sabherwal RK, Tanwar BS (1975) Tritium tracer studies on ground water recharge in the alluvial deposits of Indo-Gangetic plains of western U.P., Punjab and Haryana. In: Athavale RN (ed) Proceedings of indo-german workshop on approaches and methodologies for development of ground water resources. NGRI, Hyderabad, pp 309–322

Guhathakurta P, Rajeevan M (2008) Trends in the rainfall pattern over India. Int J Climatol 28:1453–1469

Healy RW, Cook PG (2002) Using groundwater levels to estimate recharge. Hydrogeol J 10:91–109

Healy RW (2010) Estimating groundwater recharge. Cambridge University Press, 245 pp

Hendrickx J, Walker G (1997) Recharge from precipitation. In: Simmers I (ed) Recharge of phreatic aquifers in (semi-)arid areas. AA Balkema, Rotterdam pp 19–98

Kummerow C et al (2000) The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. J Appl Meteorol 39(12):1965–1982

Lerner DN, Issar AS, Simmers I (1990) Groundwater recharge, a guide to understanding and estimating natural recharge. International Association of Hydrogeologists, Kenilwort, Rep 8, 345 pp

Mukherjee A, Fryar AE, Howell PD (2007) Regional hydrostratigraphy and groundwater flow modeling in the arsenic-affected areas of the western Bengal basin West Bengal India. Hydrogeol J 15(7):1397–1418

Mukherjee A, Saha D, Harvey CF, Taylor RG, Ahmed KM, Bhanja SN (2015) Groundwater systems of the Indian sub-continent. J Hydrol Reg Stud 4:1–14

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore, ISBN 978-981-10-3888-4

Rangarajan R, Deshmukh SD, Prasada Rao NTV, Athavale RN (1995) Natural recharge measurements in Shahdol district, Madhya Pradesh using injected tritium method. Technical report no. NGRI-95-GW-174, 26 pp

Rangarajan R, Deshmukh SD, Ramesh GVN, Prasad ALV, Athavale RN (1997) Natural recharge studies using injected tritium technique in Bankura, North 24 Paraganas and South 24 Paraganas districts of West Bengal. Technical report no. NGRI-97-GW-214, 45 pp

Rangarajan R, Deshmukh SD, Sarma MVBM, Kesava Ramprasad B, Athavale RN (1998) Natural recharge measurements in GAETEC watershed near Hyderabad city, Andhra Pradesh. Technical report no. NGRI–98–GW–223, 25 pp

Rangarajan R, Athavale RN (2000) Annual replenishable ground water potential of India—an estimate based on injected tritium studies. J Hydrol 234(1):38–53

Rodell M et al (2004) The global land data assimilation system. Bull Am Meteorol Soc 85(3): 381–394

Rushton K (1997) Recharge from permanent water bodies. In: Simmers I (ed) Recharge of phreatic aquifers in (semi) arid areas. AA Balkema, Rotterdam, pp 215–255

Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol J 10(1):18–39

Scanlon BR, Mukherjee A, Gates J, Reedy RC, Sinha AK (2010) Groundwater recharge in natural dune systems and agricultural ecosystems in the Thar Desert region Rajasthan, India. Hydrogeol J 18:959–972

Siebert S, Henrich V, Frenken K, Burke J (2013) Update of the global map of irrigation areas to version 5. Project report, 178 pp

World Bank and Government of India (1998) India-water resources management sector review: groundwater regulation and management report. World Bank and Government of India, Washington, D.C. and New Delhi

Yatagai A, Kamiguchi K, Arakawa O, Hamada A , Yasutomi N, Kitoh A (2012) APHRODITE: Constructing a Long-Term Daily Gridded Precipitation Dataset for Asia Based on a Dense Network of Rain Gauges, American Meteorological Society

Chapter 4
Groundwater Storage Variations in India

Soumendra Nath Bhanja, Abhijit Mukherjee and Matthew Rodell

Abstract In recent years, intense abstraction of groundwater has led to depletion in groundwater storage (GWS) in India, the second most populous country in the world. In this chapter, we demonstrate our work on estimating groundwater storage over India by using data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission to study long-term (2003–2014) change in GWS over India. Rapid depletion of GWS is observed in the Indus–Ganges River basin in the northern and eastern parts of the Indian subcontinent at rates of about −1.25 ± 0.14 (−12.56 ± 1.37 km^3/year) and −1.05 ± 0.35 cm/year (−13.12 ± 4.36 km^3/year), respectively. The fertile alluvial plains of this semi-arid basin support huge areas of irrigated agriculture, leading to depletion of GWS. On the other hand, the southern and western parts exhibit groundwater replenishment.

Keywords Groundwater storage anomaly · Indian subcontinent
GRACE

S. N. Bhanja · A. Mukherjee (✉)
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee
Hydroscience and Policy Advisory Group, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

M. Rodell
Hydrological Sciences Laboratory, NASA Goddard Space Flight Center,
Greenbelt 20771, MD, USA

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_4

4.1 Introduction

Groundwater, being the largest freshwater resource available on earth, plays a crucial role in human sustenance and global food security by supporting irrigated agriculture where surface waters are inadequate (Aeschbach-Hertig and Gleeson 2012). This is particularly true in the Indian subcontinent (ISC), which comprise only ~4% of the world's land but hosts about 24% of its population and more than 30% of global irrigated land (FAO 2013). Groundwater-fed irrigated area has expanded from 30% in 1960 to ~50% of the total irrigated areas in 1995 in India (Scanlon et al. 2010). The ISC faces acute shortages of freshwater for drinking and other purposes, as it is witnessing a steep rise in water demand combined with changes in water use patterns because of rapid urbanization and economic/lifestyle changes.

Rapid groundwater storage (GWS) depletion in some of the densest populated areas in the globe (Rodell et al. 2009; Feng et al. 2013; Voss et al. 2013; Bhanja et al. 2014) has the potential to make billions of people suffer from socioeconomic stress in the near future. Effective water management is complicated by changes in hydrological cycle (Fig. 4.1) in the form of enhancement of atmospheric water vapor content; alteration in patterns of precipitation extremes; snow cover reduction

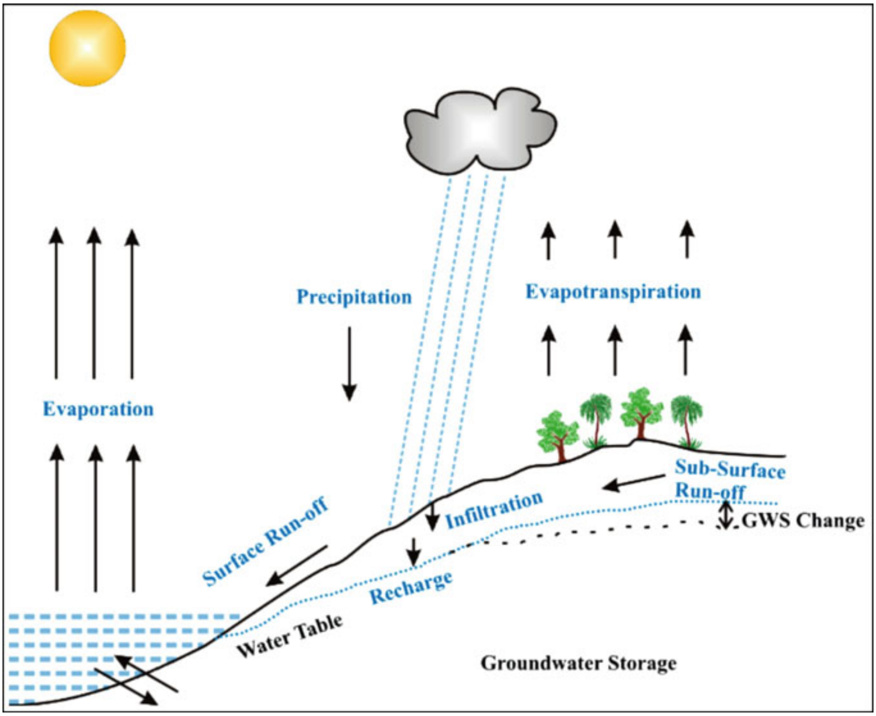


Fig. 4.1 Hydrological cycle

and extensive melting of ice sheets; and changes in soil moisture quantity and runoff amount, in the current global warming scenario (Bates et al. 2008). Most global hydrological models do not simulate groundwater storage variations accurately enough (if at all) to be applied for water management. In particular, groundwater pumping, irrigation, and reservoir impoundment are not well modeled (Sacks et al. 2009), and deficiencies exist in the simulation of groundwater and surface waters (Maxwell and Miller 2005).

Intensive irrigational activities have been observed in the parts of the ISC, which also happens to have the highest percentage of arable land under irrigation in the world (Siebert et al. 2013). More than half of the freshwater demand for irrigation in India is currently supplied by groundwater (CGWB 2009) and the Ganges–Brahmaputra basin is reported to be the most groundwater-stressed region in the world (Richey et al. 2015). According to Gleeson et al. (2012), the Upper Ganges aquifer possesses the world's largest groundwater footprint (the area that is essential for sustaining groundwater use and groundwater-dependent systems). In this study, groundwater storage variations have been quantified for parts of the densely populated ISC using a combination of satellite and land surface model-based estimates. More related information regarding groundwater of South Asia is available in Mukherjee et al. (2018).

4.2 Methods

4.2.1 Study Area

Groundwater abstraction in the study region, India (Chap. 1, Fig. 1.1), is the most intense in the world (Mukherjee et al. 2015). The area is drained by some of the largest river networks like the Indus–Ganges–Brahmaputra (IGB) system. Annual precipitation varies significantly across the region (Fig. 4.2). To overcome meteorological inhomogeneity, the region is divided into five different hydrometeorological zones (HMZs) (Fig. 4.2) on the basis of their precipitation pattern. Long-term monthly mean precipitation data sets [Global Historical Climatological Network (GHCN)] are used from the year 1960–2010 on numerous locations within the study region. Continuous data were not available for several locations, and hence, the selection of locations was performed using an inter-quartile range (IQR) filter. We identified 37 locations distributed over the study area which fulfilled the criteria.

Specific humidity (SH) data were obtained from the archives of the European Center for Medium-Range Weather Forecasting (ECMWF)-simulated reanalysis (Dee et al. 2011) (ERA-Interim) project output between 1979 and 2012. Precipitation and SH data exhibited higher values during monsoon season. The monsoon patterns differ across the country; therefore, we used the shift in precipitation and SH data to determine the boundary between monsoon and non-monsoonal seasons on all the five HMZs. Pre-monsoon and post-monsoon seasons were defined

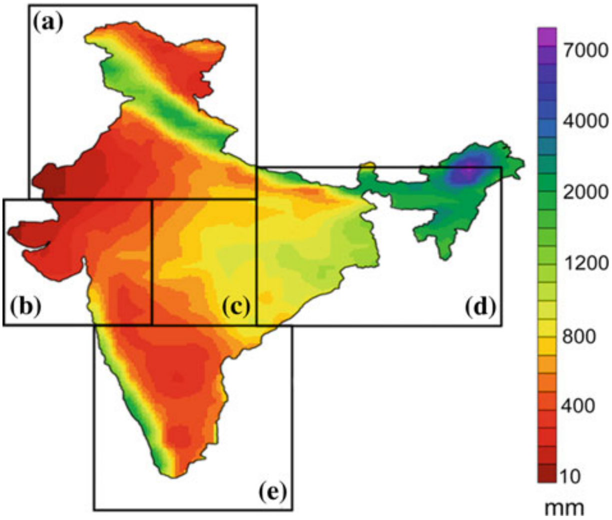


Fig. 4.2 Annual mean precipitation (mm/year) between 1979 and 2014. Rectangular outlines indicate the five hydrometeorological zones (**a**–**e**) delineated based on the duration of the hydrometeorological seasons (monsoon, post-monsoon, and pre-monsoon)

by determining the change in SH, which was more skillful than using precipitation data. SH decreases immediately after the monsoon ends. Later, SH increases gradually up until the start of the next monsoon. This point of inflection of SH (decreasing to increasing) marks the boundary between post-monsoon and pre-monsoon. After defining hydrological seasons, we imposed an IQR filter to select the months that composed the season on each of the zones. The seasons were defined as follows: (a) Northern region [monsoon: June–September; post-monsoon: October–January; pre-monsoon: February–May]; (b) Western region [monsoon: June–September; post-monsoon: October–February; pre-monsoon: March–May]; (c) Central region [monsoon: June–September; post-monsoon: October–March; pre-monsoon: April–May]; (d) Eastern region [monsoon: June–September; post-monsoon: October–January; pre-monsoon: February–May]; (e) Southern region [monsoon: June–October; post-monsoon: November–January; pre-monsoon: February–May].

4.2.2 Gravity Recovery and Climate Experiment (GRACE)

Monthly, gridded (1° × 1°) liquid water equivalent thickness (LWET) data files (Landerer and Swenson 2012) from the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL) archive were used in this study. These data are based on the RL05 GRACE spherical harmonics (SH) solutions. We used the mean of the three TWS solutions from the Center for

Space Research at the University of Texas at Austin, NASA JPL, and the German Space Agency (GFZ). Scale factors provided with the product were applied in order to restore the signal that may have been altered due to smoothing, destriping, and filtering of the data (http://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land/, Accessed on 26 Apr, 2016).

4.2.3 *Other Hydrological Components*

GWS anomaly (anomaly has been computed by removing the all-time mean data from the individual data) was estimated (GWSA) by removing the soil moisture anomaly (SMA) from the TWS anomaly. Non-availability of ground-based measurements for the soil moisture restricted us to use global land surface model outputs. To remove bias associated with any single model simulated output (Bhanja et al. 2016), an average of output from three Global Land Data Assimilation System (GLDAS) (Rodell et al. 2004) models was used, i.e., the Community Land Model (CLM), the Variable Infiltration Capacity (VIC) model, and the Noah land surface model. The number of major dams present in the study region (Table 4.1) is not increased much during the study period. As we used groundwater storage (GWS) anomaly instead of absolute GWS for all of our analyses, we believe the

Table 4.1 State-wise distribution of large dams in India (NRD 2015)

States	Large dams			Dams of national importance		
	Up to 2000	After 2000	Total	Up to 2000	After 2000	Total
Andaman	1	1	2			
Andhra Pradesh	119	10	129	2	0	2
Arunachal Pradesh	0	1	1			
Assam	2	1	3			
Bihar	21	2	23			
Chhattisgarh	218	30	248	1	0	1
Goa	5	0	5			
Gujarat	575	46	621	3	0	3
Himachal Pradesh	8	8	16	3	0	3
Haryana	0	1	1			
Jammu and Kashmir	8	6	14	2	1	3
Jharkhand	50	0	50	3	0	3
Karnataka	216	14	230	10	0	10
Kerala	55	3	58	5	0	5
Madhya Pradesh	832	66	898	2	1	3
Maharashtra	1580	113	1693	4	0	4

(continued)

Table 4.1 (continued)

States	Large dams			Dams of national importance		
	Up to 2000	After 2000	Total	Up to 2000	After 2000	Total
Manipur	2	1	3			
Meghalaya	5	2	7			
Nagaland	1	0	1			
Odisha	185	13	198	7	0	7
Punjab	11	3	14	1	0	1
Rajasthan	186	15	201	3	0	3
Sikkim	1	1	2			
Tamil Nadu	97	19	116	2	0	2
Telangana	159	3	162	2	0	2
Tripura	1	0	1			
Uttar Pradesh	112	3	115	2	1	3
Uttarakhand	12	4	16	2	1	3
West Bengal	24	5	29	1	0	1
Total	4486	371	4857	55	4	59

surface water storage effects of dams constructed before our study period are negated out while computing GWS anomaly by subtracting the all-time mean GWS values from individual GWS values.

4.2.4 *Uncertainty Estimates*

We estimated one-sigma trend error in the GRACE TWS anomaly values (σ_{TWS}). Uncertainty associated with soil moisture anomaly (σ_{SM}) was determined by computing the standard deviations of the trends within the three GLDAS models. Subsequently, uncertainty estimates in the trend of GWS anomaly (σ_{GWS}) were estimated following the equation,

$$\sigma_{\mathrm{GWS}} = \sqrt{[(\sigma_{\mathrm{TWS}})^2 + (\sigma_{\mathrm{SM}})^2]} \tag{4.1}$$

4.3 Result and Discussion

The GWS anomaly shows strong spatial variability in the study region (Fig. 4.3). Rapid depletion has been observed in northern (HMZ A) and eastern (HMZ D) zones with a rate of −1.25 ± 0.14 and −1.05 ± 0.35 cm/year (−12.56 ± 1.37 km^3/year and −13.12 ± 4.36 km^3/year) in the study period, respectively (Fig. 4.4).

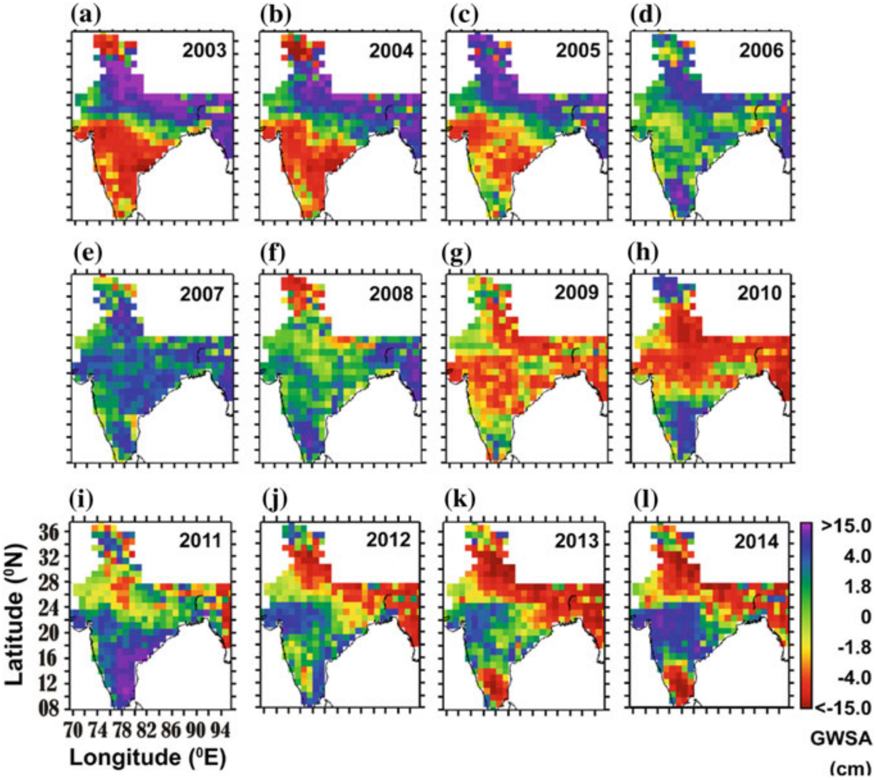


Fig. 4.3 Maps of annual groundwater storage (GWS) anomalies (cm) over the study area

These depletion observations are in line with the satellite-based findings of northwest (17.7 km^3/year, between 2002 and 2008) (Rodell et al. 2009) and northern (54 km^3/year between 2002 and 2008) (Tiwari et al. 2009) India, and Bangladesh (located at eastern zone) (Shamsuddhuha et al. 2012). Corroborating the above observations, comparison of field measured groundwater level fluctuation of decadal mean (2001–2010) to 2011 by Indian government authorities, in general, suggests groundwater decline in northern, northwestern and eastern India, and rise in southern and western India for most seasons (CGWB 2012). They reported a declining water level trend for pre-monsoon during 2007–2012 with >55% of measured wells (n = 11,024) having groundwater level drop of ≥ 1 m/year (MWR 2013).

The fertile plains of the IGB basin have been extremely favorable for irrigational activities. Consequently, the IGB plains have been one of the cradles of the human civilization, and presently is one of the most densely populated part of the world.

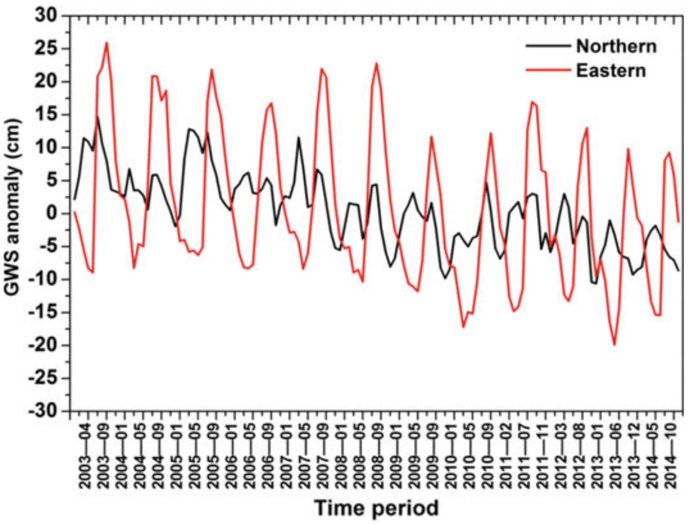


Fig. 4.4 Time series of GWS anomaly in northern and eastern parts of Indian subcontinent

The rapidly accelerating groundwater demands in these areas are directly proportional to the increasing population, introduce of water-intensive crops, changes in cropping pattern (e.g., replacing food crops by cash crops) (FAO 2013), and coincide with the areas showing highest GWS depletion (Fig. 4.5). Most of Bangladesh (percentage of gross irrigated area to gross cropped area, >60%; FAO 2013) and Indian states like Punjab (98%), Haryana (85%), Uttar Pradesh (76%), Bihar (61%), and West Bengal (56%) are all located in these depletion zones (MoA 2012). More than 4 m groundwater decline has been observed during the last decade in Indian states of Rajasthan, Punjab, Haryana, Delhi, and West Bengal (CGWB 2014).

On the other hand, groundwater replenishment trends have been observed in parts of western (HMZ B) and southern (HMZ E) zones. Implementation of sustainable water management strategies has played crucial role for replenishing the groundwater storage in those regions (Bhanja et al. 2017).

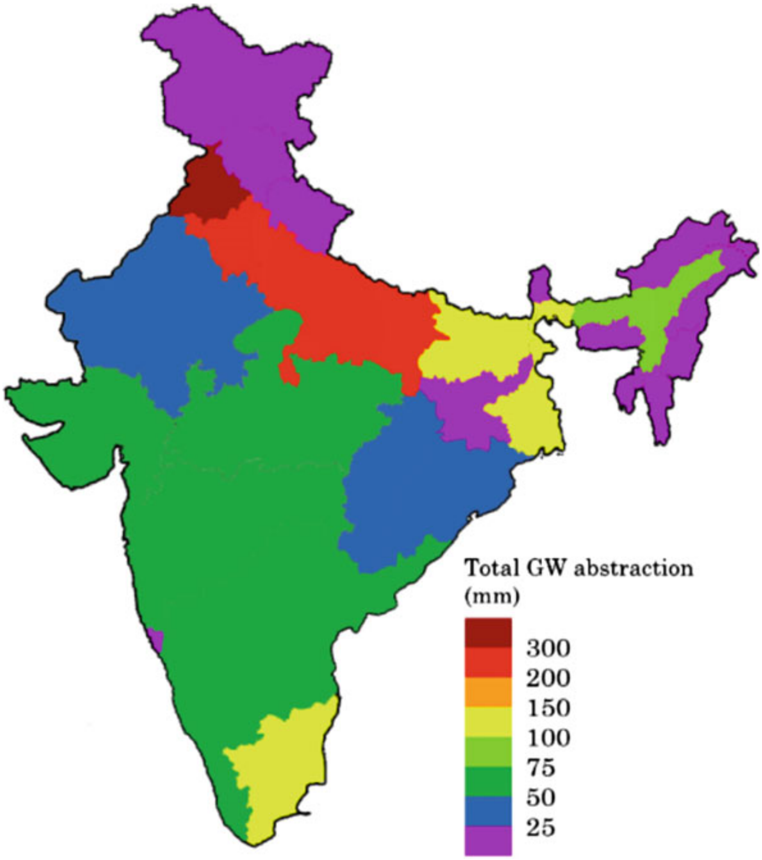


Fig. 4.5 Map showing state-wise total groundwater abstraction. *Data source* CGWB (2012)

4.4 Summary

We have studied groundwater storage anomaly in Indian subcontinent using a combination of satellite and global land surface model-based outputs between 2003 and 2014. We observed rapid declination of GWS in northern and eastern regions of ISC at the rate of about −1.25 ± 0.14 and −1.05 ± 0.35 cm/year (−12.56 ± 1.37 km^3/year and −13.12 ± 4.36 km^3/year), respectively. The northern and eastern regions are mostly comprised of highly fertile fluvial sediments of Indus–Ganges–Brahmaputra river basin, which has been subjected to intense irrigational activities leading to large-scale groundwater abstraction.

Acknowledgements SNB acknowledges CSIR (Government of India) for their support for providing the SPM fellowship. GRACE land data were processed by Sean Swenson, supported by the NASA MEaSUREs Program, and are available at http://grace.jpl.nasa.gov. The GLDAS data used in this study were acquired as part of the mission of NASA's Earth Science Division and archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC). The ERA-Interim data were obtained from the ECMWF data distribution portal http://apps.ecmwf.int/datasets/. SNB thanks Dr. S. Verma for her advice.

References

Aeschbach-Hertig W, Gleeson T (2012) Regional strategies for the accelerating global problem of groundwater depletion. Nat Geosci 5:853–861

Siebert S et al (2013) Update of the global map of irrigation areas to version 5, Project report, 178 pp

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water. Technical paper of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change Secretariat, Geneva, Switzerland

Bhanja SN, Mukherjee A, Rodell M, Velicogna I, Pangaluru K, Famiglietti J (2014) Regional groundwater storage changes in the Indian Sub Continent: the role of anthropogenic activities. American Geophysical Union. Fall meeting, GC21B-0533

Bhanja SN, Mukherjee A, Saha D, Velicogna I, Famiglietti JS (2016) Validation of GRACE based groundwater storage anomaly using in-situ groundwater level measurements in India. J Hydrol. https://doi.org/10.1016/j.jhydrol.2016.10.042

Bhanja SN, Mukherjee A, Wada Y, Chattopadhyay S, Velicogna I, Pangaluru K, Famiglietti JS (2017) Groundwater rejuvenation in parts of India influenced by water-policy change implementation. Sci Rep 7

Central Ground Water Board (CGWB) (2009) Ministry of water resources, G. o. I. Dynamic groundwater resources, 225 pp

Central Ground Water Board (CGWB) (2012) Ministry of water resources, Government of India. In: Groundwater year book 2011–12

Central Ground Water Board (CGWB) (2014) Ministry of Water Resources, G. o. I. In: Ground water year book—India 2013–14, 76 pp

Dee DP et al (2011) The ERA-interim reanalysis: configuration and performance of the data assimilation system. Q J Roy Meteorol Soc 137:553–597

Feng W, Zhong M, Lemoine JM, Biancale R, Hsu HT, Xia J (2013) Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements. Water Resour Res 49:21102118

Food and Agriculture Organization of the United Nations (2013) FAO statistical yearbook 2013: world food and agriculture, 289 pp

Gleeson T et al (2012) Water balance of global aquifers revealed by groundwater footprint. Nature 488:197–200

Landerer FW, Swenson SC (2012) Accuracy of scaled GRACE terrestrial water storage estimates. Water Resour Res 48:W04531

Maxwell RM, Miller NL (2005) Development of a coupled land surface and groundwater model. J Hydrometeorol 6:233–247. https://doi.org/10.1175/JHM422.1

Ministry of Agriculture (MoA) (2012) State of Indian agriculture 2011–12, Government of India

Ministry of Water Resources (MoWR) (2013) Press release, Government of India. 29 April, 2013

Mukherjee A (2018) Groundwater of South Asia. Springer, Singapore. ISBN 978-981-10-3888-4

Mukherjee A, Saha D, Harvey CF, Taylor RG, Ahmed KM, Bhanja SN (2015) Groundwater systems of the Indian sub-continent. J Hydrol Reg Stud 4:1–14

National Register of Dams (NRD) (2015) Central water commission, Ministry of Water Resource, Govt. of India

Richey AS, Thomas BF, Lo M-H, Famiglietti JS, Reager JT, Voss K, Swenson S, Rodell M (2015) Quantifying renewable groundwater stress with GRACE. Wat Resour Res 51:5217–5238. https://doi.org/10.1002/2015WR017349

Rodell M et al (2004) The global land data assimilation system. B Am Meteorol Soc 85:85381–85394. https://doi.org/10.1175/BAMS-85-3-381

Rodell M, Velicogna I, Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India. Nature 460:999–1002

Sacks WJ, Cook BI, Buenning N, Levis S, Helkowski JH (2009) Effects of global irrigation on the near-surface climate. Clim Dyn 33:159–175. https://doi.org/10.1007/s00382-008-0445-z

Scanlon BR, Mukherjee A, Gates J, Reedy RC, Sinha AK (2010) Groundwater recharge in natural dune systems and agricultural ecosystems in the Thar Desert region, Rajasthan, India. Hydrogeol J 18:959–972

Shamsudduha M, Taylor RG, Longuevergne L (2012) Monitoring groundwater storage changes in the highly seasonal humid tropics: validation of GRACE measurements in the Bengal Basin. Water Resour Res 48:W02508

Tiwari VM, Wahr J, Swenson S (2009) Dwindling groundwater resources in northern India, from satellite gravity observations. Geophys Res Lett 36:L18,401

Voss KA, Famiglietti JS, Lo M, de Linage C, Rodell M, Swenson SC (2013) Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. Water Resour Res 49:904–914. https://doi.org/10.1002/wrcr.20078

Chapter 5
Groundwater of Hard Rock Aquifers of India

Prabhat Chandra Chandra

Abstract About two-thirds geographical area of India is occupied by hard rocks comprising granite, gneiss, schist, quartzite, charnockite, khondalite, banded gneissic complex, basalt and intrusive, etc. Out of the twenty-nine States in the country, in twenty-two States the spread of hard rock areas varies from about 0.3 million km^2 to more than 5000 km^2, and a number of mega-cities are located in the hard rocks. The occurrence of aquifers in these rocks is heterogeneous, in near-surface weathered zone, in underlying saprolite, in discontinuous fractured zones and along joints, veins and litho-contacts. The abstraction of these aquifers depends on their availability, storage, yielding capacity and water quality. To tap the deeper yielding fractured zone aquifer and obtain higher yield, the borewells are sunk to 200 m depth. The yield from the top weathered zone aquifer within 20–30 m depth ranges from 0.9 to 1.8 cubic metre per hour (m^3/h). The cumulative yield from the weathered zone and underlying saprolite may range up to 9–10.8 m^3/h. The yielding fractured zones are mostly encountered within 100–150 m depth and could occur deeper also, as observed in Karnataka State in southern part of India, but the frequency of occurrence is meagre. Generally, the weathered zone, saprolite and the yielding fractured zones up to 60–100 m depth are tapped by hand pumps and shallow borewells. The borewell yield less than 3.6 m^3/h is termed 'low'. In India, the groundwater investigation in hard rocks is carried out using surface geophysical surveys generally comprising resistivity sounding, profiling and imaging supported by satellite imageries and lineament maps. Heliborne electromagnetic and magnetic surveys have also been conducted. In several parts, a declining trend in groundwater level is observed, for which artificial recharge methods are adopted. The higher concentrations of fluoride in groundwater are observed in several parts.

P. C. Chandra (✉)
CGWB, Patna, India
e-mail: chandrapc67.gwgp@gmail.com

P. C. Chandra
The World Bank, New Delhi, India

P. C. Chandra
WAPCOS Ltd., New Delhi, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_5

Keywords Hard rock aquifer in India · Weathered and fractured zone aquifers
Hard rock geophysics · Heliborne geophysics · Artificial recharge
Higher fluoride concentration

5.1 Introduction

Compact and massive rocks—generally the igneous and metamorphics—which do not possess primary porosity and hydraulic conductivity are known as hard rocks. They are also known as fractured or fissured rocks. The carbonate rocks can also be considered as hard rocks but are excluded from the present discussion as the mode of groundwater occurrence differs from the igneous and metamorphic rocks. About two-thirds geographical area of India is occupied by hard rocks (Chap. 1, Figs. 1.4 and 1.5). The hard rocks comprise a variety of rock types, viz. granite, gneiss, schist, quartzite, charnockite, khondalite, banded gneissic complex, basalt and intrusive, etc. (CGWB 2012). Out of the twenty-nine States in India, in twenty-two States the spread of hard rock areas varies from about 0.3 million km^2 to more than 5000 km^2 (Tables 5.1 and 5.2), and there are a number of mega-cities located in the hard rocks. There are 112 districts in 11 states having 75% area occupied by basalts or crystallines (Krishnan et al. 2009). More related information regarding groundwater of South Asia are available in Mukherjee et al. (2018) and regarding hard rocks are available in Geological Society of India (2008) and Chandra (2015).

5.2 Hard Rock Hydrogeology

The groundwater occurrence in hard rocks is heterogeneous and complex. It occurs in the near-surface weathered zone, in the underlying saprolite, in discontinuous fractured zones and along joints, veins and litho-contacts. The abstraction of these aquifers depends on their availability, storage, yielding capacity and water quality. The weathered zone, where the original texture of the parent rock is totally destroyed, generally has good porosity and behaves as a moderately yielding granular aquifer. However, in some of the granitic terrain with abundance of clays in the weathered zone formed as alteration product of feldspars and mica, the yield is poor. In basaltic terrain also, the faster chemical weathering of mafic minerals may cause abundance of clays and consequent reduction in yield. The occurrence of groundwater in quartzite, phyllite and schist is also controlled by weathering, joints, fissures, folds, schistosity and bedding plane. In compact formations underlying the weathered zone, the occurrences of groundwater are in secondary pore spaces developed through processes of fracturing and jointing. Besides, the faults and shear zones hold better groundwater storage and flow, if mylonite which reduces the hydraulic conductivity (Gustafson and Krasny 1993) is not present. The flow of groundwater at depth depends on the interconnections of fractures. The structures like basic dyke intrusive and quartz

Table 5.1 States in India with hard rock area more than 5000 km^2

	State	Area km^2 (% area of the state) occupied by hard rock	Major rock type
1	Maharashtra	267,305 (90.19)	Basalt
2	Andhra Pradesh and Telangana	193,314 (72.09)	Banded Gneissic Complex (BGC)
3	Karnataka	184,317 (93.61)	BGC, Basalt, Schist
4	Madhya Pradesh	176,863 (59.72)	Basalt, BGC
5	Odisha	97,866 (65.77)	BGC, Khondalite
6	Tamil Nadu	88,387 (72.15)	Gneiss, Charnockite
7	Gujarat	87,524 (49.86)	Basalt
8	Jammu and Kashmir	80,168 (36.21)	Granite
9	Rajasthan	78,179 (23.65)	BGC, Gneiss, Granite
10	Chhattisgarh	70,778 (54.06)	BGC, Gneiss
11	Jharkhand	65,508 (84.41)	BGC, Schist
12	Kerala	37,201 (89.0)	Charnockite, Gneiss, Khondalite
13	Uttarakhand	35,125 (67.26)	Schist, Quartzite, Gneiss, BGC
14	Himachal Pradesh	32,941 (60.32)	Schist, Quartzite, Gneiss, BGC
15	Uttar Pradesh	16,686 (7.2)	BGC, Quartzite
16	Arunachal Pradesh	14,821 (18.68)	Granite
17	West Bengal	8717 (10.62)	BGC, Schist
18	Assam	8359 (11.06)	BGC
19	Meghalaya	8222 (38.07)	BGC, Granite
20	Bihar	6137 (6.77)	BGC
21	Sikkim	5192 (75.42)	Gneiss, Schist

Source CGWB (2012)

Table 5.2 Area covered by various types of hard rock lithology

Major hard rock aquifer	Area covered (km^2)
Basalt	512,302
BGC	478,382
Gneiss	158,753
Schist	140,935
Granite	100,991
Charnockite	76,359
Quartzite	46,904
Khondalite	32,913
Intrusive	19,895

reef may act either as barrier or conduit for groundwater flow. Also, they can store groundwater. All these depend on the dimension and orientation of these structures with respect to the general groundwater flow direction and on the compaction, weathering and fracturing in them. A classical example is of Bundelkhand Granite Gneiss Complex of Jhansi district, Uttar Pradesh, India, where groundwater occurrences and movement are controlled by a large number of linear quartz reef or giant quartz vein (GQV) oriented in NE-SW to NNE-SSW and the basic dyke swarm in NW-SE direction. The quartz reefs run for kilometres as ridges and at places appear truncated, in all probability by the numerous intersecting dykes which could be the last phase of intrusive episode in the area.

The near-surface weathered zone aquifer can be considered regionally extensive because it is present almost everywhere in the hard rock terrain. However, the thinning of saturated zone, irregular weathering and exposed compact rock surroundings in places make the weathered zone aquifer discontinuous. Also, the decline in groundwater level during summer months results in a reduction of saturated thickness. The areal extents and thickness of the weathered zone control the aquifer storage capacity. The seasonally varying saturated thickness of the weathered zone sustained by the recharging monsoon precipitation and other sources affects the well yield. The weathered zone of less than 10 m thickness can form an effective aquifer only when there is a high recharge (Larsson 1984). A weathered zone with saturated thickness about 30–40 m generally forms a good aquifer. However, its hydraulic characteristics may vary laterally as well as with depth, resulting in location-specific varied well yield. Mostly, the groundwater flow is at the base of the weathered zone (Jones 1985) which is generally characterized by relatively low porosity and high hydraulic conductivity.

The low-yielding weathered zone aquifer, generally of 10–20 m thickness, can be developed for local water supply by large-diameter dug wells and shallow hand pumps. Dug-cum-borewells or borewells can be sunk where weathered zone thickness is considerably high. As observed, in the hard rocks of Jharkhand, India, the yield from weathered zone aquifer alone ranges from 0.9 to 1.8 m^3/h and when the underlying saprolite is included, the yield increases up to about 9.6 m^3/h (Dev Burman and Das 1990; Chandra et al. 1994). However, Singhal and Gupta (1999) and Subramanian (1992) report a wider yield range of about 0.36–32 m^3/h for dug wells in different hard rock types.

A system of joints and interweaving fractures often occurs in the compact impervious rock in places and depth. It is the combined effect of cooling process, physical and geochemical properties and processes, stresses through geologic time, percolating groundwater and the palaeo-climatic conditions. The fractures related to tectonics, originate with maximum intensity from the fault zones and may continue to large distances. Fractures mostly occur within a few hundred metres from the earth surface, and the opening is generally in the order of millimetre to centimetre. The fractures, linear in nature, may occur as a distinct planer feature or as a group of close-spaced planer features. Larsson (1984) indicate dense fracturing of limited length in fine-grained rocks as compared to that in coarse-grained rocks. The fracturing is more in low-grade metamorphic rocks compared to that in high-grade metamorphics.

In the deeper fractured zones, which receive water through near-surface weathered zone and saprolite, shallow vertical fractures and joints, and also through deep weathering in fault zones, the local to regional-scale storage and movement of groundwater are controlled by the distribution of interconnected deeper fractures and their openness. The tensional fractures are more open and transmissive compared to shear fractures (Singhal 2008). The horizontal fractures and joints control the direction of groundwater flow. The interconnection between the fractures locally and regionally is necessary to maintain the hydraulic continuity over a large area and sustain the well yield. Though the volume of water in the fracture will be barely a few percent of the bulk volume, the flow through it could be high. The micro-fracturing associated with the fractured zones, having different orientations, creates and enhances the permeability locally. These micro-fractures also behave as conduits to increase the groundwater storage and in totality may form a zone of potential aquifer. Thus, the realization of the presence of the fractures and their character is essential in groundwater development and understanding the complexities in the groundwater flow regime. The information obtained from groundwater exploration up to 200–300 m depth in hard rock areas of India reveal that with depth the fractures diminish in intensity, frequency and dimension and also close. Though the chance of intersecting the fractures abruptly reduces with depth, an isolated fracture encountered at depth in the borehole can dramatically increase the yield if interconnected with other fractures hydraulically and getting recharged through the weathered zone. That is, the locally isolated deep fracture could also be productive and contribute maximum yield. The occurrences of such isolated yielding fractures increase in areas of thick weathered zone. Only with this hope, occasionally the borehole drilling is continued deeper. But, beyond a certain depth the water well drilling will be, in general, uneconomical.

The hydrogeological uncertainty prevails even within a fractured zone. The wells sunk to same depth within a few metres may have different yield as they may encounter different number of saturated fractures. That is, the findings of one well may not always be useful to pinpoint another drilling site. As far as the general hydraulic conductivity of fractured zone is concerned, qualitatively the deeper fractured zones have lesser hydraulic conductivity. The fractured zones of more regional character have better hydraulic conductivity. Krasny and Sharp (2007) indicate that areas or zones with long fractures, larger density of fracturing and greater fracture aperture have higher hydraulic conductivity. Compared to soft rock, the hydraulic conductivity is quite low ranging from 10^{-11} to 10^{-2} m/s (metre per second). For the aquifers in granites and meta-sediments of Jharkhand State, India, up to about 200 m depth, the hydraulic conductivity ranges from about 1×10^{-7} to 0.7×10^{-6} m/s and transmissivity ranges from 0.23×10^{-4} to 3.24×10^{-4} m^2/s (CGWB 2012a).

The boreholes drilled up to 300 m depth in hard rocks of Jharkhand State, in eastern part of India, revealed the occurrence of saturated and unsaturated fractured zones up to a depth of 285 m (Dev Burman and Das 1990). The unsaturated ones were either non-productive or completely dry. The saturated fractured zones are qualitatively grouped depth-wise as shallow and deep or sallow, medium depth and deep. The saturated fractured zones occurring within 50–60 m depth are grouped as shallow and are tapped by hand pumps. In this area, prominent saturated fractured zones occur up to 110 m depth in the younger granites and up to 140 m in the older granites. The poorly interconnected fractured zones yield for a short while and get dewatered. The maximum yield obtained from individual zone in younger and older granites were 10.8 and 21.6 m^3/h, respectively. A number of 500 m deep-water wells were drilled by Central Ground Water Board (2012b) in granites, gneisses and schists of Karnataka state in the southern part of India. The yielding fractured zones were encountered up to a depth of 389 m. The maximum cumulative yield of a well was reported as 54 m^3/h. The weathered zone in this area was almost dried-up as the water table was deep, at 68 m in places. The fractured zones immediately underlying the 75-m-thick weathered zone were either dry or had a very poor yield (CGWB 2009). The water in the deeper fractured zones was due to their regional connections to other distant fractured zones.

Besides the granites and gneisses, another hard rock terrain is the Deccan Trap Basalts (DTB) which occupy about 500,000 km^2 in the west-central part of India. The DTB comprises a number of horizontal to sub-horizontal lava flows. The thickness of individual lava flow varies from 1 to 160 m (Singhal 1997; Mahoney 1988). The flows are separated by ‘red bole’ or ‘green bole’ comprising tuffaceous, scoriaceous or pyroclastic material accumulated during the hiatus between the two successive flows (Kale and Kulkarni 1992; Adyalkar et al. 1975). According to Ghosh et al. (2006), the red bole is formed by weathering of basalt and the green bole is a mixture of weathered basalt and remnants of volcanic ashes. The sheet joints in the bole bed make it friable (Kale and Kulkarni 1992). The bole bed thickness varies from a few centimetres to a metre. It is regionally persistent and forms the marker bed to demarcate the flows. Generally, the flow unit is massive at its bottom and vesicular towards the top. The vesicular part constitutes about one-fourth to one-third of a flow unit (Saha and Agrawal 2006). The near-surface part of the basalt flow sequence is weathered.

The groundwater condition in DTB differs from that in the granitic terrain. The flows of basalt produce stratification, and therefore, the hydrogeological character of basalt varies from a typical fractured hard rock to heterogeneous, anisotropic near-porous rock (Custodio 2007). The secondary porosity introduced by the interconnected vesicles, cooling and sheet joints, weathering and fracturing, vertical to sub-vertical fractures and joints in the compact basalts develop the repositories of groundwater and form the basalt aquifers. The interflow zones also form aquifers where it is without clay predominance. The groundwater flow paths are formed by horizontal sheet joints and vertical fractures and joints. The sheet joints increase the transmissive capacity (Saha and Agrawal 2006). Deolankar (1980) and Surinaidu et al. (2013) report a better transmissivity for the near-surface weathered basalt compared to the vesicular and fractured-jointed basalts. The maximum yield of dug well in weathered basalt is reported as around 29 m^3/h, and in places, it is more than that from shallow borewell (Dhonde 2009).

5.3 Development of Hard Rock Aquifers

In hard rock areas, groundwater is being tapped mostly through age-old practice of hand-dug well structures. The depth of dug well is controlled by the thickness of the weathered zone. Generally, dug wells are 2.5–4 m in diameter and 10–15 m deep. In some areas, large-diameter and deeper dug wells are constructed. The dug wells are prevalent in areas with shallow water table allowing a good volume of water getting collected in the dug well. In areas with a sufficiently thick saturated weathered zone and shallow water table dug-cum borewells are constructed. To meet the increasing demand and declining water table shallow to deep borewells are constructed tapping the weathered zone, saprolite and also the underlying fractured zones. Constructing a dug well in shallow weathered zone is easy trouble-free, economical and without any financial risk and does not require much technical support. The dug wells can supply domestic water and to some extent support the local irrigation. However, in the past few decades there is a sharp reduction in dug well construction as the cost of construction is comparable to that of a shallow borewell. The yield of a borewell depends on a complex multiplicity of many factors, like rock composition, weathering, clay content in the weathered zone, presence of saprolite, its proximity to lineament, dimension of lineament, presence of joint and fractured zone, depth drilled, number of saturated fractured zones encountered within the depth drilled, topography and the annual recharge. In general, the yield of shallow wells in weathered zone is around 3.6 m^3/h (Clark 1985) and mostly caters to local needs. In granitic terrain, wells with yield less than 3.6 m^3/h are classified as low-yielding or failure wells. The wells with yield 3.6–18 m^3/h can be considered as moderate yielding and more than 18 m^3/h as high yielding.

In areas with deeper water table, where either the saturated weathered zone is hardly a few metres thick or it is totally dewatered, for a better yield borewells are drilled deeper to tap the saturated fracture zones at depths. That is, drilling depth is more in areas where yield from top weathered zone and saprolite is poor. Besides, the depth of drilling can be related to demand. For greater yields, wells are drilled deeper with the hope of encountering yielding fractures at depths. Other than groundwater condition, the depth of drilling is also controlled by the money available for it. Those who can afford, try for deep-water well drilling.

In the hard rock terrain of India, the water wells are drilled mostly by government agencies for community water supply and irrigation. Water wells are drilled by private individuals also. Generally, the wells for drinking water supply are drilled to a depth of 60–100 m. To tap the yielding deep fractured zones, wells as deep as 300 m and in places up to 500 m have been drilled by Central Ground Water Board (Government of India). The deeper drilling being quite expensive, it is avoided, unless it is essential to tap the deep fractured zones. As such, the depth of borehole drilling can be considered as minimum or economic that gets groundwater yield of adequate quantity and acceptable quality. The reduction in yield with time due to declining water table has affected the depth of drilling which has, in general,

Table 5.3 General range of weathered zone thickness, depth range of fractured zone occurrences and the yield

Rock type	Weathered zone thickness (m)	Depth range (m) of fractured zone occurrences	Range of cumulative yield (m^3/h) from borewell
Basalt	5–60	20–280	0.5–20
BGC	3–100	12–200	Up to 150
Gneiss	3–25	20–200	0.5–104
Granite	5–40	15–200	0.4–60
Schist	4–80	10–180	0.5–23.4
Quartzite	5–30	14–150	Up to 16.7
Charnockite	5–45	15–430	Up to 126
Khondalite	5–20	4–291	0.8–62.5
Intrusives	6–13	12–17, 100–150	Up to 10.75

Source CGWB (2012)

increased. The general ranges of cumulative yield of borewell tapping weathered zone, saprolite and the fractured zones in different rock types are summarized from CGWB (2012) and presented in Table 5.3.

In the hard rocks of Jharkhand state of India, for which two case studies are presented latter, the results of exploration carried out by CGWB (Government of India) up to a depth of 300 m indicated a well yield ranging from 0.72 to 9.6 m^3/h, for the weathered zone and saprolite occurring up to the depth ranging from 12 to 25 m (Dev Burman and Das 1990; CGWB 2012a). The fractured zones were encountered up to a maximum depth of 285 m. However, the saturated fractured zones mostly occurred in the depth range of 20–150 m. The yield of individual fractured zone ranged from 0.9 to 41.4 m^3/h. The yield of saprolite and underlying shallow fractured zones increased and that of the fractured zones occurring beyond 100 m depth decreased during pumping compared to drilling. The possible reason for the increase in yield of saprolite and shallow fractures during pumping test was explained by Dev Burman and Das (1990) as involvement of a large volume of rock surrounding the well and wider connectivity of shallow fractured zones during the test. It was observed that the drawdown for saprolite was less as compared to that for the fractured zones. In the Bundelkhand Granite Gneiss Complex of Jhansi and Lalitpur districts of Uttar Pradesh, though the productive fractured zones were encountered up to 200 m depth (the depth of drilling), they were mostly limited to depths about 50 m (WAPCOS 2016).

In fractured rock yield of a borewell does not increase with depth continuously like sedimentaries. The yield obtained either from uncased weathered zone or shallow fractured zone will continue as a constant yield for a depth drilled beyond these zones, and then there will be a sudden increase in yield as soon as another yielding fractured zone at depth is punctured. A dry fractured zone at depth getting connected to a yielding fractured zone will draw water and reduce the overall yield also the increase or decrease in yield will depend on relative hydrostatic head of the deeper fractured zones. A number of dry fractured zones were encountered in boreholes drilled in Jharkhand. It is observed that the probability of encountering fractured zones, in general, decreases with depth. So, for tapping the shallow fractured zones the depth of water well drilling could be 60–100 m. It could be up to 200 m depth or beyond, if there is some scientific information, say geophysical results, indicating the presence of deeper fractured zones. In DTB, the borewells are generally drilled up to about 200 m depth to tap the deeper flow units and the flow contacts. The borewell up to a depth of 352 m was drilled by CGWB in DTB (Parchure 2010). The yield of borewells in DTB varied over a wide range from less than 3.6 to 176.4 m^3/h with an average yield within 20 m^3/h.

5.4 Aquifer Mapping in Hard Rocks of India

'Aquifer mapping' is a holistic approach to aquifer management. It is to assess quantity, quality and sustainability of aquifers through multidisciplinary integrated studies. The aim is to provide comprehensive information on aquifers, on their characteristics, their interaction with surface water systems, their health, the future stress the aquifers can bear and approaches for conservation and protection required for their management.

Keeping in view the heterogeneities and rapid hydrogeological variations, the site-specific geological and hydrogeological characterization or in other words delineation of hard rock aquifers either for locating well sites or for artificial recharge structures warrants a systematic integrated regional to site-scale field investigations. This is essential because in most cases the hydrogeological uncertainty either makes the programme expensive or compels to abandon it. The aim of the investigation will vary as per the objective. It could be delineation of weathered zone and defining its saturated thickness, demarcation of area with its thickening, saprolite, fractured zone and its orientation, basic intrusive and quartz reef, etc.

Since geomorphology and structures play an important role in groundwater occurrences in hard rock, to get a regional view, the investigation is initiated through mapping of lineaments using satellite imagery. These lineaments may be associated with geological structures, and their hydrogeological relevance is ascertained through geological field observations. The areas traversed by regional lineament, higher density of lineaments and criss-crossing lineaments have better prospect for thick weathered and fractured zones. The wells located on or near lineaments generally have better yield.

According to CGWB (2012), about 1,276,000 km^2 hard rock area of the country is suitable for groundwater development and artificial recharge. Aquifer mapping can be taken up in this entire area in a phased manner with prioritization.

5.5 Surface Geophysical Survey

The subsurface investigation in hard rocks is initiated through geophysical surveys preferably across lineaments. The surveys are aimed at identifying the hydrogeological anomalies, i.e. identifying and interpreting the variations in physical properties of the subsurface and transforming them into hydrogeological inferences subjectively. The usefulness of any geophysical method rests in its capability to pick up and resolve with least ambiguity, the anomalies caused by small target occurring at depths, having less-contrasting physical properties with the host. The shallow occurrences, bigger dimensions and better physical property contrast make the target identification easier and confident. The weathered zone and saprolite, saturated shallow fractured zones, basic dykes and the quartz reefs can be delineated. The orientation of fractured zones, their connectivity, water content and quality and flow direction can only be approximated. While the weathered zone can be characterized easily, it is difficult to delineate the thin saprolite and deeper fractured zones.

The commonly used geophysical methods are electrical resistivity, electromagnetic and magnetic. The electrical resistivity and electromagnetic methods are quite popular as they are most responsive to the variations in the physical property—the electrical conductivity caused by the variations in the occurrence of groundwater and its quality in terms of electrical conductivity. These methods are employed through different techniques—the sounding and profiling to get respectively the vertical and lateral variations in electrical resistivity and approximate the subsurface structures. The modern technique of merging profiling and sounding is known as imaging. Resistivity imaging provides two (x-z plane)- or three-dimensional picture of the subsurface. The geophysical surveys are conducted mainly for two purposes —either to assess the suitability of a water well drilling site located and selected on the basis of demand and habitation or to select favourable sites geophysically in a large area and then locate suitable drilling sites based on geophysical results. For a large area study, the geophysical surveys can be conducted in two phases: the reconnaissance and detailed. The reconnoitory surveys are conducted to narrow down the zone of interest for detailing. The reconnaissance is carried out by any one of the fast-coverage methods, viz. total magnetic field, very low frequency (VLF) and single frequency electromagnetic (FEM) profiling or a combination of these methods can also be used. The location, width and extents of basic dykes, lithological contacts and also thickening of weathered zone can be assessed by the magnetic survey. The detailing is done by a combination of techniques like Gradient Resistivity Profiling (GRP) and Vertical Electrical Sounding (VES) or Electrical Resistivity Tomography (ERT) and multi-frequency and multi-spacing FEM. The dual moment time domain electromagnetic (TEM) sounding can also be conducted. Since in hard rock areas, the fractured zones are manifested on the surface mostly as lineaments, the economical approach is to first carry-out parallel profile GRP across lineaments obtained through satellite imageries and confirm the presence of associated conductive fractured zone. It is followed by VES conducted along the conductive zone delineated or ERT across the linear conductive zone picked up in GRP. Though ERT produces a 2-D picture of the subsurface and is better and faster compared to VES and resistivity profiling, which gives only 1-D information, the data acquisition cost for large-scale ERT is high. It may not be economically feasible and also not required. Selectively locating ERT across the conductive zone picked up by GRP is a better and economical approach.

5.6 Heliborne Geophysical Survey

The modern approach to aquifer mapping in hard rock is through helicopter-borne electromagnetic and magnetic surveys also known as heliTEM and heliMAG surveys. The advantage of heliborne survey is that it produces dense data coverage, fast data acquisition and provides accessibility to inaccessible areas and rugged terrains. The heliborne TEM in combination with magnetic surveys has been introduced to delineate the weathered zone and the shallow fractured zones. It has been conducted for aquifer mapping in several countries. In India, CSIR-National Geophysical Research Institute, Hyderabad, India, and Central Ground Water Board, Government of India jointly conducted the heliborne surveys for the World Bank funded aquifer mapping pilot project (AQUIM) of the Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India (Ahmed 2014 and Chandra et al. 2016). The heliTEM and heliMAG surveys were conducted in six different hydrogeological terrain of India with the objective of evaluating the efficacy of these surveys under varied hydrogeological conditions. Out of the six different hydrogeological terrain of India, three are in the hard rock terrain. They represent alluvium covered (thickness up to 70 m) highly folded and faulted hard rock area of Rajasthan, weathered fractured granite gneiss area of Karnataka and the basaltic terrain of Maharashtra. The heliMAG total field survey was conducted to decipher the subsurface structural fabric of the hard rock terrain, while the heliTEM survey was conducted with dual (low and high) moment transmitter to map the near-surface as well as the deeper hydrogeological conditions. The aquifers in the alluvial cover, in the weathered zone and in the deeper fractured zones were mapped, and the structures of hydrogeological significance were delineated. Once the heliborne results are validated through borehole drilling up to appropriate depths, the approach could be proved and established for aquifer mapping in hard rock areas.

5.7 Case Studies on Integrated Geophysical Survey

The results of integrated surface geophysical survey in three areas, viz. the Chhotanagpur granite gneiss of West Bengal (site 1), meta-sediments of Jharkhand (site 2) and Bundelkhand Gneissic Complex of Uttar Pradesh (sites 3 and 4) States of India are discussed here. The sites 1 and 2 were surveyed during 1986–88, and the sites 3 and 4 were surveyed in 2016. These are discussed here to show the efficacy of multi-technique geophysical surveys to arrive at the best common anomaly and also the variations in approach over the past 30 years. The present-day use of ERT has become a major geophysical contribution in hard rock exploration which was not available earlier. The results are shown in Figs. 5.1 through 5.6.

At all these sites, the surveys were initiated by locating the lineaments and placing the surface geophysical survey profiles across the lineaments. Since the aeromagnetic data were made available for parts of Jharkhand and West Bengal, for sites 1 and 2 the ground geophysical survey profiles were placed in areas of coincident photo lineament and aeromagnetic lineament (Figs. 5.1 and 5.3). The surveys were initiated in West Bengal and Jharkhand through reconnaissance total field magnetic profiling. At site 1 in granite gneiss (Fig. 5.1), the magnetic profiling was followed by 100 m transmitter-receiver spacing FEM profiling. The anomalies for higher transmitter frequencies were prominent (Fig. 5.2a). The FEM anomalies at higher transmitter frequencies were enhanced due to the presence of conductive overburden (weathered zone). The conductivity of the overburden was estimated by VES. The shape of the FEM anomaly revealed the presence of northwest dipping parallel relatively more conductive bodies underneath the conductive overburden. The GRP anomalies manifested three prominent resistivity lows, confirming the FEM anomalies. The interpretation of VES conducted on the GRP 'low' anomalies

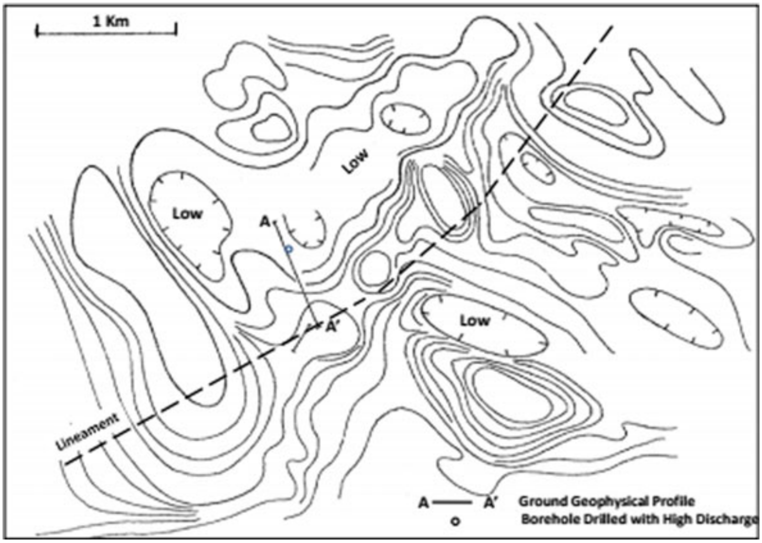


Fig. 5.1 Ground geophysical surveys (shown as profile AA') for groundwater exploration at site 1 in Chhotanagpur granite gneiss terrain of West Bengal State, India, across coincident aeromagnetic and photo lineament (Chandra et al. 1994). *Aeromagnetic data source* AMSE, Geological Survey of India

indicated 24-m-thick weathered zone and saprolite with resistivity between 148 and 212 Ω m. On the basis of these results, drilling sites were selected.

A borehole was drilled up to a depth of 198.76 m on the geophysical anomaly. The borehole encountered weathered zone and saprolite up to 25 m depth and two saturated thin fractured zones, viz. F1 in the depth range 48.36–49.36 m and F2 in the depth range of 110.32–110.53 m (Fig. 5.2b). The yield from the weathered zone was 9.0 m^3/h and that from F1 and F2 were 7.2 and 10.8 m^3/h, respectively. The borehole encountered two dry fractures at 63 and 99 m depth. In the electrical resistivity log of the borehole, the saturated fractured zones were picked up as low resistivity zones, dry fractured zones as relatively high-resistivity zones and compact formations with very high resistivity, of the order of 10,000 Ω m. The borehole drilling and logging results indicated that the thin fractured zones at depths may not get detected individually by resistivity and electromagnetic surveys. However, a reduction in bulk resistivity of the formations due to the presence of saturated fractures can definitely be deciphered.

To select another water well drilling site near site 1, the ground geophysical surveys comprising magnetic, FEM and GRP were conducted along a NE-SW profile in a nearby area. The GRP low and FEM anomaly were coincident (Fig. 5.2c). The FEM responses were enhanced at higher transmitter frequencies. It indicated a thickening of conductive overburden (weathered zone) and possible presence of saturated fractured zone immediately underlying the overburden. The borehole 2 (Fig. 5.2c) was drilled up to 200.82 m depth on this GRP-FEM anomaly. It encountered about 17 m thick weathered zone and a saturated fractured zone at 44.8 m depth. The yield from the weathered zone and saprolite was 5 m^3/h and that from the fractured zone was 6.9 m^3/h. To analyse an high-resistivity anomaly in GRP, the test borehole 3 (Fig. 5.2c) was drilled up to a depth of 300.76 m on the GRP 'high' anomaly. The borehole 3 was dry throughout the depth drilled with the only exception that a very small yield of about 0.76 m^3/h was obtained from 25.47 m thick weathered zone and saprolite. It established the essentiality of geophysical surveys in hard rocks to locate successful water wells.

Like granite gneiss terrain mentioned above, in meta-sediments of Jharkhand, India, comprising schists, quartzites and phyllites, similar ground geophysical survey approach was made to locate water well drilling site (Fig. 5.4). The meta-sediments are highly folded with steeply dipping flanks. A long total magnetic field ground survey profile was placed across the NNE-SSW aeromagnetic lineament coincident with photo lineament, shown in Fig. 5.3. The FEM profiles and GRP (profile P2) were subsequently placed on magnetic anomaly (low). The FEM profiling was conducted at two transmitter frequencies and 100 and 200 m transmitter-receiver spacings. On P2, the low-frequency EM responses for both the spacings are considerable. The high transmitter frequency response for 200 m spacing shows a step-like anomaly with kinks and enhancement of anomaly towards NW. It was attributed to thickening of overburden (weathered zone) and presence of parallel dipping conductors underlying the overburden. A similar step-like GRP anomaly with decreasing resistivity towards NW was observed. The interpretation of VES conducted at this site revealed a 7-m-thick weathered zone of 128 Ω m resistivity. It

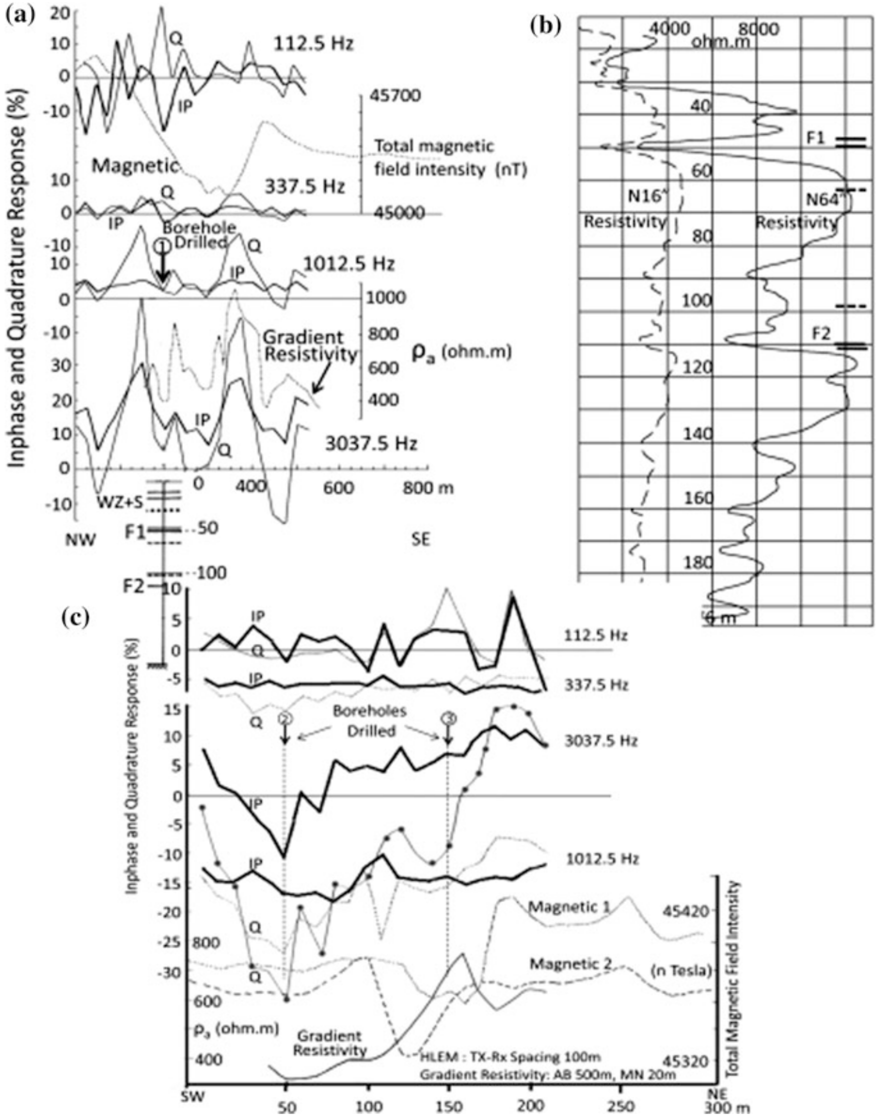


Fig. 5.2 **a** Integrated ground geophysical survey profiles along AA' comprising magnetic, gradient resistivity (GRP) and multi-frequency horizontal loop EM profiling (FEM) for site 1 in Chhotanagpur granite gneiss, West Bengal State, India, for locating borehole drilling sites, **b** N16" and N64" resistivity log of the borehole 1 drilled at site 1; the dry fractured zones at 63 and 99 m depth are shown by dotted lines, and saturated fractured zones are shown by continuous lines; the resistivity log records more than 10,000 Ω m resistivity for the compact formation; yield from weathered zone and saprolite (WZ+S) was 9 m^3/h and **c** ground geophysical survey profiles for borehole 2 and 3; borehole 2 encountered fractured zone at 44.8 m; the borehole 3 drilled on a GRP high was dry. The location of sites is shown on aeromagnetic map in Fig. 5.1

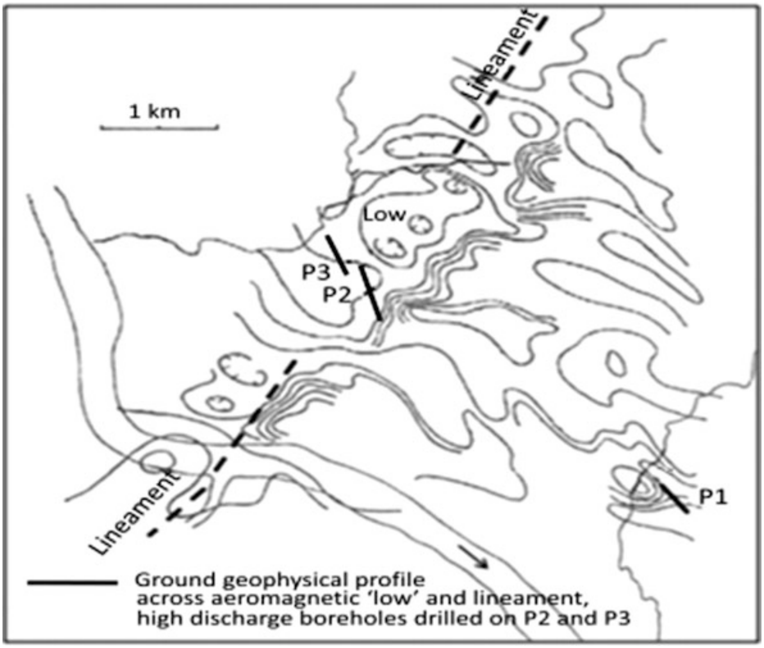


Fig. 5.3 Ground geophysical surveys conducted (shown as profiles P1, P2 and P3) for groundwater exploration at site 2 in meta-sedimentary terrain of Jharkhand State, India, across coincident aeromagnetic and photo lineament (Chandra et al. 1994). *Aeromagnetic data source* AMSE, Geological Survey of India

is underlain by 22-m-thick relatively resistive (198 Ω m) saprolite. On profile P2, two boreholes were drilled on the basis of FEM anomalies. The boreholes encountered high-yielding fractured zones up to 147 m depth (Fig. 5.4). Since the GRP on profile P2 showed a decreasing resistivity towards NW, another GRP-FEM profile (P3) in NW-SE direction was placed towards NW of P2 over a stretch of 300 m. The GRP on P3 showed lesser resistivity values compared to P2 and a decreasing trend towards NW. The high transmitter frequency FEM profile showed a prominent anomaly towards the NW end of the profile. It indicated a thick conductive overburden (weathered zone). The VES conducted at this site revealed the presence of 6–8 m thick near-surface layer of 22 Ω m resistivity. It is underlain by 35–40 m thick layer of 60–70 Ω m resistivity. A comparison of the results of VES on P2 and P3 revealed the presence of thick lesser resistive formation on P3. The presence of lesser resistive formation on P3 caused the enhancement in high transmitter frequency FEM anomaly. The borehole drilled towards NW end of profile P3 on GRP-FEM anomalies encountered a very high-yielding fractured zone in the depth range 57.86–68.10 m. The borehole could not be drilled further due to back pressure of water. Comparison of GRP-FEM anomalies of profiles P2 and P3 confirms the enhancement of FEM response due to the thick (35–40 m) relatively less resistive (60–70 Ω m)

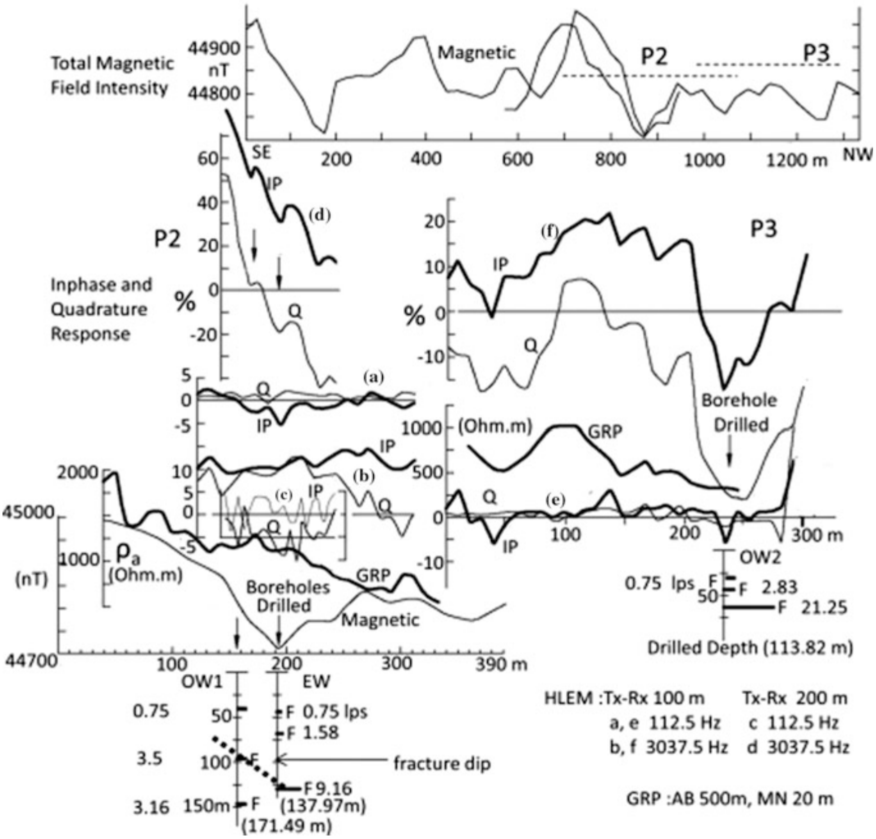


Fig. 5.4 Integrated magnetic, gradient resistivity and multi-frequency horizontal loop EM profiling at site 2 in meta-sediments, Jharkhand, India, for locating the boreholes. Location in aeromagnetic map is shown in Fig. 5.3

formation and the presence of conductive (or less resistive) fractured zones at depths around 50–70 m. The reduction in GRP resistivity in profile P3 compared to P2 is supported by the reduction in layer resistivities interpreted from the VES conducted on P3. The results of integrated ground geophysical survey in meta-sediments also substantiated its effectiveness in identifying the shallow to moderately deep (within 100 m depth) fractured zone.

These case studies reveal two important aspects, viz. (a) the usefulness of aeromagnetic and lineament maps in narrowing down the area for detailed ground geophysical survey and (b) the integration of electrical resistivity and FEM methods for ground geophysical survey. In case, aeromagnetic maps are not available for the area, at first a long total field magnetic profile is to be placed across the photo lineament and the stretches with magnetic low anomaly across a photo lineament are to be considered for GRP and FEM follow-up surveys. The shape of the total field magnetic anomaly depends on latitude of the location, and corrections are to be applied. The FEM anomalies are to be confirmed by GRP. The GRP resistivity highs are definitely negatives for locating water well drilling site. Wide and contrasting GRP low (resistivity less than 500 Ω m with the background resistivity of 1000–2000 Ω m) associated with high transmitter frequency FEM anomaly can be considered for locating a water well drilling site. Though locating high-yielding water wells by geophysical surveys is desired, the efficacy of geophysical methods cannot be judged by well yield alone. In most of the cases, the borehole is drilled on the local best geophysical anomaly which may not be a standard good anomaly.

The case studies 3 and 4 are from Bundelkhand Gneissic Complex where a systematic sequential approach through GRP, VES and ERT was made to map the weathered zone and fractured zone aquifers (WAPCOS 2016). The GRP and ERT are shown in Figs. 5.5 and 5.6. GRP was used to locate the ERT. The ERT finally helped locating the low resistivity zone associated with deeper fractures. It is evident that identifying individual thin fractured zone even by ERT is difficult but the zone which may hold the maximum possibility of fractures can be demarcated. The 200-m deep borehole drilled at site 3 (Fig. 5.5) on the relatively low resistivity (about 700 Ω m) zone inferred up to about 100 m depth in the central part of the ERT encountered 2 fractured zones at 75 and 93.5 m depths. It is corroborated by the resistivity log of the borehole (Fig. 5.5). The cumulative yield was about 30 m^3/h. Another ERT conducted to ascertain the extension of a NE-SW trending fault zone, and its suitability for well siting is shown in Fig. 5.6. The borehole drilled in the

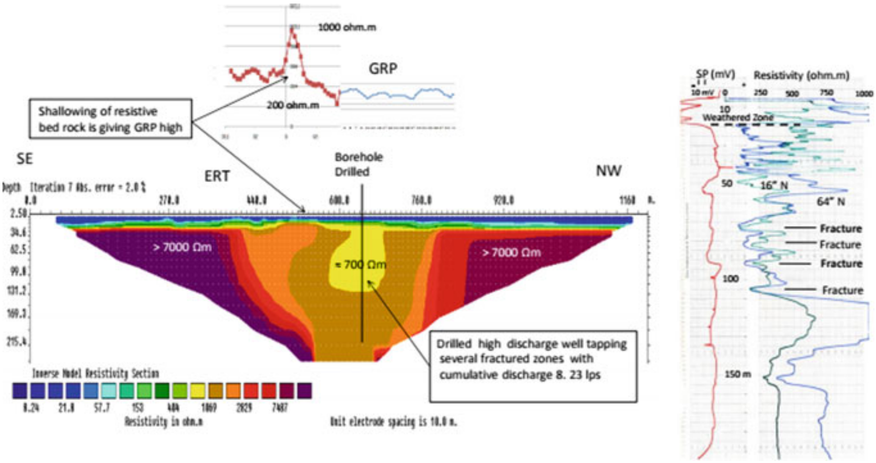
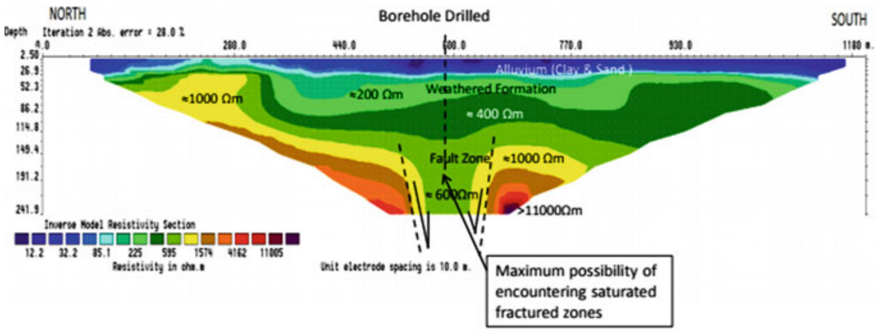


Fig. 5.5 Results of geophysical investigation comprising GRP and ERT and the electrical logging of the borehole drilled at a site 3 in Bundelkhand Gneissic Complex, Uttar Pradesh *Source* WAPCOS 2016



The ERT has confirmed the fault zone and possibility of groundwater saturation in the associated fractured zones

Fig. 5.6 Results of ERT at a site 4 in Bundelkhand Gneissic Complex, Uttar Pradesh. *Source* WAPCOS 2016

fault zone encountered fractured zones at 34.5, 40.8 and 158.5 m depth. The cumulative yield of the borehole was 12.4 m^3/h. The combination of GRP and ERT was found quite useful in locating successful boreholes in hard rock.

5.8 Managed Aquifer Recharge

The withdrawal of groundwater more than its replenishment results in declining groundwater level. The near-surface weathered zone aquifers, discontinuously available as pockets of limited storage capacity, either get dewatered and dried-up at many places or the water level in them deepens, resulting in a large number of dry wells. This is an alarming issue in the hard rock area of India. According to CGWB (2012), out of the total area under critical and overexploited stages of groundwater development in India, more than 40% area—about 32,000 km^2 under critical and more than 200,000 km^2 under overexploited stages—falls in the hard rocks (Tables 5.4 and 5.5, the limestone and the lateritic terrains are excluded). That is, a huge volume of dewatered weathered zone is available which can be locally recharged. Storing water in the dewatered space to restore or slowdown the declining water level and consequently recharging the connected underlying fractured zones requires intervention known as managed aquifer recharge (MAR) or artificial recharge. According to CGWB (2012), more than 284,000 km^2 hard area is suitable for artificial recharge.

There are several types of artificial recharge methods, of which the dug well recharge, check dam, percolation pond and recharge well are in practice in several States of India. The selection depends on subsurface and surface lithological conditions, terrain, fracture pattern, groundwater conditions and availability of adequate recharging surface water of good quality. Recharge structures are effective in

Table 5.4 Hard rock area (km^2) in various states under critical stage of groundwater development

State	Basalt	Granite	Schist	Quartzite	Charnockite	Khondalite	BGC	Gneiss	Total
Andhra Pradesh and Telangana	497	237	76				4414	28	5252
Gujarat	790	119	88	41				17	1055
Haryana				37				4	41
Jharkhand			2		42		438		482
Karnataka	2721		922				9366		13,009
Kerala					6			468	474
Madhya Pradesh	1127		9					15	1151
Rajasthan		139	2	85			13	986	1225
Tamil Nadu		94	122		3724	132	627	4330	9029
Uttar Pradesh				141			620		761
Total	5135	589	1221	304	3772	132	15,478	5848	32,479

Source CGWB (2012)

Table 5.5 Overexploited hard rock area (km^2) in various states

State	Basalt	Granite	Schist	Quartzite	Charnockite	Khondalite	BGC	Gneiss	Total
Andhra Pradesh and Telangana	198	1505	77	1675		258	11,943	1	15,657
Delhi				136					136
Gujarat	1059	57						16	1132
Haryana				201					201
Jharkhand		2	344	17			500	56	919
Karnataka	12,575		5323				46,717		64,615
Kerala								266	266
Madhya Pradesh	18,176								18,176
Maharashtra	5001								5001
Rajasthan	7433	12,157	3257	5367	173	74	17,658	15,172	61,831
Tamil Nadu		503	7		13,138	617	2207	18,939	35,411
Uttar Pradesh				11			1356		1367
Total	44,442	14,224	9008	7407	13,311	949	80,381	34,990	204,712

Source CGWB (2012)

areas with permeable soil and weathered zone and in areas with tensional fractures which are open in nature. A minimal rainfall of about 246 mm in red lateritic soil covered granitic terrain and 412 mm in black cotton soil covered basaltic terrain is required for deep percolation (Sharma and Kumar 2008).

In dug well recharge schemes, the dug well is used not only for taking out water but also for recharging the weathered zone and the connected fractures through minor modification. It is quite economical and affordable by individual farmer or group of farmers and benefits can be effectively seen only through mass participation. On an average, the availability of a dug well per hectare (100 m × 100 m area) is minimum 1 and can be utilized for the purpose. However, prior to taking up a dug well for recharge, it is necessary to investigate the subsurface hydrogeological condition around the dug well, the pre- and post-monsoon water level data and its location wise feasibility for getting adequate surface water runoff collected in the agricultural field which can be put into the dug well after sand–gravel filtering. That is, an adequate thickness of permeable weathered zone and a good catchment area should exist around the dug well. Above all, the willingness of the farmers is essential because of the common perception that they may not get the water recharged which may move out of their land (Krishnan et al. 2009). A detailed guideline on dug well recharge is available on CGWB web site.

Percolation tank is another recharge structure constructed in hard rocks over permeable near-surface layer. The rate of recharge from percolation tank varies between 9 and 12 mm/day (Sharma and Kumar 2008). Check dam is the most popular recharge structure in hard rocks. Check dams of different dimensions are constructed across the streams to impound the monsoon runoff. A series of check dams can be constructed across a stream. Muralidharan et al. (2007) indicate that by check dam the natural recharge in granitic terrain can be increased from 5–8% of the rainfall to 27–40%.

5.9 Groundwater Quality

Fluoride concentration in groundwater within the permissible limit (<1.5 mg/l) is useful, but its higher concentration in hard rock terrain of India, which is quite common, poses a health issue for drinking water. Nineteen States are affected by high fluoride contaminations (CGWB 2010). The geogenic factors like presence and solubility of fluoride-bearing minerals in the host rock, groundwater contact or residence time and climate control the fluoride concentrations. The higher concentrations of fluoride generally occur in the arid and semi-arid areas with limited flushing. Occurrences of fluoride contaminated high-yielding fractured zone are quite common. Besides, some anthropogenic sources also cause an increase in fluoride concentration above the permissible limit in the shallow zones. The drinking water supply has to be mostly from the overlying fluoride-free weathered zone and from the alluvial capping in some places supplemented by defluoridation of groundwater from the fractured zones. Where better quality surface water is available, dilution of fluoride concentration through artificial recharge could be a useful option (Muralidharan et al. 2002). The quality of water in weathered zone may vary from that in fractured zones, and also, it may vary from one fractured zone to another. Jayasena (1993) observes that due to flushing and movement of groundwater through fractured zone network, in general, locations with high fractured zone density hold a better quality groundwater, while the structural features and intrusive bodies could also control the quality of groundwater.

Acknowledgements Author is grateful to Professor Abhijit Mukherjee, Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur, West Bengal, India, for providing the unique opportunity of writing this chapter. Most of the text and figures in the chapter are taken from the book 'Groundwater Geophysics in Hard Rock' by P. C. Chandra, published by Taylor & Francis, The Netherlands, ISBN 978-0-415-66463-9. The author is extremely thankful to Taylor & Francis Group for the kind permission to use the text and figures from the book. Author is thankful to Dr. J. K. Rai, General Manager and Head, GWRDM, WAPCOS Ltd., New Delhi, India, for the permission to use some of the figures of WAPCOS geophysical survey report of Jhansi–Lalitpur districts, Uttar Pradesh.

References

Adyalkar PG, Rane VV, Mani VVS, Dias JP (1975) Evaluation of the aquifer characteristics of the basaltic terrain of Maharashtra in India. Proc Indian Acad Sci Sect A 81(3):108–117

Ahmed S (2014) A new chapter in groundwater geophysics in India: 3D aquifer mapping through heliborne transient electromagnetic investigations. J Geol Soc India 84(4):501–503

Central Ground Water Board (2009) Annual report (2008–09). Publication of CGWB, Ministry of Water Resources, Government of India

Central Ground Water Board (2010) Groundwater quality in shallow aquifers of India. Publication of CGWB, Ministry of Water Resources, Government of India

Central Ground Water Board (2012) Aquifer systems of India. Publication of CGWB, Ministry of Water Resources, River Development & Ganga Rejuvenation, Government of India

Central Ground Water Board (2012a) Groundwater studies in Kasai-Subarnarekha River basins. Publication of CGWB, Ministry of Water Resources, Government of India

Central Ground Water Board (2012b) Ground water information booklet, Kolar district. Publication of CGWB, Ministry of Water Resources, Government of India

Chandra PC (2015) Groundwater geophysics in hard rock. CRC Press/Balkema, Taylor & Francis Group Publication, The Netherlands, ISBN 978-0-415-66463-9

Chandra PC, Reddy PHP, Singh SC (1994) Geophysical studies for groundwater exploration in Kasai and Subarnarekha River basins (UNDP project). Publication of CGWB, Ministry of Water Resources, Government of India

Chandra S, Ahmed S, Auken E, Pedersen JB, Singh A, Verma SK (2016) 3D aquifer mapping employing airborne geophysics to meet India's water future. Lead Edge (Special Section: Hydrogeophysics) 770–774

Clark L (1985) Groundwater abstraction from basement complex areas of Africa. Q J Eng Geol 18 (1):25–34

Custodio E (2007) Groundwater in volcanic hard rocks. In: Krasny J, Sharp JM Jr (eds) Groundwater in fractured rocks: selected papers from the groundwater in fractured rocks international conference, 15–19 September, 2003, Prague, IAH Selected Paper Series, vol 9. Taylor & Francis/Balkema, The Netherlands, pp 95–108

Deolankar SB (1980) The Deccan basalts of Maharashtra, India—their potential as aquifers. Ground Water 18(5):434–437

Dev Burman GK, Das PK (1990) Groundwater exploration in hard rock terrain: an experience from eastern India. In: Shamir U, Jiaqi C (eds) The hydrological basis for water resources management: proceedings of the Beijing symposium, October, 1990. IAHS Publication. No. 197, pp 19–30

Dhonde UV (2009) Groundwater information, Nashik district, Maharashtra. 1614/DBR/2009, Central Ground Water Board, Min. of Water Resources, Govt. of India

Geological Society of India (2008) 'Drinking water and food security in hard rock areas of India' and 'Changing geohydrological scenario-hardrock Terrain of peninsular India' Golden Jubilee Volumes, ed. Subhajyoti Das, Geological Society of India Publication

Ghosh P, Sayeed MRG, Islam R, Hundekari SM (2006) Inter-basaltic clay (bole bed) horizons from Deccan traps of India: Implications for palaeo-weathering and palaeo-climate during Deccan volcanism. Palaeogeogr Palaeoclimatol Palaeontol 242(1–2):90–109

Gustafson G, Krasny J (1993) Crystalline rock aquifers: their occurrence, use and importance. In: Banks D, Banks Sheila (eds) Hydrogeology of hard rocks: memoires of the XXIV congress of IAH, 28 June–2 July, As, IAH Press, Oslo, Norway, pp 3–20

Jayasena HAH (1993) Geological and structural significance in variation of groundwater quality in hard crystalline rocks of Sri Lanka. In: Banks D, Banks Sheila (eds.) Hydrogeology of Hard Rocks: Memoires of the XXIV Congress of IAH, 28 June–2 July, As, Oslo, Norway, IAH Press, pp 450–471

Jones MJ (1985) The weathered zone aquifers of the basement complex areas of Africa. Q J Eng Geol 18(1):35–46

Kale VS, Kulkarni H (1992) IRS-1A and landsat data in mapping Deccan Trap flows around Pune, India: implications on hydrogeological modelling. In: Fritz LW, Lucas JR (eds) Interpretation of photographic and remote sensing data, technical commission VII, ISPRS archives-vol. XXIX, part B7, proceedings of the XVIIth ISPRS congress, August 2–14, 1992, Washington, DC, pp 429–435

Krasny J, Sharp JM Jr (2007) Hydrogeology of fractured rocks from particular fractures to regional approaches: state-of-the-art and future challenges. In: Krasny J, Sharp JM Jr (eds) Groundwater in fractured rocks: selected papers from the groundwater in fractured rocks international conference, 15–19 September, 2003, Prague, IAH Selected Paper Series, vol 9. Taylor & Francis/Balkema, The Netherlands, pp 1–30

Krishnan S, Indu R, Shah T, Hittalamani C, Patwari B, Sharma D, Chauhan L, Kher V, Raj H, Mahida U, Shankar M, Sharma K (2009) Is it possible to revive dug wells in hard-rock India through recharge? In: Strategic analyses of the National River Linking Project (NRLP) of India series 5, proceedings of the second national workshop on strategic issues in Indian irrigation, International Water Management Institute, New Delhi. https://doi.org/10.3810/2010.202

Larsson I (1984) Groundwater in hardrocks. Project 8.6 of the IHP, UNESCO, Studies & Reports in Hydrology 33, UNESCO Publication, France. ISBN 92-3-101980-5

Mahoney JJ (1988) Deccan traps. In: Macdougall JD (ed) Continental flood basalts [Online], Kluwer Academic Publishers, The Netherlands, pp 151–194

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Muralidharan D, Andrade R, Rangarajan R (2007) Evaluation of check-dam recharge through water-table response in ponding area. Curr Sci 92(10):1350–1352

Muralidharan D, Nair AP, Sathyanarayana U (2002) Fluoride in shallow aquifers in Rajgarh Tehsil of Churu District, Rajasthan – an arid environment. Curr Sci 83(6):699–702

Parchure PK (2010) Groundwater information Ahmadnagar district, Maharashtra. 1645/DBR/2010, Central Ground Water Board, Min. of Water Resources, Govt. of India

Saha D, Agrawal AK (2006) Determination of specific yield using water balance approach – case study of Toria Odha watershed in the Deccan Trap province, Maharashtra State, India. Hydrogeol J 14(4):625–635

Sharma KD, Kumar S (2008) Hydrogeologcal research in India in managing water resources. In: Ahmed S, Jayakumar R, Salih A (eds) Groundwater dynamics in hard rock aquifers: sustainable management and optimal monitoring network design, Chapter 1, Springer, pp 1–19

Singhal BBS (1997) Hydrogeological characteristics of Deccan Trap formations of India. In: Pointet T (ed) Hard rock hydrosystems, proceedings 5th IAHS international symposium April-May 1997, IAHS Publ. No. 241, Morocco, Rabat. Oxfordshire, UK, Institute of Hydrology, IAHS Press, pp 75–80

Singhal BBS (2008) Nature of hard rock aquifers: hydrogeological uncertainties and ambiguities. In: Ahmed S, Jayakumar R, Salih A (eds) Groundwater dynamics in hard rock aquifers: sustainable management and optimal monitoring network design, Chapter 2, Springer, pp 20–39

Singhal BBS, Gupta RP (1999) Applied hydrogeology of fractured rocks. Kluwer Academic Publishers, The Netherlands

Subramanian P (1992) Hydrogeology and its variations in the granites and associated rock formations in India. In: Proceedings of the workshop on artificial recharge of groundwater in granitic terrain, Bangalore, 19 October 1992, pp 1–13

Surinaidu L, Bacon CGD, Pavelic P (2013) Agricultural groundwater management in the Upper Bhima basin, India: current status and future scenarios. Hydrol Earth Syst Sci 17(2):507–517

WAPCOS (2016) Geophysical survey for aquifer mapping in Jhansi and Laltpur districts, Uttar Pradesh, Report submitted to C.G.W.B., Min. Water Resources River Development & Ganga Rejuvenation, Government of India

Chapter 6
Assessment of Groundwater in Karst System of Kashmir Himalayas, India

Ghulam Jeelani, Rouf Ahmad Shah and Rajendrakumar D. Deshpande

Abstract In Kashmir Valley, the carbonate rocks cover an area of about 1100 km^2, of which 58% lie towards the southern part. Carbonate lithology in the form of Triassic Limestone constitutes significant karst geomorphologic imprints including solution features, swallow holes, conduits, shafts, caves and large springs. Hydrochemical data of major springs of Kashmir Valley indicate that the spring water chemistry is dominantly contributed from weathering of carbonate rocks. The karst spring waters are undersaturated with respect to calcite and dolomite, and PCO_2 of the spring water is more than atmosphere, suggesting the groundwater in karst system is highly aggressive and capable of dissolving the host rock in most of the seasons. During winters, when there is negligible recharge, the spring waters are not aggressive as the carbonic acid is consumed and not replenished, leaving the waters saturated with respect to calcite and dolomite. The observed large fluctuations of spring discharges from daily or seasonal to annual scales reflect the quick flushing of groundwater and the extent of development of subsurface karstification in the region. The karst springs were found to respond immediately to ambient temperature, which causes snow/ice melting, and rainfall, which increases the recharge. Given the high relief of the Kashmir Valley and strong isotopic variability, the vertical isotopic gradients were estimated in different mountainous catchments. Keeping in view the high permeability, short transit times and multifaceted importance of karst springs in the region, effective approaches are required for the management and protection of these vital groundwater resources.

G. Jeelani (✉) · R. A. Shah
Department of Earth Sciences, University of Kashmir, Srinagar 190006, India
e-mail: geojeelani@gmail.com

R. D. Deshpande
Geosciences Division, Physical Research Laboratory, Navrangpura,
Ahmedabad 380009, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_6

6.1 Introduction

Within the realm of geomorphology, each geomorphic/geologic process leaves a distinct assemblage of landforms (Thornbury 1969). For karst, this imprint is expressed as solutional morphology. Karst geomorphology defines the processes and conditions that influence the physical, morphological, and structural characteristics of carbonate rock terrains (Nohegar et al. 2012), which are shaped by solutional processes (Bögli 1980; Stokes et al. 2010). Karst is a geomorphic landscape that arises from the combination of high rock solubility and well-developed subsurface drainage networks on rock types that are easily dissolved by water, notably carbonate rocks such as limestone, dolomite or marble (Culver and White 2005; Ford and Williams 2007) and to a lesser extent evaporites such as gypsum, anhydrite and halite (Klimchouk 2002). Calcite and, to a lesser extent, dolomite are the most significant karst minerals, easily dissolving in carbonic acid or aqueous solutions of CO_2 (Carroll 1970). The solutional capability of water with respect to these minerals is related directly to its carbon dioxide content. The CO_2 is derived directly from the atmosphere through precipitation and taken from the biogenic sources at the surface and subsurface (Waltham et al. 1997). Therefore, the solubility/dissolution of carbonate rocks involves interrelated air (gas), water (aqueous) and rock (solid) phases of the chemical environment. The dissolution rate of karst rocks depends on the concentration of the CO_2 held in karstic systems (Bogli 1980; Sheen 2000). The acidic waters infiltrate along the existing joints, fractures, and bedding planes in the carbonate bedrock, developing the secondary and tertiary porosities and therefore, leading to development of vertical and horizontal karst drainage (Field 2002). The dissolution and the subsequent karstification have resulted in exceptional landscapes across the world, and in various countries, karst areas have been designated as national or state parks (Ford and William 2007).

Globally, examples of karst topography can be found at all latitudes and elevations and cover a substantial portion (20–33%) of the Earth's land surface (Milanovic 1988; Jamali et al. 2015). The best-developed karst regions of the world are found in tropical (e.g., southern China, Vietnam, Jamaica) and temperate (e.g., Yugoslavia) regions. The karst landscapes represent Earth's most diverse, scenic and resource-rich terrains with much of their wealth underground, including minerals, oil, natural gas and limestone, apart from beautiful housing sites for urban development (Nohegar et al. 2012). Besides, karstic rocks are the most important hydrogeological formations worldwide (Bakalowicz 2005). It is observed that nearly 40–50% of the human population utilizes drinking water derived from karst aquifer systems either directly or indirectly (COST ACTION-65 1995; Cooper et al. 2011). Apart from their rich natural resources, the subsurface environments of karst landscapes offer many opportunities for scientific and educational research as well as recreational benefits (Hall and Day 2011). In particular, subsurface karst environments provide a porthole into landform development and past environmental circumstances (Latham et al. 2007). The cave networks and deposition of speleothems represent some excellent sedimentary archives and are among the richest sources of paleoclimate information (Mylroie and Mylroie 2007).

The unique hydrologic, geomorphologic and hydrogeologic features of karst pose the greatest problems in theoretical analysis and water resource evaluation (Vesper et al. 2001; Ford and Williams 2007) and make these aquifers more vulnerable to pollution and contamination (Bonacci 2004; Parise 2010). Sinking streams, solution hollows or dolines provide direct entry points to groundwater, with little or no filtration or attenuation of contaminants (Sauro 2006), and therefore pose great threats to sensitive karst environments and water quality (Gunn 2007; North et al. 2009). The delicate equilibrium of karst ecosystems changes very easily, sometimes dramatically and irreversibly up to its destruction as a consequence of both natural and anthropogenic controls (Parise 2012). Consequently, karst groundwater requires specific and appropriate protection against contaminants and pollutants. The dumping and/or throwing of solid/municipal wastes at recharge sites are one of the most important confronting environmental issues (Gunn 2007). Attention to such contamination and its management has become critical because of its far-reaching impact on human health, as the value of groundwater lies not only in its widespread occurrence and availability but also in its consistent good quality (Rajmohan et al. 2000; UNESCO 2000). This depends upon delineating the catchments and actual source areas that feed the aquifer to prevent the important resource from contamination.

In India (Chap. 1, Fig. 1.1) including the Kashmir Valley, the karst studies are limited (Venkatanarayana and Rao 1989; Coward et al. 1972; Adyalkar 1977; Singh 1985; Murty 1988; Brooks and Smart 1995; Jeelani 2005; Soni 2007; Meijerink 2007; Dar et al. 2011, 2014; Jeelani et al. 2011). Kashmir karst has a substantial socio-economic importance as it provides a relatively pristine water supply for drinking and irrigation purposes. It is also used for extraction of limestone for cement production, building stones and for roads, and it supports unique ecosystems and popular recreation areas. Although the Kashmir karst has tremendous societal importance, very little information is available on the karst geomorphology, hydrology, karst functioning, potential recharge areas and geometry of karst networks (Coward et al. 1972; Jeelani 2005). The present chapter aims to give a detailed account of Kashmir karst with special reference to its formation, hydrology, hydrochemistry, sources of recharge and vulnerability of karstic groundwater to contamination. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

6.2 Overview of the Study Area

The intermountain Valley of Kashmir (Fig. 6.1) formed by the bifurcation of great Himalayan range west of Ravi occupies a bowl-shaped depression between two major orogenic axes of upheaval, namely the folded Pir Panjal range to the southwest and the highly sheared ranges of north Kashmir to the northeast. The area

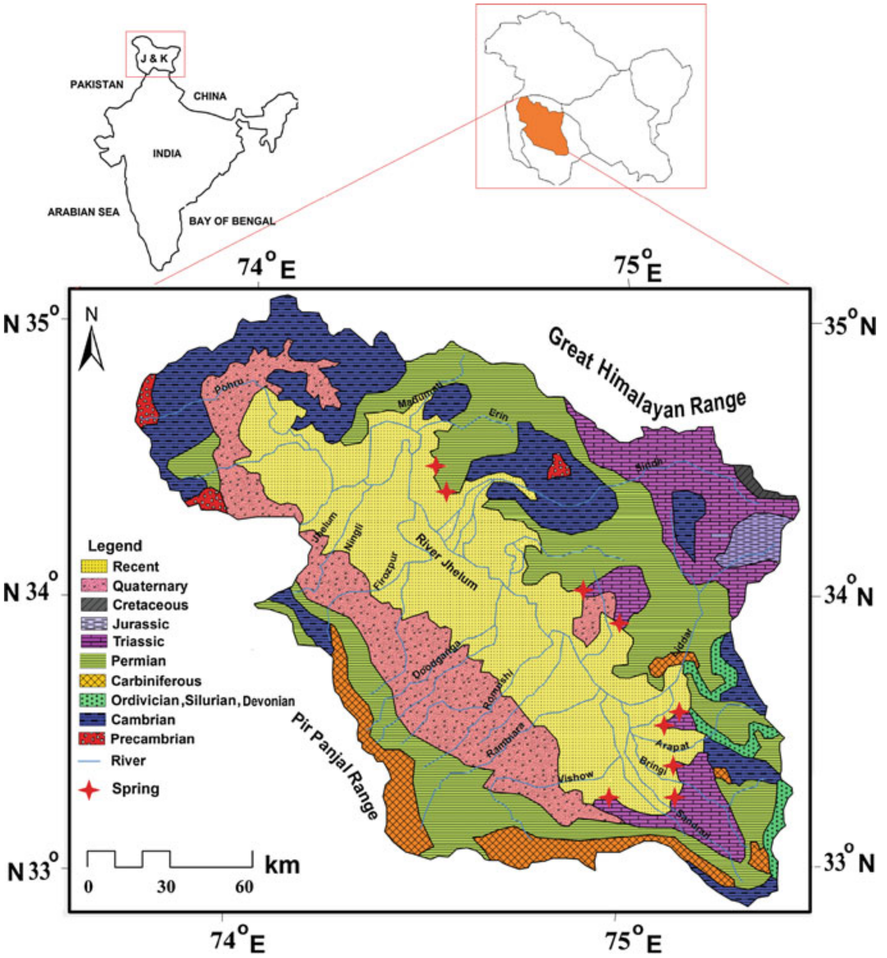


Fig. 6.1 Geology of the study area showing location of some major karst springs in the Kashmir Valley

is located between latitudes 32° 17′N and 36° 58′N and longitudes 73° 26′E and 80° 30′E. The Kashmir Basin is about 140 km long and 40 km wide and covers an area of 5200 km^2, with an average elevation of 1850 m amsl (Jeelani et al. 2014).

Kashmir Valley preserves a geological record of the Himalayan orogenesis, sedimentation and volcanic activity from Archaean to Recent (GSI 1977). Palaeozoic (silicate and carbonate rocks), Triassic (carbonate rocks), Quaternary (Karewa deposits) and Recent (alluvium) are the dominant geological units in the study region. Triassic rocks are surrounded by Palaeozoic rocks and are overlain by Pleistocene and Recent sediments.

The complex series of sedimentary formations, affected by intrusions of igneous rocks, folding, faulting, jointing and geomorphologic dissimilarities, provides the basic framework for the hydrogeology and has resulted in independent or semi-independent hydrogeological units. Within the study area, there are four major hydrogeologic units: the Triassic Limestone aquifer, Panjal Traps aquifer, alluvial aquifer and Karewa aquifer, with first two being the main aquifers (Jeelani 2008). The Triassic Limestone and Panjal Traps are fractured and inherit high hydraulic conductivity (K), which is ~ 6 m/day for the fractured Traps and up to 1000 m/day for the karstified limestone. The low K values for alluvium (0.1–5 m/day) and Karewa (1–10 m/day) are due to the existence of fine detrital sediments (sand, silt and clay). The springs emerge from Triassic carbonate rocks along the foothills of Pir Panjal and in contact with alluvium (Jeelani 2008).

6.3 Carbonate Rocks and Karst Landforms in Kashmir

Karst in Kashmir is widespread due to the wide distribution of carbonate rocks, particularly towards the southern fringe of the region (Shah et al. 2018). The diversity of surface karst features, among which some imply the existence of a well-developed subsurface karst, has created a unique landscape. It was observed that the carbonate rocks cover an area of about 1100 km^2 in Kashmir Valley, of which 58% (631 km^2) lies towards the southern part of the Valley (Shah et al. 2018). Triassic Limestone constitute has significant karst geomorphic imprints, including solution features such as swallow holes, conduits, shafts, caves and large springs, which also demonstrate the importance of this formation as a groundwater reservoir (Shah et al. 2018). In Kashmir, the karst areas occur in the form of dissected ridges and are well distributed in Kokernag (>170 km^2), Verinag (>250 km^2), Achabal (85 km^2), Mattan (47 km^2), Anantnag Town (9 km^2), Zajibal-Sheshnag (70 km^2), Beerwah (14 km^2), Tral (59 km^2), Manasbal (>36 km^2) and Bandipora (>50 km^2). Each carbonate karst ridge exhibits peculiar exokarst and endokarst features with their own distinctive characteristics. These characteristics are largely imposed by the structural development and the relationships between lithology and topography. Many of the carbonate ridges (Triassic Limestone surfaces) are covered with the thick Quaternary fluvio-glacio-lacustrine Karewa deposits that seem to have limited the exposure of most surface karst geomorphic features. The large including both cold and warm springs (Fig. 6.2) are the prominent surficial karst features in the Kashmir Valley, though diverse types of surface karst features are also developed on a wider range and on different scales. Karst features, such as sinkholes, caverns, conduits, shafts, karren fields and pits (Fig. 6.3), are well developed in Triassic Limestone towards southern part of Kashmir Valley.

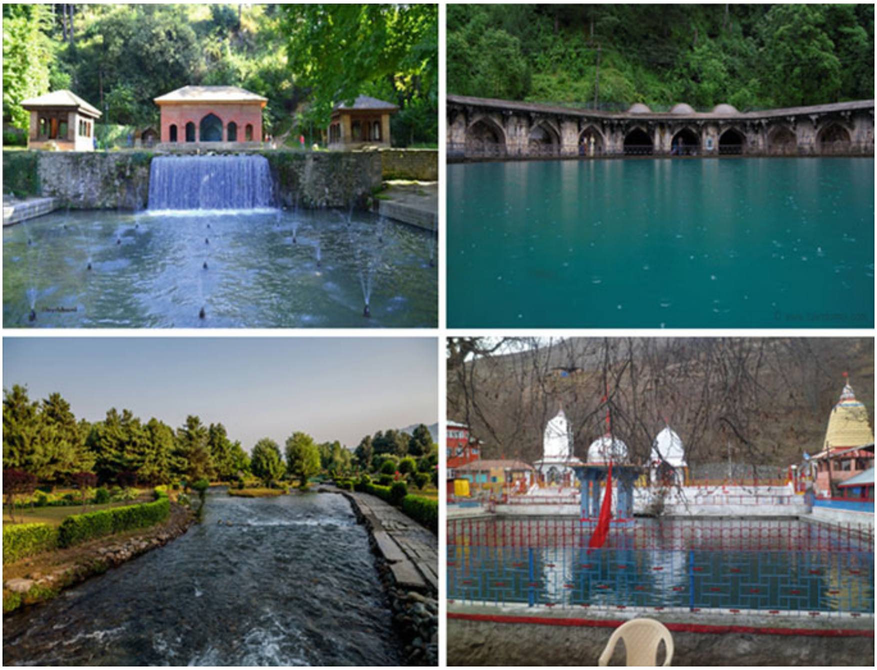


Fig. 6.2 Representative karst springs of the Kashmir Valley

Fig. 6.3 Development of surface and subsurface karstic features

6.4 Hydrochemistry

Geochemical processes occurring within the aquifer due to water–rock interaction have a profound effect on water quality and its composition. Among the cations (TZ^+), the calcium (Ca) dominated the cation budget by 53% followed by magnesium (Mg) 29%, sodium (Na) 14%, potassium (K) 4% and iron (Fe) 1.5%. Similarly, bicarbonate (HCO_3) made 90% of anion budget followed by sulphate (SO_4) 4.7%, chloride (Cl) 3.4%, nitrate (NO_3) 0.75 and fluoride (F) 0.18%, except in some spring (Malakhnag and Gujnag) where SO_4 mark second place in abundance order. Hydrochemical data of major springs of Kashmir Valley are presented in scatter plots (Fig. 6.4). The scatter plot of (Ca + Mg) versus HCO_3 molar concentrations, with an approximate slope of 1, suggests carbonate dissolution as a major source of solutes (Jeelani and Shah 2006). To quantify calcite and dolomite weathering, Mg^{2+}/Ca^{2+} molar ratios are used (Szramek et al. 2011). Mg^{2+}/Ca^{2+} of less than 0.1 indicates pure calcite dissolution, whereas the ratio approaching 1 refers pure dolomite dissolution and Mg^{2+}/Ca^{2+} ratio of 0.33 represents equal contribution from both (Szramek et al. 2011). The karst springs within the study region tend to have a relatively wider range (0.09–1.1) in Mg^{2+}/Ca^{2+} ratios, but 77% of water samples showed calcite dissolution, whereas 33% water samples showed dolomite dissolution. Na versus Cl plot indicates some contribution from silicate lithology, because Cl is mostly associated with alkalies rather than alkaline earth elements. About 99% of the samples showed Na/Cl ratio >1, which indicates that sodium is released from silicates as a result of silicate weathering. Quantification of silicate weathering compared to carbonate weathering is more difficult due to the incongruent degradation of silicates (Das and Kaur 2001). However, the ratio between Na^+ K and total cations (TZ^+) gives a useful estimation of silicate weathering (Stallard and Edmond 1983; Sarin et al. 1989). It was observed that Na and K are dominantly released through the silicate weathering, as the $(Na^+ K)/TZ^+$ ratio ranges from 0.4 to 1.3. The chloro-alkaline index, also known as Schoeller index (Schoeller 1977), expressed as

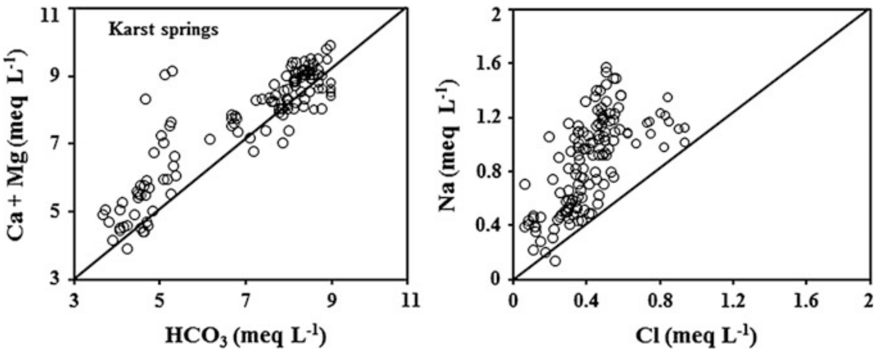


Fig. 6.4 Scatter plots from which can be inferred the possible sources of major ions in karst springs of the region

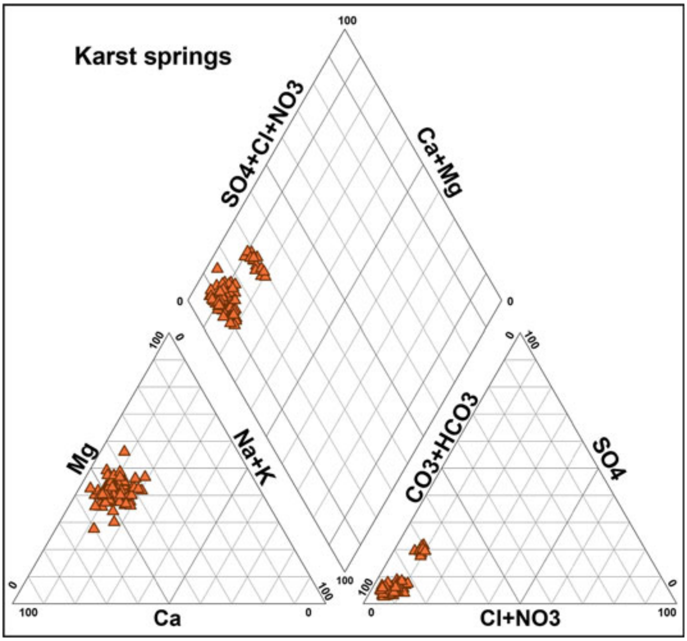


Fig. 6.5 Piper trilinear diagram showing the water types in karst springs

follows: CAI = Cl-Na^+ + K^+/Cl^-, is another hydrogeochemical parameter, which is used to understand ion exchange between groundwater and the host rock during groundwater movement (Rajmohan and Elango 2004). A majority of samples (81%) showed a negative CAI, indicating monovalent cation exchange, while 19% showed a positive CAI indicating base exchange.

The hydrogeochemical facies identified from the Piper trilinear diagram (Fig. 6.5), Ca-HCO_3 and Ca-Mg-HCO_3 types, indicate the strong influence of carbonate lithology on the chemistry of the spring waters in the study region. Ophori and Toth (1989) described such type of water as young recharging water.

Saturation index is an important geochemical parameter used for identifying the existence of minerals in the groundwater system (Liu et al. 2015). The SI values calculated for the karst springs of the region suggest undersaturation with respect to calcite and dolomite in most seasons of the year, reflecting active recharge due to widespread melting of snow and/or glaciers, except in winter. The computed partial pressure pCO_2 for the karst springs is slightly higher (2.7×10^{-2} to 2.5×10^{-1}) than the atmospheric level ($10^{-3.5}$) indicating that the springs are not in equilibrium with the atmosphere. The higher pCO_2 values could be attributed to significant contribution from CO_2 from soil and epikarst zones. These results suggest that the groundwater in karst system is highly aggressive and capable of dissolving the host rock in most seasons. During winter, the spring waters are not aggressive as the carbonic acid is consumed and not replenished, leaving the waters saturated with respect to calcite and dolomite. In open systems, the soil CO_2 reacts with the infiltrating waters to produce a consistent supply of carbonic acid.

The chemical quality of karst springs was assessed by analysing the water samples for eighteen trace elements including Zn, Cu, Se, Mn, Mo, Fe, Cr, B, Ni, Si, V, Pb, Cd, Hg, Al and Li, and seven major elements including Na, K, Mg, Ca, Cl, NO_3 and F (Jeelani et al. 2012a). Li, B and Al ranges from 0.2 to 4, 7 to 111 and 1.1 to 158 µg L^{-1}, respectively. The concentrations of Se, Mn and Si varied from 0.1 to 0.8, 0.2 to 275, 0.3 to 9 µg L^{-1}. V, Cr and Mo lie in the range 0.2–23.4, 0.6–16.4 and 0.2–28.8 µg L^{-1}, respectively. Similarly, Cu, Ni, Cd, Pb and Zn concentrations in the spring water varied from 0.4 to 32, 1.6 to 55, 0 to 1, 0 to 2 and 3 to 140 µg L^{-1}, respectively. Except Cr, Fe and Al, all the observed essential elements are well within the permissible limit of WHO (2006) standard in all the karst springs like, Andernag, Achabalnag, Martandnag, Daidnag, Sayeednag, Malakhnag and Gujnag. Malakhnag, Gujnag and Sayeednag springs exhibited higher concentration of trace elements than rest of the karst springs where these chemical constituents followed similar trend.

6.5 Dynamics of Karst Springs and Karst Functioning

One of the most important characteristics of karst springs is their high amplitude of discharge. The discharge fluctuations are found to be diurnal, seasonal and even annual. It is the high hydraulic conductivity of the carbonate rocks that causes a quick response of karst springs to the recharge conditions. The discharge of the karst springs measured in different flow conditions ranges from 0.29 to 2.5 $m^3 s^{-1}$. The overall discharge pattern of the springs reflects the different levels of heterogeneity of subsurface karstification and the recharge area. During the monitoring period, highest discharge of karst springs was observed in late spring and summer seasons (May–July), whereas minimum discharge was recorded during winter and late autumn seasons (November–February).

It is clear from the spring hydrograph (Fig. 6.6) that the temporal trend of the spring discharge is similar to that of the ambient temperature trend. With the rise of ambient temperature, the discharge shows a steeply increasing trend up to early April in some springs and up to May for others. The hydrograph thereafter almost stabilizes until September. This overall pattern indicates melting of precipitation (snow), due to progressive and continuous increase of temperature, is responsible for this increasing trend in the spring discharge. From April onwards, temperature continues to increase with the same gradient but discharge increases only slightly, in spite of the fact that there is considerable precipitation from April to June. From July end onwards, temperature starts decreasing but discharge remains at the same level in some springs, indicating that during August the precipitation is in the form of rain. However, fluctuations in discharges of other springs indicate a response to local precipitation events. From August to September, discharge reaches its peak although precipitation continues in October–November. The high spring flow in

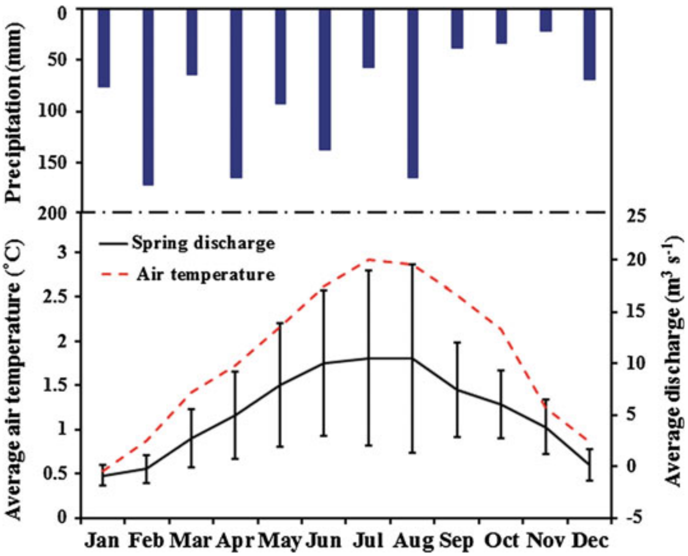


Fig. 6.6 Temporal variation of spring discharge (average of all karst springs) with error bars representing standard deviation. Average monthly ambient temperature and precipitation is also plotted

September indicates the maximum potential of the karst aquifer. From November onwards, the decrease in ambient temperature is correlated with the decrease in spring flow. Temperature strongly governs the discharge in the beginning of the year when snow/ice of the previous season starts melting. There was a greater decrease in spring discharge during the high flow season in 2013 relative to 2014, which is attributed to shorter snow cover persistence and less precipitation in 2013.

6.6 Recharge Catchments

The spatio-temporal variation in the $\delta^{18}O$ and $\delta^{2}H$ isotopic signatures of precipitation is widely used to provide the variable input functions that are effective in tracing groundwater. Vertical isotopic gradient is considered a powerful tool for tracing groundwater origin as it distinguishes isotopic signatures of water recharged from different elevations; i.e., water recharged at high elevation will exhibit lighter isotopic signatures compared to the recharge at lower elevations (Clark and Fritz 1997; Jeelani et al. 2010; Bhat and Jeelani 2015). Given the high relief of the Kashmir Valley (altitude ranges from 1585 to 5200 m amsl) and strong isotopic variability, the estimated vertical isotopic gradients in different mountainous

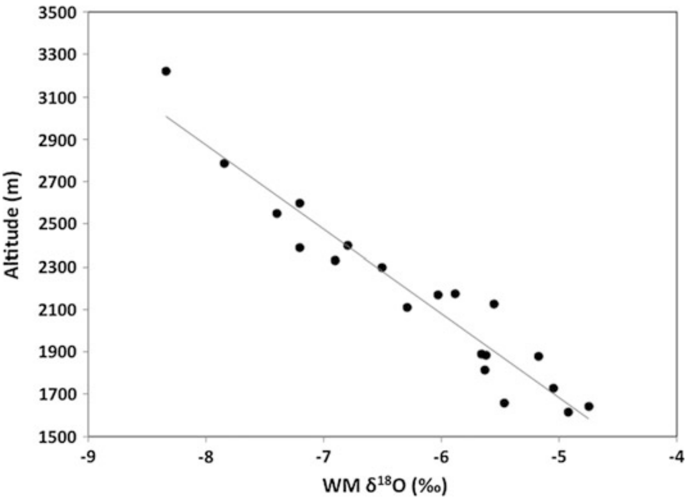


Fig. 6.7 Weighted mean δ^{18}O of precipitation versus altitude showing vertical isotopic gradients in the region

catchments ranged from −0.15 to −0.64‰ (for δ^{18}O) and −1.2 to −2.8‰ (for δ^{2}H) per 100 m change in elevation (Fig. 6.7). These catchment-wise isotopic gradients, obtained from the weighted mean δ^{18}O, δ^{2}H and altitude of precipitation, were used for the determination of the mean recharge altitudes of the karst springs in each catchment. It was found that the mean recharge elevation of the springs varied significantly from 1800 to 3700 m asl, as calculated using the following regression equation (Eq. 6.1):

$$y = (a \times x) + b \tag{6.1}$$

where *y* is the mean recharge altitude (plotted as *y*-axis), *a* is the slope of the regression equation, *x* is the mean annual weighted δ^{18}O (or δ^{2}H) of the spring and *b* is the intercept of the regression equation. The weighted mean of δ^{18}O and δ^{2}H values can be calculated from individual sample results as follows:

$$\mathrm{X_{WM}} = \sum \mathrm{Pi}\ \times \mathrm{Xi} / \sum \mathrm{Pi} \tag{6.2}$$

where Pi denotes the amount of precipitation of individual precipitation sample measured at the precipitation site and Xi is the corresponding isotopic value of the sample. The inferred recharge altitude estimated by these tracers could be sometimes overestimated or underestimated in areas where the depleted seasonal snowmelt at higher altitudes is brought down by the stream flow to lower altitudes (recharge sites) without much fractionation.

6.7 Karst Vulnerability

Understanding the sources of recharge and processes that control groundwater quality, timing and magnitude of groundwater vulnerability to potential contamination are critically important for groundwater protection (Wong et al. 2012). This is especially true in karst terrains where infiltrating surface water can rapidly affect groundwater quality. Travel time of groundwater in karst terrains is widely recognized technique to assess the vulnerability because travel time is directly related to the diversity of flow paths in a catchment and/or reservoir (Perrin et al. 2004; Ford and Williams 2007; Farlin et al. 2013). Keeping in view the high permeability, short transit times and multifaceted importance of karst springs in the region (Jeelani et al. 2014; Shah et al. 2017), effective approaches are required for the management and protection of these vital groundwater resources. Deterioration of quality of water and variation in the magnitude of flux are the two main consequences of short travel time of karst groundwater in the region (Shah et al. 2017). Jeelani (2010) reported increasing concentrations of Fe and Cr and microbial bacteria (coliform and streptococci), in karst springs. The author observed total coliform, faecal coliform and faecal streptococci in the range of 13–260, 2–92: 3–15 (MPN/100 mL), which is far above the permissible and desirable limits of WHO (2006). We have observed the rapid change of water colour from transparent to muddy (turbidity) soon after rainfall events in some karst springs. The point sources of recharge of these springs are located near residential areas and cultivated agricultural fields. There was a significant increase in NO_3, Cl and Fe concentration, from ~ 2 to ~ 12, ~ 12 to ~ 31 and 0.7 to 5.8 mg L^{-1}, respectively. The increase in turbidity, in NO_3 and Cl, makes spring water unsafe for drinking during and after these rainy events, until the turbidity reduces to background (1–7 NTU). Besides, the stone quarrying has exposed the solution features and internal drainage system of the carbonate aquifers in the region. Water quality has also been degraded by open disposal of municipal waste in recharge areas. Similarly, the dependency of karst springs on meltwater (Jeelani 2008; Jeelani et al. 2014) suggests that the change in pattern, form and amount of precipitation due to global warming (Jeelani et al. 2012b) might cause considerable variability in spring discharges. There would be sharp increase in spring flow after major rainfall events, and there would be limited perennial recharge, if the winter precipitation as snow decreases. This may affect the timing and magnitude of the spring flow. The situation may be worst during summer season when the demand for water is high for agricultural and horticultural purposes. The greater variability in precipitation as rain can affect the flux and storage of water in these aquifers. In 2001, the discharge of the springs was drastically reduced to 40–70% compared to 1999 (Jeelani 2008). In 2013, a significant decrease in discharge was observed in some springs (Shah et al. 2017). The decrease in spring discharge is attributed to below normal precipitation in the preceding winter. Similarly, changes in timing, amount and type of precipitation and differential melting behaviour of snow and glaciers resulted variation in peak flows in most of the karst springs. For example, in 2013 and 2015, the peak flow recorded in July and August during 2013 and 2014 shifted to August and October in 2015 in most of the karst springs. Therefore, delineated recharge areas of the karst springs (Bhat and Jeelani 2015; Shah et al. 2017) must be protected, restricted and conserved.

6.8 Conclusions

The Kashmir karst, which covers an area of about 1100 km^2, has substantial socio-economic importance as it provides a relatively pristine water supply for drinking and irrigation purposes. Triassic Limestone exhibits significant karst solution features, including swallow holes, conduits, shafts, caves and large springs. Hydrochemical data of major springs of Kashmir Valley indicate that the spring water chemistry is dominated by weathering of carbonate rocks. The study suggests that the groundwater in karst system is highly aggressive and capable of dissolving the host rock in most seasons. However, in winters the spring waters are not aggressive as the carbonic acid is consumed and not replenished, leaving the waters saturated with respect to calcite and dolomite. The chemical quality of karst springs suggests that the chemical quality of the karst springs is excellent. Except Cr, Fe and Al, all the observed essential elements such as, Zn, Cu, Se, Mn, Mo, B, Ni, Si, V, Pb, Cd, Hg, As, Li and Sn, and seven major elements including Na, K, Mg, Ca, Cl, NO_3 and F are well within the permissible limit of WHO (2006) standard. The observed large fluctuations of spring discharges from daily or seasonal to annual scales reflect the quick flushing of groundwater and the extent of development of subsurface karstification in the region. The karst springs responded quickly to increase in air temperature, which causes snow/ice melting, and rainfall, which increases the recharge. The catchment-wise vertical isotopic gradients were used for the determination of the mean recharge altitudes of the karst springs. The karst springs showed some signs of deterioration of water quality due to the increase in the concentration of NO_3 and coliform and streptococci bacteria during summer months. Karst vulnerability analysis suggested that magnitude of spring discharge and water quality of karst springs could be substantially reduced if the recharge zones, which are mostly located near residential areas and cultivated agricultural fields, are not protected and restricted.

Acknowledgements The research work was funded by Department of Science and Technology (DST) Govt. of India, under the research project, DST No: SERB/F/1554/2012.

References

Adyalkar PG (1977) Hydrogeology of karstic terrains (limestone areas). Exploration techniques for groundwater. COSTED, Chennai, India, pp 128–142

Bakalowicz M (2005) Karst groundwater: a challenge for new resources. Hydrogeol J 13:148–160

Bhat N, Jeelani G (2015) Delineation of the recharge areas and distinguishing the sources of karst springs in Bringi watershed, Kashmir Himalayas using hydrochemistry and environmental isotopes. J Earth Syst Sci 24:1667–1676

Bögli A (1980) Karst hydrology and physical speleology. Springer, Berlin

Bonacci O (2004) Hazards caused by natural and anthropogenic changes of catchment area in karst. Nat Hazards Earth Syst Sci 4:655–656

Brooks S, Smart S (1995) Caving in the abode of the clouds: caves and karst of Meghalaya, North East India. Meghalaya 94, Bradford on Avon, UK, 68 pp

Carroll D (1970) Rock weathering. Plenum Press, New York, p 203

Clark I, Fritz P (1997) Environmental isotopes in hydrogeology. Lewis Publishers, New York

Cooper AH, Farrant AR, Price SJ (2011) The use of karst geomorphology for planning, hazard avoidance and development in Great Britain. Geomorphology 134:118–131

COST ACTION-65 (1995) Hydrogeological aspects of groundwater protection in karstic areas. E.16457. Brussels, European Commission, Directorate-General XII Science, Research and Development: European Commission Office. Publication of European Communities, Luxembourg, 446 pp

Coward JM, Waltham AC, Bowser RJ (1972) Karst springs in the valley of Kashmir. J Hydrol 16:213–223

Culver DC, White WB (2005) Encyclopedia of caves. Elsevier Academic Press, Amsterdam, p 654

Dar FA, Perrin J, Riotte J, Gebauer HD et al (2011) Karstification in the Cuddapah Sedimentary Basin, southern India: implications for groundwater resources. Acta Carsol 40:457–472

Dar FA, Perrin J, Ahmed S et al (2014) Review: carbonate aquifers and future perspectives of karst hydrogeology in India. Hydrogeol J 22(7):1493–1506

Das BK, Kaur P (2001) Major ion chemistry of Renuka lake and weathering processes, Sirmaur district, Himachal Pradesh, India. J Environ Geol 40:908–917

Farlin J, Drouet L, Galle D et al (2013) Delineating spring recharge areas in a fracture sandstone aquifer (Luxembourg) based on pesticide mass balance. Hydrogeol J 21:799–812

Field MS (2002) The QTRACER2 program for tracer-breakthrough curve analysis for tracer tests in karstic aquifers and hydrologic systems. United States Environmental Protection Agency, EPA/600/R-02/001

Ford D, Williams P (2007) Karst hydrogeology and geomorphology. Wiley, New Jersey, 554 pp

GSI (1977) Geology and mineral resources of states of India. Part X: Jammu and Kashmir State. Geol Surv India 30:1–70

Gunn J (2007) Contributory zone definition for groundwater source protection and hazard mitigation in carbonate aquifers. In: Parise M, Gunn J (eds) Natural and anthropogenic hazard in karst areas, vol 279. Geological Society of London, pp 97–109

Hall AB, Day MJ (2011) Water as a focus of ecotourism in the karst of Puerto Rico. Tourism Karst Areas 4(1):17–25

Jamali M, Moghimi E, Jafarpour ZA (2015) Geomorphology of Karst features of Shiraz City and Arjan Plain and development limitations. Int J Environ Chem Ecol Geol Geophys Eng 9:1. doi: scholar.waset.org/1999.6/10000362

Jeelani G (2005) Chemical quality of the spring waters of Anantnag, Kashmir. J Geol Soc India 66:453–462

Jeelani G (2008) Aquifer response to regional climate variability in a part of Kashmir Himalayas in India. Hydrogeol J 16:1625–1633

Jeelani G (2010) Chemical and microbial contamination of Anantnag springs, Kashmir Valley. J Himalayan Ecol Sustain Dev 5:176–183

Jeelani G, Shah Q (2006) Geochemical characteristics of water and sediment from the Dal Lake, Kashmir Himalaya: constraints on weathering and anthropogenic activity. Environ Geol 50:12–23

Jeelani G, Bhat NA, Shivanna K (2010) Use of ^{18}O tracer to identify stream and spring origins of a mountainous catchment; a case study from Liddar watershed, Western Himalaya, India. J Hydrol 393:257–264

Jeelani G, Bhat NA, Shivana K et al (2011) Geochemical characterization of surface water and stream water in SE Kashmir Valley, Western Himalaya: implications to water-rock interaction. J Earth Syst Sci 120:921–932

Jeelani G, Shakeel A, Absaar A (2012a) Essential and toxic elements in karst springs of Kashmir. Curr Sci 43(9):992–994

Jeelani G, Feddema JJ, van der Veen CJ et al (2012b) Role of snow and glacier melt in controlling river hydrology in Liddar watershed in the (western Himalaya) under current and future climate. Water Resour Res 48:1–16

Jeelani, G, Kumar US, Bhat NA et al (2014) Variation of δ^{18}O, δ^{2}H and ^{3}H in karst springs of south Kashmir, western Himalayas (India). Hydrol Process. https://doi.org/10.1002/hyp.10162

Klimchouk A (2002) Subsidence hazards in different types of karst: evolutionary and speleogenetic approach. Int J Speleol 31(1/4):5–18

Latham AG, McKee JK, Tobias PV (2007) Bone breccias, bone dumps, and sedimentary sequences of the western Limeworks, Makapansgat, South Africa. J Hum Evol 52:388–400

Liu F, Song X, Yang L et al (2015) Identifying the origin and geochemical evolution of groundwater using hydrochemistry and stable isotopes in the Subei Lake basin, Ordos energy base, Northwestern China. Hydrol Earth Syst Sci 19:551–565

Meijerink AMJ (2007) Covered karst: example of Borunda, Rajasthan, India. Remote sensing applications to groundwater. UNESCO, Paris

Milanovic PT (1988) Artificial underground reservoirs in the karst experimental and project examples. In: Karst hydrogeology and karst environment protection, vol 1. Proceedings of 21st congress of IAH, Guilin, China, pp 76–87. IAHS Publ. no. 176

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Murty KS (1988) Karst hydrogeology: India. In: Karst hydrogeology and karst environment protection, vol 10–15. Proceedings of 21st IAH congress, Guilin, China, pp 446–450

Mylroie JR, Mylroie JE (2007) Development of the carbonate island karst model. J Cave Karst Stud 69:59–75

Nohegar A, Norouzi A, Hosseinzadeh MM (2012) The role of karst formations in groundwater resources development. Int J Geol Earth Environ Sci 2:284–292

North LA, Van-Beynen PE, Parise M (2009) Interregional comparison of karst disturbance: west-central Florida and southeast Italy. J Environ Manage 90:1770–1781

Ophori DU, Toth J (1989) Patterns of groundwater chemistry. Ross Creek Basin, Alberta, Canada. Groundwater 27:20–26

Parise M (2010) Hazards in karst. In: Bonacci O (ed) Proceedings of the international interdisciplinary conference on “Sustainability of the karst environment”, vol 2, Plitvice Lakes (Croatia), 23–26 Sept 2009, IHP-UNESCO, Series on Groundwater, pp 155–162

Parise M (2012) Management of water resources in karst environments, and negative effects of land use changes in the Murge area (Apulia, Italy). Karst Dev 2:1

Perrin J, Pochon A, Jeannin PY et al (2004) Vulnerability assessment in karstic areas: validation by field experiments. Environ Geol 46:237–245

Rajmohan N, Elango L (2004) Identification and evolution of hydrogeochemical processes in the groundwater environment in an area of the Palar and Cheyyar River Basins, Southern India. J Environ Geol 46(1):47–61

Rajmohan N, Elango L, Ramachandran S et al (2000) Major ion correlation in groundwater of Kancheepuram region, south India. Indian J Environ Prot 20:188–193

Sarin MM, Krishnaswamy S, Dilli K et al (1989) Major ion chemistry of the Ganga–Brahmaputra river system: weathering processes and fluxes to the Bay of Bengal. Geochim Cosmochim Acta 3:997–1009

Sauro U (2006) Changes in the use of natural resources and human impact in the karst environment of the Venetian Prealps (Italy). Acta Carsol 35:57–63

Schoeller H (1977) Geochemistry of groundwater. In: Groundwater studies, vol 15. An International Guide for Research and Practice, UNESCO, Paris, pp 1–18

Shah R A, Jeelani G, Goldscheider N (2018) Karst Geomorphology, Cave Development and Hydrogeology in the Kashmir Valley, Western Himalaya, India. Acta Carsologica (under review)

Shah RA, Jeelani G, Jacob N (2017) Estimating mean residence time of karst groundwater in glacierized catchments of Western Himalaya, India. Hydrol Sci J 62(8):1230–1242

Sheen SW (2000) A world model of chemical denudation in Karst Terrains. Prof Geogr 52:397–406

Singh Y (1985) Hydrogeology of the karstic area around Rewa, MP, India. In: Karst water resources, Proceedings of the Ankara-Antalya symposium, July 1985, IAHS Publ. No. 161, IAHS, Wallingford, UK

Soni AK (2007) Evaluation of hydrogeological parameters associated with limestone mining: a case study from Chandrapur, India. Mine Water Environ 26:110–118

Stallard RF, Edmond JM (1983) Geochemistry of the Amazon: influence of geology and weathering environment on the dissolved load. J Geophys Res 88:9671–9688

Stokes T, Griffiths P, Ramsey C (2010) Karst geomorphology, hydrology and management, pp 373–400

Szramek K, Walter LM, Kanduč TA et al (2011) Dolomite versus calcite weathering in hydrogeochemically diverse watersheds established on bedded carbonates (Sava and Soča Rivers, Slovenia). Aquat Geochem. https://doi.org/10.1007/s10498-011-9125-4

Thornbury WD (1969) Principles of geomorphology. Wiley, New Jersey, 583 pp

UNESCO (2000) Groundwater pollution. International Hydrological Programme

Venkatanarayana B, Rao TV (1989) Geological and geophysical investigations for delineating karstic structures of the southwestern portion of Cuddapah basin, Andhra Pradesh, India. In: Berry BF (ed) Proceedings of 3rd multidisciplinary conference on sinkholes and the engineering and environmental impacts of Karst, USA, Balkema, Dordrecht, The Netherlands, pp 59–64

Vesper DJ, Loop CM, White WB (2001) Contaminant transport in karst aquifers: speleogenesis and evolution of Karst aquifers. Theor Appl Karstol 13–14:101–111

Waltham AC, Simms MJ, Farrant AR et al (1997) Karst and caves of Great Britain. Conservation review series. Chapman and Hall, London

WHO (2006) Guidelines for drinking water quality, First addendum to 3rd edn., Recommendation, Geneva, 595 pp

Wong CI, Mahler BJ, Musgrove M et al (2012) Changes in sources and storage in a karst aquifer during a transition from drought to wet conditions. J Hydrol 468(9):159–172

Chapter 7
Groundwater Availability of Northern and Southern Bank Aquifers of the Middle Ganga Plain, India

Dipankar Saha and S. N. Dwivedi

Abstract The Gangetic Plain covering ~0.25 million km^2 is the primary repository of groundwater in India and is also home to nearly one-third of the ~27 million wells in the country, catering the irrigation sector. The Middle Ganga Plain (MGP) occupying the central part of the Gangetic Plains represents an active depositional basin and represents the thickest sequences of Quaternary sediments in India except the Bengal Basin. The fluvio-lacustrine deposits of MGP have been laid over northerly dipping Precambrian basement. The present paper examines the hydrogeological framework, aquifer characteristics, groundwater flow regime and development potential in two nearly placed segments in MGP; one at the northern bank of the Ganga, occupying southern fringe area of Gandak fan, and the other on the southern bank, located on the northern fringe of the Son fan, a prominent feature of the SGP. The northern segment represents an intensely cultivated area while the southern one is characterized by a wide array of land use, ranging from the urban settlement (Patna town, Population 2.7 million) in the eastern part, semi-urban settlement in the middle and north-western part and typical cultivated areas in the southern part. The aquifers and groundwater regime in the northern and the southern banks of the River Ganga are assessed and measures for aquifer management in this highly groundwater-dependent region are suggested.

Keywords Middle Ganga plain · Groundwater · Hydrogeology
Aquifer characteristics · Irrigation

7.1 Introduction

The Gangetic Plains covering ~0.25 million km^2 is the primary repository of groundwater in India (Chap. 1, Figs. 1.3 and 1.4). The aquifers in the plains are tapped for all societal uses since historic times. However in the last four decades,

---

D. Saha (✉) · S. N. Dwivedi
Central Ground Water Board, Faridabad, India
e-mail: dsaha002@yahoo.com

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_7

the entire Indian subcontinent and the Gangetic Plains in particular have witnessed tremendous increase in groundwater extraction to cope up with burgeoning demand particularly from agricultural sector. Besides, there is a considerable increase in drinking demand from swelling population, urbanization and lifestyle change. A major chunk of demand from this sector is also met up from groundwater. Presently there are ~27 million wells in the country, catering the irrigation sector; more than one-third of them are confined in the Indo-Gangetic Plains.

The Middle Ganga Plain (MGP) represents an active depositional basin and one of the important sequences of Quaternary sediments in India. The sedimentation, geomorphology and tectonics of this unit have attracted interest of national and international workers (Acharya 2004; Sinha et al. 2005). However, few published literatures are available on aquifer framework and their hydraulic characterization, within the Quaternary sediments. Saha et al. (2007) have documented the disposition of aquifers and their hydraulic properties in the southern part of MGP. In further researches, Saha et al. (2009a, b) delineated, using multi-parametric approach, the potential zones for further development of groundwater resources and Saha and Alam (2014) assessed the vulnerability of the aquifers, which is affected by nitrate and fluoride contamination. Both the studies were taken up on the southern flank of MGP. With the reporting of arsenic contamination in groundwater in MGP (Chakraborty et al. 2003; Saha 2009), a number of studies were taken up targeting the spatio-temporal variation of arsenic in groundwater, health impact of arsenic depositional process of sediments, mobilization process of arsenic in groundwater (Saha 2009; Saha et al. 2009a; Sahu and Saha 2014a, b; Mukherjee et al. 2012, 2015; Acharya 2004). The Younger Alluvial Plain along the Ganga stem is found to be affected by elevated concentration of arsenic (Saha and Sahu 2015). Both the Younger and Older Alluvial Plains are underlain by thick fluvio-lacustrine deposits holding multi-aquifer system. The shallow aquifer (<80 m below ground) is marked with elevated concentration of arsenic in groundwater (>0.05 mg/L), whereas the deeper aquifers are observed to be free from contamination (Saha et al. 2010). The deeper aquifer holds groundwater under semi-confined conditions with storativity value ranging from 1.6×10^{-3} to 6.4×10^{-4} (Saha et al. 2010). The hydraulic head of the deeper aquifer lies between 4.2 and 6.5 m bgl, and they are found to be highly potential with transmissivity ranging from 5160 to 6970 m^2/day. The aquifer disposition and the hydraulic characters offer the deeper aquifer, which holds low groundwater arsenic level, as potential source of potable water source of potable water supply. The multilayer aquifer system in MGP has a varied recharge path and mechanism. In a research using stable oxygen and hydrogen isotope supported by C-14 and tritium analysis, it is revealed that the shallow aquifers get direct recharge from rainfall, whereas the deeper aquifer holds much older water with ages record as couple of thousands years (Saha et al. 2011). The deeper aquifer gets its recharge from a far-off place.

This paper deals with the hydrogeological framework, aquifer characters, groundwater flow regime and potential of parts of two nearly placed segments in MGP; one at the northern bank of the Ganga, and the other on the southern bank

(Fig. 7.1a, b). There is an apparent difference in the depositional history and framework between the areas in northern bank (part of the Gandakmegafan having sediment provenance in the Himalayas) and the southern bank (sediments derived from the peninsular India by the River Son and its tributaries). This region is considered to be holding the most prolific aquifer system in India with ample recharge from copious rainfall. The entire domestic, irrigation and industrial demand of the area is met up from groundwater. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

7.2 Geologic Set-Up

7.2.1 Regional Geology

The Gangetic Plain is an active fluvial depositional basin, occupying the central part of the Indo-Gangetic foreland system. The system has actively responded to extra- and intra-basinal tectonics, climatic changes and eustatic sea-level-related base-level change (Singh 2004). Morphologically it is shallow asymmetrical depression with a gentle easterly slope. The sedimentation rate exceeded the down-flexing rate of the foreland system in geological history, keeping the basin surface always above the sea level where the deposition underwent in a fluvio-lacustrine environment without any marine incursion (Singh 2001). The central part of east–west elongated Gangetic Plains is refereed as Middle Ganga Plain (MGP), which is bounded by Faizabad Ridge in the west and Munger–Saharasa Ridge in the east (Saha 2009).

The MGP is divided into two major geomorphic units by the axial River Ganga; the North Ganga Plain (NGP) and the South Ganga Plain (SGP). MGP represents an active dispositional basin drained by the Ganga stem and its tributaries. The prominent left-hand tributaries originated from Himalayas are Ghaghra, Gandak, Kosi and Burhi Gandak, which drains the NGP (Fig. 7.1). All the tributaries are dynamic and exhibit evidence of avulsions (Sinha et al. 2005). For example, the Gandak has shifted west to east for a distance of 80 km in the last 5000 years aided by neotectonic activities (Sahu et al. 2010). The River Kosi has also shifted considerably towards west through avulsion (Sinha 2005). The SGP is drained mainly by the right-hand tributaries like the River Son and a few smaller tributaries originated from peninsular uplands (Fig. 7.1).

7.2.2 Quaternary Geology

The MGP is underlain by thick fluvio-lacustrine deposits of Quaternary age, laid over northerly dipping Precambrian basement (Saha et al. 2007). In the study

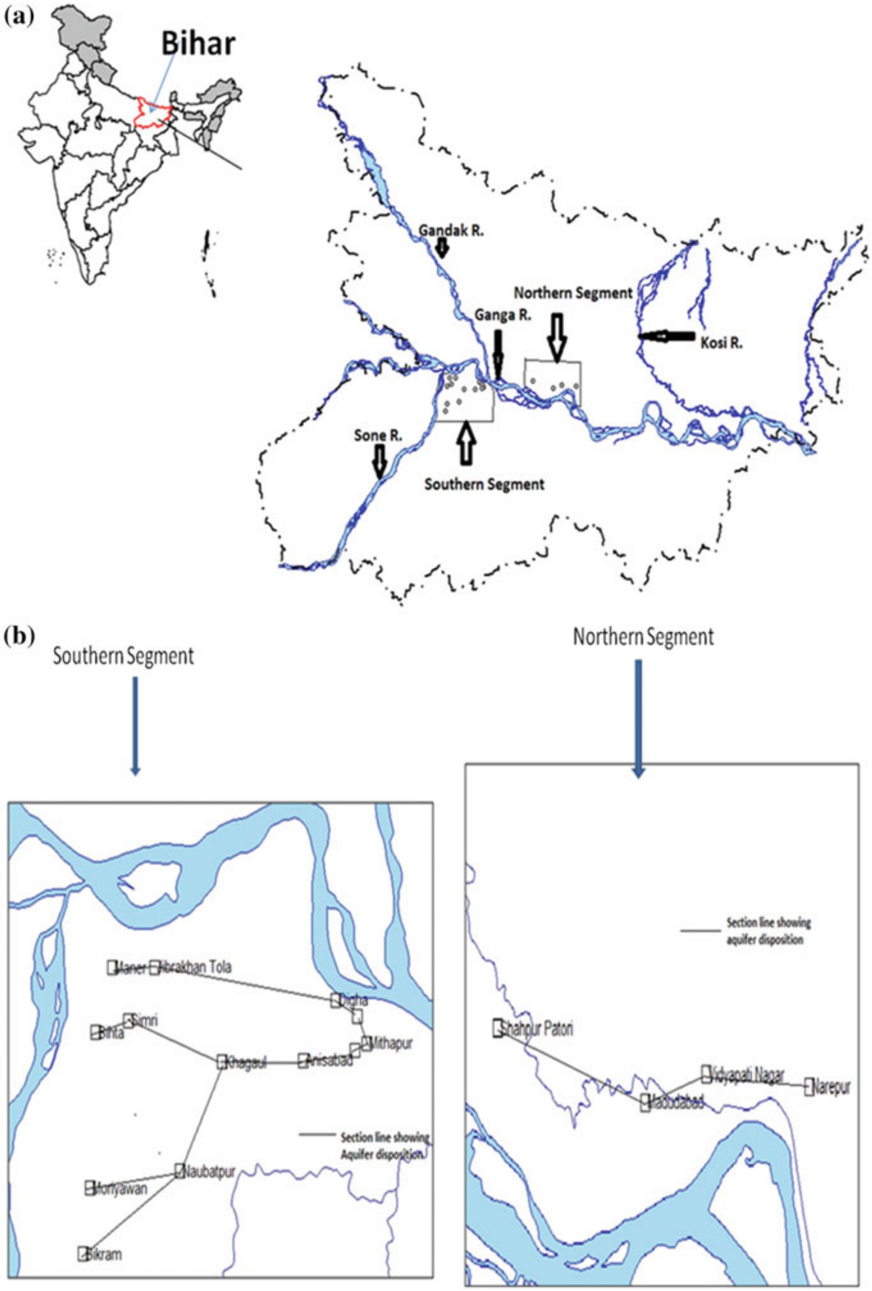


Fig. 7.1 **a** Location map of the study area. **b** Map showing the location points of lithological logs in the southern and the northern segment considered for depicting aquifer disposition in the study area

region, the thickness of Quaternary deposits has been estimated as 700 m. (op.cit.). The area is marked with rapid aggradation of land owing to huge sediment load brought by the rivers like Gandak, Kosi and Son from the upper catchment areas lying in Middle and Upper Himalayas, and also by the right-hand tributaries from peninsular India. No specific data is available on aggradations rate of the study region. However, in NGP part of MGP, it has been estimated as 0.7–1.5 mm/year in last 2400 years (Sinha et al. 2005).

The Quaternary sequence of the NGP is conveniently subdivided into Older Alluvium (Pleistocene age) and Newer Alluvium (Holocene age) (Acharya 2004). The Older Alluvium covers large swath of land in SGP and was assigned Upper Pleistocene to Lower Holocene age by Chakroborty and Chattopadhyay (2001). The Oder Alluvium is also marked in the NGP, but spread over in lesser area. The boundary between Older and Younger Alluvium is marked by an erosional unconformity. The younger unit covers 10–25 km wide stretch in SGP and is characteristically unoxydized and consists of sediments deposited in a fluvial and fluvio-lacustrine set-up (Singh 2004).

The sedimentary architecture of the area is characterized by alternating sequence of sand, clay, sandy clay with occasional gravel beds. The sand are of various size grades, but predominantly medium-to-coarse-grained.

7.3 Study Area

The present study covers two segments of MGP. One area is on the northern bank of the River Ganga, administratively falling in Samastipur district spread over an area of 1200 km^2. The other segment is located on the southern bank of the river, occupying the confluence area of the Son and the Ganga. This segment covers an area of 1000 km^2 and administratively lying in the Patna district (Fig. 7.1). Both the areas are falling within the Younger Alluvial Belt along the River Ganga. The entire water demand from domestic irrigation and industrial sectors are met up from aquifers. Both the area represent monotonously flat topography with altitude ranging from 64 to 48 m above msl in the southern segment and 52–40 m above msl in the northern segment. The area receives an annual rainfall of 1000 mm, 90% of which falls during monsoon months between June and September. The northern segment represents an intensely cultivated area while the southern one is characterized by a wide array of land use, ranging from the urban settlement (Patna town, Population 2.7 million) in the eastern part, semi-urban settlement in the middle and north-western part, and typical cultivated areas in the southern part. The cropping intensity of the area is about 150%.

Tube wells (40–80 m depth) are the main source of irrigation where as handpumps (30–50 m depth) are the backbone of rural water supply. The Patna urban area is covered by piped water supply which is heavily dependent on deep tube wells of 150–180 m depth range. Besides, the semi-urban settlements are also dependent on deep tube wells for domestic demand. The handpumps in the area are reported to be affected at many places by elevated concentration of arsenic in groundwater (>0.05 mg/l). Except the Patna urban area (Fig. 7.1), the remaining area is considered largely as arsenic contaminated.

The present study aimed to unravel the hydrogeological framework of the area and to delineate the aquifers down to the depth of 300 m bgl, based on existing lithological logs available from the State Government departments and CGWB. The aquifer hydraulic property and the interrelation among the aquifers have also been studied. A comparison has also been made on those aspects of the aquifers in the northern and southern segments of the study region. The paper also deals with the large-scale groundwater extraction and its impact on the aquifer in Patna urban area, which is located in the southern segment.

7.4 Hydrogeological Framework and Aquifer Configuration

The aquifer configuration through a north–south transect across SGP between the Chotanagpur upland in the south and the axial part of the Ganga basin passing at about 40 km east of the southern segment, revealed wide variation in aquifer configuration (Saha et al. 2007). Within the Older Alluvium part, along the basin margin areas the thickness of the sediment is less and lithology is dominated by clay. Two to four number of aquifers (each 6–15 m thick) made up of medium-to-coarse sand and separated by clayey aquitards are observed in 100-m-thick sediment sequence overlying the basement. As one move towards north, further away from Precambrian exposed rocks, the intervening clay layers pinch out and finally a thick (>90 m) aquifer made up of fine-to-medium sand appear at the top of the succession in the Newer Alluvial areas adjoining the course of the Ganga River. Transmissivity of aquifer in Newer Alluvium areas is recorded as 7000–10,400 m^2/day which is considerably higher than Older Alluvial areas, ranging from 360 to 2300 m^2/day (Maitra and Ghose 1992).

Southern Segment: The subsurface geology in the southern segment is marked by alteration of sand (fine-to-coarse), clay, and sandy clay with occasional gravel beds up to the depth of 300 m bgl (drilling depth). A two-tier aquifer system has been encountered within 300 m bgl. The thickness of sediment sequence overlying the Precambrian basement is estimated to be $\sim$600 m (Saha et al. 2007). The first aquifer is made up of fine- to medium-grained sand and remains under leaky (semi-confined) condition because of an overlying layer of aquitard, whereas the deeper aquifer remains under semi-confined to confined condition. The generalized sub-regional disposition of the aquifer in this part is outlined as under:

The aquifer sequence commences with an aquitard layer at the top, characterized by frequent facies variation—which locally behaves as a low-potential aquifer owing to the presence of sand lenses of 2–5 m thickness within a mixed layer of silty clay, sandy clay and clay. This layer is capable of sustaining the dug wells and shallow handpumps, and its thickness in general increases from southern and south-western part towards north and north-eastern part closer to River Ganga. This top layer is followed by the first principal aquifer which starts from the depth range of 30–55 m and goes up to 80–130 m bgl in general. The thickness of the first principal aquifer in general is about 50 m. The clay/sandy clay layer between the first and the second aquifer is thin in north-eastern part in comparison to the other parts of the area. The second aquifer system is significantly thick in comparison to the first aquifer and occurs at the depth range of 130–265 m bgl. Thin layers of clay and sandy clay (4–6 m) occur within the second aquifer at different depths but generally do not continue laterally beyond 200 m. Below the second aquifer occurs a fairly thick clay and sandy clay bed forming the base of the second aquifer. At certain location like at Simri and Bikram, a third aquifer has been identified below the clay layer forming the bottom of the second aquifer. An open panel diagram depicting the three-dimensional configuration of aquifer is presented in Fig. 7.2.

Northern Segment: The northern study region is underlain by thicker fluvial and fluvio-lacustrine sequences of Quaternary age, directly overlying the Precambrian basement. The thickness of the Quaternary sediments is estimated as ~1000 m. Subsurface geology up to 300 m bgl (drilling depth) is similar as observed in the southern segment and is marked by alteration of sand (fine-to-coarse), clay, sandy clay with occasional gravel beds. Sandy clay samples

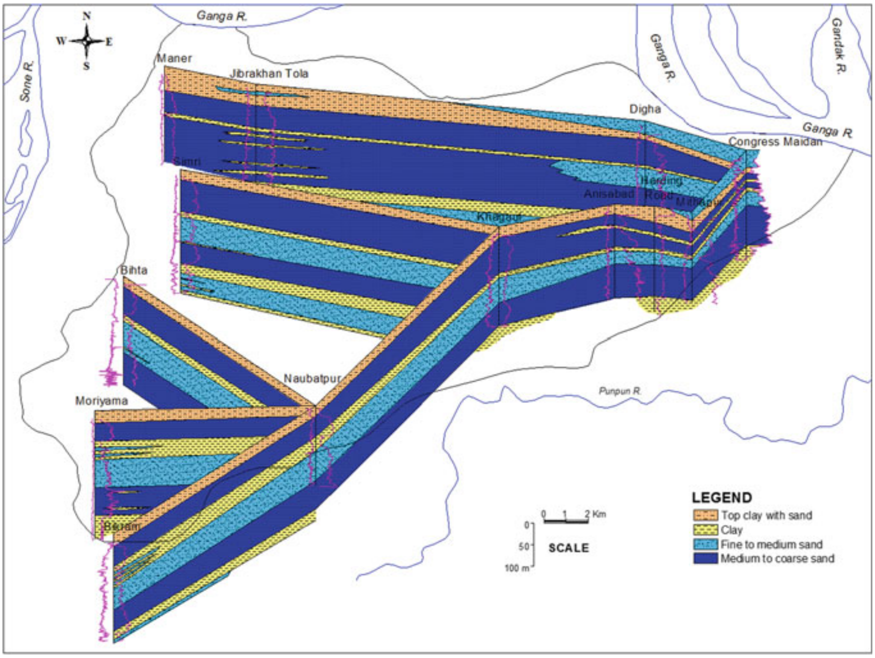


Fig. 7.2 Panel diagram depicting the three-dimensional configuration of aquifer in the southern segment

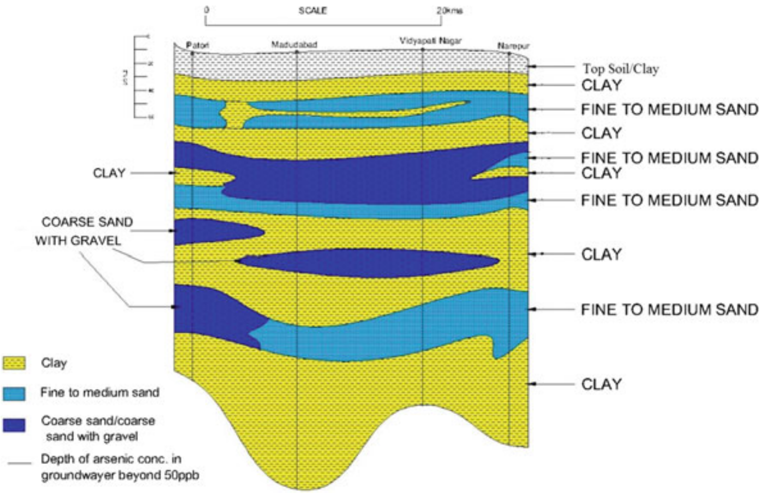


Fig. 7.3 Disposition of aquifer in the northern segment

were sticky, low in sand content and thus have been clubbed with clay forming aquitard group. At Patori (Fig. 7.3), clay dominates the top ~60 m of the succession with occasional interruption of thin (2.5–8.0 m) fine sand lens. The argillaceous unit at Madudabad is about 50 m thick and invaded by two sand layers (8–10 m thick). The top aquitard zone continues towards east; however, it becomes thinner and is ~30 m thick at Narepur. The top argillaceous unit is underlain by 80–120-m-thick sand, the lower part of which is predominantly coarse and occasional gravely. This sand layer is recognized as first aquifer, which terminates at ~140–150 m depth with appearance of thick clay. Another 20–25-m-thick medium-to-coarse sand layer appears below this clay with lateral continuity forming the second aquifer system. The second aquifer system is again underlain by thick clay/sandy clay which continues for 50–60 m further below (Fig. 7.3). The aquifer–aquitard disposition indicates that groundwater in shallow aquifer occurs in unconfined to locally semi-confined condition, whereas in deeper aquifer it occurs under semi-confined to confined condition.

7.5 Groundwater Flow Regime

The water level in the Gangetic Plains, as also observed in entire India, follows the season. The shallowest level is observed during monsoon, whereas the deepest is recorded before the onset of the monsoon. Well hydrograph prepared based on monthly water level at a permanent monitoring station at Dumri (well depth 14.8 m), located in the northern segment, reveals shallowest water level during August and deepest in May (Fig. 7.4). The hydrograph confirms that the monsoon

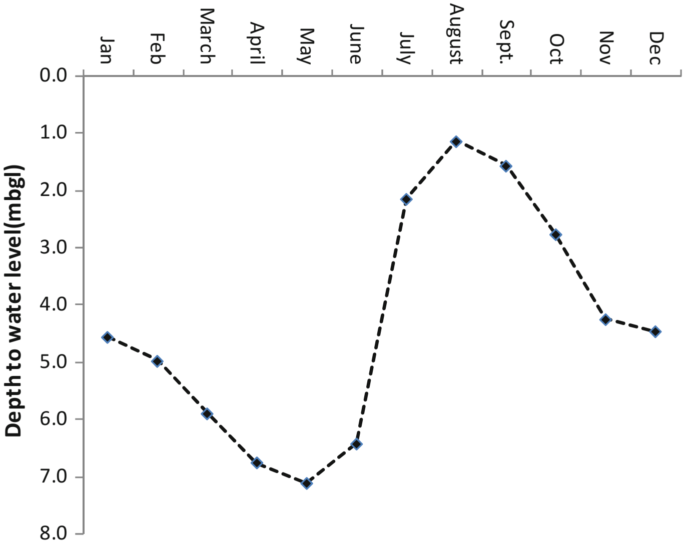


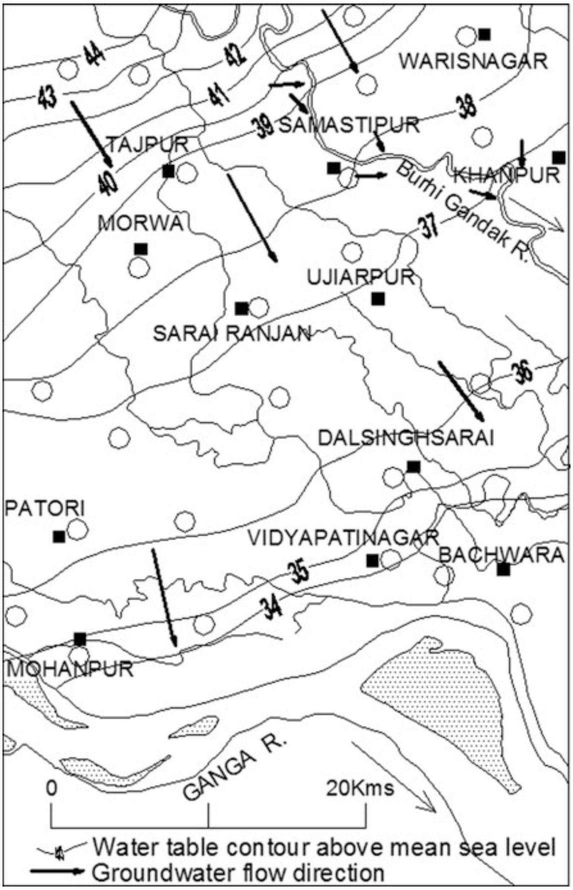
Fig. 7.4 Well hydrograph of Dumri located in northern segment

rainfall is the main source of recharge to the shallow aquifer system. Post-monsoon recession in water level continued till the onset of next monsoon. The recession curve could be separated into two segments; steeper between August and November (3.1 cm/month) and gentler between November and May (1.7 cm/month).

The water level representing the upper aquifer remained at shallow level in the entire study area, mostly within 7 m bgl. During pre-monsoon period, in over 85% of the wells the recorded levels remain between 6 and 8 m bgl while in the remaining wells it rests at <6 m bgl. The water levels referred to mean sea level (msl) revealed that during pre-monsoon it remained between 34 and 44 m above msl. The groundwater flow direction is towards SSE, indicating that the Ganga is fed by the shallow aquifer system and thus effluent in nature. The minor flow lines between 37 and 42 m above msl in the northern part influenced in local-scale along the Budhi Gandak River were also indicative of its effluent nature. The hydraulic gradient in the northern part of the study area remained to be 1:2500, whereas near the Ganga, the gradient reduces to 1:5750, resulting in sluggish movement of groundwater (Fig. 7.5).

The long-term behaviour of water level representing the upper aquifer has been studied at Maner located in the southern segment for the period of 1995–2010. The post-monsoon (November) depth to water level has remained between 1 and 3 m bgl during the period 1995–2010 (Fig. 7.6) while during the pre-monsoon (May) it has oscillated between 4 and 6.5 m bgl. However, long-term trend both during the pre- and the post-monsoon season exhibits a modest falling trend of about 8 cm/year.

Fig. 7.5 Groundwater flow contours in northern segment



In the southern segment, the depth to water level representing the upper aquifer has been found ranging between 1.36 and 9.39 m bgl during pre-monsoon; however, in >90% of the wells it remains within 5 m bgl. Water level beyond 5 m bgl has been observed only in small area along northern part adjoining River Ganga. During post-monsoon (November), the depth to water level remains within 2 m bgl in major part of the area and only in small patches scattered throughout the area it lies between 2 and 5 m bgl. The water-level fluctuation between mid- and pre-monsoon remains ~2.5 m in about 60% of the wells. The pre-monsoon water table maps indicate that the water table elevation varies from 54 m above mean sea level in the SW part near Bikram to 36–38 m in the NE part (Fig. 7.7) with an average hydraulic gradient of 0.0009. The groundwater flow contour indicates that the overall flow is towards NE, revealing effluent nature of the River Ganga flowing along the northern boundary. However in the north-eastern tip, a groundwater depression has been noted due to overpumping in Patna urban area. In this part, the Ganga has become effluent in nature.

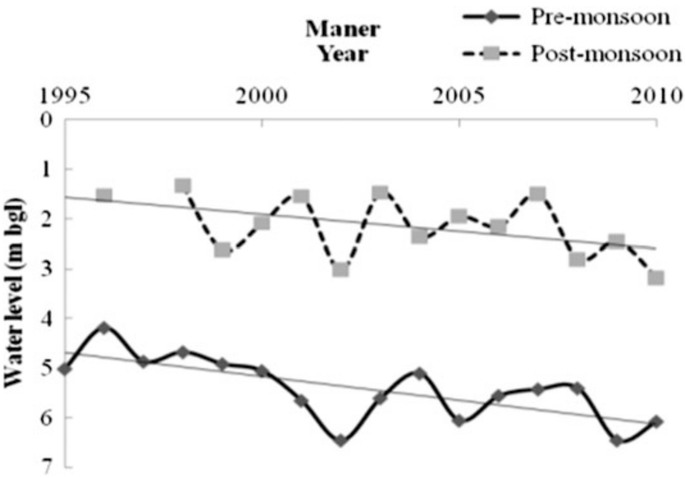


Fig. 7.6 Long-term trend of pre- and post-monsoon water levels at Maner station

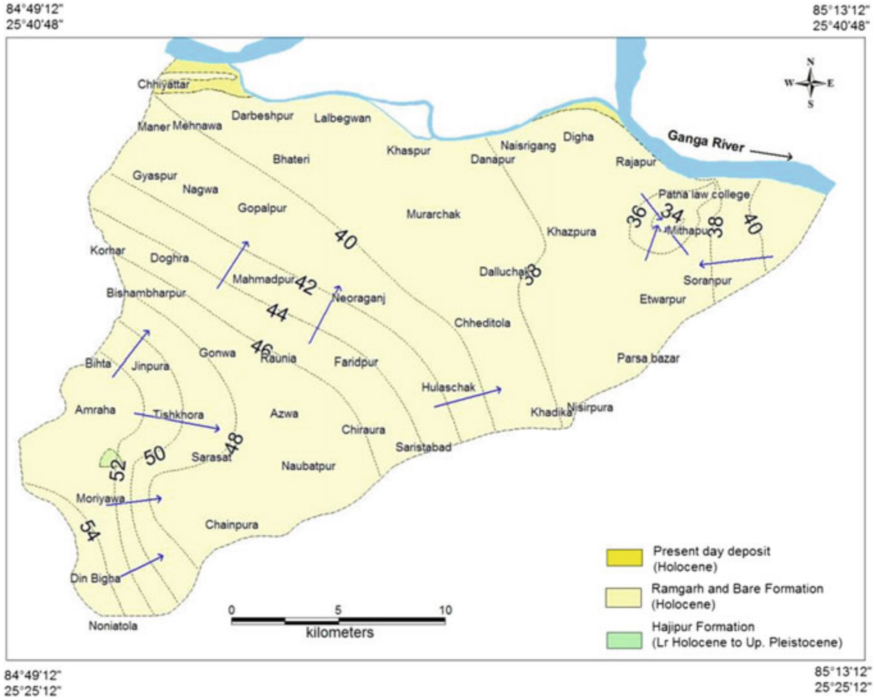


Fig. 7.7 Groundwater flow contour in the southern segment

7.6 Aquifer Hydraulic Parameters

The aquifer hydraulic parameters have been determined by conducting long-duration pumping tests. In the northern segment, two pumping tests were conducted; (i) Vidyapati Nagar and (ii) Shahpur Patori. At Vidyapati Nagar, the targeted aquifer was the deeper one, whereas at Shahpur Patori the tests were conducted for the shallow aquifer. Pre-pumping water levels were 3.77 and 4.52 m bgl, whereas drawdowns were recorded as 2.81 and 5.78 m, respectively. Pumping test data were analysed by Walton (1962) method with the following assumptions; (i) flow of water in the well is under unsteady condition and (ii) the storage in the overlying aquitard is insignificant. The transmissivity value of Shahpur Patori worked out to be 5340 m^2 day^{-1}, while a lower value of 1863 m^2 day^{-1} has been assessed at Vidyapati Nagar. The storativity value (6.36×10^{-3}) revealed occurrence of groundwater under unconfined to semi-confined condition at Shahpur Patori, while confined condition at Vidyapati Nagar ($S = 1.26 \times 10^{-4}$).

In the southern segment, aquifer performance tests were conducted at two locations at Simri and Moriyawan. During the pumping test, a constant discharge of 130 and 150 m^3/h, respectively, was kept. The maximum drawdown observed in the observation well located at 4.80 m after 1170 min of pumping at Simri was 0.415 m. At Moriyawan, the maximum drawdown observed in the observation well located at 47.2 m after 635 min of pumping was 0.27 m. The time-drawdown plots are produced in Fig. 7.8a, b. The analysis of the pumping test data by Jacob straight-line method (Jacob 1950) resulted in transmissivity value of 6323 m^2/day at Simri and 10,135 m^2/day at Moriyawan. This storativity value of 1.28×10^{-2} at Simri reveals that the groundwater occurs under unconfined condition. While a lower value of 4.98×10^{-4} at Moriyawan indicates occurrence of groundwater under semi-confined conditions. The transmissivity values of the aquifers in the southern segment are comparatively higher than that in the northern segment (Sahu and Saha 2016).

7.7 Intense Groundwater Usage: Patna Metropolitan City

Patna urban area is located in the eastern part of the southern segment. The city is presently entirely dependent on groundwater for meeting its water demand. Groundwater-based piped water supply system was first introduced in Patna in 1916 when water supply was made through a large diameter dug well. During 1920, three tube wells were constructed with an average depth of 122 m. In the 1934 earthquake, most of the wells were destroyed following which the city switched over completely to a groundwater-based piped water supply system. The present water supply of city is done through a network of 89 deep tube wells tapping the deeper aquifer system in the range of 150–200 m below ground. As per an estimate, these wells cover about 52% of the population and the estimated annual production of water through these wells is ~140 Million Cubic Metre (MCM). About 40% of

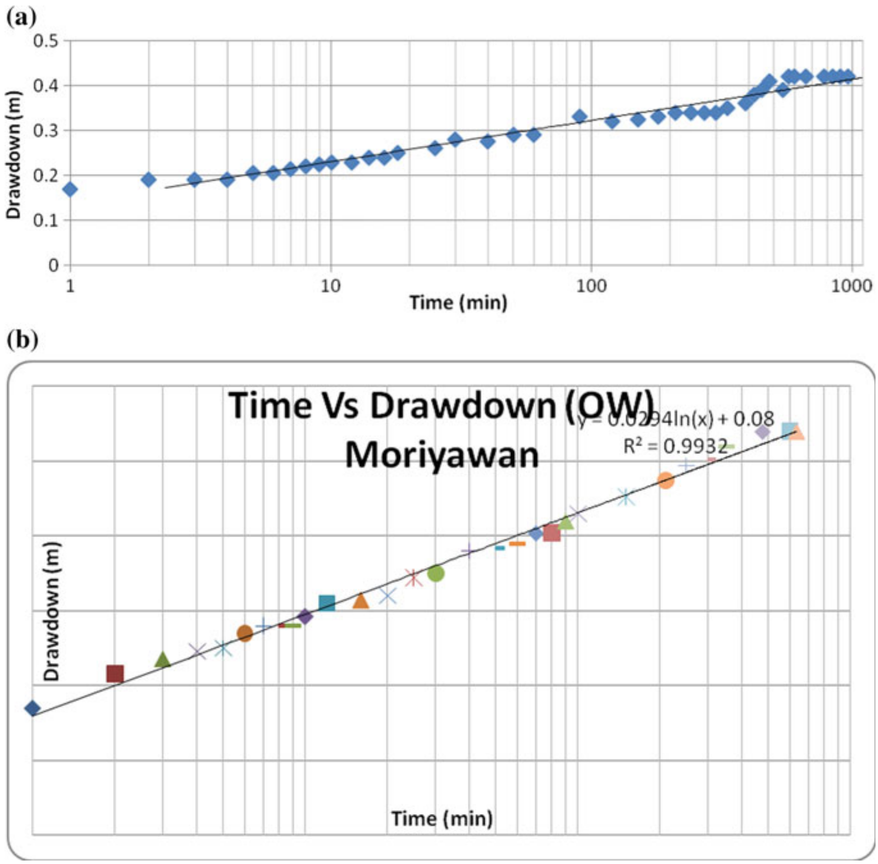


Fig. 7.8 **a** Time-drawdown plot of observation well at Simri located in south segment. **b**. Time-drawdown plot of observation well at Moriyawan located in the south segment

the households have their own tube wells, having a depth range of 40–100 m having an additional annual abstraction as ~40 MCM. The progressive increase in the number of deep tube wells for water supply in the municipal area and annual production of water from these wells is shown in Table 7.1.

The first or upper aquifer and the second or lower aquifer detected in the southern segment represent two distinct hydraulic heads in the Patna urban area. Systematic monitoring of the piezometric level of the deeper aquifer measured during 2008–2010 and its comparison with the data of 1960–1986 available from Maitra and Ghose (1992) are shown in Fig. 7.9. The figure clearly indicates that the piezometric level has gone down to the tune of 4–8 m during the last five decades. The piezometric level exhibits moderate seasonal fluctuation of ~2.5–4.0 m. Despite significantly high transmissivity and significant source of recharge to the aquifers, a fall in piezometric head has been observed in the urban area over the

Table 7.1 Progressive increase in water supply wells and annual production of water

Year	No of water supply wells	Total installed capacity m^3/h	Annual abstraction of water (MCM)
1972	18	0.5×10^4	33.44
1980	44	1.40×10^4	81.76
1988	59	1.83×10^4	107.3
2008	89	2.97×10^4	136.87

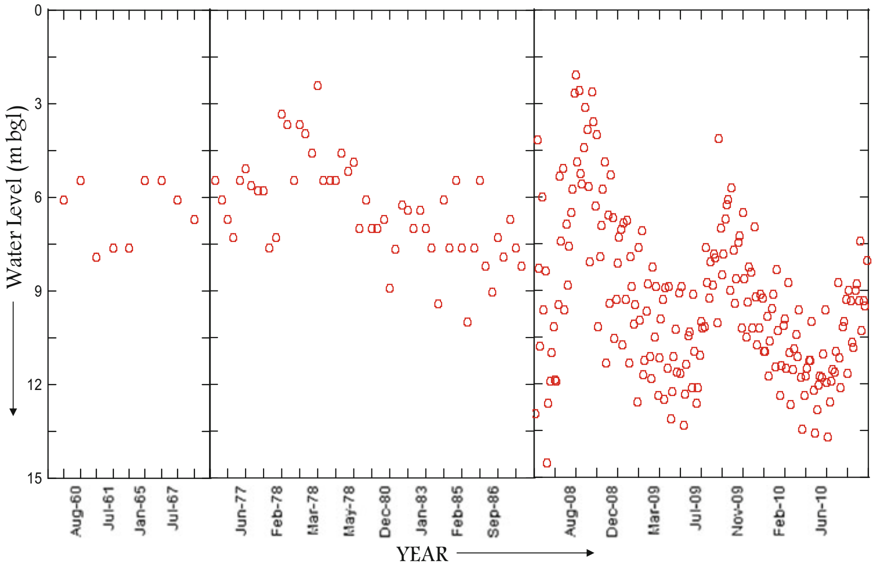


Fig. 7.9 Long-term behaviour of piezometric level representing the second aquifer in Patna urban area

years. The change in mean pre-monsoon piezometric heads of 2008, 2009 and 2010 with that of the levels recorded in 1980–1981 at three locations in different parts of the city, viz. Danapur, Raj Bhawan and Kadamkuan, reveals a decline of ~4 m coupling with high transmissive capacity of aquifer, pointing towards heavy extraction exceeding the natural replenishment. The decline is also affected by interference of cone of depression of numerous wells working simultaneously in the urban area which fail to recoup due to the long transient period of water moving into the area (Custodio 2002). A close look of the aquifer hydraulic conductivity reveals that the decline due to interference of cone of depression will not be a significant component. The modest fall in hydraulic heads from 1980 to 2010 is not found to be as alarming as has observed in other groundwater-dependent city like Dhaka (Bangladesh). Here the piezometric level still remains much above the base of the top aquitard zone. However, it has prompted the residence with private bore well to tap the aquifers at greater depths because of overall apprehension possibility of lowering of water level in near future. A study on installed depth of the slotted pipe versus time of the public deep tube wells indicates that during 1955–2004 periods the lowermost point of the slotted pipe has gone down by >40.0 m. On the other hand, the mid-point of the slotted pipe has gone down for only about 20.0 m, revealing that as the wells tapped deeper sand layers, and also there was an effort to trap the aquifer as thick as possible. As already discussed, pumping yield of wells with 40 and 60 hp pumps remained same over the years, and a marginal increase has been observed for 100 hp pumps.

It has been found that overall abstraction of groundwater is much in excess of the present requirement; however, there is lack in supply in different parts of the city primarily due to high water loss during transmission through the old distribution network.

The total groundwater availability in the deeper aquifer within the urban area has been assessed as 1500 MCM. The depletion in aquifer storage in the last 40 years has been assessed as 15 MCM (Saha et al. 2013a, b). It is thus apparent that the high potential deeper aquifers of Patna urban area can sustain the future water demand; however, increased abstraction (pumping) would result in reduced outflow downstream because of capture (Kalf and Wooley 2005).

7.8 Conclusions and Recommendation

The Gangetic Plains, elongated in east–west direction covering the major parts of Uttar Pradesh and Bihar, hold thick quaternary deposits. The thickness of the deposits, except the boarding area of peninsular upland, known as marginal alluvium deposits, is more than 300 m. The deposits hold some of the most potential aquifer system in the world. The present study has assessed the aquifer configuration, water-level behaviour, aquifer hydraulic character and groundwater flow regime of the Middle Ganga Plain (MGP) occupying the central part of the Gangetic Plains. The study focused on two areas; one located on the northern bank of the Ganga, occupying southern fringe area of Gandak fan. While the other area is located on the southern bank of the Ganga located on the northern fringe of the Son fan, a prominent feature of the SGP. The city of Patna, the capital of Bihar State, with a population of 2.2 million and entirely dependent on groundwater is located within the southern segment area.

The study reveals the prominent two-tier aquifer system made up of different grade of sands and occasional gravel beds within a depth of 300 m bgl, the depth of investigation. The entire stack of fluvio-lacustrine deposit holding the aquifer is of Quaternary age. In both the cases, a 10–30-m-thick sandy clay layer, which appears to be of Holocene age, lies at the top of the succession rendering the upper aquifer system locally under semi-confined condition; however, there occur certain differences in the aquifer disposition in the two segments. In the northern bank, the clay layer separating the first and the second aquifer is thicker (20–35 m) and occurs in the depth range of 130–145 m, whereas, in south of the River Ganga, the clay layer separating the first and the second aquifer is comparatively much thinner (8–12 m) and occurs at the depth range of 85–100 m. The second aquifer system is much thicker in the southern segment ($\sim$100 m) in comparison to those in the northern part ($\sim$25–30 m).

Both the upper and lower aquifer systems are highly potential in northern as well as southern segments. However, the transmissivity is significantly higher in the southern segment. This implies better hydraulic conductivity of the sediment derived by the River Son, in comparison to the Gandak River of Himalayan origin. The reason may be attributed to the better sorting of Son sediments which travel longer distances from far-off provenance in peninsular India, rather than the sediments derived by the Gandak from Himalayas. The seasonal water-level behaviours on both the banks of the Ganga are similar and the groundwater flow regime revealed effluent nature of the River Ganga. In Patna urban area due to excessive groundwater extraction, a groundwater depression has been formed resulting in the Ganga contributing to the aquifers in some patches. In spite of huge extraction ($\sim$200 MCM/year) in Patna urban area, the aquifer shows resilience to decline in the hydraulic head of the exploited aquifer during the past three decades. The reason is the high transmissive capacity of the aquifer and significant recharge at the south where the aquifer is exposed.

Sustainable management of the aquifers in Patna urban area warrants a detailed study for comprehensive understanding of its recharge mechanism and formulation of an artificial recharge plan for the heavily exploited deeper aquifers. Significant wastage of supply water through leakage of pipelines and extraction of groundwater by individual households by over 20–30% more than requirement because of easy availability and no regulation in force demand immediate attention. Measures like limiting the pumping hours and/or imposition of higher electricity tariff for running pumps beyond a fixed limit along with providing incentives for higher water use efficiency may be attempted by the municipality to curb the losses due to unregulated pumping in the urban area for better management of the groundwater resources.

Acknowledgements The authors express their deep sense of gratitude to the Chairman, CGWB, for his unstinted help and support. Thanks are also due to colleagues of CGWB for their constructive suggestions and discussions during the preparation of this manuscript.

References

Acharya SK (2004) Arsenic trends in groundwater from quaternary alluvium in Ganga plain and Bengal basin, Indian subcontinent. Insights into influences of stratigraphy. Gondwana Res 8:55–66

Chakroborty C, Chattopadhyay GS (2001) Quaternary geology of South Ganga Plain in Bihar. Indian Miner 55(3 and 4):133–142

Chakraborty D, Mukherjee SC, Pati S, Sengupta MK, Rahman MM, Chowdhury UK, Lodh D, Chanda CR, Chakraborty AK (2003) Arsenic groundwater contamination in Middle Ganga Plain, Bihar, India: a future danger? Environ Health Perspect 111:1194–1200

Custodio E (2002) Aquifer overexploitation: what does it mean? Hydrogeol J 10:254–277

Jacob CE (1950) Flow of groundwater. In: Rouse H (ed) Engineering hydraulics. Wiley, New York, pp 321–386

Kalf FRP, Wooley DR (2005) Applicability and methodology of determining sustainable yield in groundwater systems. J Hydrol 13:295–312

Maitra MK, Ghose NC (1992) Groundwater management—an application. Ashish Publishing House, New Delhi

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Mukherjee A, Scanlon BR, Fryar AE, Saha D, Ghosh A, Chowdhuri S, Mishra R (2012) Solute chemistry and arsenic fate in aquifers between the Himalayan foothills and Indian craton (including central Gangetic plain): influence of geology and geomorphology. Geochim Cosmochim Acta 90:283–302

Mukherjee A, Saha D, Harvey CF, Taylor RG, Ahmed KM, Bhanja SN (2015) Groundwater systems of the Indian sub-continent. J Hydrol Reg Stud. http://dx.doi.org/10.1016/j.ejrh.2015.03.005

Saha D (2009) Arsenic groundwater contamination in parts of middle Ganga plain, Bihar. Curr Sci 97(6)

Saha D, Alam F (2014) Groundwater vulnerability assessment using DRASTIC and pesticide DRASTIC models in intense agriculture area of the Gangetic plains, India. Environ Monit Assess. https://doi.org/10.1007/s10661-014-4041-x

Saha D, Sahu S (2015) A decade of investigations on groundwater arsenic contamination in Middle Ganga Plain, India. Environ Geochem Health. https://doi.org/10.1007/s10653-015-9730-z

Saha D, Upadhyay S, Dhar YR, Singh R (2007) The aquifer system and evaluation of its hydraulic parameters in parts of South Ganga Plain, Bihar, India. J Geol Soc India 69:1031–1041

Saha D, Dhar YR, Vittala SS (2009a) Delineation of groundwater development potential zones in parts of marginal Ganga Alluvial Plain in South Bihar, Eastern India. Environ Monit Assess. https://doi.org/10.1007/s10661-009-0937-2

Saha D, Sarangam H, Diwedi SN, Bhartariya KJ (2009b) Evaluation of hydrochemical processes in the arsenic contaminated alluvial aquifers in parts of Mid-Ganga basin, Bihar, India. Environ Earth Sci. https://doi.org/10.1007/s12665-009-0392-y

Saha D, Sahu S, Chandra PC (2010) Arsenic-safe alternate aquifers and their hydraulic characteristics in contaminated areas of Middle Ganga Plain, Eastern India. Environ Monit Assess. https://doi.org/10.1007/s10661-010-1535-z

Saha D, Sinha UK, Dwivedi SN (2011) Characterization of recharge processes in shallow and deeper aquifers using isotopic signatures and geochemical behavior of groundwater in an arsenic-enriched part of the Ganga Plain. Appl Geochem. https://doi.org/10.1016/j.apgeochem.2011.01.003

Saha D, Dwivedi SN, Roy GK, Reddy DV (2013a) Isotope-based investigation on the groundwater flow and recharge mechanism in a hard-rock aquifer system: the case of Ranchi urban area, India. Hydrogeol J. https://doi.org/10.1007/s10040-013-0974-3

Saha D, Dwivedi SN, Singh RK (2013b) Aquifer system response to intensive pumping in urban areas of the Gangetic plains, India: the case study of Patna Urban area. Environ Earth Sci. https://doi.org/10.1007/s12665-013-2577-7

Sahu S, Saha D (2014a) Correlation between stratigraphy, flood plain geomorphology and arsenic distribution in groundwater of in Middle Ganga Plain, Bihar, India. Environ Earth Sci. https://doi.org/10.1007/s12665-014-3637-3

Sahu S, Saha D (2014b) Geomorphologic, stratigraphic and sedimentologic evidences of tectonic activity in Sone-Ganga alluvial tract in Middle Ganga Plain, India. J Earth Syst Sci 123(6):1335–1347

Sahu S, Saha D (2016) Empirical methods and estimation of hydraulic conductivity of fluvial aquifers. Environ Eng Geosci XXII(4):319–340

Singh IB (2001) Proxy records of neotectonics, climate changes and anthropogenic activity in Late Quaternary of Ganga plain. In: National symposium on role of earth sciences in integrated development and related societal issues, vol 21. Geological Survey of India Special Publication, pp 161–172

Singh IB (2004) Late quaternary history of the Ganga Plain. J Geol Soc India 64:431–454

Sinha R (2005) Why do Gangetic rivers aggrade or degrade? Curr Sci 89(5):836–840

Sinha R, Tandon SK, Gibling MR, Bhattachargee PS, Dasgupta AS (2005) Late quaternary geology and alluvial stratigraphy of the Ganga basin. Himalayan Geol 26(1):223–240

Walton WC (1962) Selected analytical methods for well and aquifer evaluation. Ill State Water Surv Bull 49:81

Chapter 8
Exploration of Groundwater-Enriched Aquifers of Central Gangetic Basin, India Using Geomorphic Signatures

A. Shaw, P. Das, M. K. Layek, M. Chakraborty, M. S. Jamal, P. Sengupta, A. Basu, J. Sen and A. Mukherjee

Abstract The alluvial plains of the Ganges River system are known to hold one of the best aquifer systems in the world. The unique depositional pattern of the varied fluvial geomorphic features, e.g., channels versus floodplains, controls the disposition of varied lithology within the sediment assemblage, which in turn lays down the foundation for the aquifer-aquitard architecture within the Ganges basin. Hence, geomorphology is often used as a primary tool to understand the aquifer architecture that lies beneath at a shallow level. This article is aimed at establishing the effectiveness of using the fluvial geomorphic signatures to understand the shallow aquifer architecture of central Gangetic basin. The central Gangetic basin is mostly clay capped thus depicting a confined shallow aquifer, but a number of paleolake have been encountered at places due to migration of river through time. This area also exhibits dominance of active or abandoned channels, meander scrolls and point bars, with deposition of sand or coarser grained sediments. These geomorphic features being infiltration zones play a dominant role in increasing aquifer thickness and groundwater movement within the basin.

A. Shaw · P. Das · M. K. Layek · M. Chakraborty · P. Sengupta
A. Basu · A. Mukherjee (✉)
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee
Applied Policy Advisory to Hydrogeosciences Group, IIT Kharagpur,
Kharagpur 721302, India

J. Sen
Department of Architecture and Regional Planning, Indian Institute of Technology,
Kharagpur 721302, West Bengal, India

M. S. Jamal
Department of Civil Engineering, Indian Institute of Technology (BHU),
Varanasi 221005, Uttar Pradesh, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_8

8.1 Introduction

The river Ganges (Chap. 1, Fig. 1.3), with a length of 2525 km, is the world's third largest river in discharge. Geologically, the Gangetic plain lies sandwiched between the active subduction zone and the rising Himalayas to the north and the Indian craton boundary to the south. Geographically, the Gangetic plain extends from the Siwaliks along the Himalayan Frontal Thrust (HFT) in the north to the Bundelkhand-Vindhayan plateau–Hazaribag plateau to the south, and stretches from the Aravalli–Delhi ridge to the west and merges with the Meghna-Brahmaputra Delta to the east forming the Bengal basin (Singh 1996).

The Ganges river basin covers an area of 1,060,000 km^2 out of which the most extensive Gangetic plain constitutes the world largest alluvial plain (Singh 1996; Sinha et al. 2005). The Gangetic plain has a prolonged history of sedimentation forming extensive deposits of Quaternary alluvial fills, as thick as several kilometers to tens of kilometers at places. These alluvial plains are also known to host some of the best aquifers in the world, holding large volumes of fresh groundwater within it. The unconsolidated sediments form a highly intricate fabric of gravel, sand, silt, and clay. The lithological architecture of the sediments lay down the foundation of the aquifer-aquitard framework and the resultant groundwater flow paths. The Ganges aquifer system is known to be highly productive and rich, serving as the main source of drinking water and irrigation for millions of people living in the basin.

The Gangetic plain is an area of low relief and is mostly flat with a very low slope toward the flow direction. The geomorphology of the area is dominated by fluvial landforms with active and abandoned channels, floodplains, river avulsions and cutoff relicts, meander scars, piedmont plains and standing water bodies. Each of these surface geomorphic features is associated with its unique depositional pattern and sediment characteristic, which in turn shapes up the shallow aquifer disposition. Fluvial landforms dominated by coarser sediments such as the abandoned streams and paleolake serve as areas of high permeability and act as preferred pathways for groundwater infiltration and flow. On the contrary, the silty floodplain deposits act as low permeability capping on land surface, preventing free passage of surface water into the ground. Hence, these geomorphological features can be used as signatures to decipher the framework of the shallow aquifer systems.

This article discusses the control of geomorphology on shallow aquifer architecture and establishes the effectiveness of studying the geomorphic signatures to have a preliminary understanding of the shallow aquifer architecture in the Central Gangetic Basin. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

8.2 Geomorphology of Central Gangetic Basin

The central Gangetic basin is one of the largest fluvial controlled depositional systems in the world and is a major component of the Himalayan orogenic system (Shrivastava et al. 2003). The basin consists of river Ganges with its tributaries Yamuna and Son (South), Ghaghara, Gandak, Kosi (North) starting from Meerut in the west continuing up to Rajmahal in the east (Fig. 8.1). The northern tributaries of the Ganges are mostly responsible for transportation and deposition of Himalayan derived sediments in the Basin. The fluvial basin primarily consists of upper impermeable clay and silt layer along with occasional calcretes which is underlain by permeable fine to coarse sand layer. The calcrete layer represents the presence of small paleo-channels and paleolakes (Shrivastava et al. 2003). The abandoned channels and lakes act as highly permeable areas with preferred pathways for groundwater infiltration and flow (Mulligan et al. 2007). It has been established through satellite imageries that the basin consists of numerous paleo-channels and paleolakes thus making it one of the largest aquifer systems in the world. The recent Holocene silt and clay deposits of the floodplains induce an impermeable cap layer preventing infiltration. Thus, the study of surficial geomorphology is very important in order to understand the subsurface aquifer characteristics.

The geomorphology of the central Gangetic basin is believed to be evolved under dynamic climatic conditions, intra- and extrabasinal tectonics and sea-level changes (Singh 1996, 2004; Shukla et al. 2001; Shrivastava et al. 2003;

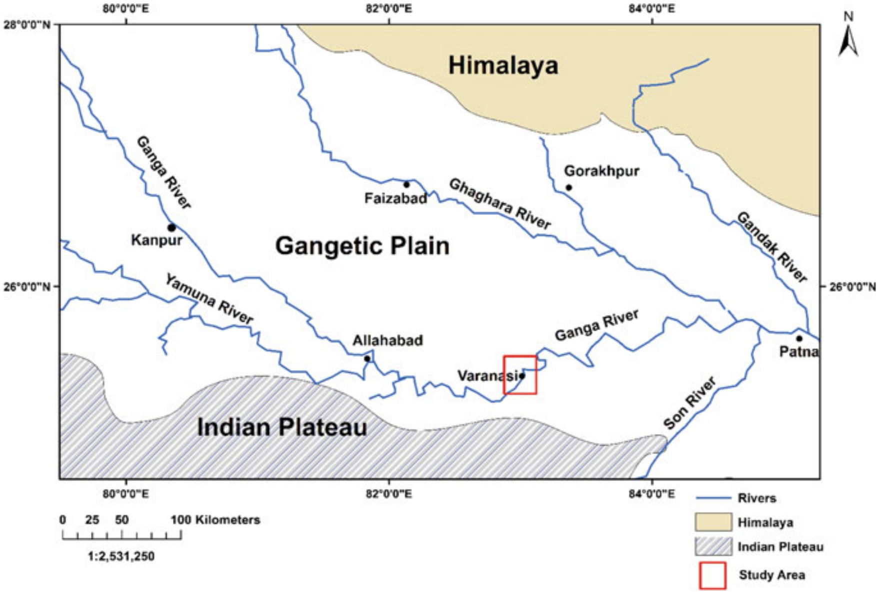


Fig. 8.1 Map displaying the Gangetic Plain and the Study Area Varanasi (shown in Red Box)

Srivastava and Shukla 2009). Different geophysical studies have indicated presence of numerous lineaments, faults, and other structural deformations which also acted as a major control for the basin-fill history (Shukla et al. 2009, 2001; Singh et al. 1999; Singh 1996). It additionally influenced the morphology of river channels on the surface (Singh 2001). The southern cratonic peripheral bulge of the Himalayan foreland is minimal beneath the Gangetic plain, due to rigid crust, resulting in the formation of wide but shallow basin with a thin wedge-shaped sediment layer (Singh 1996, and Shrivastava et al. 2003). The path of river Ganges at places is controlled by the structure of the underlying cratonic peripheral bulge which is characterized by lineaments, normal faults and graben-like structure. The area is dominated by channel incision, conjugate fractures and deformations like bending, tilting and up-doming of sedimentary deposits (Singh et al. 1999; Srivastava et al. 2000, 2003; Singh 2001).

8.3 Case Study 1: Paleolake Investigation in Varanasi Combining Surface Geomorphic Feature and Subsurface Sedimentary Architecture

A case study has been done to understand the role of surface geomorphic features in development of subsurface hydrogeological units. The city of Varanasi (Banaras or Kashi) is selected for this purpose since it is located on the central Gangetic Basin and thereby offers a great site to understand the role on river in characterizing subsurface aquifers.

The geology of the city consists of two major formations: newer alluvium and older alluvium aging from upper Pleistocene to recent and from middle to upper Pleistocene respectively (Raju et al. 2009). The newer alluvium formations comprise unconsolidated sand, silt and clay while the Older alluvium is enriched in consolidated clay with kankar, fine to medium sand and some gravel. The sand beds with or without kankar in the study area form the main aquifer zones of the multi-tier aquifer system (Shukla and Raju 2008). Near-surface groundwater occurs under water table condition, while deeper aquifers occur in semi-confined to confined conditions.

The present work integrates both the surface geomorphology and subsurface geology to carefully delineate the presence of aquifers, especially shallow aquifers. It is quite difficult to study the surface geomorphology in a densely populated area like Varanasi. So, the surficial geomorphic features have been identified with limited resources. Paleolake mapping has been done on the basis of the distribution of paleo-ponds using the ancient map of Varanasi, prepared by James Princep (dated between 1882 and 1829). The northeastern and middle part of the city is characterized by several paleolakes which lie along the current trend of river Ganges (Fig. 8.2).

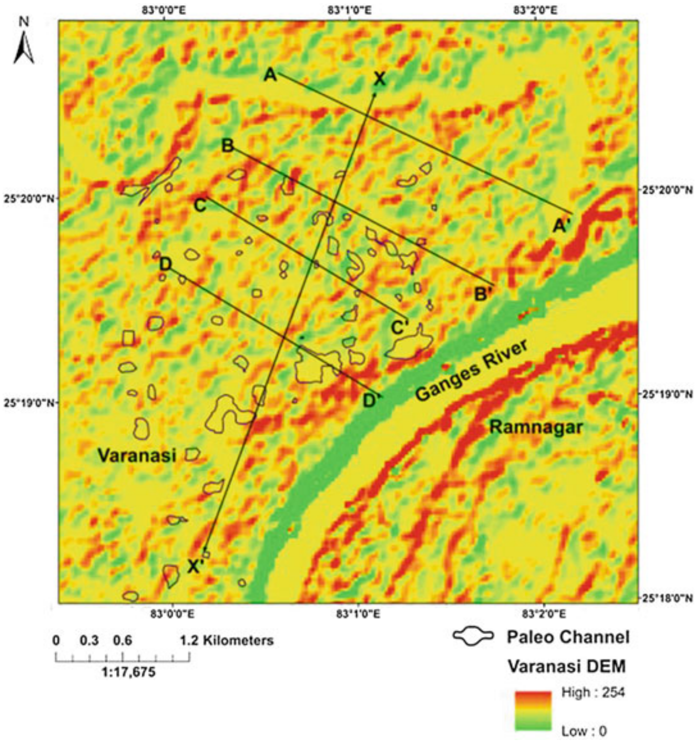


Fig. 8.2 Location map showing paleolakes distribution and selected transects for subsurface investigation

The subsurface geology is identified through drilling up to a depth of 100 m all around the city. Few transects have been carefully selected to visualize the subsurface hydrogeology of the area, especially where the paleolakes are distributed. Fence diagram has been produced with the help of Rockworks software perpendicular to the river trend to understand the spatial variation of shallow aquifers due to the presence of paleolakes in surface (Fig. 8.3). It shows that the shallow aquifers represented by sand bodies are mainly concentrated in the eastern part of the sections where paleolakes are present.

On the other hand, the X-X′ transect along the trend of the river Ganges also shows multilayered aquifers just below the paleolakes (Fig. 8.4). A 3D block model has been proposed by integrating the above investigations to visualize the subsurface sedimentary architecture which in turn helps to understand the effect of surficial geomorphic features in the development of shallow aquifers (Fig. 8.5).

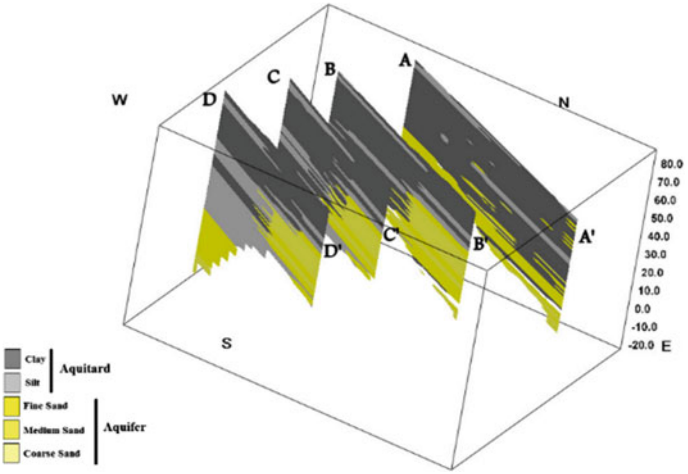


Fig. 8.3 Fence diagram displaying distribution of aquifer and aquitard along selected transects

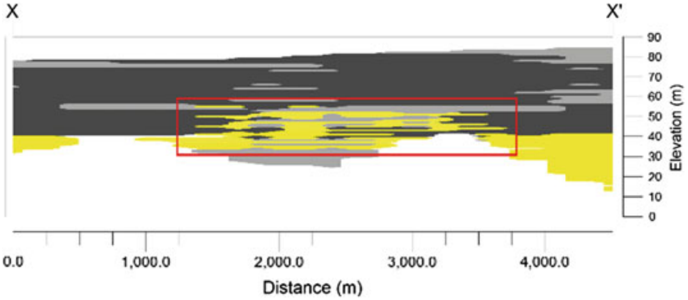


Fig. 8.4 Presence of shallow aquifers (Red Box) along X-X′ profile section

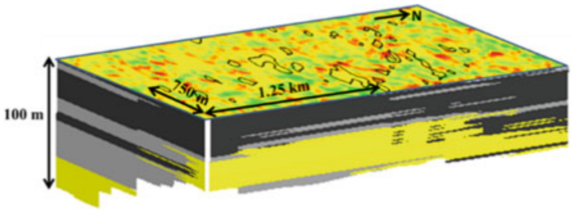


Fig. 8.5 Block model representing the relationship between surface geomorphology and subsurface aquifer characteristics in Varanasi, Central Gangetic Basin

8.4 Case Study 2: Shallow Aquifer Investigation in Point Bar of Single-Channel Ganges River at Varanasi Using Ground Penetrating Radar

Point bar is characterized by fining upward sedimentary sequence with several secondary channel and facies boundary. Bar form basically depends on the discharge rate, sediment load and grain types (Nanson 1980; Smith 1987; Slowik 2016). Ground Penetrating Radar (GPR) study has been proved to be an effective and accurate shallow subsurface imaging process which employs electromagnetic method (Davis and Annan 1989). For the last two decades, it has been used widely in shallow aquifer investigations along with DC resistivity survey (Annan 2005; Doolittle et al. 2006). Water table within a coarser grained bar formation can be mapped as a unique, high-amplitude and continuous reflections which appears as a series of bands due to oscillation of reflected electromagnetic pulse (Doolittle et al. 2006). This unique boundary between unsaturated and saturated sand layers of the bar formation develops high dielectric contrast which helps to obtain a high-amplitude water table reflection at receiver. Secondary channels or scour are identified as concave up and high-amplitude reflections, whereas the channel fill deposits overlie this erosive surface (Skelly et al. 2003). The negative relief in the subsurface and its fill, generally, contain moisture or water which could be used as a shallow aquifer.

Present course of the Ganges River in Varanasi is characterized by incised meanders (8–10 km wavelength) and a huge point bar (2 km long and 0.70 km wide) on the eastern bank toward Ramnagar (Shukla and Raju 2008). Two transects, PBx1 and PBx5 having a length of ~740 m, are surveyed across the point bar with the help of 200 MHz monostatic antenna which is equipped with GSSI SIR-3000 control unit (Fig. 8.6). This chapter utilizes two small sections along these transects to provide a detailed subsurface hydrogeological investigation of the area (Figs. 8.7 and 8.8).

Soil covers along these profiles basically consisted of fine sand with a very thin layer of dry clay which was deposited during the floods. The data processing phase employed GSSI Radan7™ software which routinely involves time zero correction, finite impulse response (FIR) filtering, static corrections. Analysis of the raw GPR data along these profiles helped to reveal the depth of water table and scour-and-fill features. Here, landward section of PBx1 and riverward section of PBx5 have been presented in this chapter (Figs. 8.7 and 8.8).

GPR profile PBx1 is taken from the cliffside to riverside along the maximum bulging position of the point bar. GPR profile PBx1 clearly demarcates the associated stratigraphic reflectors up to 7.5 m depth within a shallow unconfined aquifer. Water table depth varies in between 1.2 and 1.7 m where it goes down in the middle of the point bar and rises in both land and riverside. Older scour-and-fill structure is revealed in between 3.44 and 4.7 m depth having a width of ~15 m (Fig. 8.7). The channel fill comprises fine sands with gravel/coarser sand as channel lag deposits. The lithological boundaries are delineated through variable dielectric

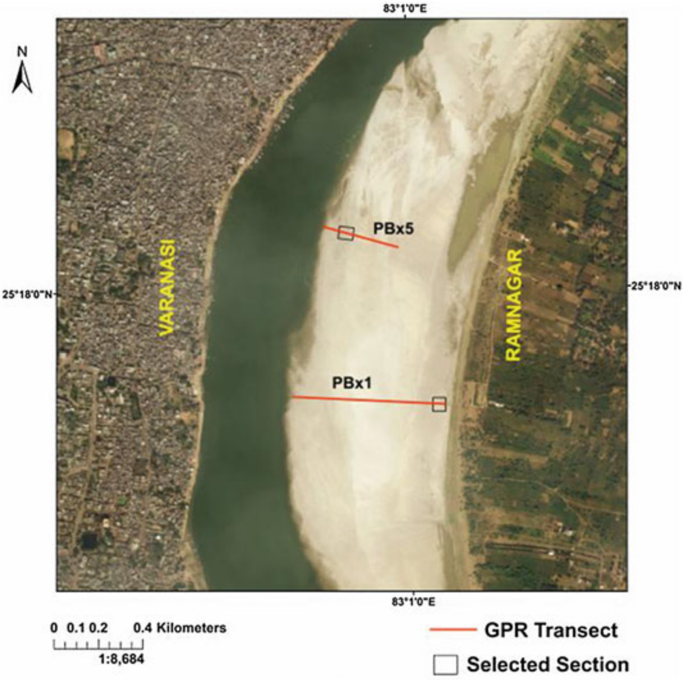


Fig. 8.6 Map representing the location of GPR survey in Varanasi. Red lines indicate GPR transect, PBx5 and PBx1 while the squares indicate selected sections for detailed subsurface hydrogeological investigation

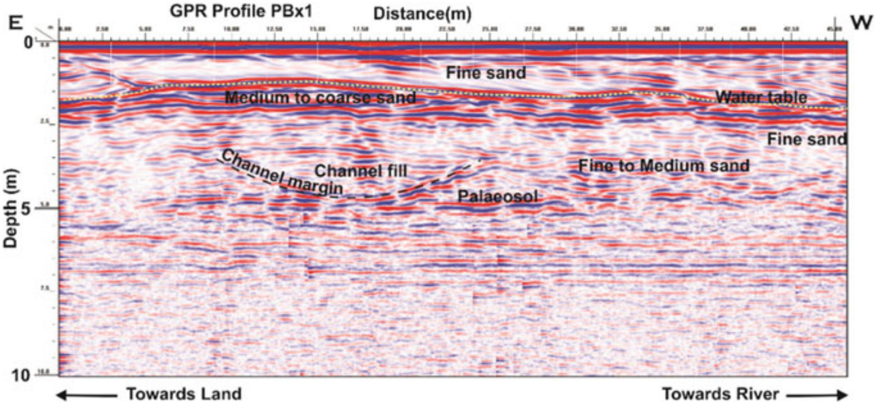


Fig. 8.7 Radar section along the profile PBx1 showing shallow subsurface architecture

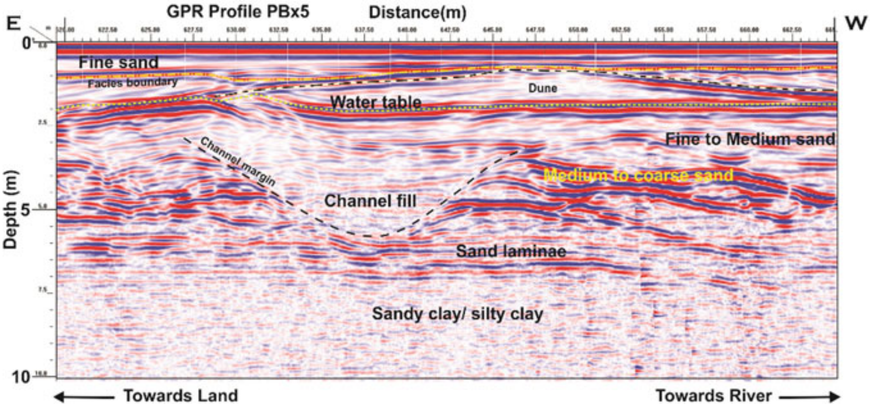


Fig. 8.8 Radar section along the profile PBx5 displaying shallow subsurface architecture

contrast due to different moisture content of the sediments which in turn helps to visualize the internal geometry of the channel fill structure. The upper surface is dominated by fine sand deposits which appears as a set of very low-amplitude reflections on the radargram. The water table is found within the coarser sediments below this finer sediment layer which shows highest amplitude on radargram.

The radar section of the profile PBx5 which is near the riverside also display same geometry where the upper surface is characterized by unsaturated finer sediments (Fig. 8.8). The water table is delineated at a depth of 2 m from the surface where the sediments are relatively coarser. The channel fill below the water table has been identified at a depth of 3.3–6.6 m. The coarser sediments are dominated within this channel fill rather than finer sediments found in the channel fill of PBx1 section.

The geometry of the shallow aquifer structure is different across the point bar. It is characterized by high energy scouring near river along PBx5 section when comparing with the section PBx1 near cliffside (toward Ramnagar). The depth of water table is not constant across the point bar. It becomes shallower in both cliffside and riverside while getting relatively deeper in the middle part of the point bar.

Surface geophysical methods play an important role in understanding the aquifer property thoroughly as well as minutely. Focusing on the cross-sectional profile, small-scale channel deposits could be clearly delineated with gravel to coarser sand at the bottom and finer at the top representing a finning upward sequence. The rest of the sediments in the point bar mostly consist of coarse to fine sand with silty and clayey layer at the bottom. These fluvial deposits act as potential local groundwater storages. On identification of soil moisture through electromagnetic signal of GPR, the water table could be clearly delineated along the point bar deposit since reflections mark the interfaces where there are changes in dielectric constant.

The depth of water table from the surface in the point bar is within 2–2.5 m which is much low relative to the other areas of the city and also the channel depth of Ganges at places.

Since most of the point bar encounters coarse to fine sandy deposit, the infiltration rate is quite high. The whole of the point bar acts as a huge zone of infiltration during the dry season resulting in high groundwater level. The surface runoff gets seeped through the sandy deposit and gets discharged into the river since during dry season the river stage gets highly lowered while during monsoon just the opposite scenario occurs. Due to heavy flow of water through the channel, the point bar remains totally under water and acts as a good pathway for groundwater recharge.

The point bar deposit in this study area is underlain by silty and clayey deposit which acts an impermeable layer for the water to percolate through. Thus, the shallow groundwater remains totally detached from the deeper ones. Pressure generated effect is possible in the deeper aquifer on accommodation of huge amount of water in the point bar deposit but it does not hold any direct connectivity for groundwater recharge in deep aquifer.

8.5 Discussion

The aquifers of the Gangetic plain have been known to be one of the richest aquifers in the world, in terms of its productivity. The aquifer architecture for any fluvial system depends upon the sediment disposition in the area. Spatial variance in sediment characteristics is caused by difference in depositional regime, unique to each fluvial landform (e.g., channels vs. floodplains). Hence, surficial geomorphology can serve as a handy tool in understanding the shallow aquifer disposition in an area. Two discussions were undertaken to understand the effectiveness of use of geomorphic features in understanding the shallow aquifer geometry in the Central Gangetic Basin (in the Varanasi area) separately. The study shows that the subsurface is characterized by shallow aquifers where the paleolakes are dominant in the surface which in turn depicts the relationship of surface and subsurface geological processes. Most of the area in and around Varanasi city is also clay capped which signifies that infiltration rate is very low. However, the paleolake acts as an area for infiltration thus the thickness of the shallow aquifer beneath it, is observed to be higher relative to the surrounding places. On the other hand, the point bar acts as a huge infiltration zone discharging groundwater to the Ganges during dry season and adjacently provides a pathway for shallow groundwater recharge during monsoon. So, it can be concluded that paleolakes and point bars exhibit a direct relation to the shallow aquifer structure in a fluvial setting.

References

Annan A (2005) GPR methods for hydrogeological studies. Hydrogeophysics 185–213

Davis JL, Annan AP (1989) Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. Geophys Prospect 531–551

Doolittle JA, Jenkinson B, Hopkins D, Ulmer M, Tuttle W (2006) Hydropedological investigations with ground-penetrating radar (GPR): estimating water-table depths and local ground-water flow pattern in areas of coarse-textured soils. Geoderma 131:317–329

Mukherjee A (2018) Groundwater of South Asia. Springer, Singapore. ISBN 978-981-10-3888-4

Mulligan A, Evans RL, Lizarralde D (2007) The role of paleolake in groundwater/seawater exchange. J Hydrol 335:313–329

Nanson GC (1980) Point bar and floodplain formation of the meandering Beatton River, northeastern British Columbia, Canada. Sedimentology 27:3–29

Raju NJ, Ram P, Dey S (2009) Groundwater quality in the lower Varuna River Basin, Varanasi District, Uttar Pradesh. J Geol Soc India 73(2):178–192

Shrivastava P, Singh IB, Sharma S, Shukla UK, Singhvi AK (2003) Late Pleistocene-Holocene hydrologic changes in the interfluve areas of the central Ganga Plain, India. Geomorphology 54:279–292

Shukla U, Raju N (2008) Migration of the Ganga river and its implication on hydro-geological potential of Varanasi area, UP, India. J Earth Syst Sci 489–498

Shukla UK, Singh IB, Sharma M, Sharma S (2001) A model of alluvial megafan sedimentation: Ganga Megafan. Sed Geol 144:243–262

Shukla UK, Bora DS, Singh CK (2009) Geomorphic positioning and depositional dynamics of river systems in Lower Siwalik Basin. Kumaun Himalaya 73(Mar):335–354

Singh IB (1996) Geological evolution of Ganga plain—an overview. J Palaeontol Soc India 41:99–137

Singh IB (2001) Proxy records of neotectonics, climate changes and anthropogenic activity in late Quaternary of Ganga Plain. In: National Symposium Role of Earth Science: Integrated Development and Related Societal Issues: Geological Survey of India Special Publication, 65(1)

Singh IB (2004) Late Quaternary history of the Ganga Plain. J Geol Soc India 64:431–454

Singh IB, Srivastava P, Sharma S, Sharma M, Singh DS, Rajagopalan G, Shukla UK (1999) Upland interfluve (Doab) deposition: alternative model to Muddy Overbank Deposits, Facies, pp 197–210

Sinha R, Tandon SK, Gibling MR, Bhattacharjee PS, Dasgupta AS (2005) Late Quaternary geology and alluvial stratigraphy of the Ganga Basin. Himalaya Geol 26:223–240

Skelly RL, Bristow CS, Ethridge FG (2003) Architecture of channel-belt deposits in an aggrading shallow sandbed braided river: the lower Niobrara River, Northeast Nebraska. Sed Geol 158:249–270

Slowik M (2016) The influence of meander bend evolution on the formation of multiple cutoffs: findings inferred from floodplain architecture and bend geometry. Earth Surf Proc Land 41:626–641

Smith DG (1987) Meandering river point bar lithofacies models: modern and ancient examples compared. In: Recent developments in fluvial sedimentology, pp 83–91

Srivastava P, Shukla UK (2009) Quaternary evolution of the Ganga River system: new quartz ages and a review of luminescence chronology. Himal Geol 30:85–94

Srivastava P, Shukla UK, Mishra P, Sharma M, Sharma S, Singh IB, Singhvi AK (2000) Luminescence chronology and facies development of Bhur sands in the interfluve region of central Ganga Plain, India. Current Sci 78:498–503

Chapter 9
Groundwater System of National Capital Region Delhi, India

Suman Kumar, Aditya Sarkar, Shakir Ali and Shashank Shekhar

Abstract Water scarcity in National Capital Region (NCR), Delhi, has gradually become one of the most crucial issues for its citizens in the last few decades. The rapid decline in groundwater level due to heavy abstraction, change in land use pattern, and climate can be seen throughout the NCR. Further; this decline coupled with deterioration of groundwater quality also raises serious concerns. The NCR Delhi is identified as a low-rainfall region, yet by its location in the Yamuna River Basin it has always sustained itself against water scarcity for years in the past. The understanding of groundwater system of NCR Delhi and recent changes are very important for evaluating groundwater environment of NCR. This is a necessary prerequisite for regulated groundwater development and management in this region. Thus, this article reports all the facets of groundwater of NCR. The information and findings in the article will be useful for planners, scientists, engineers, and administrators.

9.1 Introduction

The National Capital Region (NCR) of India (Fig. 9.1) constitutes whole National Capital Territory (NCT) Delhi (1,483 km^2) along with parts of Haryana (12,069 km^2), Rajasthan (8,380 km^2), and Uttar Pradesh (10,853 km^2) and covers a total area of approximately 32,785 km^2. Ganga and Yamuna are main rivers flowing north to south in NCR (Fig. 9.1). NCR Delhi is a water scarce region (Shekhar 2006; Chatterjee et al. 2009; Shekhar et al. 2009; Sarkar et al. 2016a; Macdonald et al. 2016). However, it has been established that if available resource is properly managed, it will cater to this scarcity (Rao et al. 2007; Shekhar et al. 2009, 2015; Shekhar and Rao 2010). Though Indo-Gangetic Plain has high potential of groundwater (Macdonald et al. 2016; Saha et al. 2016), still it requires proper understanding of the system for effective utilization of the resource.

S. Kumar · A. Sarkar · S. Ali · S. Shekhar (✉)
Department of Geology, University of Delhi, Delhi, India
e-mail: shashankshekhar01@gmail.com

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_9

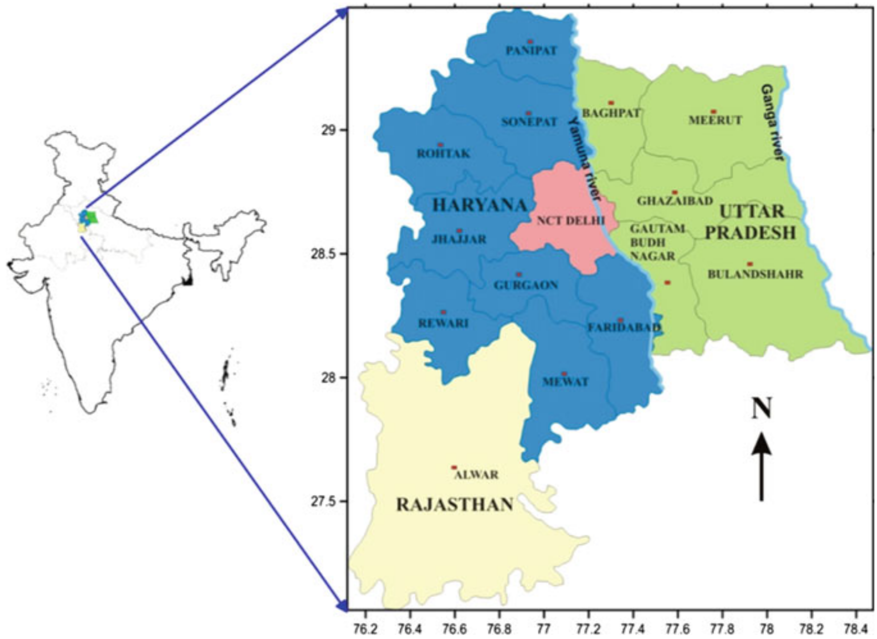


Fig. 9.1 Location map of Delhi, NCR. It covers subregions of three neighboring states (i.e., Haryana, Uttar Pradesh, and Rajasthan) and whole Delhi, NCT. Two major rivers, Yamuna and Ganga, flow from north to south direction. River Yamuna passes almost through the middle while River Ganga flows in the east (After Shekhar 2014; *source* http://ncrpb.nic.in/). More related information regarding groundwater of South Asia is available in Mukherjee (2018)

9.2 Population

The population in NCR has increased drastically in a decade due to employment and better lifestyles. The comparison of area of Delhi and other districts of NCR and the changes in population density over 2001–2011 is shown in Fig. 9.2.

The cumulative area of NCR is 32,785 km^2 in which about 36,268,118 people were living in the year 2001 and it increased to 45,026,595 people in 2011 (Indian Census 2011). Delhi has the highest population density followed by Ghaziabad and Faridabad. However, the population is increasing at a highest rate in Gurgaon (74%), followed by Ghaziabad (42.3%), Mewat (37.9%) over a decade (2001–2011; Fig. 9.2). Delhi stands at eighth position in ascending/descending order in terms of population growth rate for 2001 and 2011.

The average male percentage in the NCR was about 53.3% (2001), which increased to 53.88% (2011). Figure 9.3 clearly shows that the Delhi has the highest population (2011) and 97.5% of them resides in urban areas (Indian census 2011).

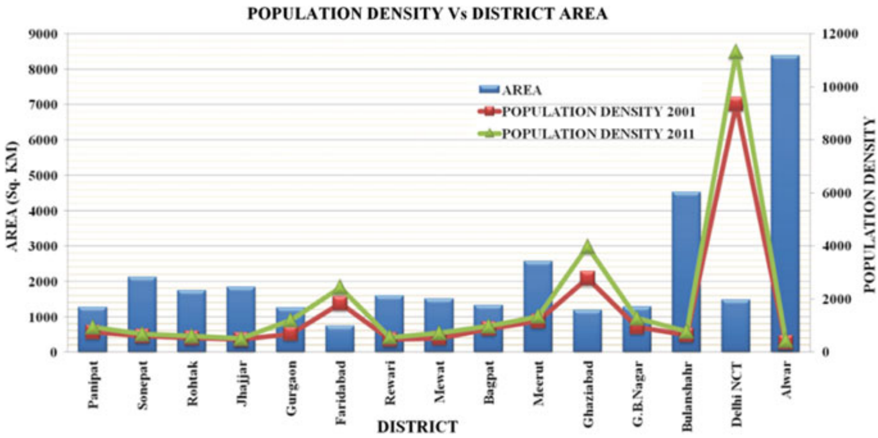


Fig. 9.2 Comparison of area and change in population density over a decade period (Indian census 2011)

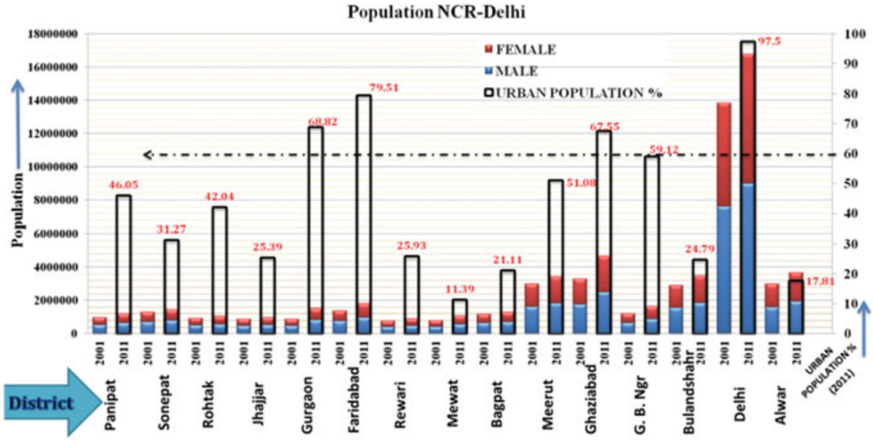


Fig. 9.3 Population distribution in terms of gender and dwelling. *Source* Indian census (2011)

Regions sharing the Delhi border, e.g., Faridabad, Gurgaon, Ghaziabad, and Gautam Buddha Nagar are those areas where more than 60% of their populations are residing in the urban regions which clearly indicate accelerated urbanization. Other districts such as Meerut and Panipat are also approaching the scenario where about 60% of population would be living in cities (Fig. 9.3).

9.3 Land Use/Land Cover

Migration of population toward NCR has influenced the land use pattern. Changes in land use/land cover for the years 1999 and 2012 are shown in Fig. 9.4. Migration to the NCR region has increased the buildup area by 34.6%, while green areas, wastelands, and water bodies have decreased by about 22.5, 40, and 6%, respectively, in the year 2012 with respect to 1999. But the agricultural practices have decreased by a very negligible percentage of 0.77% in NCR (Fig. 9.4). The minor decrease in the water bodies may affect the groundwater recharge.

9.4 Geology/Geomorphology of NCR Delhi

The NCR is mainly covered with Indo-Gangetic Alluvial Plains of Quaternary age (Chhabra et al. 2010; Table 9.1). The main sources of alluvium are the two major rivers namely Yamuna and Ganga which flow through the region (Fig. 9.5).

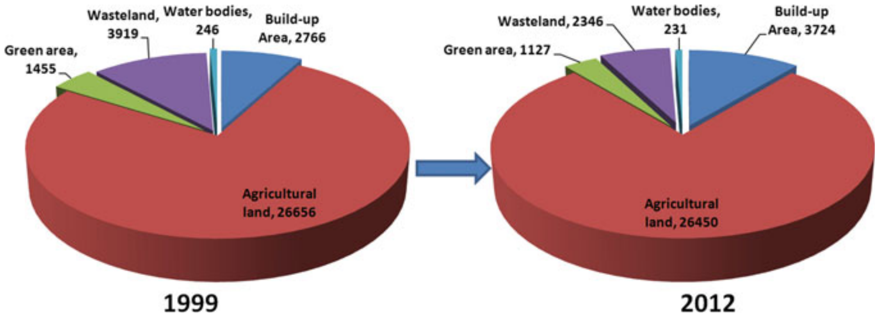


Fig. 9.4 Land use/land cover classification of NCR Delhi (NRSC 2016, available from www.bhuwan.nrsc.gov.in). *Note* Area in the figure is in km^2

Table 9.1 Stratigraphic successions of Delhi and adjoining areas (Sharma (Anon.); Thussu 2006)

Age	Group	Formation
Pleistocene and recent (Quaternary)	Quaternary alluvium	Recent alluvium comprising sands "kankar," gravel, silt, clay, etc.
		Older alluvium and piedmont gravels, pebbles, cobbles, sand, clay, and calcareous concretions
Unconformity		
Post-Delhi intrusive		Quartz veins, pegmatites, granites, amphibolites
Precambrian Delhi super group	Ajabgarh group, Alwar group	Quartzite, phyllites, mica schist, calc-schist, gneiss, marble, basic flows quartzite, conglomerate, and minor schist

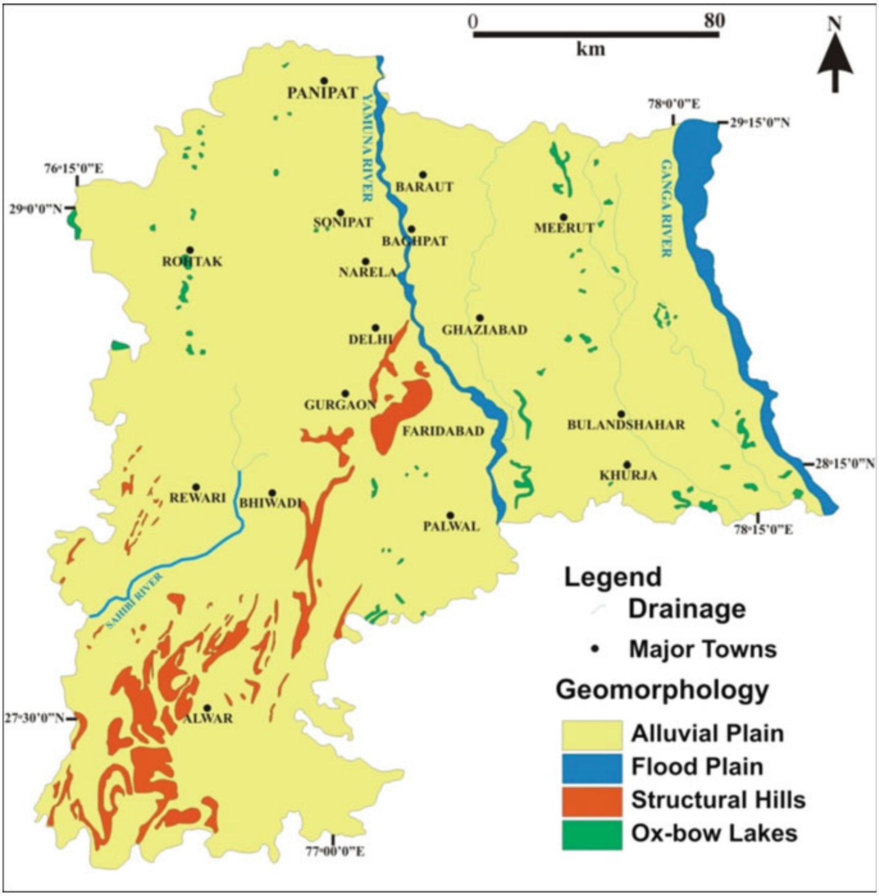


Fig. 9.5 Geological and geomorphologic map of NCR Delhi. Modified after NCRPB (Anon.)

Further, the region is broadly divided into four geomorphic units (Fig. 9.5). These include: alluvial plains, active floodplain areas, upland areas in the form of structural hills and depression covered by oxbow lakes and other isolated water bodies (Kaul and Pandit 2004; NCRPB (Anon.); Bawa et al. 2014). While the active floodplains are confined to areas in the vicinity of the rivers, the structural hills are mainly exposed in southern part of the region. These hills are the parts of Aravalli Ranges and are found exposed with a trend of NE–SW direction (Fig. 9.5).

The stratigraphic succession of the NCR is dated from Precambrian to recent age (Thussu 2006; Table 9.1).

The basement rock is found at variable depths as we move away from the Delhi Ridge (Shekhar and Sarkar 2013). For example, in Panipat, basement is not encountered even after drilling up to 460 m, whereas in Rohtak and Jhajjar, it has been encountered at 370 and 315 m, respectively (CGWB 2013a, b and c).

Similarly, in Ghaziabad, in the vicinity of ridge, basement was found at 116.4 m but as we move away, the rocks are at 330 m depth (CGWB 2009a). In the south of Delhi, basement is near surface to 300 m in central and eastern part of the Mewat (CGWB 2012a) and about 350 m deep in the vicinity of Yamuna in Faridabad (CGWB 2013d).

9.5 Hydrogeology

The hydrogeology of NCR Delhi has a strong link with geomorphology. Alluvial plains are best potential aquifer in the NCR. The varied grade of sand, along with gravels and kankars, forms good aquifers for the groundwater (CGWB 2013b, c, d and e). The groundwater of NCR aquifers is recharged from rainfall, rivers, canal seepage, irrigation, return flow, and water bodies. The alluvial aquifer in the western part of NCR (i.e., Haryana subregion) is medium- to fine-grained sand. Gravels and coarse-grained sand are also reported at a few places which forms potential aquifers. But these zones laterally and vertically are of small extent. In western part of NCR, clay zones dominate over the sandy aquifer (CGWB 2013b, c and e). In Faridabad and Mewat, alluvial aquifers are also reported to have calcareous concretions (CGWB 2012a, 2013d). The aquifer in eastern part of NCR encompassing Uttar Pradesh subregion is mainly composed of coarser sand except the trans-Hindon region (CGWB 2009a).

As the eastern part of the NCR is near to the River Ganga, they are likely to be dominated by the sediments of the Ganga (CGWB 2009a). The central portion of NCR is dominated by River Yamuna, and the small portion in the west is a part of Ghaggar Basin (CGWB 2013e). In between Ganga and Yamuna, tributaries like Hindon meet Yamuna downstream of Okhla barrage.

9.5.1 Aquifer Characteristics

Regionally, there are three major aquifer groups in the NCR. The first aquifer is in unconfined condition; second one is semi-confined to confined state; and third aquifer group is deeper, also confined in nature (CGWB 2009a, 2013a, d, and f). Sand and gravels are aquifer horizon and are underlain and overlain by impermeable clay layers. First aquifer group is up to 200 m thick as in northern part Ghaziabad (CGWB 2009a), and second aquifer group lies between 130 and 250 m in Panipat (CGWB 2013a), 90–200 m in Sonipat (CGWB 2013f), and 170–350 in Ghaziabad (CGWB 2009a). The third aquifer system can be found at depth range of 286–366 m in Panipat (CGWB 2013a), 250–400 m in Sonipat (CGWB 2013f), and 350–450 m in Ghaziabad (CGWB 2009a).

According to the yielding capacity of aquifer, NCR is broadly classified into three zones (Shekhar 2014; Fig. 9.6).

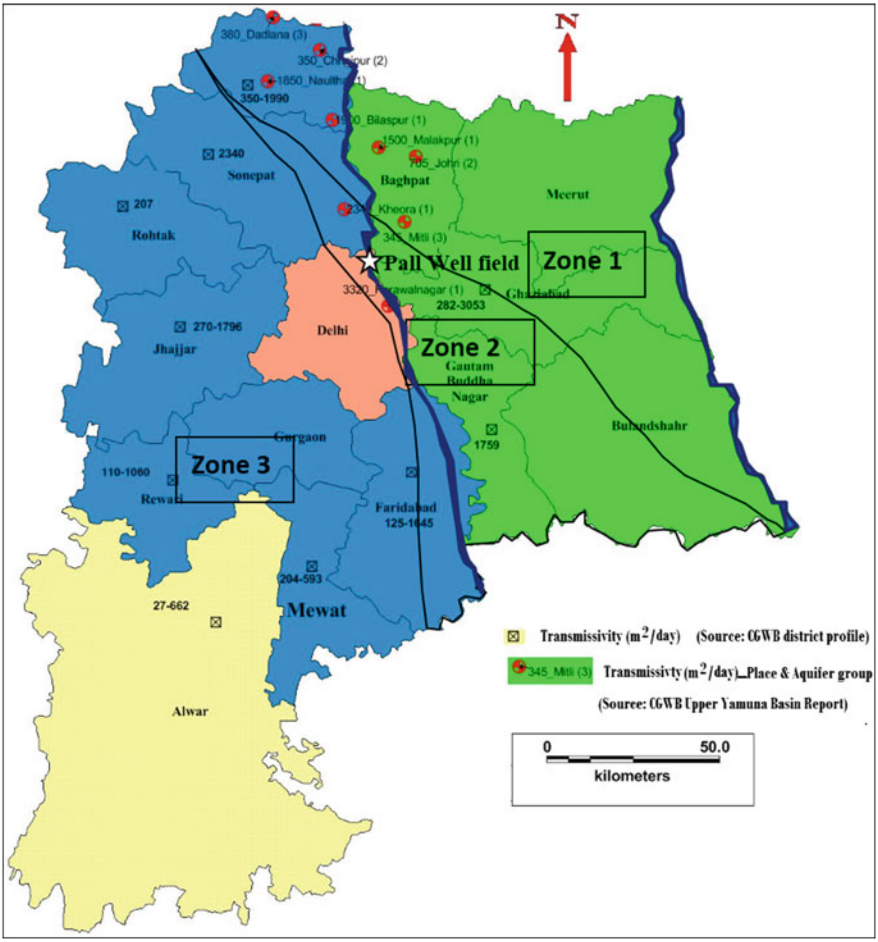


Fig. 9.6 Aquifer zoning and transmissivity variation in NCR. Modified after (Shekhar 2014; CGWB 1985, 2009a, b, 2012a, 2013a, b, c, d, e, f, and g; NCRPB (Anon.), WAPCOS). The figure shows the variation in transmissivity of aquifer across the NCR. Values against red symbol show transmissivity (m^2/day) followed by the site name and aquifer group

Zone 1 is the region which is in the vicinity of Ganga River and upper stretch of Yamuna in NCR. Regions such as Panipat, Meerut, eastern Ghaziabad, and eastern Bulandshahr fall under zone 1. This zone has freshwater in whole aquifer column and can yield significant amount of groundwater. Zone 2 can be broadly classified into two horizons. The upper horizon is younger and higher yielding aquifer than the lower one which has comparatively low yield capacity. The water in upper horizon is fresh, whereas the water in lower horizon is saline in nature (Shekhar et al. 2009, 2015; Shekhar and Prasad 2009; Sarkar et al. 2016a). The quality of groundwater deteriorates as we move from zone 1 to zone 2 in Ghaziabad

Table 9.2 Different hydrogeological properties of NCR and command area

District	Transmissivity	Discharge	Irrigation		
	(m^2/day)	(lpm)	Tube well (km^2)	No. of tube well	Canal (km^2)
Panipat	350–1990	605–3258	680	83,855	280
Sonipat	2340	4541	600	37,385	850
Rohtak	207	870		16,995	840
Jhajjar	270–1796	124	640	29,008	600
Gurgaon		400–1000			
Faridabad	125–1645	200–6629	870		230
Rewari	110–1060	358–2911	1010	28,102	
Mewat	204–593	410–910	720	31,669	160
Ghaziabad	282–3053	1003–2842	1066.36	30,509	207.71
G.B.Nagar	1759	480–960			
Delhi NCT		100–2400			
Alwar	27–662.4	10–1003		3246	7.89

Source (CGWB (Anon.), 2009a, b, 2012a, 2013a, b, c, d, e, f and g); CGWB Delhi state profile (lpm—liter per minute)

(CGWB 2009a). Zone 3 mainly covers the entire subregions of Haryana, Delhi, and Rajasthan state (Fig. 9.6).

The aquifer of third zone is of low yielding capacity. These zones have limited freshwater in upper aquifer horizons. The freshwater under zone 3 region is mainly tapped by tube wells/dug wells or hand pumps of shallow aquifer (CGWB 2013b, c and f). In hard rock aquifers of districts such as Gurgaon, Rewari, Faridabad, Mewat and Alwar and Delhi (Zone 3), freshwater is trapped in joints, fractures, and crevasses (CGWB 2012a, 2013d, e and g). Sahibi River Basin also has fair capacity to yield the groundwater at the rate of 100–300 m^3/day for more than 10–12 h (CGWB 2013g). The variation in the discharge capacity of the aquifer, number of tube wells, and area which is irrigated by tube wells and canals in different districts are shown in Table 9.2.

9.5.1.1 Experimentation for Aquifer Characterization

For determining the aquifer potential on Yamuna River Bank in Delhi stretch, a pumping test was conducted in Palla well field through a project financed by M/s WAPCOS Ltd.

Two observation wells were installed at radial distance of 36 and 48 m far from the pumping well to monitor the effect of pumping on the aquifer. Subsequently, the recovery of water level in both observation wells was also recorded. The effect of pumping in aquifer, along with the site plan, is shown in Fig. 9.7.

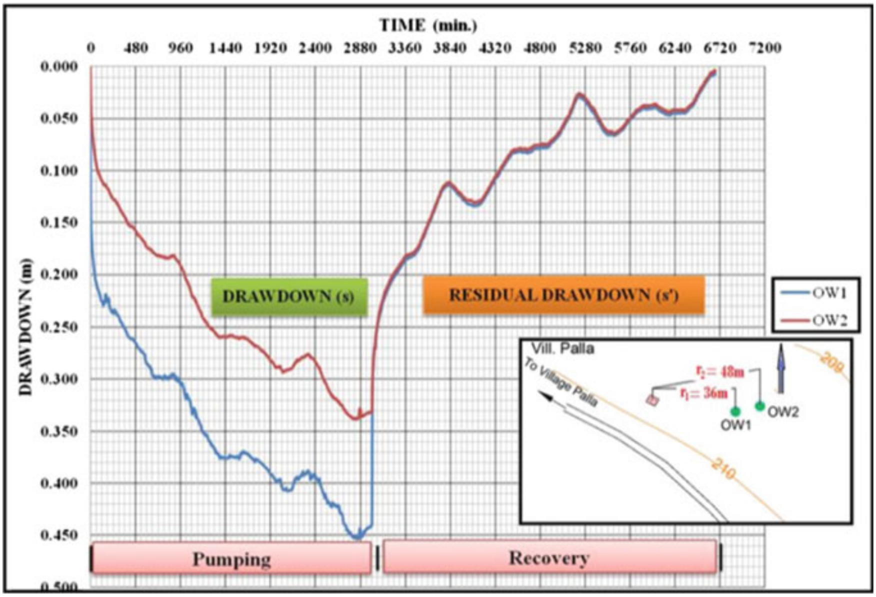


Fig. 9.7 Effect of long-duration pumping test in aquifer and its recovery. The figure shows drawdown in the aquifer during pumping and recovery after the cessation of pumping

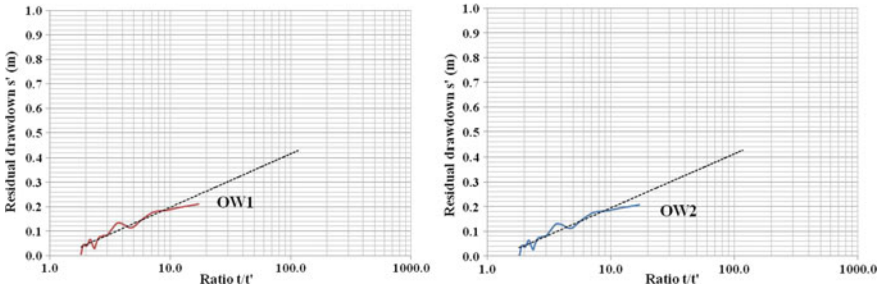


Fig. 9.8 Residual drawdown versus t/t′ ratio for determining the aquifer transmissivity

The pump was run for a long duration of about 50 h, at the discharge rate of 1980 liter per minute (lpm), and its post pumping-recovery was observed for about 61 h. At the end of pumping, drawdowns of 0.44 and 0.33 m were recorded from observation well 1 and 2, respectively. Both observation wells showed recovery of about 99% in 61 h.

The recovery data of this stress test were analyzed using this recovery straight-line fitting approach (Fig. 9.8; CGWB 1982).

For estimation of transmissivity, we used recovery data for the period 187–3660 min. The initial recovery data had fluctuations, and it was difficult to be used for interpretation. With the given data, a plot of residual drawdown (s') versus ratio of time after pumping started (t) and time after pumping closed (t') was drawn for both observation wells (Fig. 9.8). A straight line was fitted through the data, and change in water level during recovery ($\Delta s'$) for a complete log cycle was observed.

The formula used for calculating the transmissivity is given below:

$$\text{Transmissivity}(T) = (2.3 * Q)/(4\pi\Delta s') \quad \text{(CGWB 1982)} \tag{9.1}$$

where

T transmissivity (m^2/sec)
Q discharge rate (m^3/sec)
$\Delta s'$ change in residual drawdown for one log cycle

For OW1, $\Delta s'$ was observed as 0.22 m on log cycle of t/t' which resulted in transmissivity of 0.02745 m^2/sec, and for OW2, $\Delta s'$ is observed as 0.23 m for one log cycle of t/t' producing transmissivity of 0.0263 m^2/sec. The well was placed in the younger alluvium of 110 m thickness (WAPCOS 2012). The hydraulic conductivity estimated from recovery data of OW1 and that of OW2 were 21.5 and 20.6 m/day, respectively.

The high value of transmissivity indicates high potential of aquifer near the Yamuna floodplain in Delhi stretch. The full post-pumping recovery of water level reveals that aquifer can maintain its original condition even after a long high stress condition. However, resilience capability of the aquifer depends on the threshold of stress and it may take much more time to regain its original condition.

9.6 Groundwater Availability

The annual dynamic groundwater resources in NCR is approximately 8.48 BCM while the net abstraction is estimated to be around 7.58 BCM (Sharma (Anon)). This shows that there is recharge availability of around 0.90 BCM annually over and above abstraction. However, most of the blocks in the NCR are at critical stage of groundwater development (CGWB 2011; Fig. 9.9).

It is clear from the figure that fourteen out of twenty-three blocks are overexploited (limit marked as red line). The stage of groundwater development is ratio of gross groundwater draft for all the purposes to net annual groundwater availability and calculated as percentage. Data of subregions of Haryana, Uttar Pradesh, and Rajasthan are taken from CGWB (2011) while those of Delhi NCT are taken from Chatterjee et al. 2009).

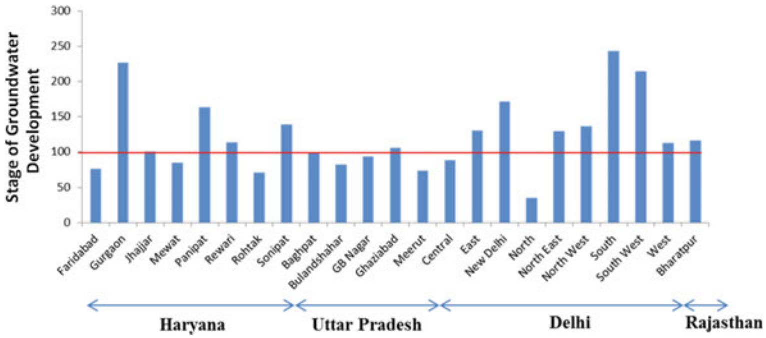


Fig. 9.9 Stage of groundwater development of all blocks in Delhi NCR

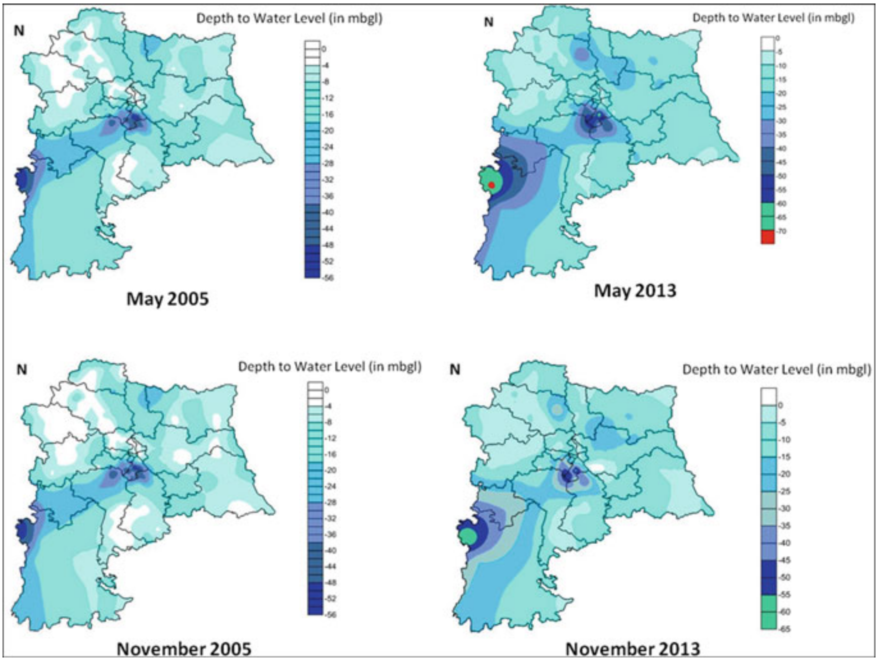


Fig. 9.10 Depth to water level of NCR Delhi for the years 2005 and 2013 (CGWB 2015, accessed from http://gis2.nic.in/cgwb/Gemsdata.aspx)

9.6.1 Decline in Water Level

The depth to water level maps for pre- and post-monsoon seasons (Fig. 9.10) for NCR indicate water level decline during 2013 with respect to 2005.

The water level maps for the year 2005 show the presence of a large shallow groundwater zone (with water level <5 mbgl) in parts of northwest Delhi, Sonipat, Rohtak, extending to Panipat and Jhajjar districts in Haryana. On the other hand, only small parts of South Delhi and western Alwar seem to have water level in range of 45–55 mbgl (Fig. 9.10).

In respect of 2005, the water level maps for the year 2013 show an overall decline in water level across the region. This trend of decline was observed for pre-monsoon as well as post-monsoon seasons. The rate of decline is so rapid that virtually no location in NCR seems to have shallow groundwater levels of <5 mbgl in pre-monsoon season of 2013. In deeper water level areas like western part of Alwar District, the decline has been quite substantial. In fact, the depth to water level has reached 70 mbgl from the depth of 56 mbgl reported in 2005 (Fig. 9.10).

9.6.2 Recharge Possibilities

There are many manmade bunds and natural ponds in the NCR and are much crucial from the groundwater recharge point of view (Fig. 9.11).

Further, Bajpai (2011) highlighted the relevance of understanding the hydrogeomorphic conditions in groundwater management strategies in NCT Delhi. Thus, development of water harvesting structures with the help of basic understanding of local environ is of utmost important. In addition, Shekhar et al. (2015) also suggested considering and studying quality of groundwater before strategizing any groundwater management plan.

Hence based on the suggestion and observations of previous workers (Chatterjee et al. 2009; Shekhar and Prasad 2009; Bajpai 2011; Shekhar 2014; Soni et al. 2014; Shekhar et al. 2015), following measures could be implemented to enhance recharging possibility and better management of existing freshwater resources in different parts of NCR:

- Preservation of the active floodplains as strategic potential water resource to meet drinking water requirement of NCR.
- Development of the active floodplain water resource in NCR as natural disaster mitigation strategy.
- Preservation of water bodies in Alwar quartzites of NCR for augmentation of groundwater resource.
- Stringent action against anthropogenic activities that violates the regulations on groundwater development, particularly in overexploited and critical areas.
- Rainwater harvesting in urban areas for augmenting groundwater resources.
- Rejuvenation of defunct or extinct groundwater recharge structures such as ponds or "*baolis*."

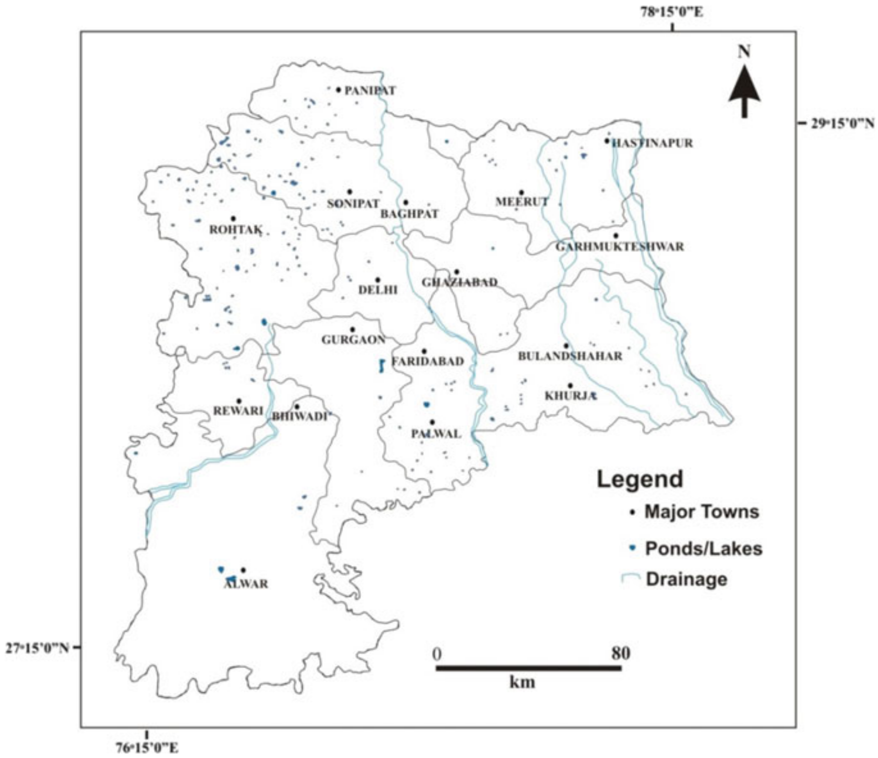


Fig. 9.11 Recharge structures in Delhi NCR. *Source* NCRPB (Anon.)

9.7 Groundwater Quality

The groundwater quality of the Nation Capital Region (NCR) has become a serious concern for policy makers and citizens in the last few years. Although traditionally, the groundwater quality in parts of this region is primarily controlled by geogenic factors (Sarkar et al. 2016a), in recent years, anthropogenic sources also led to drastic changes. These include large-scale urbanization linked to heavy abstraction of groundwater. This also leads to up-coning of saline water throughout the NCR (Shekhar et al. 2005; Shekhar 2006; Sarkar and Shekhar 2015). Groundwater contamination by infiltration of wastewater in shallow aquifers through localized point and nonpoint sources has also been reported (CGWB 2012b; Shekhar and Sarkar 2013; Sarkar and Shekhar 2015; Sarkar et al. 2016a, b). The extent of groundwater contamination, however, is uneven. This can be seen by looking into major ion chemistry represented by spatial hydrochemical facies variation as well as other contaminants.

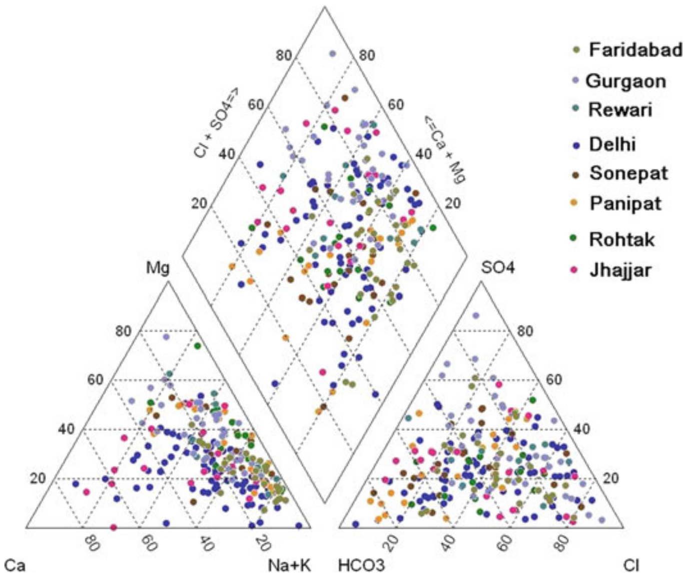


Fig. 9.12 Hydrochemical facies variation in parts of NCR for 2010. Based on CGWB (2012b, c)

9.7.1 Hydrochemical Facies Variation in Parts of the NCR

The extent of groundwater contamination is uneven as seen in spatial hydrochemical facies variation in parts of NCR (Fig. 9.12).

The hydrochemical facies variations observed in parts of NCR give a clear dominance of Na-K cations over Ca-Mg cations. However, there seems to be no distinct spatial trend for facies variation in general. The groundwater samples representing hydrochemical facies from different parts of NCT Delhi (dark blue points) vary from typical Ca-HCO_3-type to Na-Cl-type facies. Detailed evaluation of these facies by Sarkar et al. (2016a) reveals a geomorphic control on facies with presence of HCO_3-dominant facies in active floodplains and chloride-type facies in parts of older alluvial plains. Hydrochemical facies from Jhajjar District (dark pink points) also varies from typical Ca-HCO_3-type to Na-Cl-type facies (Fig. 9.12).

Facies variations in other parts of NCR such as Panipat, Sonipat, and Rohtak (represented by orange, brown, and dark green points, respectively) show Na-K-dominant mixed facies. On the other hand, groundwater samples from south Haryana (Rewari, Gurgaon, and Faridabad) show predominantly Na-K-Cl-SO_4-type facies (Fig. 9.12).

Studies conducted in other parts of NCR such as NOIDA in Gautam Buddha Nagar (Singh et al. 2011) and Baghpat (Alam and Umar 2013) highlight the presence of Ca-HCO_3-dominant to mixed-type facies. The spatial variation in hydrochemical facies indicates multiple sources for groundwater contamination in the entire region; a fact also reflected by studies related to other groundwater contaminants such as nitrate, fluoride, iron, boron.

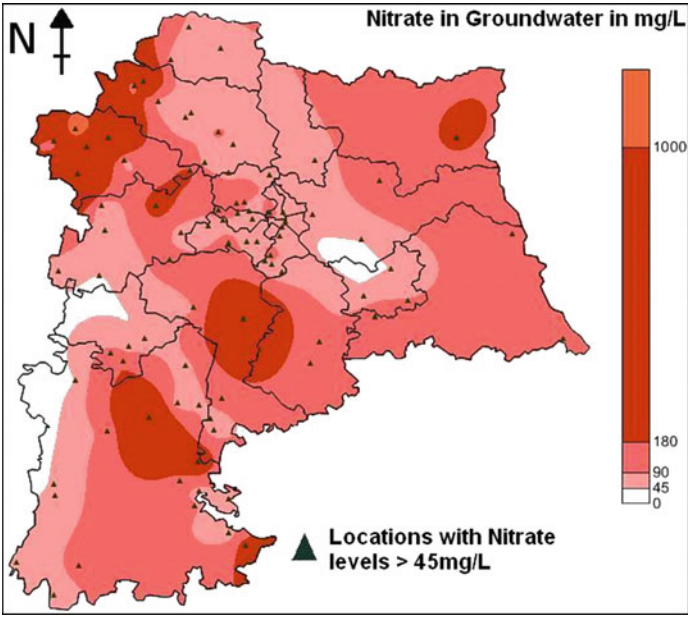


Fig. 9.13 Nitrate contamination in NCR. Based on CGWB (2010)

9.7.2 *Nitrate*

Nitrate is a groundwater contaminant which is usually linked to anthropogenic processes. These include infiltration of the wastewater in groundwater (Shekhar and Sarkar 2013) or pollution to groundwater due to either return irrigation water or contamination by sewage (CGWB 2012b). The permissible limit for nitrate in drinking water as set by BIS (1991, 2012) is 45 mg/l.

Based on this specification, CGWB (2010) reported more than 85 locations in NCR (Fig. 9.13) where groundwater had nitrate levels beyond the permissible limit.

Further, it was also observed that certain parts of Rohtak District (Haryana) had extremely high level of nitrate contamination with Nidana in Rohtak having nitrate levels of 1292 mg/l in groundwater followed by 765 and 760 mg/l in Samargopalpur and Kalanaur in the same district. A recent survey published by CGWB (2012b) and reported in Sarkar et al. (2016a) has reported even higher nitrate levels in some localities in NCT Delhi with 1500 mg/l in Tikri Kalan locality, thus highlighting widespread contamination of groundwater by nitrate in the region.

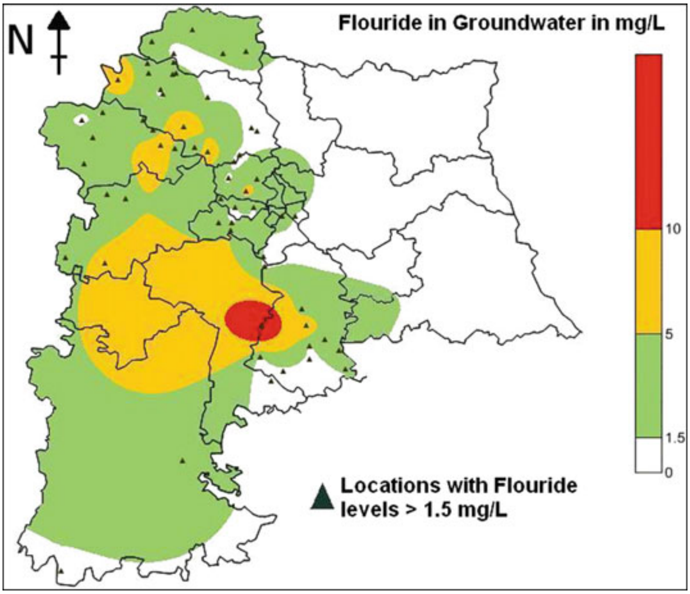


Fig. 9.14 Fluoride contamination in NCR. Based on CGWB (2010)

9.7.3 Fluoride

Fluorine is the lightest, electronegative element in the halogen group and also abundant (625 mg/kg) in the earth's crust, and it is mobile at a higher temperature (Edmunds and Smedley 2001). The sources of fluoride include fluorine-bearing minerals such as fluorite, cryolite, topaz, apatite, micas (Hem 1985; Pickering 1985; Datta et al. 1996; Ali et al. 2016).

In NCR, CGWB (2010) reported the presence of fluoride in different parts of NCR Delhi (Fig. 9.14), with around 60 locations showing fluoride level more than the permissible limit of 1.5 mg/l set by BIS (2012). It could be observed that almost all high contaminated locations are confined to the western parts of the Yamuna Basin with a zone of very high fluoride levels in Gurgaon and Faridabad districts of Haryana (Fig. 9.14), with highest level of fluoride in NCR (17 mg/l) reported from Nuh in Gurgaon District (CGWB 2010).

9.7.4 Iron

The presence of Iron in NCR could be linked to both geogenic and anthropogenic sources. It can occur as both ferrous (Fe^{2+}) and ferric (Fe^{3+}) ion linked to oxidation–reduction reactions in subsurface (Freeze and Cherry 1979; CGWB 2010). On the

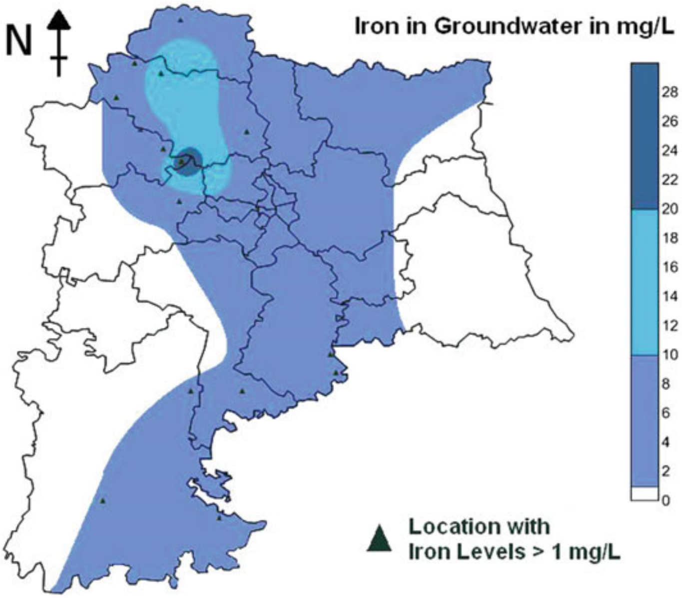


Fig. 9.15 Iron contamination in NCR. Based on CGWB (2010)

other hand, anthropogenic sources such as infiltration from waste effluents present in discharge (CPCB 2008) or the corrosion of steel and cast iron pipes during water distribution (WHO 2008) could also lead to iron enrichment in groundwater.

CGWB (2010) reported 15 locations in NCR having iron concentration more than 1 mg/l, which is the permissible limit set by Bureau of Indian Standards (BIS) at that point of time (Fig. 9.15; BIS 1991). The highest level of Iron in NCR (30 mg/l) was reported from Hassangarh in Rohtak District (CGWB 2010).

9.7.5 Arsenic and Other Heavy Metals

The reports about presence of arsenic and other heavy minerals such as lead, cadmium, copper, and nickel in groundwater of the NCR have become frequent in recent years. However, most of these reports indicate localized contamination of groundwater due to anthropogenic sources.

Alam and Umar (2013) reported 0.006 mg/l of arsenic from groundwater of Baghpat District. Similarly, Dubey et al. (2012) reported arsenic levels in groundwater as high as 107–180 ppb near Badarpur thermal power plant in Delhi.

There are reports of high chromium and cadmium levels in groundwater (7.85 and 0.017 mg/l, respectively) from old landfill site in Bhalaswa, northwest Delhi (CGWB 2012b; Sarkar et al. 2016a).

The presence of Boron in groundwater could be linked to both geogenic and anthropogenic sources. Sarkar et al. (2016b) reported presence of boron concentration in groundwater in parts of NCR Delhi. They observed that the contamination was highly localized which over the years have spread possibly by anthropogenic activities.

Based on the studies conducted by government agencies and researchers, it can be inferred that the groundwater quality of NCR has been primarily controlled by geogenic factors that had led to uneven contamination in parts of the region. However in last few years, groundwater quality degradation has enhanced and become more widespread due to influence of anthropogenic factors.

9.8 Surface Water Quality and Remedial Measures

The major source of surface water pollution in NCR includes untreated wastewater from the drains such as the Najafgarh Drain in NCT Delhi—that makes it highly unsuitable for various purposes.

In NCT Delhi, there were overall 22 drains discharging about 42.65 m^3/sec in the year 2005 (CPCB 2006). The 22 km stretch of River Yamuna in NCT is most polluted section of its whole river path. Since the rivers are in dynamics with the groundwater, pollutants discharged in rivers not only pollute them but also degrade the groundwater quality. So, it is very necessary to treat the generated wastewater before discharging it in the main river system so that quality of surface water, groundwater, and river ecology could be maintained.

Delhi has sewers of about 6000 km in length. There are three major drains namely Najafgarh, Shahdara, and supplementary drains which meet the River Yamuna in Delhi stretch. First and last drains meet river at downstream of Wazirabad barrage and another one at downstream to Okhla barrage. The pollution in River Yamuna is also a major factor for groundwater contamination in parts of NCR with significant contribution from cities such as Delhi, Baghpat, Sonipat, and Panipat to the pollution load in the river (Upadhya et al. 2011). CPCB (2006) reports pollution load contribution to River Yamuna as: 3% from Panipat, 2% from Sonipat, 2% from Baghpat, and 79% from Delhi.

The Delhi Jal Board (DJB) had initiated an interceptor project for decreasing the pollution level of the river. The approach behind this project was to trap the small drain and treat them before they meet the main drains so that the pollution level in Yamuna could be minimized (CSE 2009).

At present (as on September 20, 2015) Delhi Jal Board has achieved the capacity of treating 450 million gallon per day (2250 million liters per day) of sewage through 30 sewage treatment plants (STPs) installed at 17 locations across Delhi (Press release by DJB). Similarly, other STPs are also installed for the treatment of wastewater in different locations across NCR. In Haryana subregion of NCR, STPs are installed in Panipat, Sonipat, Gohana, Gurgaon, HUDA, and Faridabad. Similarly, in Uttar Pradesh subregion, Two STPs are installed in Ghaziabad and NOIDA (CPCB 2008).

9.9 Conclusions

The NCR Delhi has a good potential of groundwater development that could be integrated in holistic and sustainable management of its water resources. The subsurface lithology indicates the presence of localized high yielding aquifers that could be exploited judiciously for mitigation of drinking water crisis. The pressure of population along with urbanization is turning the NCR Delhi into a water scarce region. However, simple steps of rejuvenating preexisting water harvesting structures, preservation of active floodplains, ensuring environmental flows in rivers, prudent concretization together with constant vigilance on groundwater quality front may help in sustaining the water supply system of the region. It may also be advisable to adopt suitably planned conjunctive use of surface and groundwater for urban water supply in NCR. This may reduce stress on groundwater system. Further; cooperation among local authorizes and citizen could help in the improvement of overall groundwater management in the region.

Acknowledgements S.K. thanks the Department of Geology, University of Delhi, for a CAS fellowship. A.S. acknowledges the Council of Scientific and Industrial Research (CSIR) for a financial grant toward a senior research fellowship. S.A. acknowledges the Department of Geology, University of Delhi, for a non-NET scholarship. The financial support for experimentation in Palla area by M/S WAPCOS limited, Government of India, is also duly acknowledged.

References

Alam F, Umar R (2013) Trace elements in groundwater of Hindon-Yamuna interfluve region, Baghpat District, Western Uttar Pradesh. Jour Geol Soc India 81:422–428. https://doi.org/10.1007/s12594-013-0053-3

Ali S, Thakur SK, Sarkar A, Shekhar S (2016) Worldwide contamination of water by fluoride. Environ Chem Lett 14:291–315. https://doi.org/10.1007/s10311-016-0563-5

Bajpai VN (2011) Hydrogeological studies in the National Capital Territory of Delhi with reference to land use pattern and effective groundwater management. Proc Indian Natl Sci Acad 77:31–49

Bawa N, Jain V, Shekhar S, Kumar N, Jyani V (2014) Controls on morphological variability and role of stream power distribution pattern, Yamuna River, Western India. Geomorphology 227:60–72

BIS (1991) Indian standard specification for drinking water. BIS 10500, 1st edn

BIS (2012) Indian standard specification for drinking water. BIS 10500, 2nd edn

Census (2011) Population census 2011. Available from: http://www.census2011.co.in/district.php

CGWB (1982) Manual: evaluation of aquifer parameters Central Ground Water Board. Ministry of Irrigation, GOI

CGWB (1985) Water balance studies in Upper Yamuna Basin, technical report no. 19, Central Ground Water Board, Ministry of Irrigation and Power, Upper Yamuna Project, Chandigarh

CGWB (2009a) District Brochure of Ghaziabad district, U.P. Groundwater Central Ground Water Board. http://www.cgwb.gov.in/District_Profile/UP/Ghaziabad.pdf

CGWB (2009b) District Brochure of Gautambuddh Nagar, U.P. Groundwater Central Ground Water Board. http://www.cgwb.gov.in/District_Profile/UP/GB%20Nagar.pdf

CGWB (2010) Groundwater quality in shallow aquifers of India, report. Central Ground Water Board, Ministry of Water Resources, Government of India

CGWB (2011) Dynamic groundwater resources of India. Central Ground Water Board, Ministry of Water Resources, Government of India, Faridabad, Haryana

CGWB (2012a) Groundwater information booklet, Mewat district Central Ground Water Board, North Western Region, Chandigarh. http://www.cgwb.gov.in/District_Profile/Haryana/Mewat.pdf

CGWB (2012b) Groundwater quality of NCT Delhi, report. Central Ground Water Board, Report, Ministry of Water Resources, Government of India

CGWB (2012c) Groundwater yearbook, Haryana, 2010–2011. Central Ground Water Board, North West Region, Chandigarh

CGWB (2013a) Groundwater information booklet, Panipat district, Haryana, Central Ground Water Board, North Western Region, Chandigarh. http://www.cgwb.gov.in/District_Profile/Haryana/Panipat.pdf

CGWB (2013b) Rohtak district, Haryana, Central Ground Water Board, North Western Region, Chandigarh. http://www.cgwb.gov.in/District_Profile/Haryana/Rohtak.pdf

CGWB (2013c) Jhajjar district, Haryana, Central Ground Water Board, North Western Region, Chandigarh. http://www.cgwb.gov.in/District_Profile/Haryana/Jhajjar.pdf

CGWB (2013d) Faridabad district, Haryana, Central Ground Water Board, North Western Region, Chandigarh. http://www.cgwb.gov.in/District_Profile/Haryana/Faridabad.pdf

CGWB (2013e) Rewari district, Haryana, Central Ground Water Board, North Western Region, Chandigarh. http://www.cgwb.gov.in/District_Profile/Haryana/Rewari.pdf

CGWB (2013f) Sonipat district, Haryana, Central Ground Water Board, North Western Region, Chandigarh. http://www.cgwb.gov.in/District_Profile/Haryana/Sonepat.pdf

CGWB (2013g) Groundwater information, Alwar district, Rajasthan, Central Ground Water Board, Western Region, Jaipur. http://www.cgwb.gov.in/District_Profile/Rajasthan/Alwar.pdf

CGWB (2015) Groundwater information system. Available from: http (Accessed 23.04.2015)

CGWB (Anon.) Gurgaon district, Haryana, Central Ground Water Board, North Western Region, Chandigarh. http://www.cgwb.gov.in/District_Profile/Haryana/Gurgaon.pdf

Chatterjee R, Gupta BK, Mohiddin SK, Singh PN, Shekhar S, Purohit R (2009) Dynamic groundwater resources of National Capital Territory, Delhi: assessment, development and management options. Environ Earth Sci 59:669–686. https://doi.org/10.1007/s12665-009-0064-y

Chhabra A, Manjunath KR, Panigrahy S (2010) Non-point source pollution in Indian agriculture: estimation of nitrogen losses from rice crop using remote sensing and GIS. Int J Appl Earth Obs Geoinf 12.3 (2010):190–200

CPCB (2006) Water quality status of Yamuna River (1999–2005) Central Pollution Control Board (Ministry of Environment & Forests, Govt. of India), Parivesh Bhawan, East Arjun Nagar, Delhi

CPCB (2008) Status of groundwater quality in India Part—II, Groundwater Quality Series: GWQS/ 10/2007–2008, Central Pollution Control Board (Ministry of Environment & Forests, Govt. of India), Parivesh Bhawan, East Arjun Nagar, Delhi

CSE (2009) Review of the interceptor plan for the Yamuna, Report, River Pollution Unit, Centre for Science and Environment Delhi

Datta PS, Deb DL, Tyagi SK (1996) Stable isotope (18O) investigations on the processes controlling fluoride contamination of groundwater. J Contam Hydrol 24:85–96. https://doi.org/10.1016/0169-7722(96)00004-6, https://doi.org/10.1007/s12665-015-4399-2

Dubey CS, Mishra BK, Shukla DP, Singh RP, Tajbakhsh Sakhare P (2012) Anthropogenic arsenic menace in Delhi Yamuna Flood Plains. Environ Earth Sci 65:131–139. https://doi.org/10.1007/s12665-011-1072-2

Edmunds WM, Smedley PL (2001) Fluoride in natural waters. In: Selinus O (ed) Essentials of medical geology. Springer, Netherlands, pp 311–336

Freeze RA, Cherry JA (1979) Groundwater. Published by Prentice Hall Inc. ISBN 0-13-365312-9

Hem JD (1985) Study and interpretation of the chemical characteristics of natural water, vol 2254. Department of the Interior, US Geological Survey, Virginia

Kaul BL, Pandit MK (2004) Morphotectonic evaluation of the Delhi region in northern India, and its significance in environmental management. Environ Geol 46:1118–1122

MacDonald AM, Bonsor HC, Ahmed KM, Burgess WG, Basharat M, Calow RC, Lark RM (2016) Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. Nat Geosci 9(10):762–766

Mukherjee A (2018) Groundwater of South Asia. Springer, Singapore. ISBN 978-981-10-3888-4

NCRPB (Anon.) Functional plan for ground water recharge in NCR, National Capital Region Planning Board

NRSC (2016/2015) Bhuvan, National Remote Sensing Center. Available from: http://bhuvan.nrsc.gov.in/. Accessed 10.08.2016

Pickering WF (1985) The mobility of soluble fluoride in soils. Environ Pollut Ser B Chem Phys 9(4):281–308

Rao SVN, Kumar S, Shekhar S, Sinha SK, Manju S (2007) Optimal pumping from skimming wells from the Yamuna River flood plain in north India. Hydrogeol J 15(6):1157–1167

Saha D, Shekhar S, Ali SR, Vittala SS, Raju NJ (2016) Recent hydrogeological research in India. Proc Indian Nat Sci Acad 82(3):787–803

Sarkar A, Shekhar S (2015) The controls on spatial and temporal variation of hydrochemical facies and major ion chemistry in groundwater of South West District, Delhi, India. Environ Earth Sci 74(12):7783–7791

Sarkar A, Ali S, Kumar S, Shekhar S, Rao SVN (2016a) Groundwater environment in Delhi, India. Groundwater environment in Asian Cities: concepts, methods and case studies, 1st edn. Elsevier Inc., Publisher, pp 77–108

Sarkar A, Arora S, Shekhar S (2016b) Boron in groundwater of National Capital Region Delhi. J Water Pollut Purif Res 3(2):30–36

Sharma SK, (Anon.) Proposal for ground water recharge in National Capital Region (NCR). Available on: http://www.indiawaterportal.org/articles/proposal-groundwater-recharge-national-capital-region-report-sk-sharma-and-green-systems. Accessed on 21.10.2016

Shekhar S (2006) An approximate projection of availability of the fresh groundwater resources in the South West district of NCT Delhi, India: a case study. Hydrogeol J 14(7):1330–1338

Shekhar S (2014) Sustainable groundwater management strategies for potential aquifers of NCR to serve as disaster management tool. Workshop on water conservation and sustainable management of groundwater in National Capital Region, Vigyan Bhawan, New Delhi. https://doi.org/10.13140/rg.2.1.1373.9365

Shekhar S, Prasad RK (2009) The groundwater in the Yamuna flood plain of Delhi (India) and the management options. Hydrogeol J 17:1557–1560. https://doi.org/10.1007/s10040-008-0430-y

Shekhar S, Rao SVN (2010) Groundwater management in Palla well field of Delhi using numerical modeling technique-a case study. Silver Jubilee Publication-II 25(3&4):46

Shekhar S, Sarkar A (2013) Hydrogeological characterization and assessment of groundwater quality in shallow aquifers in vicinity of Najafgarh drain of NCT Delhi. J Earth Syst Sci 122(1):43–54. https://doi.org/10.1007/s12040-012-0256-9

Shekhar S, Singh SB, Romani S (2005) The controls to the variation in depth to Fresh/Saline interface in the groundwater of Southwest District, NCT, Delhi-a Case Study. Geol Soc India 66(1):17–20

Shekhar S, Purohit R, Kaushik YB (2009) Groundwater management in NCT Delhi. Technical paper included in the special session on Groundwater in the 5th Asian Regional Conference of INCID

Shekhar S, Mao RSK, Imchen EB (2015) Groundwater management options in North District of Delhi, India: a groundwater surplus region in over-exploited aquifers. J Hydrol Reg Stud 4:212–226. https://doi.org/10.1016/j.ejrh.2015.03.003

Singh AK, Tewari BK, Sinha A (2011) Hydrochemistry and quality assessment of groundwater in Part of NOIDA Metropolitan City, Uttar Pradesh. J Geol Soc India 78:523–540

Soni V, Shekhar S, Singh D (2014) Environmental flow for the Yamuna river in Delhi as an example of Monsoon Rivers in India. Curr Sci 106(4):558–564

Thussu JL (2006) Geology of Haryana and Delhi. Geol Soc of India, Bangalore

Upadhyay R, Dasgupta N, Hasan A, Upadhyay SK (2011) Managing water quality of River Yamuna in NCR Delhi. Phys Chem Earth 36:372–378

WAPCOS (2012) Experimental investigation report, WAPCOS Limited. A govt. of India undertaking

WHO (2008) Guidelines for Drinking-water quality third edition incorporating the first and second addenda. WHO Press, World Health Organization, Geneva, Switzerland

Chapter 10
Groundwater Resources of Myanmar

Than Zaw, Aung Kyaw Moe, Myint Ko and Ye Myint Swe

Abstract The Republic of the Union of Myanmar is with an area coverage of 676,557 km^2, has a coastline of 2000 km, population about 52 million and 135 tribes are living together. The geological units of Myanmar range from Precambrian to Recent and morphologic and tectonic features of the stratigraphic units follow a general north–south trend, more or less related to the neighboring countries of India, China, Thailand, Malaysia, and Indonesia. Myanmar receives ninety percent of its annual rain from southwest monsoon from mid of May to mid of October. The rainfall intensity, pattern, and rainfall duration vary depending on the locality and elevation of the region like 2030–3050 mm in the deltaic area, 2030–3810 mm in the north, about 1500–2000 mm in eastern hilly region, rising to 5080 mm in the coastal regions of Rakhine and Tanintharyi and only 760 mm in the central dry zone. Water loss by evaporation is high and ranging from 1500 to 2000 mm. The four major river systems apart from those in Rakhine State and Tanintharyi Region are the Ayeyarwaddy, the Thanlwin, the Chindwin, and the Sittaung. The total surface and groundwater potential of Myanmar are approximately 1080 and 495 km^3 per year, respectively. On the basis of stratigraphy, there are eleven different types of aquifers with varying groundwater quality and quantity. The water use in Myanmar is appreciably increased, especially in agriculture (89%) compared to domestic (8%) and industrial sectors (3%).

T. Zaw (✉)
Irrigation and Water Utilization Management Department, Ministry
of Agriculture, Livestock and Irrigation, Naypyidaw, Myanmar
e-mail: tzaw.wrud@gmail.com

A. K. Moe · M. Ko · Y. M. Swe
Department of Geological Survey and Mineral Exploration, Ministry
of Natural Resources and Environmental Conservation, Naypyidaw, Myanmar
e-mail: aungkymoe@googlemail.com

M. Ko
e-mail: Myintko788@gmail.com

Y. M. Swe
e-mail: ymswe@gmail.com

© Springer Nature Singapore Pte Ltd. 2018
A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_10

Keywords Groundwater · Myanmar

10.1 Introduction

Myanmar (Chap. 1, Fig. 1.1) is geographically located between 9° 32′ and 28° 31′ north latitude and 92° 10′ and 101° 10′ east longitude. It is one of the South Asian nations with a total land area of (676,557) km^2. Myanmar is bordered in the west by Bangladesh, in the northwest by India, in the north and northeast by China, in the east by Lao People's Democratic Republic, and in the southeast by Thailand, covering the total length of the country's border is 4000 km. The Union includes seven states and seven regions. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

10.2 Climate and Rainfall

Myanmar has three distinct seasons. The cold season starts from November to end of January; dry season starts from February to April followed by the wet season. Myanmar receives its annual rain mainly from southwest monsoon from mid of May to mid of October. The 90% of annual rainfall in different regions of Myanmar is monsoonal. The rainfall intensity, pattern, and rainy duration are varied depending on the locality and elevation of the region. Rainfall receives 2030–3050 mm in the deltaic area, 2030–3810 mm in the north, about 1500–2000 mm in eastern hilly region, rising to 5080 mm in the coastal regions of Rakhine and Tanintharyi, and only 760 mm in central dry zone. And incidentally such localities experience temperature of 40 °C during summer, and dropping to 10–16 °C in some hilly regions. Water loss by evaporation is high and ranging from 1500 to 2000 mm. Due to the climatic variation; scarcity of water during dry season becomes a main issue over most of the area of the country. The annual rainfall isohyets map is shown in Fig. 10.1.

10.3 Physiography and Drainage

The physiography of Myanmar closely reflects its geology. Then, the country can be divided into four physiographic units. Major drainage lines in Myanmar are from north to south. The deeply dissected Shan Plateau rises to an average elevation of about 914 m (3000 ft) above sea level. Much of the surface of this plateau is of a steeply rolling, hilly nature. Several of the shorter streams in this plateau flow sluggishly through broad valleys, but the largest river, the Thanlwin, is deeply entrenched. The major part of the Central Belt is composed of ancient valleys that

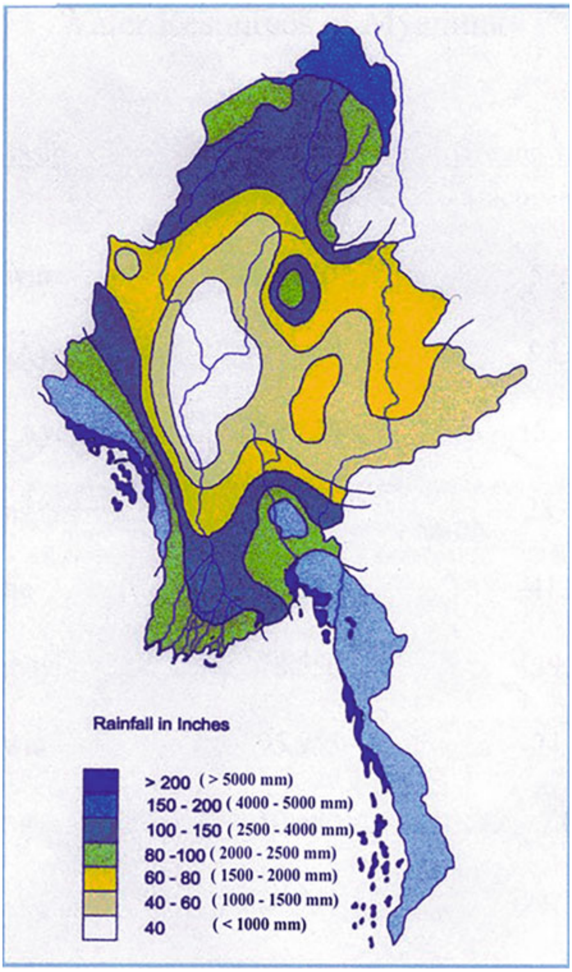


Fig. 10.1 Annual rainfall map of Myanmar. *Source* WRUD

have been covered by deep, alluvial deposits through which the Ayeyarwaddy, its tributary the Chindwin, and the Sittaung rivers flow. The relief of the northern portion of the Central Belt where the ridges of the Himalayan Mountains curve southward becomes the mountain system of Myanmar eastern frontier. These mountains are very high and rugged, and the Hkakabo Razi, the highest peak in the nation, rises about 6,096 m (20,000 ft). The western mountain belt is composed of ranges that originates in the northern mountains and continues southward to the extreme southern corner of the country. The Rakhine Coastal Strip is a narrow, predominantly alluvial belt lying between the Rakhine Mountains and the Bay of Bengal. In its northern portion, there is a broad area of level land formed by floodplains of several short streams that come down from the mountains.

10.4 Geological Setting

The geological age of stratigraphic units of Myanmar ranges from Precambrian to Recent, and morphologic and tectonic features of the stratigraphic units follow a general north–south trend. They are more or less related to the stratigraphy and tectonic setting of neighboring countries of India, China, Thailand, Malaysia, and Indonesia. The territory of Myanmar is traditionally divided into five parallel north–south trending morpho-tectonic belts from east to west. They are the Eastern Highlands and Upper Irrawaddy Province, the Central Lowlands, the Western Ranges or Western Fold Belts, and the Arakan Coastal Belt, where each belt has its own outstanding stratigraphic succession, geological structures, and metallogenic characteristics.

10.4.1 The Eastern Highlands and Upper Irrawaddy Province (Tagaung–Myitgyinar Belt)

The Eastern Highland and Upper Irrawaddy Province comprise the Eastern Ranges of Kachin State in the north, Shan Plateau in the middle, and the Mon-Tanintharyi ranges and the Myeik Shelf in the south. The stratigraphic units of Precambrian to Tertiary ages are included in this belt predominantly with carbonate rocks.

The crystalline rocks of Mogok Series with gneiss, marble, calc-silicate, granulite, schists, and quartzite are well outcropped along the western margin of the belt from Kachin State in the north to Bay of Mottama in the south. Flysch-like sediments of the upper Precambrian Chaungmagyi Group are exposed at the boundary of Kachin State and northern Shan States. These are overlain by thick sequence of upper Paleozoic carbonate rocks throughout the Shan Plateau Region. Plateau Limestone unit in Shan Dolomite Group goes up Permian to middle Triassic and tectonically and partially consolidated with low-grade metamorphic rocks of Paleozoic and Mesozoic sediments from the northwestern edges of northern Shan State to the Southern Tanintharyi ranges.

In addition, upper Cambrian–lower Ordovician Pangyun Formation, including Bawdwin Volcanic Formation, Molohein Group and Mawchi-Mergui series of upper Paleozoic, clastic sediments are present in the west and southernmost part of the belt.

The upper Paleozoic thick and extensive clastic metasedimentary assemblages of Slate Belt comprising quartzite, graywacke, pebbly mudstone with minor limestone, conglomerate agglomerate, and volcanic ash with different names of stratigraphic units are recognized in Shan, Kayah, Kayin, Mon States and Tanintharyi Region. Triassic to Upper Jurassic-Cretaceous sediments of Namyau Group with evaporites exposed chiefly in the western part of this domain and some of the carbonates of the same age in Kayin State.

The Tertiary sediments bearing coal measures are found in the small separate structural intermountain basins and troughs which developed mainly in Tanintharyi and Shan Plateau Region. Quaternary sequences are also present in the form of cultivated lowland areas.

The Granitoid Plutons of Mesozoic-to-early Tertiary age emplaced multiple phases along the western margin of the belt where major weak zones took place with sharp tectonic features composing both lateral and up-and-down movements. Among them, the Sagaing-Tagaung Wrench Fault System and Shan Scarp Fault are outstanding.

10.4.2 The Central Lowlands

The Belt of Central Lowlands is a large, wide, and long graben-like structure bounded by N–S running parallel faults both in the east, at the foothill of Shan Scarp and in the west, at the foothill of Western Ranges. It is the structural continuation of Sunda Arc, related to eastward and northeastward subduction of the oceanic flow.

The southern extension of this belt fades out to the gulf of Mottama under the huge deltaic deposits of Sittaung and Ayeyarwaddy Rivers. The Central Volcanic Arc along the central axis of the belt exists a well-demarcated series of andesitic volcanic rocks of Mt. Popa, Mt. Taung Thone Lone, Mt. Loimye and older Mesozoic intermediate to basic volcanic rocks with Granodiorite and Granitoid Plutons in the Wuntho Massif Area and western Part of Kumon Ranges, Kachin State. The uplifted Jade Mines Belt is mainly composed of Paleozoic Marble, Triassic flysch, ophiolite and garnet-mica schist units which divides the Chindwin Basin and Hukaung Basin.

To the east of the axis of Central Volcanic Arc is interpreted as Back Arc Basin and as Fore Arc basin to the west. Back Arc Basin deposition of Tertiary sediments started only in Miocene, and Fore Arc Basin of some Albian carbonate and sediments continues up to Recent. The Myanmar Arc can be traced southward through Barren and Narcondam Islands, the Sunda Arc of Sumatra, and the inactive volcanic Islands north of Timor to the Banda Arc.

In addition, gently folded Cenozoic molassic sediments of mostly shallow marine, interlocking marine, and fluviatile and deltaic facies were laid down in two majors basins of Minbu Basin in the south and Chindwin Basin in the north, which are favorable sites for coal, oil and gas and intensive production of oil was made before World War II and early 1960.

10.4.3 The Western Ranges (or) Western Fold Belts

This belt is bounded in the east with Central Lowlands by a N–S curving linear fault system. It is an elongated, slightly arcuate, and highly folded belt composed mainly of Cretaceous–Tertiary flysch sediments with pelagic limestone and their metamorphosed equivalents together with metamorphosed ultramafic units.

This belt is underlain by a nervous N–S trending strip of upper Triassic turbidites strata in the east, a parallel stretch of upper Cretaceous flysch-type strata in the middle, and a unit of similar flysch-type but containing more exotic blocks of

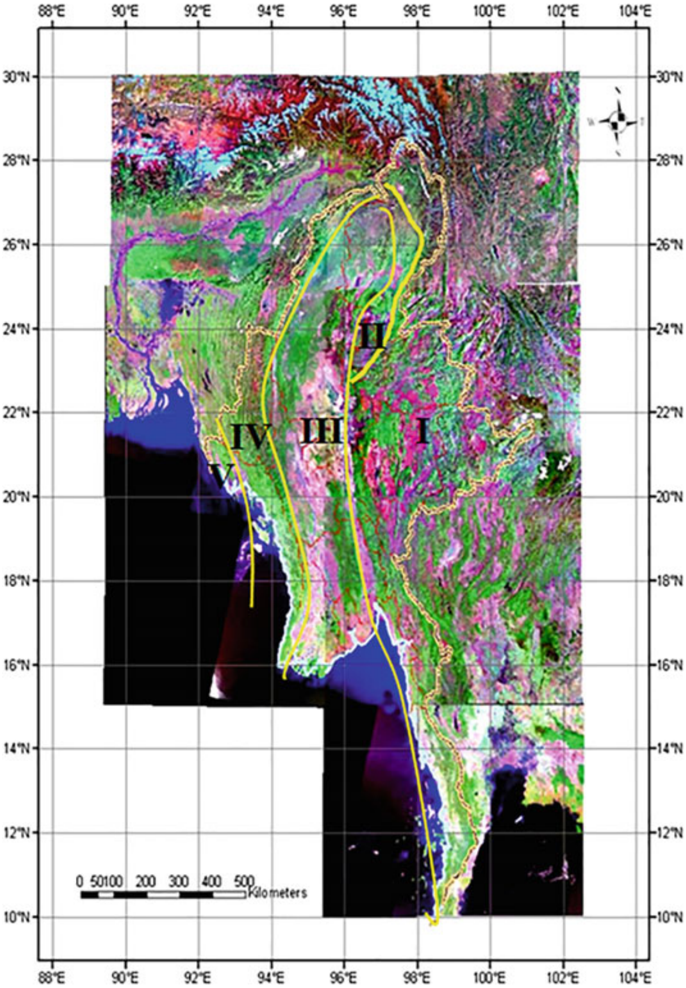


Fig. 10.2 Morpho-tectonic belts of Myanmar. *Source* D.G.S.E

Eocene age in the west. Along the eastern margin of the Triassic rocks, there is ophiolitic ultramafics and bedded cherts well exposed up to northern Nagaland.

The whole belt is penetratively deformed, highly folded and imbricate westward thrusts are common in the areas of Cretaceous limestone and incomplete ophiolite suite outcrops forming chaotic tectonic style of mélanges probably due to north-eastward or eastward subduction of northern continuation of Sunda Arc in the West of Bengal Fan.

This tectonic setting and depositional pattern during Mesozoic–Early Tertiary is partially similar to California borderland of Western USA. The Western Ranges disappear in the Bay of Bengal and again emerges as the Andaman and Nicobar Islands in the south. The morpho-tectonic belts are shown in Fig. 10.2.

10.4.4 Arakan Coastal Belt

It is located to the west of Western Ranges and underlain by the upper Tertiary clastic sedimentary strata of molasses facies with low lying hills in the south and higher mountain ranges at Assam State of India in the north. The Miocene strata are frequently steeply tilted, intensely faulted, locally folded, and overthrust. This belt also favors for oil and gas same as the Central Lowlands with the indications of sizable mud volcanoes. The Geological Map of Myanmar (2008) is shown in Fig. 10.3.

10.5 Water Resource Potential

Among the water-resource-rich countries, Myanmar could still be classified as low water stress country. There are four major river systems, namely, the Ayeyarwaddy, the Thanlwin, the Chindwin, and the Sittaung. Besides, there are some river systems in Rakhine State and Tanintharyi Region. These river systems contribute to the surface water resources of the country. Due to favorable climatic condition and physiographic features, there are eight river basins and total surface and groundwater potential of Myanmar are approximately 1080 and 495 km^3 per year, respectively. Details are mentioned in Table 10.1 (Fig. 10.4).

10.6 Groundwater Resources in Myanmar

On the basis of stratigraphic unit, Myanmar has eleven different types of aquifers. Depending on their lithology and depositional environment, groundwater from those aquifers varies in quality and quantity. Of these, groundwater from alluvial and Irrawaddian aquifers is more potable for both irrigation and domestic uses.

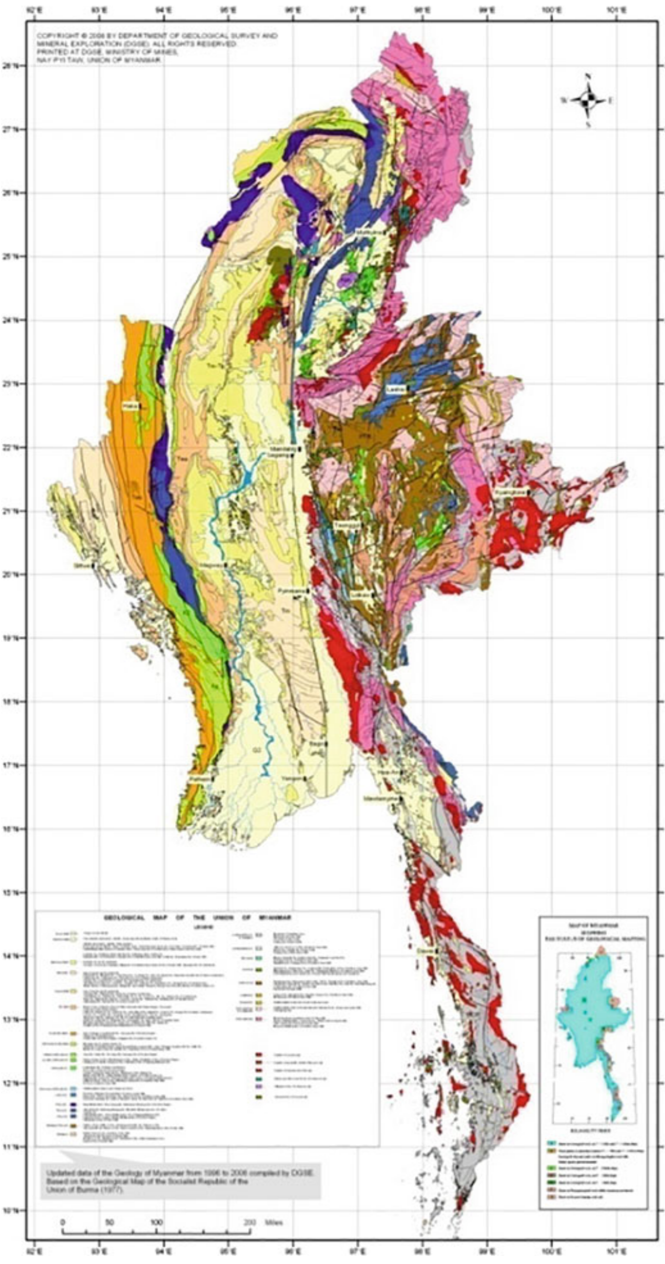


Fig. 10.3 Geological map of Myanmar. *Source* D.G.S.E (2008)

Table 10.1 Myanmar's annual average water resource potential by river basin

Sr. No.	River basin	Catchment area (thou. km^2)	Est. average annual surface water (km^3)	Est. groundwater potential (km^3)
I	Chindwin	115.3	141.293	57.578
II	Upper Ayeyarwaddy (up to its confluence with Chindwin)	193.3	227.92	92.599
III	Lower Ayeyarwaddy (from confluence with Chindwin to its mouth)	95.6	85.8	153.249
IV	Sittaung	48.1	81.148	28.402
V	Rakhine	58.3	139.245	41.774
VI	Tanintharyi	40.6	130.927	39.278
VII	Thanlwin River (from Myanmar boundary to its mouth)	158	257.918	74.779
VIII	Mekong (within Myanmar Territory)	28.6	17.634	7.054
	Total	737.8	1081.88	494.71

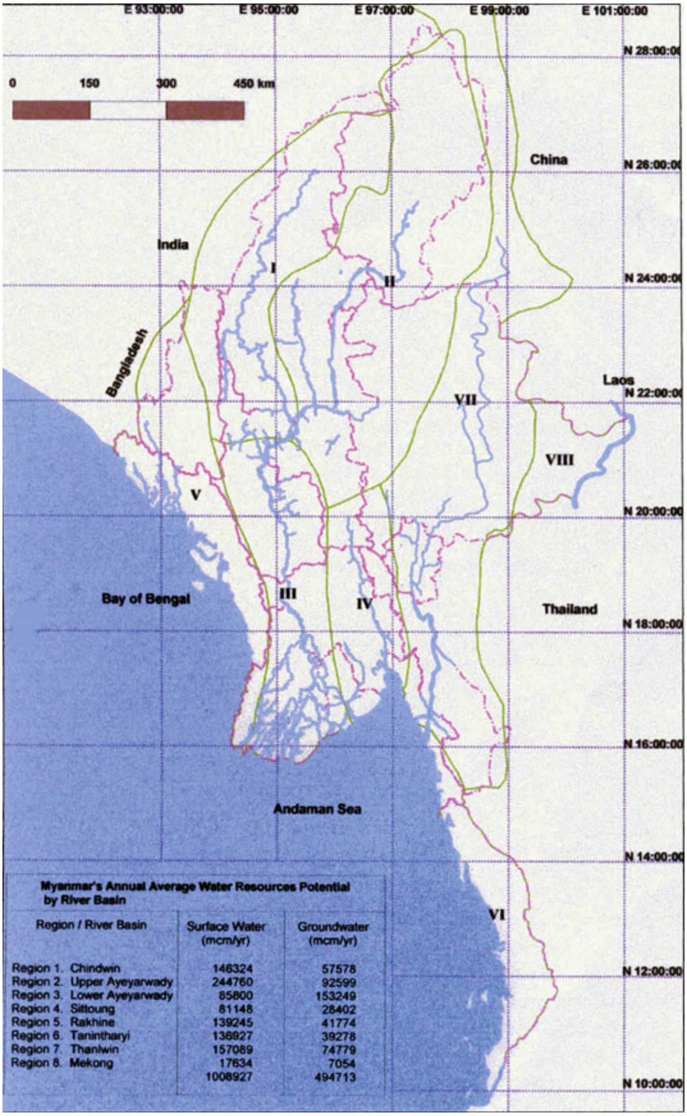
Groundwater extracted from Peguan, Eocene, and Plateau limestone aquifers for domestic use in water scarce areas, even though these are not totally suitable for drinking purposes. The groundwater resources of Myanmar by administrative region can be summarized as follows (Fig. 10.5; Table 10.2).

10.6.1 Kachin State (Northern Areas)

Generally, groundwater is found mainly in Oligocene-to-mid-Miocene and Eocene rocks. It is mainly brackish and rarely fresh. In the valley areas, groundwater from alluvial deposits is fresh and yield may be high, but it is found only in localized areas.

10.6.2 Sagaing Region (Northwestern Area)

In the northern part of the Region, groundwater is situated in Oligocene-to-mid-Miocene rocks and is brackish in quality. Groundwater in the Chindwin Basin is of mid-Pliocene age and occurs in lowland areas. Groundwater quality in the southern part of the Region is suitable for irrigation and domestic usage mostly in alluvial beds of Quaternary age, mainly freshwater, and has a good yield.



Myanmar's Annual Average Water Resources Potential by River Basin

Region / River Basin	Surface Water (mcm/yr)	Groundwater (mcm/yr)
Region 1. Chindwin	146324	57578
Region 2. Upper Ayeyarwady	244760	92599
Region 3. Lower Ayeyarwady	85800	153249
Region 4. Sittoung	81148	28402
Region 5. Rakhine	139245	41774
Region 6. Tanintharyi	136927	39278
Region 7. Thanlwin	157089	74779
Region 8. Mekong	17634	7054
	1008927	494713

Fig. 10.4 River basin map of Myanmar

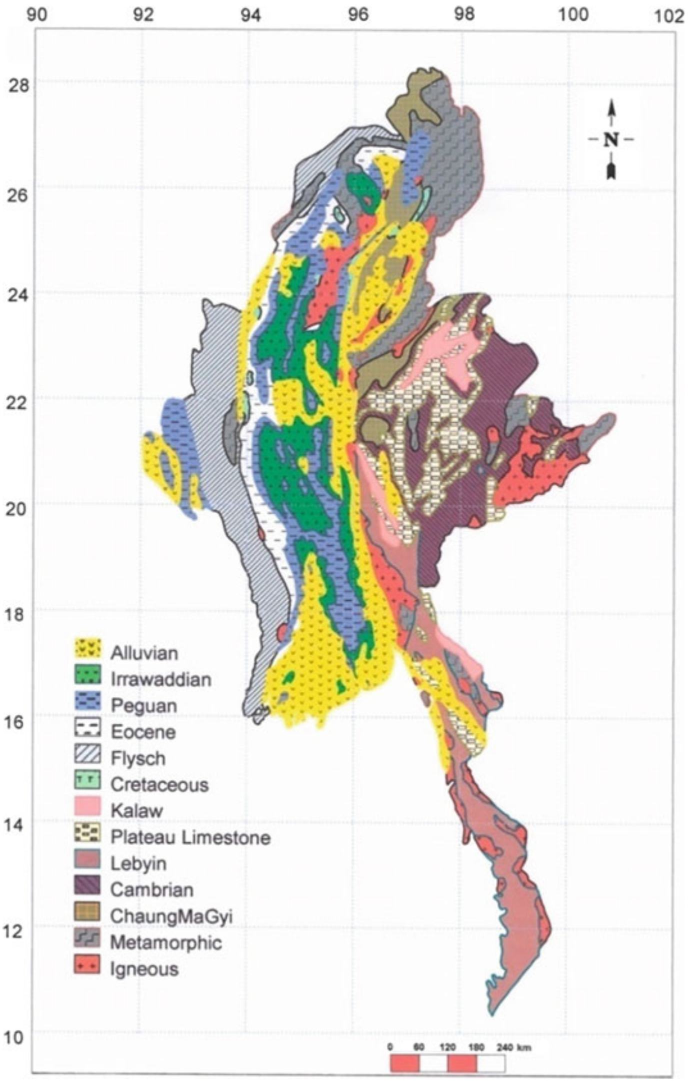


Fig. 10.5 Aquifers in Myanmar. *Source* WRUD

10.6.3 Shan, Kayah, Kayin, Mon States and Tanintharyi Region (E and SE Area)

Groundwater occurs mainly in limestone of the Carboniferous–Permian age. In the eastern part of the area, it lies in beds of Mesozoic and Precambrian ages. Groundwater in volcanic rocks is found in the southeastern part. Generally, it is

Table 10.2 Descriptions of aquifers in Myanmar

Sr. No.	Name of aquifer	Major rock units	Area of occurrences	Remark
1.	Chaungmagyi aquifer	Low-grade metamorphic rocks	Eastern Highland	To be studied in detail
2.	Cambrian–Silurian aquifer	Molohein Group, Pindaya Group, and Mibayataung Group	Eastern Highland	To be studied in detail
3.	Lebyin-Mergui aquifer	Graywacke, quartzite, argillite, slate, mudstone, gravel, etc.	Western boundary of Eastern Highland and Tanintharyi ranges	To be studied in detail
4.	Plateau limestone aquifer	Limestone and dolomite	Eastern Highland, Western boundary of Eastern Highland, and Tanintharyi ranges	GW is being extracted in some places
5.	Kalaw-Pinlaung-Lashio aquifer	Loi-an Group and Kalaw Red Beds	Eastern Highland	To be studied in detail
6.	Cretaceous aquifer	Flysch units and limestone units	Northern Kachin, Western Ranges	To be studied in detail
7.	Flysch aquifer	Interbedded units of sand, siltstones, shale, and mudstone	Western Ranges	Probable GW source area
8.	Eocene aquifer	Sandstones, siltstones, and shale	Periphery of Central Lowland	Probable GW source area
9.	Pegu Group aquifer	Sandstone, siltstones, and shale	Central Lowland and Rakhine Coastal Strip	Mostly saline and brackish water, some freshwater in recharged areas
10.	Irrawaddian aquifer	Mainly sands, unconsolidated sandstones with gravels, grits, siltstones, and mudstones	Central Lowland and Rakhine Coastal Strip	Thick aquifer fresh GW with iron contents
11.	Alluvial aquifer	Sands, gravels, and mud	River basins and its tributaries, base of mountains and ranges	Fresh GW, seasonal water table changes

fresh and mostly suitable for drinking and irrigation. To exploit economically, drilling method may be limited.

10.6.4 Rakhine and Chin States (Western Area)

In the eastern part of the states, groundwater occurs in Eocene rocks. The groundwater is mainly brackish, and freshwater is rarely encountered in this area. On the western side, groundwater is of Oligocene–mid-Miocene and is brackish in quality. Natural reserves of freshwater are limited, and seawater intrusion may be encountered.

10.6.5 The Central Area (Mandalay and Magway Regions)

Fresh groundwater is found in Quaternary and Mio-Pliocene rocks. But salinity of groundwater in Mio-Pliocene beds increases with depth. Small supplies of groundwater have been achieved from boreholes tapped in upper and lower Pegu Group in some areas. They are of Miocene and Oligocene ages. Groundwater in these sediments is mostly saline and rarely fresh.

10.6.6 The Delta Area (Yangon and Ayeyarwaddy Regions)

Groundwater occurs in alluvial beds of Quaternary age. It is mostly fresh and in some parts brackish. In coastal area, the water quality may be saline.

10.6.7 Bago Region (Southern Area)

The central area of the Region is north–south trending folded mountain called Bago Yoma, and it has the rocks of Oligocene–Miocene age bearing mainly brackish water. Natural reserves of freshwater are limited. In the eastern and western parts of the Region, groundwater of alluvial beds is exploited. Groundwater reserves are considerable and suitable for drinking and irrigation purposes.

10.7 Water Quality of Three Major Aquifers

According to the previous hydrogeological studies, water chemistry of three major aquifers from Sagaing, Mandalay, Magway, Bago, Yangon, and Ayeyarwaddy Regions can be identified and mentioned as following Table 10.3.

Table 10.3 Hydrochemical characteristics of representative water samples from three main aquifers

Region	Aquifer	Type of water						Total no. of representative sample
		HCO_3–SO_4	Cl–HCO_3	HCO_3–Cl	SO_4–HCO_3	Cl–SO_4	SO_4–Cl	
t								
Magway	Alluvial	78	15	47	6		3	149
	Irrawaddian	63	36	50	10	18	7	184
	Peguan	10	6	8	1	8	1	34
	Subtotal							367
Mandalay	Alluvial	42	20	45	9			116
	Irrawaddian	17	8	11	12	2		50
	Peguan	4	1	7	4	3		19
	Subtotal							185
Sagaing	Alluvial	7	10	32		1	1	51
	Irrawaddian	12	10	28	16	1	3	70
	Peguan	2	3					5
	Subtotal							126
i								
Ayeyarwaddy	Alluvial		18	2		4		24
	Irrawaddian	1	13			3		17
	Peguan		6			1		7
	Subtotal							48
Yangon	Alluvial	6	2	5	5		4	22
	Irrawaddian		15	1	7	6	3	32
	Peguan		4	1	2	1		8
	Subtotal							62
Bago	Alluvial	29	1					30
	Irrawaddian	6		1	4		2	13
	Peguan		1					1
	Subtotal							44
	Total	277	169	238	76	48	24	832

Table 10.4 Water use in Myanmar

Sr. No.	Use	Surface water	Groundwater	Total
1.	Domestic	1.15 (3%)	2.55 (68%)	3.70 (8%)
2.	Industrial	1.17 (3%)	0.33 (9%)	1.50 (3%)
3.	Irrigation	41.97 (94%)	0.85 (23%)	42.82 (89%)
	Total	44.29	3.73	48.02

Unit in million acre feet

Fig. 10.6 Annual review of individual technical activities

10.8 Groundwater Usage

The water use in Myanmar is appreciably increased, especially in agriculture. Other water use such as domestic and industrial sectors is very small compared with agriculture water use. Surface water use and groundwater use are mentioned separately as follows in Table 10.4 (Fig. 10.6).

10.9 Conclusions

The future activities will include to carry out construction of groundwater monitoring stations across the country, basin-wide estimation for groundwater potential, assessment of country-level groundwater extraction, preparation of countrywide hydrogeological map, searching the new groundwater prospect areas, preparation of hazard maps, and establishment of groundwater database management system using geospatial technology by the cooperation of international organization.

Data Source

Department of Geological Survey and Mineral Exploration (D.G.S.E), Ministry of Natural Resources and Environmental Conservation, Myanmar

Irrigation and Water Utilization Management Department, Ministry of Agriculture, Livestock and Irrigation, Myanmar, (January, 2016)

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Chapter 11
Groundwater Resources of Nepal: An Overview

Surendra R. Shrestha, Ganesh N. Tripathi and Dipendra Laudari

Abstract Nepal, a beautiful mountainous country in South Asia, accommodates about one-third of entire length of the Himalaya and eight of ten highest peaks in the world. Nepal is ranked among the richest country in terms of water resource availability. Physiography of Nepal is unique due to the extreme contrast in topography ranging from 64 to 8848 masl within a very short span of 150 km from Terai Plain in the south to higher Himalayan mountains to the north. Groundwater is available in most parts of the country, but the amount and depth vary from place to place. In the Terai, the upper unconfined aquifer (50–60 m) has been considered as good productive shallow zones and most of groundwater production is limited to upper 250 m. Recharge in the Terai is estimated to be 8800 MCM/year. At present, only about 22% of the available dynamic groundwater recharge in *Terai* is being utilized. The quality of groundwater is generally suitable for irrigation as well as drinking purpose. The groundwater in Kathmandu Valley is overexploited. The natural recharge of groundwater in the valley is estimated at about 5.5 MCM/year. The draft exceeds this recharge due to which water level in the valley in some places is going down by 2 m/year. Groundwater from both deep and shallow aquifers is suitable for irrigation without any treatment, but for drinking and industrial uses, treatment is necessary.

Keywords Nepal · Groundwater · Recharge · Overexploitation

S. R. Shrestha
Groundwater Resources Development Board, Ministry of Irrigation,
Government of Nepal, Kathmandu, Nepal

G. N. Tripathi (✉)
Department of Mines and Geology, Ministry of Industry,
Government of Nepal, Kathmandu, Nepal
e-mail: ganeshtri@gmail.com

D. Laudari
Groundwater Irrigation Development Divisions, Ministry of Irrigation,
Government of Nepal, Kathmandu, Nepal

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_11

11.1 Introduction

11.1.1 Background

Nepal (Chap. 1, Fig. 1.1), a beautiful mountainous country in South Asia, accommodates about one-third of entire length of the Himalaya and eight of ten highest peaks in the world. Nepal is ranked among the richest country in terms of water resource availability. Significant proportion of water resources is distributed throughout the country in the form of different water bodies: glaciers, snow covers, rivers, springs, lakes, and groundwater. The area covered by glaciers in the Nepal Himalaya is estimated to be more than 5000 km^2 containing about 480 km^3 of ice (Bricker et al. 2014). The total renewable water resources estimated from various studies amount 237 km^3/year, while the contribution from groundwater sources accounts for about 12 km^3/year.

The major river systems in Nepal ultimately drain to the Ganga River, and these rivers contribute to sustain approximately 70% of dry season flow and 40% of annual flow of Ganga River. There are more than 6000 rivers (including rivulets and tributaries) in Nepal with drainage density of about 0.3 km/km^2 and cumulative length of 45,000 km (WECS/DHMN 1996; Bricker et al. 2014). Almost 1000 of the rivers exceed 10 km in length, and about 100 of them are longer than 160 km (Bricker et al. 2014). Based on their origin, rivers of Nepal can be broadly classified into three groups:

Snow-fed types: The major river systems such as the Koshi, the Gandaki, the Karnali, and the Mahakali fall into this category. They originate from snow and glaciated regions in Himalayas, and their flow regimes are mostly governed by the melting of snows and glaciers. As a result, flow in these rivers sustain flow even during the dry season.

Rivers originating from the middle mountains and hilly regions: Their flow regimes are affected by both monsoon precipitation and groundwater. Contribution from groundwater yield maintains the minimum flow level and prevents from drying during non-monsoon periods. The Bagmati, Kamala, Rapti, Mechi, Kankai, and Babai rivers fall into this group.

Rivers originating from Siwalik Zone: Tinau, Banganga, Tilawe, Sirsia, Manusmara, Hardinath, Sunsari, and other smaller rivers are examples of rivers falling in this group. Flow in these rivers is mostly dependent on monsoon precipitation, and their flow level could deplete significantly during the non-monsoon period. Approximately 60–85% of annual runoff of all river systems in Nepal occurs during the summer monsoon period (July through September) (Fig. 11.1; Table 11.1).

Groundwater resources in inter-mountain basins and Terai regions of the country have been relatively well explored; however, groundwater resources in the hills and mountain regions are yet to be investigated and assessed in detail. Groundwater occurs in different natural settings in Nepal due to the diversity in geology, geomorphology, and physiography. Intra-mountain valleys such as Kathmandu,

Fig. 11.1 Major rivers of Nepal

Table 11.1 Surface water resources of Nepal

River basin	Estimated catchment area in Nepal (km^2)[a]	Average discharge (m^3/s)	Annual discharge (km^3/year)
Rivers originating at Himalayas	105,573	4979	157
Rivers originating at middle mountains and hills	17,000	461	14.5
Rivers originating at Siwalik Zone	23,150	1682	53
Total	145,723	7122	224.5

Source Water and Energy Commission Secretariat (2005)

[a] Total catchment area of each river basin is larger than shown in the table. Areas of the basins excluded in the table lie either in China or in India

Dang and other similar valleys have isolated groundwater basins, whereas groundwater in the southern *Terai* Plain is a part of the larger system in the Gangetic Basin. The Terai regions, southern part of the country and the northern edge of the Ganga Basin, mostly depend on groundwater to meet domestic water demand and industrial use. However, both surface and groundwater have been utilized for irrigation, and groundwater is the year-round reliable source of irrigation in the Terai. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

11.1.1.1 Physiography

Physiography of Nepal is very unique due to the extreme contrast in topography ranging from 64 to 8848 masl within a very short span of distance (approximately 150 km) from Terai Plain in the south to higher Himalayan mountains to the north (Dhital 2015). The effect of physiographical and topographical diversities is reflected in a diverse climatic condition ranging from tropical and humid to alpine climate. Hagen (1969) successively divided Nepal into eight well-defined physiographic units those run more or less parallel from northwest to southeast. Table 11.2 gives a generalized description, and Figs. 11.2 and 11.3 illustrate the generalized physiographic profile of Nepal.

11.2 General Hydrogeology of Nepal

Groundwater is available in most parts of the country, but the amount and depth vary from place to place. Based on the preliminary hydrogeological studies, unfractured high-grade metasediments of Midland Group and crystalline rocks of higher Himalaya are considered to constitute poor aquifer quality formations. Unconsolidated loose sediments of *Terai* and inner *Terai*, karstified and fractured carbonate rocks of midland and Tethys group has developed good potential source for groundwater. Likewise, unconsolidated sediments of Kathmandu and Surkhet valleys, intra-mountain valleys in middle mountains, form moderate to highly productive aquifers. The molasse sediments of Siwaliks and non-karstic but fractured carbonate rocks in Lesser Himalaya and Tethys Group are interpreted as moderately productive aquifers (Fig. 11.4).

The *Terai* Plain contains multiple layers of good aquifers at different depths, some of them are interconnected and some are not. Average transmissivity values for these aquifers commonly exceed 1000 m^2/day and, well yields range between 5 and 60 L/s. Extremely rugged topography and complex geology of the Lower Himalayan Series and the Crystalline Complexes are the real challenges in terms of groundwater assessment. Carbonate sequences within this group could be a potential target for groundwater investigation, but their extension may be limited to a certain area only. It is very common to find significant changes in rock mass quality from place to place which is a reason of occurrence of locally confined aquifer in this group of geological unit.

The Higher Himalayan metamorphosed Crystalline Complexes contain no groundwater resources worth mentioning, though there are (apart from carbonates) some permeable rocks at least in the upper part of the succession. Granites and gneisses have been classified as being generally poor aquifers because of indurated and unfractured rock mass characteristics, but the possibilities of finding potential aquifer in highly fractured granites and gneisses cannot be overruled.

Table 11.2 Physiographical division of the Nepal Himalaya

S. No.	Geomorphic unit	Width (km)	Altitudes (m)	Main rock types	Age
1	Terai (northern edge of the Gangetic Plain)	10–50	100–200	Alluvium: coarse gravels in the north near the foot of the mountains, gradually becoming finer southward	Recent
2	Churia Range (Siwaliks)	10–50	200–1300	Sandstone, mudstone, shale, and conglomerate	Mid-Miocene to Pleistocene
3	Dun Valleys	5–30	200–300	Valleys within the Churia Hills filled up by coarse to fine alluvial sediments	Recent
4	Mahabharat Range	10–35	1000–3000	Schist, phyllite, gneiss, quartzite, granite, and limestone belonging to the Lesser Himalayan Zone	Precambrian and Paleozoic occasionally also Cenozoic
5	Midlands	40–60	300–2000	Schist, phyllite, gneiss, quartzite, granite, limestone geologically belonging to the Lesser Himalayan Zone	Precambrian and Paleozoic to Mesozoic
6	Fore Himalaya	20–150	2000–5000	Gneisses, schists, phyllites, and marbles mostly belonging to the northern edge of the Lesser Himalayan Zone	Precambrian
7	Higher Himalaya	22–190	>5000	Gneisses, schists, migmatites, and marbles belonging to the Higher Himalayan Zone	Precambrian
8	Inner and Trans Himalaya	10–60	2500–4500	Gneisses, schists, and marbles of the Higher Himalayan Zone and Tethyan sediments (limestones, shale, sandstone, etc.) belonging to the Tibetan–Tethys Zone	Precambrian and Cambrian to Cretaceous

Source Upreti (1999)

Limestone and quartzites of Tethys Group are considered to have developed some good aquifers; however, there are other impervious rocks of substantial thickness with apparently no groundwater potential.

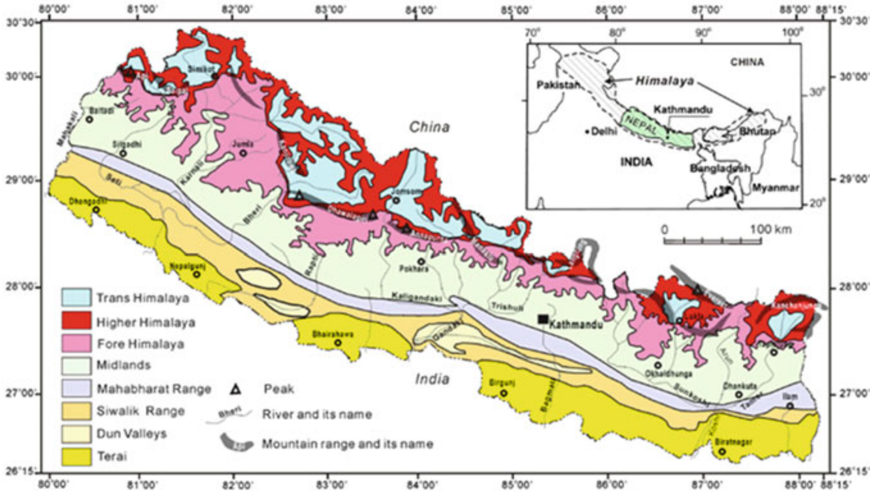


Fig. 11.2 Physiographic of the Nepal Himalaya (after Dahal and Hasegawa 2008)

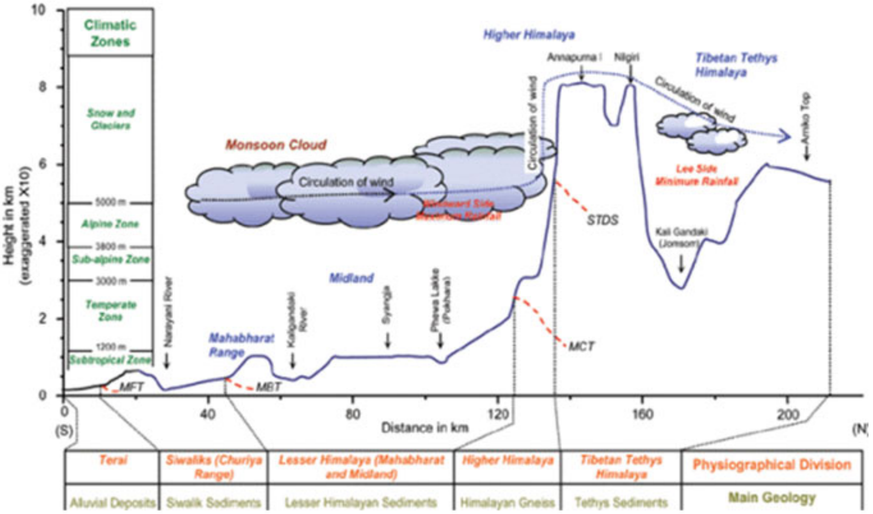


Fig. 11.3 Generalized geographical cross section of the Nepal Himalaya (after Dahal et al. 2006)

11.3 Hydrogeology of the Terai

11.3.1 Regional Hydrogeology

The Terai Plain was created nearly one million years ago when the Churia hills came into existence. The Precambrian basement rock of Vindhyan Group of India

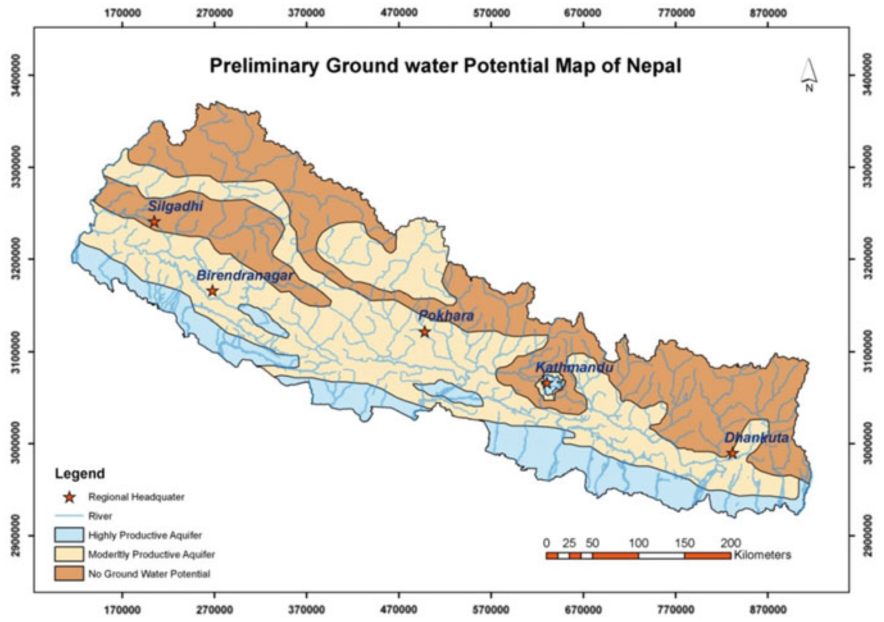


Fig. 11.4 Groundwater potential map. Modified after Grimmelmann (1984)

occurs at a depth of about 6000–7600 m from the surface in the Nepalese Terai (Mathur and Kohli 1963). It is underlain by about 4500-m-thick Siwalik successions of molasse sediments which in turn overlain by about 1500-m-thick Quaternary to recent fluvial deposits (Sharma 1974). This thick sequence of alluvium consists of sand and clay. The alluvium in the Terai Plain has been deposited by the rivers flowing across the mountains to the north.

The Terai Plain, continuation of Indo-Gangetic Plain, lies at the southern part of mountain range of Nepal. The Terai aquifers occur in the following two hydrogeologically significant depositional units:

- ***Bhabar Zone*** is situated in the foothill of the Siwalik range consisting of alluvial and colluvial coarse sediments (boulder, cobble, and pebbles). This is the major recharge area of Terai Plain. It is estimated that the total area of Bhabar in Nepal is about 4700 km^2. The thickness of the Bhabar layer ranges from few meters to more than a hundred meters. The Bhabar Zone sediments consist of permeable, unconfined aquifer with deep water table. Relatively high rainfall occurs in this zone (about 1700 mm) as compared to the southern area.
- ***The Southern Zone*** (Terai Plain), which consists of thick sediments of Indo-Gangetic floodplain, comprises clay, silt, sand, and gravels. Due to the noticeable topographical breaks between the Siwaliks and Terai, the coarser sediments were deposited along the Siwalik foothills forming the Bhabar Zone and finer sediments were carried away and deposited farther south to form the

present Terai Plain and this process is still ongoing. Fine sediments are predominant toward the Indian border. This zone gets relatively low rainfall than the Bhabar Zone; however, recharge amount is higher due to greater areal extent of unconsolidated sediments.

11.3.2 Representative Geological Cross Sections of Different Parts of Terai Region

Geological cross sections representing parts of mid-western, western, and central Terai region have been presented to have a broad perspective of aquifer system in Terai Nepal (Fig. 11.5). North–south geological cross section constructed from five well log data in Banke and Bardia, mid-western Nepal, represents generalized aquifer system in this region (Fig. 11.5a). The depth of individual tube well varied from about 1000 to more than 1200 ft and separated approximately 4 miles apart. Similarly, north–south geological cross section of Lumbini area, western Nepal, was prepared from twelve well log data (Fig. 11.5b). The depth to each tube well extended up to about 100 ft from the surface. The cross section covers more than 26 miles horizontally in north–south direction. The cross section in Birganj area, central Nepal, was produced by compiling data from three different well logs (Fig. 11.5c). The depth of individual well extended up to 600 ft from the surface and separated approximately 800 miles apart. All three different regions of Terai mentioned above include shallow unconfined to deep confined aquifer systems. Clay represents the principal confining unit for all the aquifer systems. Several isolated perched aquifers can be inferred from the geological cross sections.

11.3.3 District-Wise Groundwater Level and Transmissivity

Groundwater levels at about 400 shallow tube wells in Terai were measured by Groundwater Development Board since 1991. In most of the districts, the water level was measured both in shallow and deep tube wells. Based on the monitoring data, following chart shows the maximum and minimum water levels measured in 2013/2014 in different wells in the *Terai* districts of Nepal (Figs. 11.6 and 11.7).

The data indicate that the water level depths for shallow aquifers vary from surface flow condition to about 16 m below ground level (bgl). The deepest water level of 16.5 m bgl was encountered at the Dang District which lies at the mid-western part of the country. The average shallow water level was found to be about 4.55 m bgl.

The water level data collected from deep aquifers indicate that the average water level is about 5.92 m bgl. The maximum water level (about 30.69 m bgl) was encountered at Mahottari District which lies in southern central part of the country.

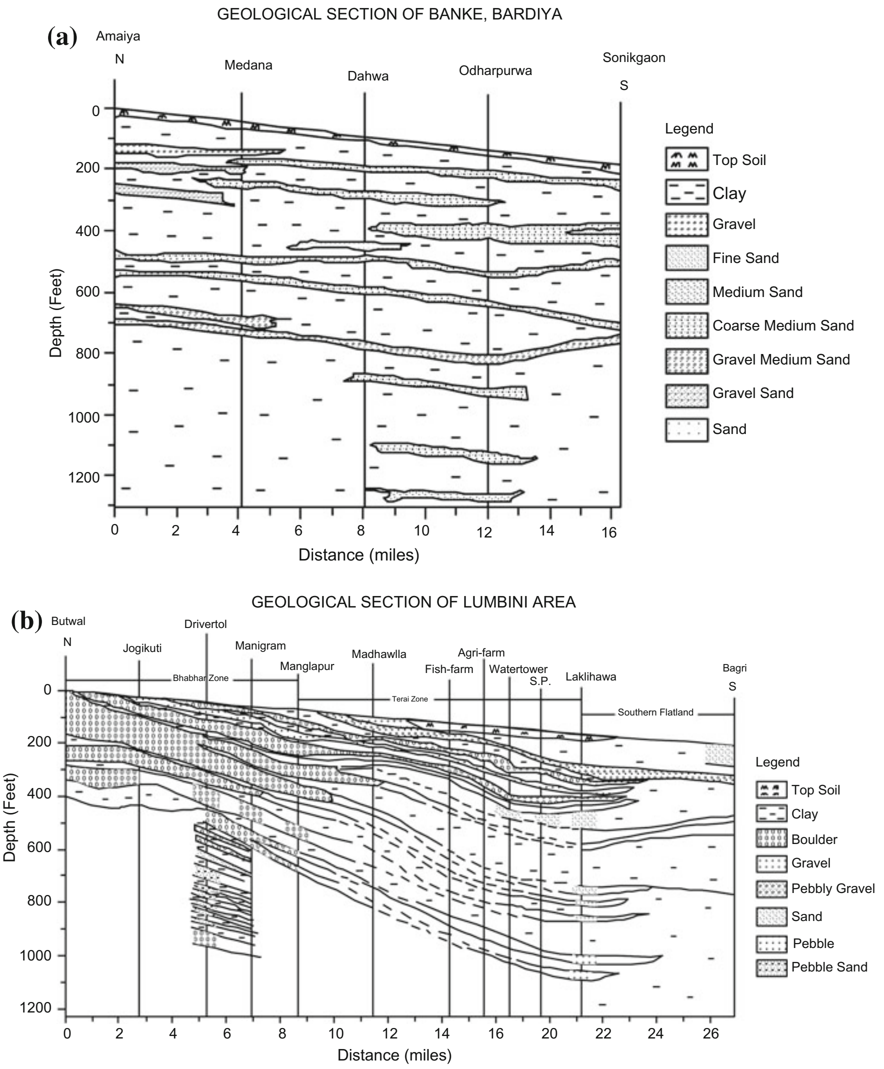


Fig. 11.5 Geological cross sections: **a** mid-western, **b** western, and **c** central Terai regions. *Source* Sharma (1974)

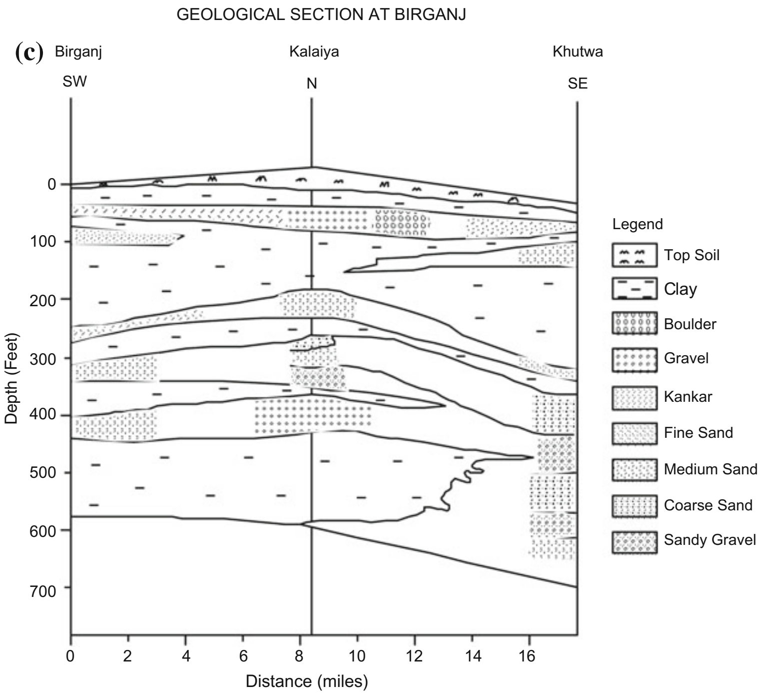


Fig. 11.5 (continued)

The aquifer system in the Terai Plain is represented by both unconfined to semi-confined shallow aquifers and confined deep aquifers. Perched aquifers are also common in this region. The upper unconfined aquifer material (50–60 m) has been considered as good productive shallow zones, while the most of groundwater production in Terai is limited to upper 250 m (Shrestha et al. 2004).

The transmissivity value of the shallow aquifer in the Terai region ranges from less than 10 to over 10,000 m^2/day. This is based on the study jointly carried out by the United Nations Department of Technical Co-operation for Development and the Ground Water Resources Development Board. The investigation program was started in 1987 and was completed in 1992 with special focus on shallow aquifers (UNDP/GWRDB 1987–1992). A total of 430 wells were established in spatially justified locations to cover the whole Terai region. Out of the 430 wells, 344 wells and other available private wells were subjected to aquifer test to determine different aquifer properties. The minimum and maximum ranges for each district are shown in Fig. 11.8.

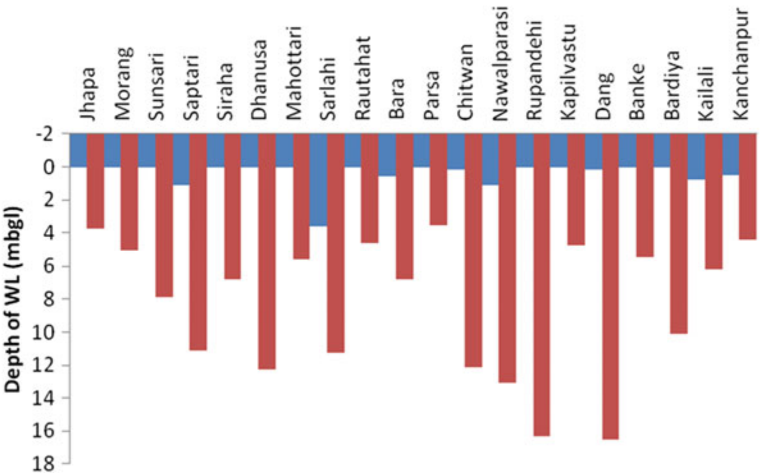


Fig. 11.6 Districts-wise water level depths in shallow aquifers

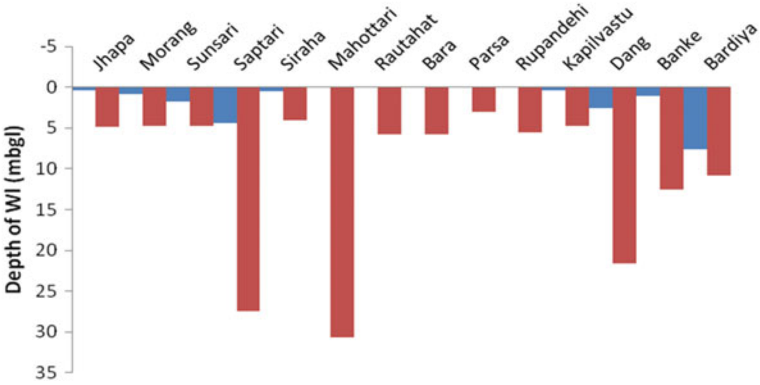


Fig. 11.7 Districts-wise water level depths in deep aquifers

11.3.4 Groundwater Recharge

The northern edge of the Terai, the Bhabar Zone, along the Siwalik foothills is considered as the primary recharge zone for groundwater aquifers in Terai (Fig. 11.9). Direct infiltration of rainwater as well as lateral recharge from Bhabar Zone is the major source of groundwater recharge in this zone. Subsurface inflow and seepage losses through the streams and rivers also provide significant input to the groundwater recharge. The exact demarcation of potential recharge area for Terai groundwater basin has not been made till to date.

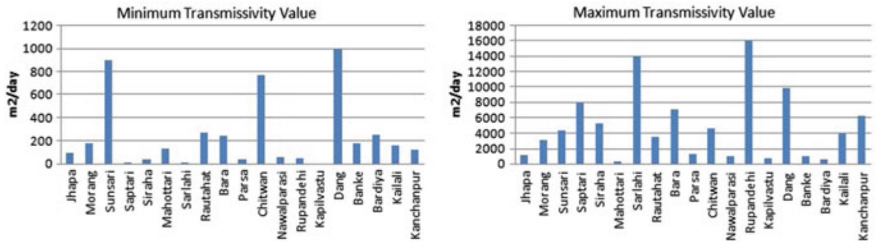


Fig. 11.8 Transmissivity values of shallow aquifers in Terai districts

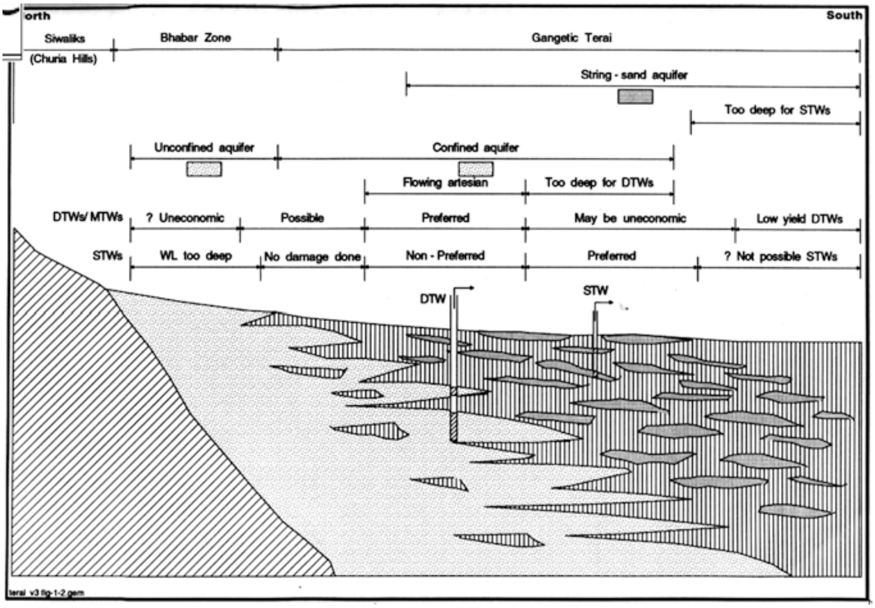


Fig. 11.9 General aquifer system of Terai Nepal. *Source* GDC (1994)

Many studies have been carried out in the past to estimate groundwater recharge potential of Terai. Duba (1982) estimated 9629 million cubic meters (MCM) total annual dynamic recharge in Terai based on rainfall percolation data. Almost one-third of this recharge (3114 MCM) occurred through the Bhabar Zone, and rest was found to occur in the Terai plains. About 460 mm of an estimated 600 mm annual recharge in the Terai region takes place through direct rainfall percolation and remaining 140 mm through leakage recharge (GDC 1987). Based on this study, about 75% of annual recharge can be safely exploited which amount to about 10,745 MCM/year for the whole Terai region.

Similarly, Electrowatt (1984) estimated about 465 mm of annual recharge to occur through Bhabar Zone while Tahal Consultant (1992) estimated 1100 mm of annual recharge for whole Terai.

Groundwater recharge in Terai was estimated independently using three different methods during the Shallow Aquifer Investigation Project (UNDP/GWRDB), and the results obtained were considerably different from each other. The first method (Duba 1982) of estimation is based on the assumption that 22.2 and 33.6% of rainfall in Terai and Bhabar, respectively, is the main source of groundwater recharge. An estimated amount of 9600 MCM annual recharge has been proposed for Terai aquifer with this method.

The second and the most conservative method of recharge estimation assumes that 20% and 15% of the rainfall percolates from Bhabar and Terai zones, respectively. About 5800 MCM of annual recharge has been estimated from this method.

The third method utilizes water level fluctuation and specific yield data for the recharge estimation. The estimated recharge from this method has been widely accepted recharge value for Terai. Pre- and post-monsoon water level fluctuation and specific yield for Terai region were considered 2.5 m and 15%, respectively, for this calculation. Based on this method, the recharge is estimated to be about 8800 MCM/year.

According to Department of Water Supply and Sewerage, an estimated 1,050,000 domestic shallow borewells are in use in *Terai* for daily domestic water supply. These wells extract groundwater mostly from phreatic or unconfined aquifers. The municipal and community water supply systems in *Terai* mostly tap groundwater from the deeper aquifers. Kansakar in (2011) calculated total groundwater extraction for domestic use purpose based on the WHO recommended figure for per capita daily water requirement for rural lifestyle, i.e., 45 L per day per capita. According to him, the total annual domestic water requirement is 462 MCM. This figure also contains the daily consumption by domestic cattle population.

There are about 1050 deep and 129,000 shallow tube wells installed by the government agencies in the *Terai* till 2013 AD. They are used for irrigation purposes. It is assumed that there are about 32,250 (25%) of the total STWs installed under government programs. Generally, it is assumed that the deep tube wells have discharge capacity of 40 L/s and are operated for about 1000 h/year. Based on this assumption, the groundwater use for irrigation by deep tube well is about 151 MCM/year. Similarly, the groundwater use from shallow tube well in Terai is about 1161 MCM (based on the assumption that the shallow tube well has the discharge capacity of 10 L/s and they are operated for about 200 h/year). The total irrigation use is estimated to be 1312 MCM/year.

The exact number of tube wells installed by the various industries that are running in the *Terai* is not available. It is assumed that about 161 MCM (35% of domestic use) of groundwater is used for the industrial uses.

Table 11.3 Groundwater balance at present in the *Terai* region

Available annual groundwater recharge	8800 MCM
Groundwater extraction for irrigation	
By STWs	1161 MCM
By DTWs	151 MCM
Groundwater extraction for domestic uses	462 MCM
Groundwater extraction for industrial use	161 MCM
Annual balance	6865 MCM

Based on these assumptions, the total groundwater balance with respect to the recharge is presented in Table 11.3.

At present, only about 22% of the available dynamic groundwater recharge in *Terai* is being utilized. In 2013, 2011, and 1996, this *figure* was only about 20, 16, and 10%, respectively.

11.3.5 Water Quality

There is a lack of nationwide water-quality data except from the Kathmandu Valley. Available groundwater-related data are only from the shallow groundwater in Terai. Table 11.4 shows the concentration of different chemicals in groundwater mostly from shallow aquifer across the Terai parts of the country.

The table indicates that the concentration of most of the chemical constituents is within the national standard guideline value except for the iron and ammonia in shallow groundwater of most of the districts. The ammonia concentration in shallow groundwater might be high due to the use of excessive fertilizer. The presence of iron and manganese in the shallow groundwater of the Terai will depend on the degree of aeration of these aquifers (BGS 2001). The concentrations of iron in the shallow groundwater suggest the anaerobic condition of the aquifer.

The quality of groundwater is a matter of utmost concern and serious attention as it is the major source of drinking water in the Terai region where more than 50% of country’s total population resides (NPHC 2011). The groundwater quality of Terai, in general, is suitable for both irrigation and drinking purpose. Water quality of confined aquifers is considered safer for drinking purpose as compared to the unconfined aquifers.

Arsenic contamination was recognized as the major groundwater quality issue in the Terai area. A systematic groundwater quality assessment focusing on arsenic contamination was initiated by the Department of Water Supply and Sewerage (DWSS) with support from the World Health Organization (WHO) in 1999. In 2000, Nepal Red Cross Society in collaboration with Japanese Red Cross Society measured arsenic concentration in groundwater samples from several locations in Terai. Findings of these studies provided the evidence of arsenic contamination in groundwater of Terai. Similarly, a detail study on arsenic in groundwater of Terai

Table 11.4 Groundwater chemistry

Parameter	Unit	Districts													Nepal drinking water standard
		Jhapa	Sunsari	Saptari	Mahottari	Rautahat	Parsa	Chitwan	Nawalparasi	Rupandehi	Banke	Bardiya	Kailali	Kanchanpur	
pH		4.78–5.91	6.4–6.9	6.1–6.9	6.5–8.2	6.4–6.9	6.1–7.5	6.3–8.8	5.05–9.32	6.83–7.11	6.2–7.3	6–7.5	6–7.17	5.5–6.92	6.5–8.5
Ammonia	mg/L	<0.01–3.34	0.3–3.0	0.7–3.2	NA	<0.1	<0.1	NA	0.017–2.65	<0.05–0.32	<0.01–0.38	<0.01–0.37	<0.01–0.648	0.112–1.688	1.5
Iron	mg/L	0.02–1.56	0.1–2.2	1.8–18	0.1–4.68	0.2–0.8	<0.1–18	0.004–2	0.1–5.75	0.014–2.527	0.04–2.96	0.03–2.21	0.03–3.39	<0.001–3.8	0.3
Total hardness	mg/L	20–186	80–500	80–350	NA	178–274	61–249	NA	29–539.4	145–452	149.5–383	181.8–686.6	113.1–363.6	99.58–419.08	500
Electric conductivity	µs/cm	50–330	50–500	80–380	140–415	100–570	122–988	100–450	100–1130	410–750	420–1540	300–900	150–640	210–710	1500
Total alkalinity	mg/L	22.16–177.29	90–375	45–270	78–150	184–315	82–335	41–226	83–504	12.64–351.42	77.4–324.2	154.4–347.4	81.06–393	125–341	NA
Chloride	mg/L	8–12.82	4.5–10.1	2–28.4	3.02–6.6	4.9–13.9	1–47	1.1–15.2	10.3–138.5	0.2–5.12	12.8–134.6	10.9–112	9.62–64.1	5.128–41.024	250
Nitrate	mg/L	<1	ND	0.1–0.2	<0.005–10	1.4–4.9	<0.1–18.4	<0.005–12.63	0.004–1.32	<0.001–0.019	<0.1–0.5	<0.1–0.5	<0.1–0.5	<0.001–2.15	50
Phosphate	mg/L	NA	<0.1	<0.1	NA	<0.1	<0.1	NA	NA	<0.2–1	NA	NA	0.6–3	NA	NA
Sulfate	mg/L	8–24	<1	<1	<1	<1	1.1–26	<1–20	0.00–41.00	1–17	1–71	1–75	1–26	0–31	250
Sodium	mg/L	1.24–2.305	1.2–3.2	1–47	5.79–63.24	4.1–8.8	2.8–42	0.34–7.82	0.4–94.6	3.5–31	6.6–84.7	4.3–118.2	2.73–39.6	0.425–60.72	NA
Potassium	mg/L	<0.01–14.04	1.5–3	NA	<1	NA	1–117	<1–6.68	0.137–12.77	1–11	0.4–5.9	1.8–3.7	1.2–4.2	0.345–7.59	NA
Total dissolved solid	mg/L	NA	50–480	NA	120–217	NA	53–430	45–285	NA	NA	273–1001	195–611	NA	NA	1000

Table 11.5 District-wise arsenic concentration in Terai

Classification of arsenic concentration								
Districts	0–10 ppb		11–50 ppb		Above 50 ppb		Total	% of TW above 10 ppb
	No.	%	No.	%	No.	%		
Kanchanpur	151	85.3	17	9.6	9	5.1	177	14.7
Kailali	202	67.1	65	21.6	34	11.3	301	32.9
Bardiya	507	77.9	120	18.4	24	3.7	651	22.1
Banke	748	88.7	84	10.0	11	1.3	843	11.3
Dang	187	95.4	9	4.6	0	0.0	196	4.6
Kapilbastu	2203	88.5	190	7.6	97	3.9	2490	11.5
Rupandehi	1779	87.1	221	10.8	43	2.1	2043	12.9
Nawalparasi	1698	52.9	687	21.4	826	25.7	3211	47.1
Chitwan	203	100.0	0	0.0	0	0.0	203	0.0
Parsa	1991	88.6	204	9.1	52	2.3	2247	11.4
Bara	1719	88.0	189	9.7	46	2.4	1954	12.0
Rautahat	891	43.4	963	46.9	199	9.7	2053	56.6
Sarlahi	246	75.5	68	20.9	12	3.7	326	24.5
Mahottari	190	95.5	8	4.0	1	0.5	199	4.5
Dhanusha	238	83.5	39	13.7	8	2.8	285	16.5
Siraha	186	79.5	40	17.1	8	3.4	234	20.5
Saptari	492	86.3	71	12.5	7	1.2	570	13.7
Sunsari	159	92.4	13	7.6	0	0.0	172	7.6
Morang	184	92.0	15	7.5	1	0.5	200	8.0
Jhapa	244	87.1	35	12.5	1	0.4	280	12.9
Total	14,218	76.3	3038	16.3	1379	7.4	18,635	23.7

Source Shrestha et al. (2004)

Nepal entitled "The State of Arsenic in Nepal" was conducted in 2003 jointly by National Arsenic Steering Committee (Nepal) and Environment and Public Health Organization (Nepal) undertaking a project funded by USGS through a US Government Public Diplomacy Grant from the US Embassy in Kathmandu. The result of this study is presented in Table 11.5 which provides the evidence of arsenic contamination in groundwater of Terai. According to this report, the percentage of wells contaminated above 50 ppb varies at district level from 0% in Dang, Chitwan, and Sunsari to 25.7% in Nawalparasi. Over half of the arsenic-tested tube wells in Rautahat and nearly half of those tested in Nawalparasi contain more than 10 ppb of arsenic. The highest concentrations of arsenic (up to 2620 ppb) were measured in Devedaha VDC of Rupandehi District, near the border with Nawalparasi. Arsenic test in the Terai indicates that about 23.7% of total tube wells tested were found to be contaminated above WHO guideline value of 10 ppb while 7.4% exceeded Nepal Interim Standard of 50 ppb (Shrestha et al. 2004). The study suggests non-uniform distribution of arsenic concentration in the entire Terai region. Higher arsenic concentrations were measured in the wells less than 50 m deep, while the reported arsenic concentrations were below the national standard (50 ppb) in the tube wells deeper than 50 m. Higher concentration of arsenic was measured in 11–30 m deep tube wells. The correlation between the level of arsenic and the age of the well suggests no direct link between the two parameters. The cause of arsenic content in the Terai areas is still to be known by detail investigation.

11.4 Groundwater Resources in Kathmandu Valley

Kathmandu Valley, which contains the urbanized centers of Kathmandu (capital city of Nepal), Lalitpur and Bhaktapur cities, is an intermontane circular basin covering an area of about 650 km^2 (Fig. 11.9). The average altitude of the valley floor is about 1350 m above mean sea level (amsl), and surrounding hills are 2800 m amsl.

Kathmandu Valley is surrounded by the mountains and hills of Lesser Himalayan range. They are composed of intensely folded, faulted, and fractured bedrock including igneous and meta-sedimentary rocks of Precambrian to Devonian. Major rock types include quartzite, phyllites, schists, slates, limestone, and marbles with occasional intrusions of acid and basic rocks. These rocks also form the basement complex beneath the floor of Kathmandu Valley. The valley is filled with a thick succession of late Pleistocene and Quaternary unconsolidated sediments of fluvio-lacustrine origin. The sediments cover has a thickness of about 550–600 m in the central part of the valley.

11.4.1 Hydrogeology of Kathmandu Valley

There are mainly three types of sediments in the valley. They are:

I. Arenaceous sediments (sandy),
II. Argillaceous sediments (clayey),
III. Intermediate type of arenaceous and argillaceous deposits.

Based on the types and distribution of sediments within the valley, the Kathmandu Valley has been divided into three groundwater districts (Fig. 11.10).

- The Northern District is the main recharge zone with high transmissivity (83–1963 m^2/day) and potential source for good quality groundwater.
- The Central District has shallow aquifers supporting stone spouts, dug well, and shallow tube wells. These shallow aquifers are underlain by thick impermeable clay layers and permeable coarse sediments respectively forming deep aquifers of Kathmandu Valley. These deep aquifers have rather low transmissivity

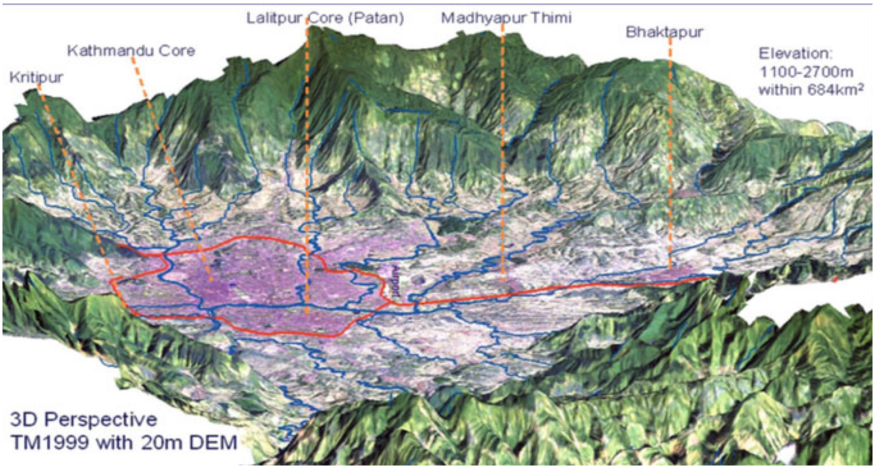


Fig. 11.10 Kathmandu Valley with its catchment area

(32–960 m^2/day) and contain methane and hydrogen sulfide gases. Groundwater in this deep zone is non-rechargeable, and according to radioactive isotope dating, its age is about 200,000 years.

- The Southern District has thick impermeable clay layer with underlying gravel deposits of low transmissivity, and the aquifers are not developed much as other two GW districts (Fig. 11.11).

11.4.2 Water Demand

At present, population of the Kathmandu Valley has been increasing day by day and so as the water demands. Kathmandu Upatyaka Khanepani Limited (KUKL) (then Nepal Water Supply Corporation—NWSC) is the main responsible agency to address the increasing demand of water in Kathmandu Valley. The KUKL has been supplying water from 35 surface water sources around the Kathmandu Valley peripheries, 78 deep tube wells (currently functional—57 DTWs), 15 dug wells (functional—11), and tankers. KUKL has been operating 43 groundwater reservoirs with total capacity of 41,500 cubic meters and 20 treatment plants with total treatment capacity of 117 million liters per day (MLD). The total water demand in the year 2012 was 350 MLD, and the production capacities of KUKL system were 144 and 84 MLD in wet and dry seasons, respectively. The trend of water demand and supply scenarios in Kathmandu Valley is shown in Table 11.6.

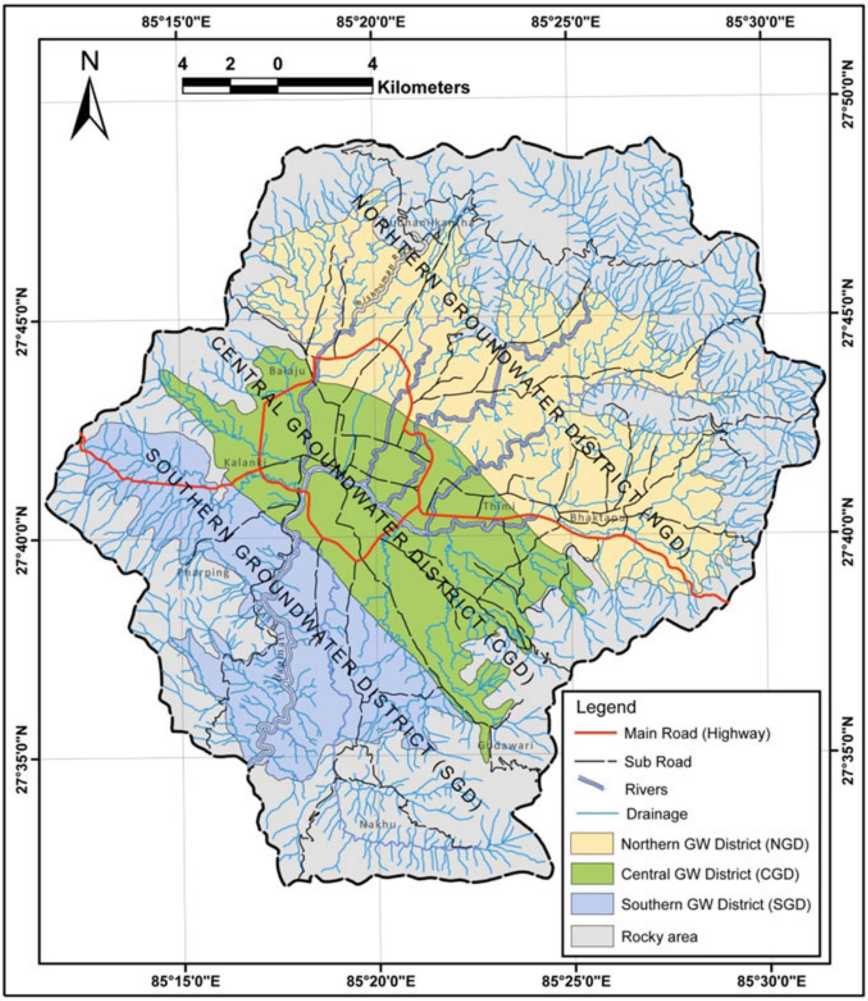


Fig. 11.11 Groundwater potential map of Kathmandu Valley. *Source* JICA

The total sustainable withdrawal of groundwater from the valley's aquifers is approximately 26.3 MLD (Stanley 1994). The natural recharge of groundwater in the valley has been variously estimated at about 30,000–40,000 m^3/day (Binnie and Partners 1988), about 15,000 m^3/day (JICA 1990), and about 13,000 m^3/day (Gautam and Rao 1991).

Different well inventory studies in Kathmandu Valley show that there are 759 numbers of deep tube wells. Total groundwater extraction by private (hotels, industries, companies, and housing companies) and community tube wells (organizations, offices, etc.) is 31.15 MCM. The annual groundwater extraction by NWSC/KUKL wells in Kathmandu Valley is 38.29 MCM (KVWSMB 2010).

Table 11.6 Water demand, production, and supply scenarios in Kathmandu Valley

S. No.	Description	Quantity		
		2010	2011	2012
1	Demand (in MLD)	320	350	350
2	Production (in MLD)			
	Minimum	89.23	90.59	84
	Maximum	149.1	149.62	144
3	Supply (considering 20% real losses)			
	Dry season	75.72	75.48	67
	Wet season	105.17	104.91	115
4	Unaccounted for water (KUKL estimates)	35–40	35–40	35–40

Source KUKL Annual Report

This shows that the annual extraction of groundwater from Kathmandu Valley is 69.44 MCM.

There are no reliable data available for shallow groundwater abstraction within the valley floor. An earlier study has estimated that, in 1999, more than 5000 privately owned small diameter shallow tube wells (operated with manual or small mechanized pumps) and unknown number of open dug wells were in use in the valley (Metcalf and Eddy 2000). The numbers of household-level wells must have increased since then, because the gap between water demand and supply has further widened during the past one decade. Recent study indicates that 50% of houses have alternate shallow water sources available for domestic uses (KVWSMB 2012). Since most of these wells are private, no reliable discharge data are available.

A huge gap between demand and supply exists in the Kathmandu Valley. The deficit of supply is generally fulfilled by the private sectors, mainly from the groundwater sources such as tube wells and natural spring sources. A recent study on the water market in the valley has shown that, in an average, 25.5 MLD of water was sold in the market during dry seasons and 8.5 MLD during other seasons during the year 2009 (Shrestha and Shukla 2010). Most of this water comes from shallow aquifers.

There is supply gap of about 61.32 MCM of water in the valley. It is assumed that 50% of this deficit is being met by groundwater from shallow aquifers. Hence, the rate of shallow groundwater abstraction is considered to be about 30.66 MCM.

11.4.3 Stone Spout Discharge

There is lack of data about the exact numbers of stone spouts in the valley. Some reports mentioned that there are about 103, 43, and 78 numbers of them, respectively, in Kathmandu, Lalitpur, and Bhaktapur. Among three towns, Lalitpur is the best in terms of discharge from stone spouts (locally called Hitis) and their seasonal

Table 11.7 Details of stone spouts in Kathmandu Valley

S. No.	District	Discharge			
		LPS			MCM (based on average discharge)
		Maximum	Minimum	Average	
1	Lalitpur	60.02	47.81	53.915	1.7
2	Kathmandu	13.64	11.39	12.515	0.39
3	Bhaktapur	1.28	1.05	1.165	0.03
Total					2.13

Situation of traditional water spouts in Kathmandu Valley, ICON/UNESCO/RCUWM

variations. Out of reported 47 stone spouts, 37 are perennial, 3 seasonal, and 7 with no discharge. Most of these spouts in Kathmandu are dried up. Only 27 of 78 spouts in Bhaktapur city are in operation. All these stone spouts are fed by the groundwater.

Table 11.7 shows the district-wise details of discharge of the stone spouts within the valley floor.

11.4.4 Recharge to Aquifers (Rg)

The groundwater basin of the Kathmandu Valley covers approximately 327 of 650 km^2 of total watershed area. According to JICA (1990), the watershed is divided into three parts: Northern, Central, and Southern Groundwater districts. The total area of the northern part is about 157 km^2 out of which 59 km^2 has been considered as the potential recharge area. The central part is composed of thick, stiff black clay with some lignite to the depths of more than 300 m. The unconsolidated, low permeability, coarse sediments underlie the thick black clay. The central part occupies an area of 114 km^2, and the sand and gravel formations covering approximately 6 km^2 area near Chapagaun are the potential recharge area for this part. Similarly, the southern part of the basin, occupying 55 km^2 area, is characterized by a thick clay formation. Recharge takes place through 21 km^2 area of sand and gravel deposits lying to the eastern extension of the southern part of the Kathmandu groundwater basin. Altogether, total recharge area for the Kathmandu Valley has been estimated to be about 86 km^2 (JICA 1990) (Fig. 11.12).

Based on the outcomes of “Groundwater Management Project in Kathmandu Valley,” it is recommended that groundwater in Kathmandu Valley can be drawn only about 15 MLD (JICA 1990). The well fields of the NWSC in the deep aquifer have shown a drawdown of the surface by 15–20 m since the construction of the wells in 1984/85 indicating substantial overexploitation. A report of Metcalf and Eddy/CEMAT consultant and the ADB (Asian Dev. Bank) as a part of Melamchi Water Supply Project noted that both static and pumping water levels have been depleted in most part of the Kathmandu Valley. It is reported that water level in

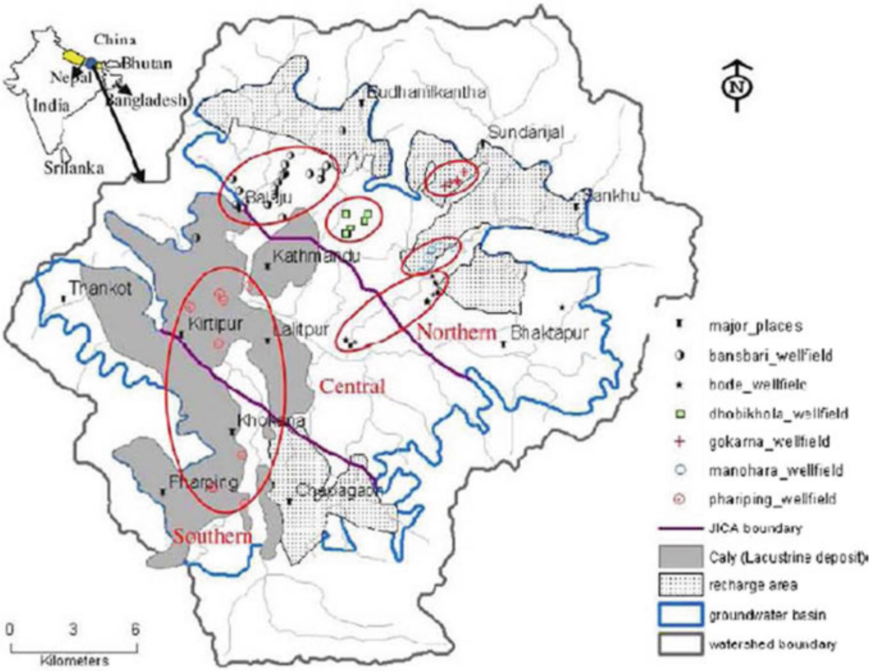


Fig. 11.12 Kathmandu groundwater basin map with potential recharge area. *Source* JICA (1990)

Kathmandu Valley is lowering at an average rate of 2.5 m/year. It has been found that more than two dozens of valley's stone spouts, which is an alternative source to the water scarce in the valley gone dry and water levels at "Ranipokhari" (might be constructed in medieval times for infiltration pond), are declining.

The available groundwater level monitoring data of the four monitoring deep tube wells in the valley show an obvious indication of water level decline (Fig. 11.13).

11.4.5 Water Quality

Groundwater from both deep and shallow aquifers is suitable for irrigation without any treatment, but for drinking and industrial uses, treatment is necessary. Mostly, the shallow aquifer pollution is high in the area beneath the main cities in the valley. The shallow aquifers are polluted by industrial effluents and also from the polluted rivers. Shallow tube wells are less contaminated than dug wells, and deep tube wells are least affected. Pollution concentrations are higher during rainy period.

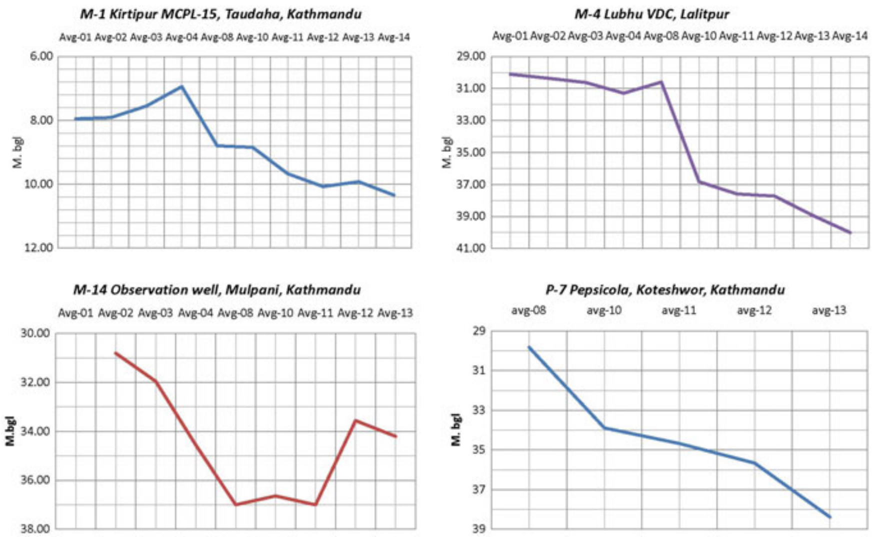


Fig. 11.13 Water levels in monitoring deep tube wells

A study revealed that the groundwater quality of Kathmandu Valley is severely affected by iron (1.9 and 1.5 mg/L in deep and shallow tube well, respectively) and coliform bacteria (267 and 148 CFU/100 mL in shallow and deep tube well, respectively), well above the WHO guideline value (0.3 mg/L for iron and 0 for total coliform bacteria), compared to the other pollutants (Pant 2010). Arsenic concentration slightly above the WHO guidelines has been reported in few samples from deeper aquifer; however, none of them were above the Nepalese Interim Standard (50 ppb). Similarly, few sources tapping shallow aquifer exceeded the WHO guideline value for mercury but other heavy metal concentrations were below both WHO and Nepali guidelines (Warner et al. 2008).

11.4.6 Alternative Sources of Groundwater in the Valley

The limestones of the Precambrian to Devonian period have been observed around the Kathmandu Valley. Intensely folded, faulted, and fractured limestones are distributed SE and SW rims of the valley (Fig. 11.14). The estimated area of the limestone distribution is about 50 km^2.

Numerous springs from limestone zones are noticed in the southern frame of the valley. Discharge in these springs increases in post-monsoon period. The springs originate at the slopes and base of the mountain slopes, mostly from the fractured limestone or other bedrocks. Continuous but seasonal variation in discharge from these springs shows interconnection between the springs and the potential limestone

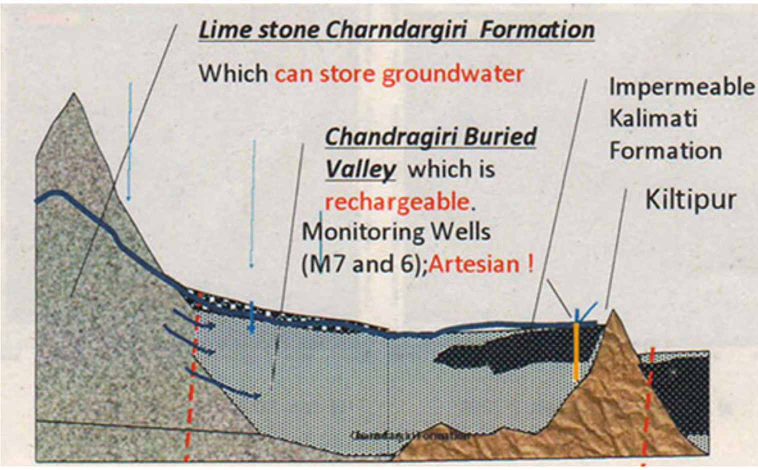


Fig. 11.14 Schematic diagram of Chandragiri Limestone. *Source* ADB, JWA

reservoir. The nature and the total potential of this source has not yet been studied. Total yield remains unchanged throughout the year, and these hard rock zones may have enough potential to supply the present demand in the valley. If these sources are found satisfactorily, it would be of great help to solve the problem of water demand in Kathmandu Valley to some extent.

References

BGS/Wateraid (2001) Groundwater quality: Nepal. British Geological Survey and Wateraid, 4 pp

Binnie and Partners (1988) Water supply for Kathmandu and Lalitpur from outside the valley. Final report on feasibility study, Appendix-L (Groundwater Resources within the valley)

Bricker SH, Yadav SK, McDonald AM, Satyal Y, Dixit A, Bell R (2014) Groundwater resilience Nepal: preliminary findings from a case study in the middle hills. British Geological Survey Open Report OR/14/069, 67 pp

Dahal RK, Hasegawa S, Masuda T, Yamanaka M (2006) Roadside slope failures in Nepal during torrential rainfall and their mitigation. In: Marui H et al (eds) Disaster mitigation of debris flow, slope failures and landslides, Proceedings of INTERPRAEVENT 2006, vol 2. Universal Academy Press, Tokyo, pp 503–514

Dahal RK, Hasegawa S (2008) Representative rainfall thresholds for landslides in the Nepal Himalaya. Geomorphology 100(3–4):429–443. https://doi.org/10.1016/j.geomorph.2008.01.014

Dhital MR (2015) Geology of the Nepal Himalaya. Regional perspective of classic collided orogen. Springer, Heidelberg, 499 pp

Duba D (1982) Groundwater resources in the Terai of Nepal. Water and Energy Commission Secretariat Report

Electrowatt (1984) Eastern Terai irrigation project Nepal, vol 1–4

Gautam R (1991) Groundwater resource evaluation of Kathmandu valley. J Nepal Geol Soc 7:39–48

GDC (1994) Reassessment of groundwater development strategy for irrigation in the Terai, 6 volumes

GDC (1987) Study of Groundwater development strategies for irrigation in the Terai

Grimmelmann WF (1984) Preliminary hydrogeological mapping of Nepal-Regional Mineral Resources Development Center, Report No. 201-1984 (Unpublished)

Hagen T (1969) Report on the geological survey of Nepal. Volume 1: Preliminary reconnaissance. Denkschiiften der Schweizerischen Naturforscharden Gesellschaft, Band LXXXVI/1, 185 pp (with a geological map)

JICA (1990) Groundwater management project in Kathmandu valley. Final Report to Nepal water supply corporation

Kansakar DR (2011) Regulating common pool groundwater under fugitive surface water law: limitations in laws and regulations in Nepal. A report submitted to Jalsrot Vikas Sanstha/Global Water Partnership Nepal, 31 pp

KVWSMB (2012) Annual report 2012 of Kathmandu Valley Water Supply Management Board (KVWSMB)

KVWSMB (2010) Annual report, Kathmandu Valley Water Supply Management Board

Mathur LP, Kohli G (1963) Exploration and development of the oil resources of India. In: Proceedings of 6th World Petroleum Congress, 19–26 June, Frankfurt, Germany

Metcalf and Eddy (2000) Urban water supply reforms in the Kathmandu Valley (ADB-TA Report number 2998-NEP), Completion report. Volume I & II—Executive summary, main report and Annex 1 through 7. Metcalf and Eddy, Inc. with CEMAT Consultants Ltd.

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

NPHC (2011) National Population and Housing Census 2011 (National Report), vol 1. Central Bureau of Statistics, Government of Nepal, 264 pp

Pant BR (2010) Groundwater quality of Kathmandu valley of Nepal. Environ Monit Assess. Springer. https://doi.org/10.1007/s10661-010-1706-y

Sharma CK (1974) Ground water resources of Nepal. Wonder Printing Press, Kathmandu, p 140

Shrestha D, Shukla A (2010) Private water tanker operators in Kathmandu: analysis of water services and regulatory provisions. A paper present in Regional Conference on Water & Governance, organized in Bhutan, SaciWATERs

Shrestha BR, Whitney JW, Shrestha KB (eds) (2004) The State of Arsenic in Nepal-2003. National Arsenic Steering Committee, Environment and Public Health Organization, Kathmandu, Nepal, 126 pp and CD-ROM

Stanley IL (1994) The Bagmati Basin water management strategy and investment program. Report to Ministry of Housing and Physical Planning, Government of Nepal

Tahal Consulting Engineers (1992) Bhairahawa lumbini groundwater project environmental assessment study

UNDP/GWRDB (1987–1992) Shallow ground water investigation in Terai. Technical Report, Groundwater Resource Development Board

Upreti BN (1999) An overview of the stratigraphy and tectonics of the Nepal Himalaya. J Asian Earth Sci 17:741–753

Warner NR, Levy J, Harpp K, Farruggia F (2008) Drinking water quality in Nepal's Kathmandu valley: a survey and assessment of selected controlling site characteristics. Hydrogeol J 16:321–334

WECS (2005) National water plan for Nepal. Water and Energy Commission Secretariat, Government of Nepal, Kathmandu, Nepal

WECS/DHMN (1996) Methodologies for estimating hydrologic characteristics of ungauged locations of Nepal (vol 2—Annexes). Water and Energy Commission Secretariat and Department of Hydrology and Meteorology of Nepal

Water Resources Act (1992) Government of Nepal, www.lawcommission.gov.np

Water Resources Regulations (1993) Government of Nepal, www.lawcommission.gov.np

Part III
Groundwater Quality and Pollution

Chapter 12
Groundwater Quality and Concerns of Kabul River Basin, Afghanistan

Abdul Qayeum Karim

Abstract This study is aimed at assessing water quality in Kabul Basin by integrating several scientific investigations and studies on monitoring and evaluation of water quality conducted so far by different entities. It shows that in Afghanistan lowering of groundwater table is rapidly entering into water-scarce countries. Increase in population density and decrease in water availability have become dual threat to water quality, and impact on public health. It has been estimated that in Afghanistan around 30–40% of all reported diseases and deaths are due to poor water quality. Moreover, the leading cause of deaths in infants and children up to 10 years of age as well as mortality rate of 1,600 per 100,000 live births is reported owing to diarrhea. This situation is rather worst due to being among the backward and poverty-stricken areas. Findings of this research show that the increased population of Kabul city by about 4% per year during 2002–07 affected existing shallow water supply by increased groundwater withdrawals. Increasing water use on groundwater levels indicates that a large percentage of existing shallow water-supply wells in urban areas may contain little or no water by 2057. This research presents a thorough analysis of the groundwater quality and quantity deterioration, which leads to a conclusion and a set of recommendations, which are considered useful to prevent water quality deterioration as well as quantity decrease of the groundwater in Kabul River Basin.

Keywords Kabul River basin · Groundwater quality · Public health
Polluted water

A. Q. Karim (✉)
Civil Engineering Department, Faculty of Engineering, Kabul University, Kabul, Afghanistan
e-mail: aqkarim15@yahoo.com

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_12

12.1 Introduction

Kabul River Basin (KRB) is one of the five river basins of Afghanistan (Chap. 1, Fig. 1.1), namely (a) Amu Darya River Basin, (b) Northern River Basin, (c) Harirod-Murghab River Basin, (d) Helmand River Basin, and (e) Kabul River Basin. KRB is the fourth basin in terms of area, while in terms of population and population density, it comes first. It is the basin which shows high consumption of water, while in terms of the water body area, it is the fourth one. It shows high demand for drinking water to meet the requirement. The present article is focused on integrating findings of different studies on water quality of KRB. The review shows Kabul Basin drinking water systems are contaminated by microbial pathogens and anthropogenic contamination and pose a threat to the health of Kabul's inhabitants. Therefore, there is a need to take urgent corrective measures before further deterioration of Kabul Basin drinking water systems.

The lack of potable drinking water provision and sewerage systems to meet the demand of increasing population in the KRB due to massive return of Afghan refugees and presence of international community, the water quality is under a great threat of contamination which will be harmful for the community. It is evident that focus of the study of water quality in the Kabul Basin could be used in adapting effective preventive measures of potable water shortage, contamination of drinking water, and environmental hazards in future.

The organizations/government departments that have studied or are responsible for the study of the water quality in Afghanistan and particularly in Kabul River Basin include the following.

(i) United States Geological Survey (USGS) in cooperation with the Afghanistan Geological Survey
(ii) Danish Committee for Assisting Afghan Refugees (DACAAR)
(iii) United Nations Children Funds (UNICEF)
(iv) Ministry of Public Health of the Islamic Republic of Afghanistan
(v) Ministry of Rural Rehabilitation and Development of the Islamic Republic of Afghanistan
(vi) Drainage Research Centre (DRC), Kabul
(vii) Water Resources Research Centre (WRRC) Kabul

The Kabul River runs from north to south direction and passes through many villages, hospitals, small industries, etc. These agencies dispose their waste directly to the river. Industries include cosmetics industry, garments industry, and soaps industry mainly situated in the city of Kabul. More related information regarding groundwater of South Asia is available in Mukherjee et al. (2018).

12.2 Geomorphology

As stated earlier, KRB is considered to be a geologic valley formed by the Paghman Mountains to the west and the Safi Mountains to the east. The landforms within the Kabul Basin are typical of an arid to semiarid, tectonically active region. All adjacent sub-basins except for the Central Kabul and Logar sub-basins and the Shomali and Panjsher sub-basins are separated by prominent bedrock outcrops. The central plains of the sub-basins are local depositional centers for sediments derived from the surrounding surficial deposits and bedrock outcrops. The central plains gently slope up to the adjacent mountains and hills to form piedmonts. Alluvial fans have developed on the flanks of the mountains surrounding the sub-basins and on the inter-basin ridges. The alluvial fans generally grade from course material near the source to finer material at the distal edges. The study area encompassed about 3,600 km^2 is primarily composed of Tertiary and Quaternary valley-fill sediments filling fault-bounded structural basins.

12.3 Topography

The topography of the Kabul River Basin is strongly influenced by regional and local tectonic activity and by fluvial processes. The basin is bounded by mountain ranges; the highest range, reaching 4,400 m in altitude, is the Paghman Mountains to the west of the study area. The Kohe Safi range to the east of the study area is as high as 3,000 m, and most of the range slopes out of the study area to the east. The inter-basin ridges generally rise about 200–500 m above the adjacent valley floors. The central plains of the sub-basins are generally flat, rising gradually to the surrounding bedrock outcrops. Altitudes of the central plains range from around 1,800 m in the Central Kabul and Logar sub-basins to 2,200 m in the Paghman and Upper Kabul sub-basin. Several ephemeral streams flow from the Paghman Mountains that border the Shomali area. Perennial and ephemeral stream channels have discussed the valley-fill sediments. Active stream channels are generally narrow and shallow, rarely exceeding 10 m in width and 5 m in depth. Some isolated topographic depressions in the Central Kabul and Logar sub-basins act as catchments for surface-water runoff and are the sites of playa lakes or ephemeral marshes.

12.3.1 Geology

The Kabul River Basin is part of the tectonically active Kabul block in the transgressional plate-boundary region of Afghanistan. A generalized geohydrologic section of the Kabul Basin is presented in Chap. 2 to illustrate the general structure and major geologic and hydrologic features. The western edge of the Kabul block is defined by the Paghman fault within the Chaman fault system. The Paghman fault trends north–northeast and is evident in the continuous fault scarp and piedmont alluvium along the western boundary of the Kabul Basin. The Paghman fault marks a transition from primarily left-lateral strike-slip movement on the Chaman fault to apparent left-lateral oblique-thrust faulting and dip-slip displacement on the Paghman fault. The basin can be described as a valley-fill basin-and-range setting where the valleys are filled with Quaternary and Tertiary sediments and rocks, and the ranges are composed of uplifted crystalline and sedimentary rocks. Quaternary sediments are typically less than 80 m thick in the valleys. The underlying Tertiary sediments have been estimated to be as much as 800 m thick in the city of Kabul and may be more than 1,000 m thick in some areas of the valley.

12.4 Hydrology of Kabul River Basin (Precipitation and Runoff in the Basin)

The Kabul Basin study area is within the 25,500 km^2 Kabul River watershed. The number of major rivers flowing into the Kabul Basin undoubtedly contributed to the historical significance of the Kabul area. The Kabul River enters the study area from the south, flows north about 21 km to the city of Kabul, and then flows east, leaving the study area through a steeply cut valley in the Safi Mountains. The Paghman River flows eastward from the Paghman Mountains and enters the Kabul River in the city of Kabul near the point where the Kabul River begins to flow east. The Logar River, a large tributary to the Kabul River, enters the study area from the south through a steeply cut valley and flows northward for about 28 km. The Logar River enters the Kabul River at the eastern edge of the city of Kabul, about 17 km downstream of the mouth of Paghman River. The Chakari River enters the study area from the south, flows northward for about 35 km, and enters the Kabul River about 6 km downstream from the mouth of the Logar River. The Panjsher River enters the study area from the north through a steeply cut valley and flows south for about 24 km, southeast for about 33 km, and finally, following the regional geologic structure, south for about 38 km, joining the Kabul River 15 km east of the study area. The Ghorband River enters the study area from the northwest through a steely cut valley after flowing east for about 54 km through the Paghman Mountains. The Ghorband River enters the Panjsher River at the point where the Panjsher River turns and flows southeast. The Barik Ab River drains the central western flanks of the Paghman Mountains, flows north to the Panjsher River, and enters the Panjsher River about 16 km downstream of the mouth of the Ghorband River. General characteristics of the Kabul, Logar, Ghorband, and Panjsher River Basins are provided by Favre and Kamal (2004). Because of the limited extent of unconsolidated sediments, where the major rivers enter or leave the study area at steeply cut valleys, groundwater inflow or outflow at the margins of the Kabul River Basin occurs/takes place (one of these two terms).

12.5 Water Use in Kabul River Basin

Water use in the Kabul Basin can be grouped into two major categories—combined municipal and domestic use, and agricultural irrigation. The amount of water used for industrial purposes is unknown but is probably much less than that used for other purposes. Water for municipal and domestic use is generally supplied by community or individual wells, which are concentrated in the more populated areas. Water use for agricultural purposes has been estimated to be at least an order of magnitude greater than that for domestic use. Agricultural use is seasonal, generally from May through September and is concentrated in the northern and western areas of the basin. Water is primarily supplied by irrigation canals from streams or karezes, which are a historical type of water-supply system common in the study area and throughout Afghanistan and other arid countries of the Middle East. A kareze consists of a dug underground conduit that intersects the water table near the top of an alluvial fan and directs groundwater discharge laterally out to irrigated land at the base of the fan.

Municipal Water Use

The city of Kabul operates municipal supply and distribution systems in parts of the city; however, limited information on municipal water systems was available for this study. The municipal systems are supplied primarily by groundwater from more than 40 supply wells, and secondarily by surface water obtained from the Qargha Reservoir in the upper Paghman River watershed. In rural areas, domestic water generally is not only supplied by shallow dug or driven wells, but also may be supplied by deeper wells, karezes, springs, or surface-water sources. The per person rate of water use in the study is not known and most likely differs considerably from rural to urban areas. Estimated per person water-use rates reported for Kabul include 40–50 L/day (Niard 2007) and 60 L/day in winter to 110 L/day in summer (Böckh 1971). Estimated per person water use in rural areas is thought to be lower than previous estimates, generally about 20–30 L/day. In 2006, municipal groundwater withdrawals in the city of Kabul were reported to be $\sim$40,000 m^3/day from few pumping centers within the city. Low estimated rates of water use such as 11 L/day by Uhl (2006) may be realistic for domestic use in the more rural areas; however, in rural areas, individuals also provide water to livestock and small gardens, and the total per person use rate for both domestic and livestock uses might be close to rates for more urban areas. With increasing security improving standard of living, future per person water-use rates may be greater than current rates.

If the per person water-use rate is assumed to be 25 L/day (0.025 m^3/day), the Kabul municipal supply system serves about one million people in the city. Shallow wells equipped with hand pumps supply local domestic water needs in many urban and rural areas throughout the Kabul Basin. The Ministry of Urban Development indicates that municipal groundwater withdrawals in the city of Kabul were expected to increase to 120,000 m^3/day in 2009 with the installation of additional planned wells. The total population in the KRB was estimated to be approximately

3.5 million in 2002 (Afghan Information Management System, written communication, 2006) with ~66% of the population (2.3 million) in the Kabul district, which includes the city of Kabul. The population is anticipated to increase by approximately 20% by the year 2012.

Between 1997 and 2005, the Danish Committee for Aid to Afghan Refugees (DACAAR) installed approximately 1,500 shallow wells (with the median depth of 22 m) in the Kabul Basin with about 1,000 of these wells in the three sub-basins of the city of Kabul (Safi and Vijselaar 2007). Of these wells with status reported, about 25% in the city of Kabul were reported as dry or inoperative, whereas about 20% in the larger Kabul Basin were reported as dry or inoperative. Water levels have declined by about 0 m since 1982 in the city of Kabul's intermountain aquifers because of increased water use (Eng. Hassan Safi, DACAAR, Afghanistan, 2005). Increasing water use has reduced groundwater levels, which in turn have led to dry wells.

Agricultural Use of Water

A simplified surface-energy balance (SSEB) method was used to estimate agricultural water use in the Kabul Basin. The method uses agricultural models and remotely sensed images of the land-surface temperature to produce 1-km gridded estimates of evapotranspiration at 8-day intervals during the growing season. Evapotranspiration is the combined transport of water from the land surface to the atmosphere as a consequence of plant transpiration and direct evaporation of surface water and near-surface soil moister. Agricultural water use occurs primarily in three areas of the Kabul Basin, and irrigation is almost entirely supplied by karezes and streamflow diversions. In the northern part of the study area, irrigation is supported by diversions from the Panjsher River and its tributaries. Although many wells have recently been installed in the Kabul Basin, the use of groundwater for irrigation is still likely to be low because of prohibitive fuel costs.

12.6 Water Quality Hazards in Kabul River Basin

Groundwater in the Kabul Basin occurs in the surficial sedimentary (Quaternary) aquifers in the bottom of the basin or sub-basins, the semi-consolidated Neogene aquifer sediments, and, to a lesser extent, the sedimentary and fractured metamorphic and crystalline bedrock of the mountains and inter-basin rides in the Kabul Basin. The primary groundwater resource used in the Kabul Basin is the surficial aquifer consisting of unconsolidated Quaternary sediments. Groundwater in the semi-consolidated Neogene aquifer sediments in 2007 had little use and is presently being investigated for future use. Few wells have been completed in the underlying bedrock aquifers, and, as a result, this aquifer is relatively unused; however, this aquifer contributes water from upland areas to the overlying sedimentary aquifers.

The primary concerns of groundwater quality of Kabul River Basin groundwater include:

i. Progressive increase of microbiological contamination such as coliform bacteria with time
ii. Progressive increase of nitrate concentrations with time
iii. Presence of elevated arsenic and fluoride concentrations

The presence of high rate of fecal coliform bacteria and high concentration level of nitrate indicates that drinking water supply from KRB is contaminated by fecal coliform (microbial pathogens) and nitrate (anthropogenic) contamination. The groundwater resources of the Kabul Basin are generally considered to be the surficial (Quaternary) sediments and consist primarily of loess, river channel sands and gravels, fan alluvium and colluviums, and unconsolidated sand and gravel.

Water quality samples were collected in the Kabul Basin in 2006 and 2007. Water collected from springs and karezes was considered to be more chemically similar to groundwater than surface-water samples collected in streams and rivers. For this reason, samples collected from springs and karezes were grouped with groundwater samples for statistical analyses. The chemical compositions of the samples of surface water and groundwater collected from the different sub-basins and regions were not significantly different from each other with the exception of samples collected from the Central sub-basin. The temperature, specific conductance, and concentrations of total dissolved solids, *Escherichia coli*, and nitrate measured in groundwater collected in the Central Kabul sub-basin were significantly greater than in samples of groundwater and surface water from all other sub-basins with the exception of surface-water samples from the Paghman and Upper Kabul and Shomali sub-basins. The Central Kabul sub-basin may receive most of its recharge from leakage from the Paghman and Kabul Rivers. In the Central Kabul sub-basin alone, there are no upland areas to supply recharge through lateral groundwater inflow.

UNICEF/MRRD did a general screening of 647 wells in July 2003 for arsenic and was found in eight wells in Logar, while in Ghazni, 43% of wells were found contaminated, and large number of wells had arsenic ranging from 10 to 500 μg/L. It puts almost 500,000 people potentially at risk.

USGS (Broshears et al. 2005; Mack et al. 2010, 2014) tested groundwater samples from Kabul Basin for pollution from human excreta. The study shows that total coliform bacteria were detected in almost all samples, *E. coli* was detected in 97% samples, nitrate was found in the range of 3.3–40.2 mg/l, and arsenic was found in few samples.

DACAAR (Safi 2011; Safi and Vihselaar 2007) conducted water quality in some provinces. Excess fluoride concentration beyond WHO limits was found in Badghis, Jawzjan, Faryab, Balkh, Kandahar, Parwan, Maidan Wardak, and Kabul. Arsenic beyond permissible range was found in Ghazni, Punsher, Logar, Paktia, Maidan Wardak, Farah, Kabul, and Faryab.

References

Böckh EG (1971) Report on the groundwater resources of the City of Kabul, Report for Bundesanstalt fur Geowissenschaften und Rohstoffe [unpublished]. BGR file number: 0021016, 43 pp

Broshears RE, Akbari MA, Chornack MP, Mueller DK, Ruddy BC (2005) Inventory of ground-water resources in the Kabul Basin. U.S. Geological Survey Scientific Investigations Report 2005–5090, Afghanistan, 34 pp

Favre R, Kamal M (2004) Watershed of Atlas of Afghanistan. AIMS, Kabul

Mack TJ, Akbari MA, Ashoor MH, Chornack MP, Coplen TB, Emerson DG, Hubbard BE, Litke DW, Michel RL, Plummer LN, Rezai MT, Senay GB, Verdin JP, Verstraeten IM (2010) Conceptual model of water resources in the Kabul Basin. U.S. Geological Survey Scientific Investigations Report 2009–5262, Afghanistan, 240 pp. https://pubs.usgs.gov/sir/2009/5262/

Mack TJ, Chornack MP, Flanagan SM, Chalmers AT (2014) Hydrogeology and water quality of the Chakari Basin. U.S. Geological Survey Scientific Investigations Report 2014–5113, Afghanistan, 35 pp. http://dx.doi.org/10.3133/sir20145113

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Niard N (2007) Hydrogeology of the Kabul Basin, part III: modeling approach, conceptual and numerical models. Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany, p 103

Safi H (2011) Groundwater natural resources and quality concern in Kabul Basin. Afghanistan—a scientific investigation report, DACAAR, Afghanistan

Safi H, Vijselaar L (2007) Groundwater monitoring, evaluation of groundwater data. DACAAR, Kabul, p 99

Uhl VW (2006) Afghanistan—an overview of groundwater resources and challenges. Ground Water 44(5):626–627

Chapter 13
An Overview of Groundwater Quality in Bangladesh

Shama E. Haque

Abstract Groundwater is one of the most valuable natural resources of livelihood and food security of millions of rural people across Bangladesh. Groundwater availability in Bangladesh is governed by its subtropical monsoon climate, aquifer storage capacity, consumption rate along with changes in volume and distribution of groundwater recharge conditions. Groundwater withdrawal from the shallow alluvial aquifer (depth <150 m) is the country's source of the arsenic-enriched waters. In Bangladesh, millions of people are suffering from severe and chronic arsenic poisoning due to consumption of drinking water from contaminated groundwater sources. The groundwaters with elevated levels of arsenic abstracted from the shallow aquifers are of natural origin, which has likely been present in the groundwater for thousands of years. However, arsenic is not the only water-quality problem in Bangladesh's groundwater. In many parts of the country, the groundwaters are characterized by elevated levels of dissolved iron, manganese, and boron. Additionally, dissolved uranium concentrations appear to be a water-quality problem in certain areas; however, the nature and extent of the problem is poorly defined due to lack of sufficient data. Furthermore, climate change and rising sea levels will likely contribute to an increase in salinity in the coastal groundwater systems of the country. Consequently, access to safe drinking water is one of the greatest environmental threats in this predominantly rural country.

13.1 Introduction

Until the 1970s, surface water resources were primarily used for drinking water source in Bangladesh. However, microbial contamination of stagnant surface water resources resulted in water-borne diseases, such as cholera and dysentery that led to millions of deaths in this region alone (Nickson et al. 2000; Chakraborti et al. 2002;

S. E. Haque (✉)
Department of Civil and Environmental Engineering,
North South University, Dhaka, Bangladesh
e-mail: shama.haque@northsouth.edu

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_13

Ravenscroft et al. 2005). In an effort to prevent morbidity and mortality from water-borne diseases, during the 1970s, Department of Public Health Engineering (DPHE) of Bangladesh worked with the United Nations Children's Fund (UNICEF) to install hand-pumped tube wells to provide what was then considered a safe source of drinking water for Bangladesh's rural population (Smith et al. 2000; Kinniburgh et al. 2003). Groundwaters are generally less susceptible to microbial contamination compared to surface waters. As of 1999, roughly 97% of the population depended on groundwater for drinking water supplies along with agricultural and industrial usage (BGS and MML 1999).

Groundwater is abundant in Bangladesh. Water tables vary across the country but are relatively shallow at a depth of approximately 1–10 m below the ground surface (BGS and WaterAid 2001). In addition, the unconsolidated sediments of Bangladesh are easy to drill manually to depths of at least 50 m or more within 48 h (DPHE/BGS/MML 1999). The exact number of tube wells in Bangladesh is not known but an estimated 10 million hand-pumped tube wells have been installed across the country (van Geen et al. 2003; Cheng et al. 2004). Consequently, easy accessibility to freshwater from underground aquifers has led to indiscriminate and sometimes excessive use of groundwater (Jahan et al. 2010; Shahid 2011; Shahid et al. 2015). As of 2010, total abstraction of groundwater was 30.21 bcm annually, and 79% of groundwater withdrawal was for intense irrigation usage (Margat and Van der Gun 2013; Mukherjee et al. 2015). During the dry season (November to May), surface water supplies are inadequate to meet irrigation water demand. As a result, groundwater-fed irrigation through installation of shallow tube wells is widely used for cultivation of high-yielding rice during the dry seven months of the year (Scott and Sharma 2009). Between 1972 and 1999, the area irrigated by groundwater as a fraction of the total irrigated area, increased from 4% to 70% (Mainuddin 2002). During the past four decades, the growing demand and excessive use of groundwater has led to substantial drawdown of aquifer, and groundwater levels have reportedly receded by approximately 20–30 m (Zahid and Ahmed 2006; Jahan et al. 2010; Sumiya and Khatun 2016). In particular, significant annual decline in groundwater levels has been reported in the area neighboring the densely populated capital, Dhaka (Ahmed 1994; Alam 2006).

Climatic variations, changing river courses, poor management of water bodies along with contamination from natural and anthropogenic sources as well as saltwater intrusion in the coastal aquifers have rendered the groundwaters from some areas unfit for human consumption or agricultural uses (Zahid and Ahmed 2006; McBean et al. 2011; van Geen et al. 2011; Bodrud-Doza et al. 2016). This is alarming considering the vital role groundwater plays to support rural economies within Bangladesh. Thus, it is crucial to safeguard both the quality and the quantity of the country's groundwater, and to further understand the concerns and challenges of groundwater depletion in Bangladesh. This chapter presents a review of the existing literature and data to assess the quality of groundwaters in Bangladesh. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

13.2 Geology and Landform

Bangladesh is a low-lying riverine country that lies within the Bengal Basin in Southern Asia. The total land area in Bangladesh is approximately 143,998 km^2. Geographically, the country extends from 20° 34′N to 26° 38′N latitude and from 88° 01′E to 92° 41′E longitude (Fig. 13.1). Bangladesh shares international land borders with two nations: to the east, west, and north with India and to the southeast with Myanmar (Burma), and to the south, it is bounded by the Bay of Bengal, which opens into the Indian Ocean. Most of Bangladesh is less than 10 m above sea level,

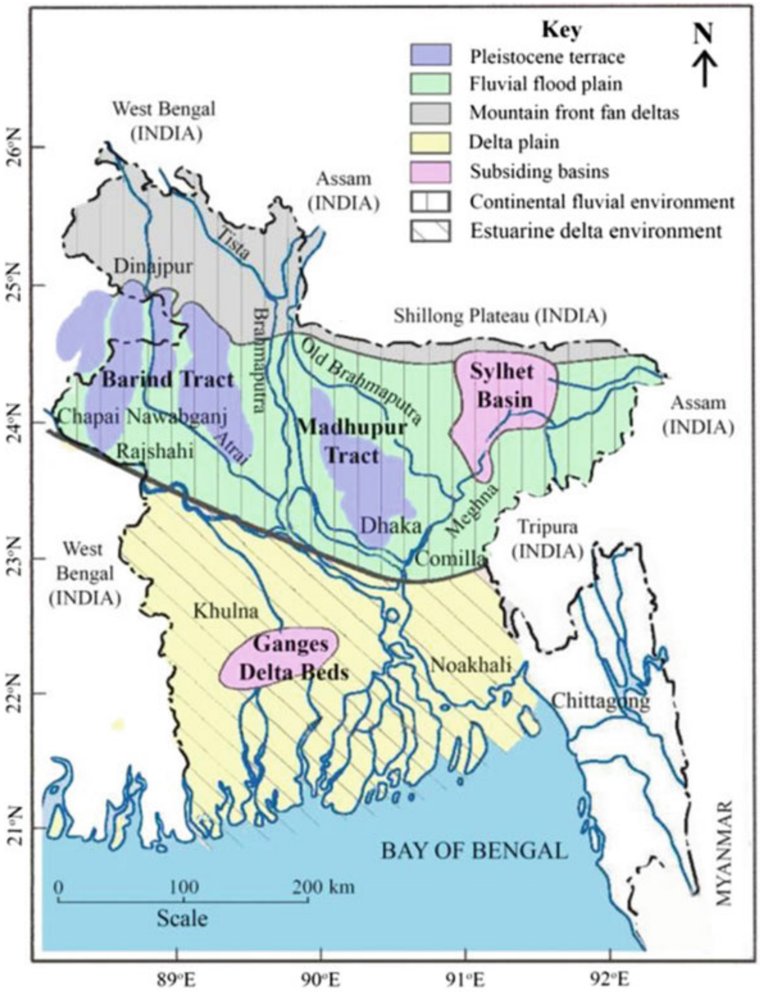


Fig. 13.1 Geology and geomorphology of Bangladesh. Map modified from BGS and DPHE (2001)

excluding the uplifted Pleistocene terraces of Barind and Madhupur Tracts, the Chittagong Hill Tracts, and the hilly area in the northeast (Datta et al. 2009; Fig. 13.1). The central and the southern region of the country is located within the floodplains of the Ganges, Brahmaputra, and Meghna (GBM; locally known as Padma-Jamuna-Meghna) river systems (Lindsay et al. 1991; Goodbred and Kuehl 2000; Mukherjee et al. 2009) and their tributaries, such as the Teesta, Dharla, Dudhkumar, Kushiayra, and Surma. The GBM river systems drain the Himalayas and Tibetan Plateau, slope from north to south, and drain into the Bay of Bengal through Bangladesh. The GBM subsurface delta mineralogy is predominantly composed of quartz, with lesser amounts of plagioclase, potassium feldspar, and volcanic, metamorphic, and sedimentary fragments (Uddin and Lundberg 1998a, b).

The Bengal Basin, which covers most of Bangladesh, is bounded by tertiary rocks of the Himalayas and Shillong Plateau to the north, the Indo-Burman ranges to the east, the Indian craton to the west, and the Bay of Bengal to the south (Morgan and McIntire 1959; Nandy 2001). The western and northwestern parts of the Bengal Basin are composed of Permian to Pleistocene age sedimentary rock sequence (Ball et al. 1981). The surface area of present-day Bangladesh is predominantly covered by Holocene fluvio-deltaic sediments of the meandering GBM river system, much of it deposited between ca 6000 BP and 10,000 BP (Morgan and McIntire 1959; BGS and DPHE 2001). During the Quaternary, sediment deposition in major river systems of the Bengal Basin was largely controlled by climatic changes and sea-level oscillation pertaining to glacial cycles (Umitsu 1993). The Quaternary alluvial sediments primarily formed aquifers in Bangladesh, except in the southeastern hilly areas of the country, where aquifers are composed of tertiary age deposits (Ravenscroft 2003; Zahid and Ahmed 2006; Shamsudduha and Uddin 2007).

The surface geology of the country can be classified into four major physiographic units: (i) tertiary sediment in the northern and eastern hills, (ii) uplifted Barind (located to the northwest) and Madhupur Tracts (located in central Bangladesh) of Pleistocene, (iii) Holocene (i.e., recent) floodplains of the GBM River Basin, and (iv) delta covering the remainder of the country (Morgan and McIntire 1959; Zahid and Ahmed 2006).

13.3 Hydrogeological Setting

Several classification schemes have been proposed to differentiate aquifers in Bangladesh (e.g., UNDP 1982; Umitsu 1993; Acharyya et al. 2000; Uddin and Abdullah 2003); however, the architecture of the aquifers is yet to be fully determined (Mukherjee et al. 2009). The first systematic classification of the aquifer systems was proposed by UNDP (1982). According to the UNDP threefold classification, the aquifers of Bangladesh, up to a depth of 140 m, were divided into:

(1) upper or composite aquifer, (2) main aquifer, and (3) deep aquifer. In a more recent study of Bangladesh aquifers, Uddin and Abdullah (2003) proposed a new classification scheme of the aquifer systems based on the sedimentological parameters and the depositional history of the aquifer sediments. Based on this new classification scheme, the major aquifers are divided into: (1) Plio-Pleistocene aquifers, (2) Late Pleistocene—Early Holocene aquifers, (3) Middle Holocene aquifers, and (4) Upper Holocene aquifers.

The Plio-Pleistocene Aquifers of the Dupi Tila Formation is overlain by the Pleistocene Madhupur Clay Formation. This aquifer consists of yellowish-brown to light gray, medium to coarse sand with pebble beds. The sediments are very weakly consolidated and depleted in mica and organic matter (Ravenscroft et al. 2005).

The Late Pleistocene-Early Holocene Aquifers are discontinuous in some areas of the country. A 10-m-thick gravel bed marks the bottom surface of the Late Pleistocene-Early Holocene, and the upper surface is formed of oxidized sediment layer. The aquifer is composed of gray micaceous, medium and coarse sand to silt with organic mud and peat (Ravenscroft et al. 2005).

Middle Holocene Aquifer overlies the Late Pleistocene-Early Holocene aquifer. The Middle Holocene is composed of mostly fine sand, and the sandy sequence varies significantly both in vertical and horizontal directions. Sediments in the uppermost part consist of clay, silt, and peat layers and were deposited in a transgressive phase of the sea level. The groundwater has been dated ca 3000 BP. Groundwater in Bangladesh is mostly extracted from this aquifer.

Upper Holocene Aquifers represent the upper most part of the sedimentary column of the delta and the recent flood plains of the GMB delta complex. The aquifers' sediments are composed of clay, silt, and fine sand. These aquifers contain a stack of several sandy layers that are interconnected and create leaky conditions. Water from this aquifer has been dated as ca 100 BP. Groundwater is available within 10 m below surface.

13.4 Hydrogeological Properties

The subtropical monsoon climate coupled with favorable geologic and hydrogeologic settings indicates high groundwater storage potential in the aquifers of Bangladesh (Zahid and Ahmed 2006). Numerous pumping tests carried out throughout Bangladesh found that in a regional scale, the near-surface Quaternary alluvium acts as a single hydraulically connected aquifer unit with reasonably good transmission and storage properties (Michael and Voss 2009; Rajmohan and Prathapar 2013). Aquifer tests conducted by the Bangladesh Water Development Board (BWDB) give hydraulic conductivity (K) values ranging from 3×10^{-5} to 1×10^{-3} m/s (Hussain and Abdullah 2001). Pumping tests reported that the shallow aquifer system in most parts of the country has a mean transmissivity of $1{,}270 \pm 770$ m^2/day and a specific yield of 0.01–0.20 (UNDP 1982; BWDB 1994; Shamsudduha et al. 2011). According to Domenico and Schwartz (1998), specific storage values typically range from roughly 10^{-5} per m (dense sandy gravel) to 10^{-2} per m (plastic clay) for materials in the Bengal Basin aquifer system.

In the dry season, groundwater levels across Bangladesh become depressed. The aquifers are replenished by heavy rainfall and flooding during monsoon season (Kahlon et al. 2012). However, the rate of recharge is variable and controlled by the properties of the overlying soil and geology of the area. According to the Bangladesh Bureau of Statistics (2005), an estimated 21.1 bcm of groundwater resources is produced within the country. In addition, an important, but unknown, quantity of groundwater flows into Bangladesh through horizontal flow paths from the Himalayan system (BanDuDeltAS 2015). During dry season, the shallow groundwater discharges to major rivers within Bangladesh (Datta et al. 2009).

13.5 Groundwater Geochemistry of Bangladesh

Most of the groundwater of Bangladesh is characterized by circum-neutral pH (6.5–7.6), and the oxidation-reduction potential (Eh) varies between +594 and −444 mV (Mukherjee and Bhattacharya 2001). Dowling et al. (2002) found that the groundwater is calcium carbonate rich, contains some sodium chloride-type water, no sulfate and background concentrations of most trace metals, except for strontium, barium, iron, manganese, and arsenic. Overall, these groundwater geochemistry results are consistent with the findings of the other investigations of groundwater of Bangladesh (e.g., BGS and DPHE 2001; Mukherjee and Bhattacharya 2001; Harvey et al. 2002; van Geen et al. 2003; Anawar et al. 2011). These past investigations found that the groundwater exhibits low dissolved oxygen concentrations, characteristically high concentrations of iron and manganese, and low levels of sulfate that are consistent with characteristics of reducing environments (Ahmed et al. 1998; Bhattacharya et al. 2002; Harvey et al. 2002; Chatterjee et al. 2013). The reducing conditions are likely due to presence of organic matter-enriched peat layers, which are interspersed throughout the aquifer sediment (McArthur et al. 2001). It is also possible that dissolved organic matter is brought to depth during recharge from surface water sources (Harvey et al. 2002). Note that in some parts of the country, conditions are even sufficiently reducing for methanogenesis (Ahmed et al. 1998; Hoque et al. 2003).

13.6 Arsenic

The discovery of widespread arsenic contamination in groundwaters of Bangladesh has linked the country with what has been dubbed “the largest mass poisoning in history” (Smith et al. 2000). An estimated 35–77 million people have been chronically exposed to arsenic through drinking water from shallow aquifers containing up to 100 times the World Health Organization's (WHO) drinking water limit of 0.01 mg/L (Smith et al. 2000; Smedley and Kinniburgh 2002; Burgess et al. 2010; Edmunds et al. 2015). In 1983, the first cases of arsenic induced dermal lesions were identified in Kolkata in neighboring West Bengal, India (Saha 1995), and by 1997, numerous other cases were identified in neighboring Bangladesh (Smith et al. 2000; Smedley and Kinniburgh 2002). Clinical manifestations of arsenic poisoning begin with various forms of skin diseases and progress by damaging internal organs, which ultimately lead to cancer and death. These symptoms of long-term arsenic poisoning may take five to fifteen years to appear. In late 1990s, it was established that the affected population were mainly drinking water from tube wells, which tapped into shallow alluvial aquifers that were laced with arsenic (Jakariya et al. 1998; Smith et al. 2000; Ravenscroft et al. 2005). Public concerns over arsenic in drinking water from groundwater sources have increased in the past few decades owing to widespread evidence of chronic arsenic poisoning from consumption of high arsenic-contaminated groundwater (Smedley and Kinniburgh 2002; Haque et al. 2008). The widespread arsenic crisis prompted many studies of hydrogeochemical processes governing the mobilization of arsenic into the groundwaters of the Bengal Basin.

In an effort to evaluate the extent of arsenic problem, the National Hydro-chemical Survey (NHS), which is the most comprehensive water-quality dataset for Bangladesh, was carried out by the Department of Public Health Engineering (DPHE), the British Geological Survey (BGS), and Mott MacDonald Ltd., UK. Between 1998 and 1999, NHS surveyed 61 of the 64 administrative districts of the country (except for the Chittagong Hill Tracts, which are mostly arsenic-free) and analyzed water samples from 3534 tube wells for arsenic and other elements. The NHS reported the aqueous concentration of arsenic range from <1 to 1,500 μg/L (Fig. 13.2); the arsenic concentrations exceeded the Bangladesh standard of 50 μg/L in approximately 27% of the tube wells, and roughly 42% of the tube wells exceeded the 10 μg/L WHO standard for arsenic in drinking water (BGS and DPHE 2001; Kinniburgh et al. 2003). More recently, the Bangladesh National Drinking Water Quality Survey (BNDWQS) of 2009 was conducted by the Bangladesh Bureau of Statistics (BBS), with participation from UNICEF. In this survey, drinking water samples were collected from 15,000 households that were randomly selected from all geographic areas of Bangladesh. The distribution of arsenic found in BNDWQS (2009) agrees with that found in the previously conducted NHS by BGS and DPHE (2001), with 13.4% of samples exceeding the Bangladesh standard and 32.0% of samples exceeding the WHO guideline value for arsenic in drinking water (UNICEF 2011).

Arsenic is now recognized to be the most important groundwater-quality problem in the GBM delta region of Bangladesh and the neighboring Indian state, West Bengal. It is well documented that the majority of the shallow (depth <150 m) alluvial aquifers under the recent floodplain are enriched with arsenic, whereas groundwater from Pleistocene and older aquifers is largely free of arsenic (e.g., BGS and DPHE 2001; Mukherjee and Bhattacharya 2001; Nordstrom 2002;

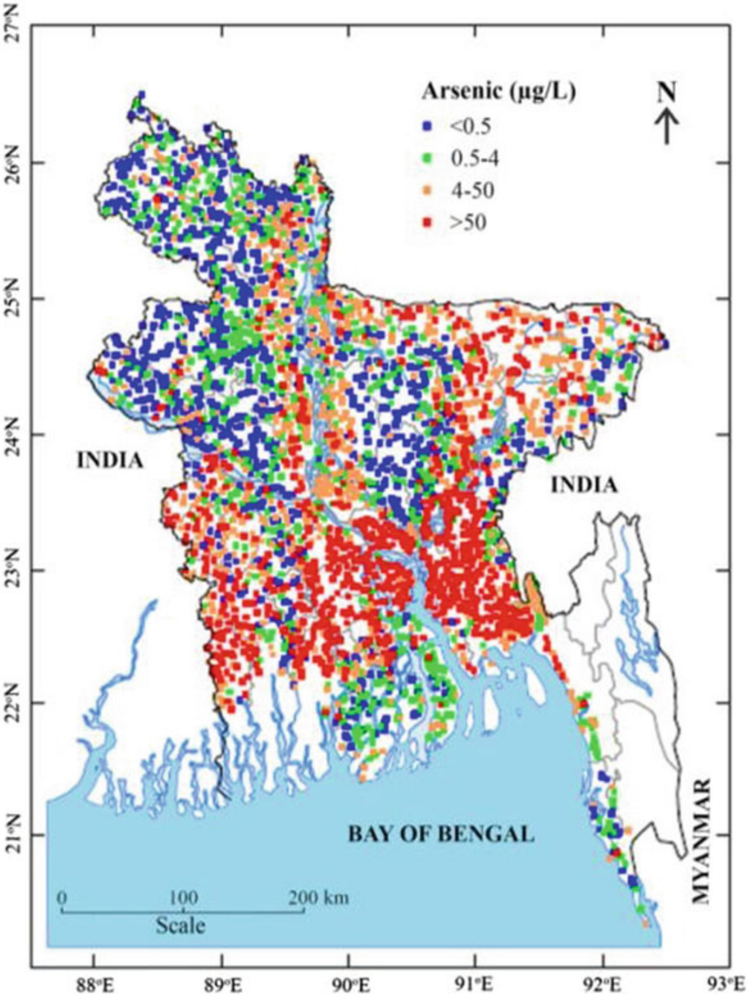


Fig. 13.2 Distribution of arsenic in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

Ravenscroft et al. 2005). It is generally agreed that the arsenic is geologic in origin, deriving from the sediments from the upland Himalayan catchments (McArthur et al. 2001; Nickson et al. 2000; Harvey 2001; Harvey et al. 2002). In particular, delta plains and flood plains of the Ganges–Brahmaputra river system exhibit moderate-to-severe arsenic enrichment with more than 60% of the tube wells affected. The worst-affected shallow aquifers lie below the Meghna floodplains and coastal plains with more than 80% of the tube wells affected (Ahmed et al. 2004). Aquifers within the Pleistocene uplands and tertiary hills and their adjacent Piedmont plains are low in arsenic (Ahmed et al. 2004).

The aquifer matrix serves as the primary source of arsenic, which under favorable condition release arsenic into the groundwaters (Hoque et al. 2009; Chakraborty et al. 2015). Past studies have reported that the arsenic-rich groundwaters are characterized by reducing aquifer conditions with notably high dissolved iron concentrations and low nitrate and sulfate levels (BGS and DPHE 2001; Nordstrom 2002). Numerous biogeochemical processes have been advanced to explain the elevated levels of arsenic in these aquifers, and it is presumed to reflect reductive dissolution of ferric oxides/oxyhydroxides as coatings on sand grains as well as biotite and release of sorbed and/or co-precipitated arsenic into the groundwaters (Nickson et al. 2000; McArthur et al. 2001; Dowling et al. 2002; Harvey et al. 2002; Haque and Johannesson 2006; Haque et al. 2008).

It is important to note that only 1% of the tube wells tapping the deep aquifers (depth >150 m) in the Bengal Basin are arsenic-enriched (BGS and MML 1999). Additionally, Ravenscroft et al. (2013) reported that between 1998 and 2011, groundwater composition remained stable in 46 tube wells from depths of more than 150 m from across the arsenic-contaminated region of southcentral Bangladesh. Moreover, there is no evidence of water-quality deterioration with respect to arsenic, iron, manganese, barium, boron, or salinity during these 13 years. Therefore, tube wells tapping the deep aquifers are likely to provide a safe and economic means of arsenic mitigation in the country.

13.7 Iron

High levels of dissolved iron are common in tube well water samples collected from various parts of Bangladesh (Fig. 13.3; BGS and DPHE 2001; Frisbie et al. 2009; Islam et al. 2015). The NHS reported that the maximum dissolved iron concentration was 61 mg/L with a median value of 1.1 mg/L. Additionally, the survey found that 23 and 10% of the tube well waters contain more than 5 and 10 mg/L dissolved iron concentrations, respectively. Whereas out of the 2896 tube well water samples analyzed by BNDWQS (2009), 60% of the samples meet the Bangladesh standard for iron in drinking water of 0.3–1.0 mg/L (Department of Environment 1991; UNICEF 2011). The notable difference in iron concentrations in the BGS and DPHE (2001) and BNDWQS (2009) may have resulted from difference in the sampling techniques employed. The BGS and DPHE survey aimed for a statistically representative sample of groundwater, whereas the BNDWQS survey targeted household water for drinking. Note that on contact with air during storage in the household, iron can react with oxygen and form insoluble precipitates (UNICEF 2011). A possible explanation is that users prefer to collect drinking water from sources which taste better (i.e., groundwater with lower levels of dissolved minerals).

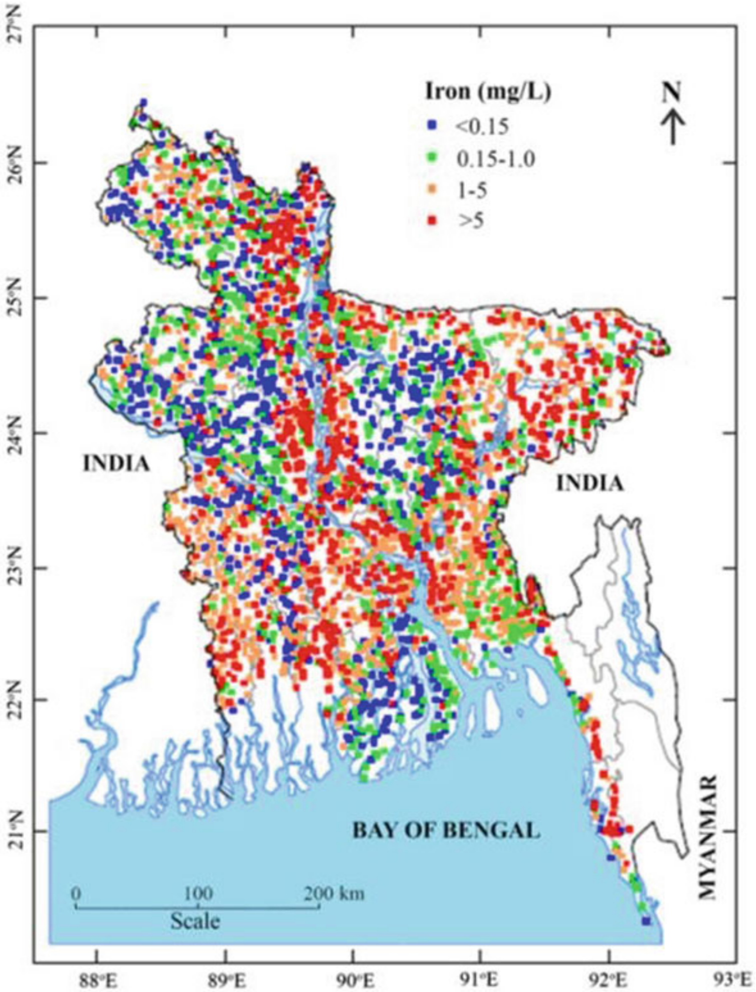


Fig. 13.3 Distribution of iron in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

Hossain and Huda (1997) analyzed well water samples from roughly 1000 deep tube wells of the 56 districts out of 64 districts, covering 86% of total area of Bangladesh. These investigators reported that 41 and 22.5% of the studied area exceed dissolved iron concentrations of 1.0 and 5.0 mg/L, respectively. Studies have linked extended exposure to dissolved iron with hemochromatosis, a disorder of iron regulation in human body (WHO 1996a; Rajappa et al. 2010).

13.8 Manganese

Roughly 39% and 65% of the BNDWQS (2009) samples met the Bangladesh standard for manganese of 0.1 mg/L and the WHO guideline value of 0.4 mg/L for manganese in drinking water, respectively (UNICEF 2011). The 3534 wells surveyed in the BGS and DPHE (2001) study found the maximum concentration of dissolved manganese at 10 mg/L with a median value of 0.3 mg/L (Fig. 13.4). Additionally, the dataset indicates that the deeper wells contain much less manganese compared to the shallower wells. Elevated manganese levels are reported in

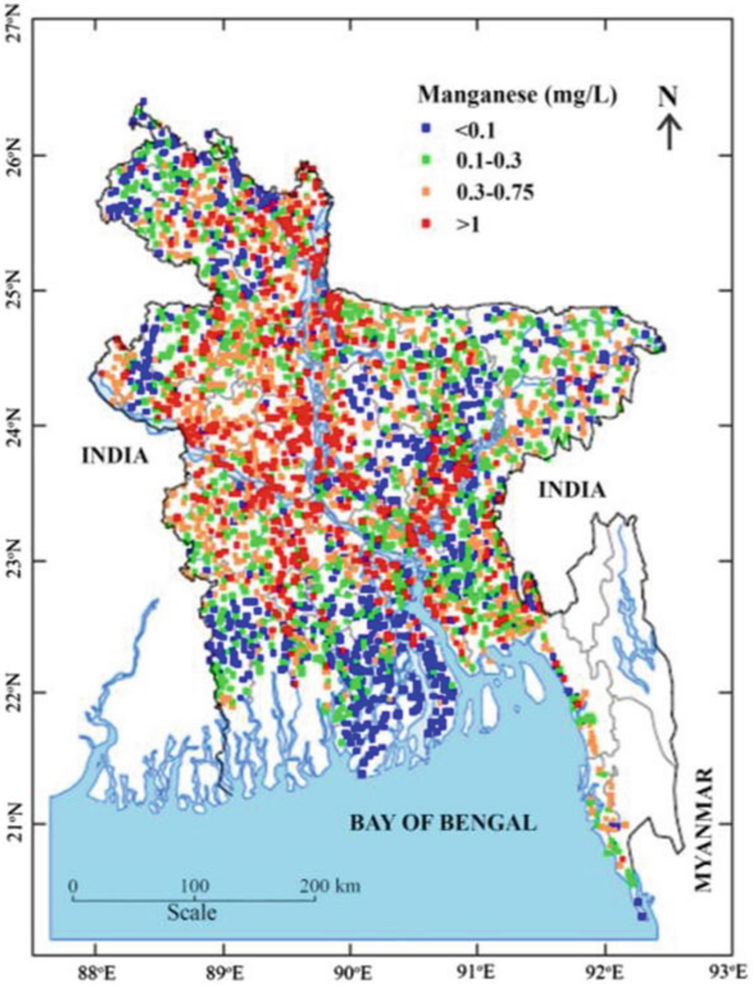


Fig. 13.4 Distribution of manganese in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

most areas of the country. However, notably high-manganese groundwaters are commonly associated with the present-day Brahmaputra and Ganges floodplains (i.e., the central, northern, and western regions of Bangladesh; Zahid and Ahmed 2006). An estimated 60 million people in Bangladesh are drinking water with manganese concentrations exceeding the WHO's guideline value (BGS and DPHE 2001; Frisbie et al. 2009; Hasan and Ali 2010). Manganese-induced neurotoxicity following prolonged exposure to very high levels of manganese in drinking water is well documented (Bouchard et al. 2007, 2011; Wasserman et al. 2006). Many studies have reported link between chronic ingestion of manganese and adverse neurological effect, such as Parkinsonian disorder in humans (e.g., Kondakis et al. 1989; Dorsey et al. 2007; Ferri et al. 2005). Manganese is also known to cause learning disabilities in children (Wasserman et al. 2006).

In the context of arsenic, numerous studies have reported a positive correlation between low arsenic and high manganese concentrations (Fig. 13.5; BGS and WaterAid 2001; Hoque 2006; Hasan and Ali 2010). Furthermore, the BNDWQS found that roughly 93% of deep tube wells meet the Bangladesh standard for arsenic; however, only 60% of deep tube wells meet the Bangladesh standards for arsenic, manganese, and iron (UNICEF 2011). This is an important finding not only in terms of well switching but also the presence of high levels of manganese further complicates an already difficult drinking water supply scenario in rural Bangladesh (Hasan and Ali 2010).

13.9 Nitrate and Ammonia

In a recent investigation by Parvez et al. (2014), groundwater samples collected from central Bangladesh were analyzed for levels of reactive nitrogen species, nitrate, and ammonia. These authors reported that levels of nitrate present in analyzed water are generally low. Majumder et al. (2008) investigated the spatial distribution of nitrate in groundwater samples in west central region of Bangladesh. This study found that in groundwater of the shallow and deep aquifers, nitrate levels range from <0.10 to 75.12 mg/L and <0.10 to 40.78 mg/L, respectively. Others have also found low levels of nitrate (4 mg/L or less) in ground water samples in Chapai Nawabganj, Faridpur, Laksmipur, and Comilla (BGS and DPHE 2001; Rasul and Jahan 2010). Additionally, high nitrate levels reported by NHS were usually restricted to a few shallow wells that had evidence of surface pollution (BGS and DPHE 2001).

Parvez et al. (2014) reported that ammonia levels in most of the ground water samples from central Bangladesh were less than 5 mg/L. Note that natural levels of ammonia in groundwaters are commonly below 0.2 mg/L (WHO 1996b). There is no WHO health-based guideline for ammonia as it is not considered to be of direct importance for human health in the concentrations to be expected in drinking water (WHO 1996a, b). However, the presence of ammonia may impart unpleasant odor to drinking water.

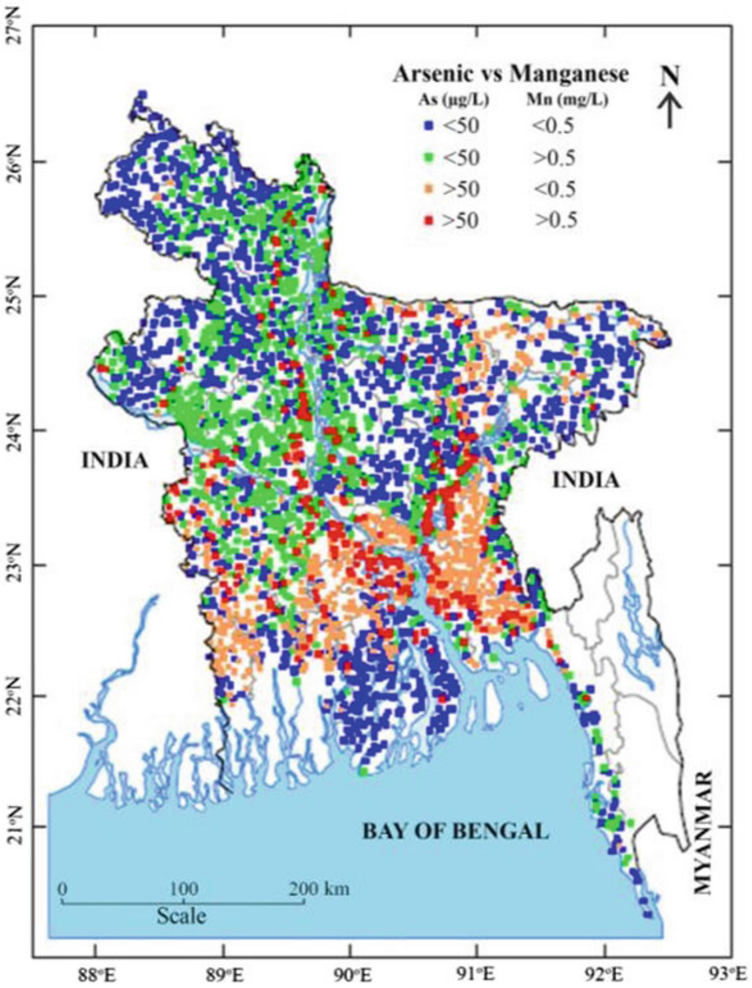


Fig. 13.5 Distribution of arsenic versus manganese in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

13.10 Sulfate

The BGS and DPHE (2001) countrywide data set reported low concentrations of sulfate with a minimum less than 0.4 mg/L and with a median value of 1 mg/L. The dataset also shows a trend of rapidly decreasing sulfate with depth that is consistent with cyclical sulfide weathering with water-table fluctuations (Harvey et al. 2006). Harvey et al. (2002) found an inverse correlation between arsenic and sulfate in the young Holocene aquifers of Bangladesh, suggesting that it is unlikely that arsenic could be liberated from sulfide minerals.

13.11 Methane

Widespread occurrence of biogenic methane has been reported in groundwaters from most parts of the country, as well as in some areas of the southeastern region (Ahmed et al. 1998; Hoque et al. 2001; McArthur et al. 2001). Biogenic methane is the ultimate end-product of microbially mediated reductive fermentation (Whiticar and Schoell 1986; Harvey et al. 2002). Ahmed et al. (1998) reported that the deltaic region of the Bengal Basin hosts conditions, such as the amount of total organic carbon and organic matter, burial depth, hydrothermal gradient along with degree of compaction, which are conducive for methane gas generation. Furthermore, the authors state that areas containing highly saline groundwater generate more methane gas than the rest of the country, suggesting an estuarine depositional environment of the aquifer materials in the areas of high salinity (Ahmed et al. 1998).

13.12 Boron

The NHS survey found that the boron-enriched groundwater samples are mostly found in the coastal region along with low-lying areas near Netrokona and Kishorganj (Fig. 13.6; BGS and DPHE 2001). The dataset shows that in 5.3% of well water samples, concentrations of boron exceed the earlier WHO health-based guideline value of 0.5 mg/L. Note that the revised WHO guideline value for boron (borate) in drinking water is 2.4 mg/L (WHO 2011). The revision is based upon a review of the toxicological data and studies in areas with high background exposures. Boron distribution of the BNDWQS (2009) shows that 94% well water samples meets the Bangladesh standard of 1.0 mg/L.

Ravenscroft and McArthur (2004) reported that concentrations of boron in groundwater reached 2.1 mg/L in the study areas from southwestern (Khulna) and coastal (Barisal, Khulna and Chittagong) regions of Bangladesh. Additionally, boron levels exceeded 0.5 mg/L across roughly 3000 km^2 of the shallow aquifer and 6700 km^2 of the deep aquifer. Typically, the high boron levels are accompanied by high levels of sodium, which is possibly due to saltwater intrusion in the southwestern region (Hassan et al. 1998; Rahman et al. 2000), or due to the presence of residual seawater in the underground aquifers (BGS and DPHE 2001; Acton 2013; Bañuelos 2015).

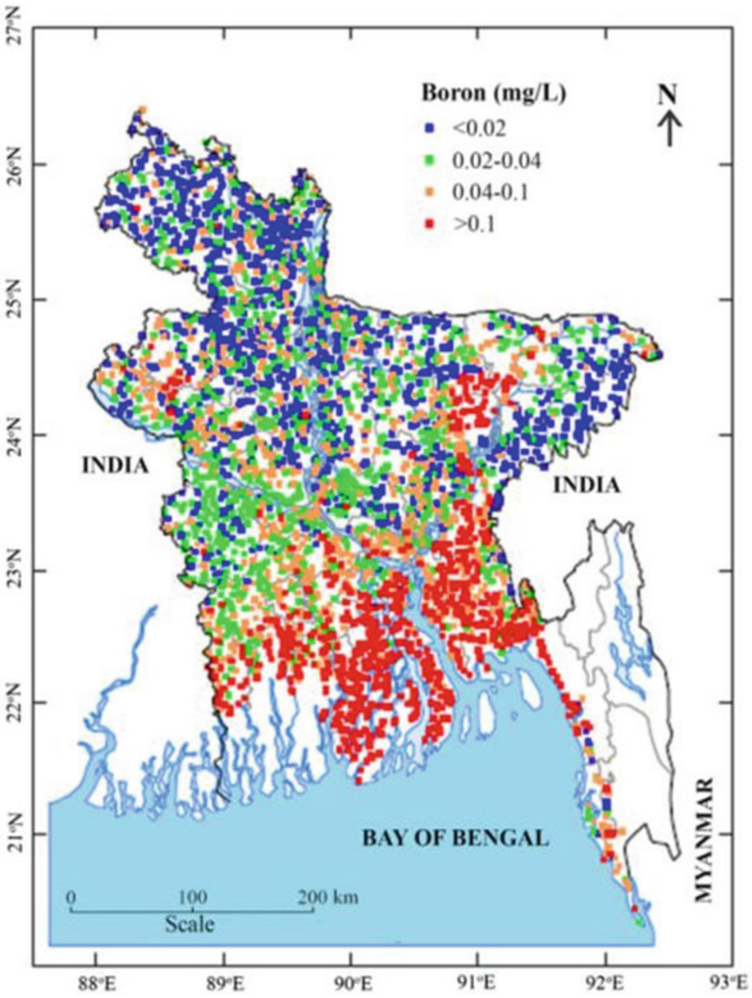


Fig. 13.6 Distribution of boron in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

13.13 Fluoride

BGS and DPHE (2001) reported that concentration of fluoride is comparatively low in the groundwater of Bangladesh, ranging from 0.01 to 0.73 mg/L, with none of samples exceeding the WHO guideline value for fluoride in drinking water of 1.5 mg/L and Bangladesh standard of 1.0 mg/L. The lowest concentrations are found in northwestern parts of the country and the Chittagong coastal region. About 99% samples of the BNDWQS (2009) meet the Bangladesh standard for fluoride, and low concentrations of fluoride were reported across the country. Approximately

1% of the BNDWQS samples exceeds the Bangladesh standard and ranged between 1.1 and 1.5 mg/L. It is important to note that fluoride deficiency-related health problems, such as dental carries, especially in children, may result in areas with low fluoride concentrations (Chouhan and Flora 2010), whereas excess intake of fluoride can lead to discolouration and dental fluorosis (UNICEF 2011).

13.14 Iodide

There is little information available about the iodide levels in the groundwater of Bangladesh. BGS and DPHE (2001) reported that the distribution of iodide levels in groundwaters is varying, ranging from 0.004 to 5.84 mg/L. The higher concentrations are usually found in the coastal region aquifers, and the iodide is seawater derived. In some parts of northern Bangladesh, the iodide levels are low (<3 μg/L) and problematic as this could cause iodine-deficiency disorders, such as high incidence of goiter (BGS and DPHE 2001). Additionally, iodine deficiency during pregnancy and infancy could cause mental retardation (Sack et al. 2000).

13.15 Barium

The WHO guideline value for barium is 0.7 mg/L, and the Bangladesh standard for barium is 0.01 mg/L, which is reportedly a typographical error (UNICEF 2011). The BGS and DPHE (2001) report that barium levels have a nearly similar range in both the shallow and deep groundwaters of Bangladesh, ranging from <0.06 to 1.4 mg/L and <0.06 to 1.0 mg/L, respectively (Fig. 13.7).

The highest concentrations are observed in the southwestern regions along with occasional highs in the Brahmaputra Valley and the Sylhet Basin. In addition, the highest concentrations roughly correspond to those of other alkaline earth elements (e.g., calcium, magnesium, and strontium). The BNDWQS (2009) dataset shows that 99% of the well water samples meet the WHO guideline value for barium (UNICEF 2011). However, barium distribution in the BNDWQS and that in BGS and DPHE (2001) samples are considerably different, with a probability of 55.4% that the BNDWQS distribution is greater than the BGS and DPHE (2001) distribution.

Significant correlations have been observed between concentrations of arsenic and barium in urine ($r = 0.774$), nail ($r = 0.719$), and hair ($r = 0.773$) samples collected from residents of the Indian State of West Bengal and Bangladesh ($n = 31$–59; Chakraborti et al. 2003). Chronic exposure to high levels of barium in drinking water has the potential to cause hypertension (WHO 2004). However, the combination of toxicity resulting from high levels of arsenic and barium in drinking water is yet to be studied for the Bangladesh population.

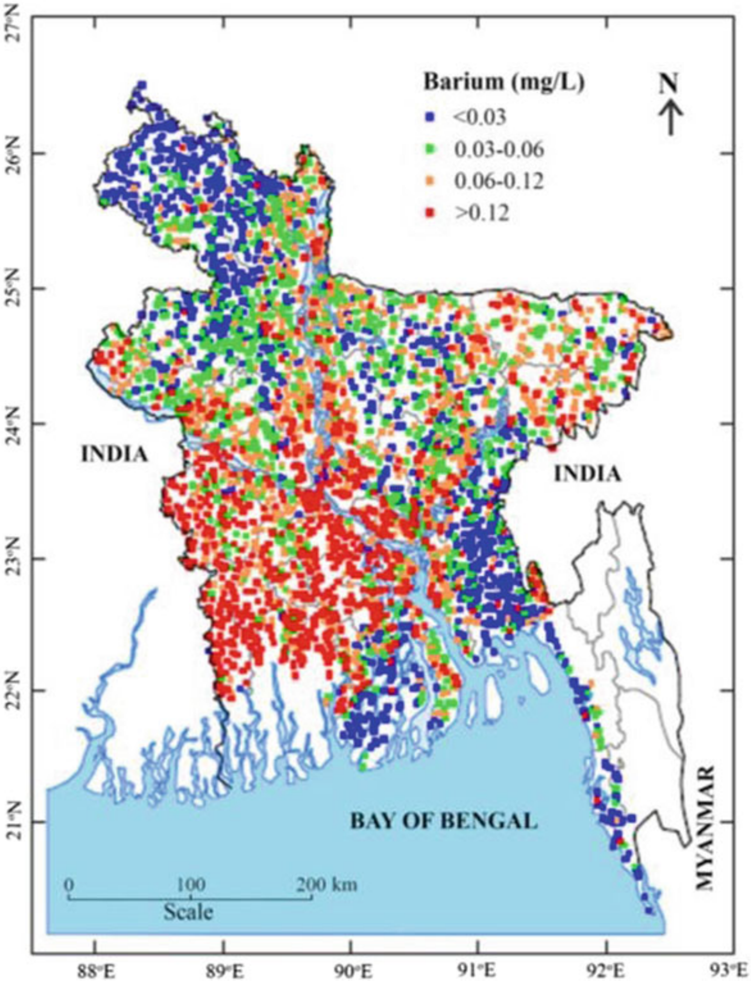


Fig. 13.7 Distribution of barium in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

13.16 Strontium

At this time, there is neither a Bangladesh standard, nor a WHO guideline value for strontium in drinking water. The BGS and DPHE (2001) reported concentrations range from <0.2 to 1.6 mg/L and <0.2 to 3 mg/L in the groundwater of the shallow and deep aquifers, respectively (Fig. 13.8). The survey reported that the regional distribution in the groundwater reflects dissolution of carbonate minerals in the aquifer matrix. Additionally, the observed increase in strontium concentrations in the southern coastal region is ascribed to seawater intrusion. The lowest

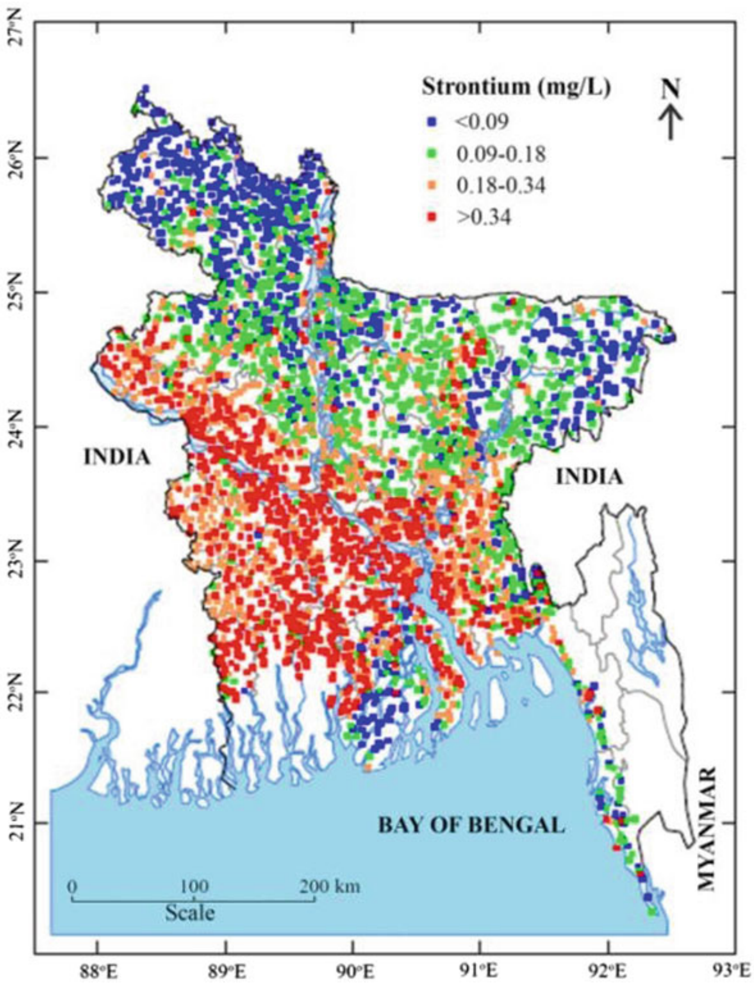


Fig. 13.8 Distribution of strontium in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

concentrations are found in the groundwater of the Tista Fan and Sylhet Basin. In general, low concentrations are observed in the deep aquifers of the extreme south coastal area. In these deep waters, strontium concentrations appear to follow a trend similar to that of calcium concentrations. There is a small difference in the magnitude of strontium contents between BNDWQS (2009) and BGS and DPHE (2001) distributions (UNICEF 2011).

13.17 Uranium

The sedimentary successions of Bangladesh have continental sandstones along with lignite and organic matter, a lithology that is favorable for uranium occurrence in sandstones (Majumder 2014). BGS and DPHE (2001) reported that well water samples collected from Chapai Nawabganj, Faridpur, and Lakshmipur showed uranium concentrations up to 47 μg/L and the average concentration found was 2.8 μg/L. The reported concentrations of uranium in BNDWQS (2009) and BGS and DPHE (2001) samples are not significantly different. Frisbie et al. (2009) analyzed groundwater samples collected from western Bangladesh and found that the uranium concentrations range from <0.2 to 10 μg/L, with 48% of the tube wells exceeding the previous 2 μg/L WHO guideline for uranium in drinking water. Note that recently, the guideline value for uranium in drinking water has been revised upward and the new provisional guideline value is 30 μg/L. The new standard is derived from epidemiological studies on human populations exposed to high levels of uranium from drinking water sources (WHO 2011). There is no Bangladesh standard for uranium.

Sultana et al. (2014) analyzed 261 well water samples from 54 administrative districts in Bangladesh to investigate the dissolved uranium. The authors report that uranium concentration ranges between 0.5 and 10 μg/L in 27% of tube well samples, 11–20 μg/L in 38% of tube well samples, 21–30 μg/L in 16% of tube well samples, and 19% of the samples exceeded the recent WHO provisional guideline for uranium in drinking water. Based on the findings of these studies, detailed investigations of uranium occurrence in the aquifers of Bangladesh are required to assess the potential for adverse human health effects of uranium-contaminated drinking water.

13.18 Fecal Contamination of Groundwater

Three past studies exploring microbial contamination of shallow tube wells of the Bengal Basin found that more than 40% of water samples collected were contaminated with human fecal organisms (Hoque 1999; Islam et al. 2001; Luby et al. 2006). Luby et al. (2006) reported that groundwater samples collected from 207 tube wells located in the flood-prone districts of Comilla, Brahmanbaria, and Sirajganj were microbiologically contaminated with total coliforms (41%), thermo-tolerant coliforms (29%), and *Escherichia coli* (13%). The study further found that 86% of tube wells were located within close proximity ($\sim$10 m) of a latrine and 70% had some source of pollution within 10 m. Cow barns, fertilizer, and surface water ingress appear to be the possible sources of contamination of the tube well waters.

More recently, van Geen et al. (2011) found that a high proportion of shallow tube wells from Araihazar and Matlab upazilas contained detectable levels of fecal indicator *E. coli* almost throughout the year. The key finding of this study is that shallow tube wells that meet the WHO standard for arsenic are more likely to contain detectable levels of *E. coli*. The significance of this inverse relationship between fecal contamination and aqueous arsenic is that well switching may expose the users of rural Bangladesh to higher levels of diarrheal disease pathogens.

13.19 Groundwater Pollution from Urban Industrial Areas

Rapid urbanization coupled with industrialization is responsible for increased heavy metal concentrations in soils and sediments in many parts of the country. High levels of chromium, aluminum, and iron have accumulated in topsoils (up to 6 m) of Hazaribagh leather processing area of Dhaka city (Zahid et al. 2004). Moreover, significant amounts of manganese, zinc, nickel, and copper are present in shallow groundwater of this area (Zahid and Ahmed 2006). Approximately 1% of tube wells exceed the 10 μg/L WHO health-based drinking water guideline for lead. Bodrud-Doza et al. (2016) reported that ceramics, brick, and pottery industries are located in the study area likely contribute to heavy metals, such as nickel and zinc in groundwaters of Faridpur district located in central Bangladesh.

13.20 Agrichemicals

Intensive agricultural practice along with generous application of commercial fertilizer and pesticides are widespread in the country. Runoff and infiltration of agrichemicals (i.e., commercial fertilizers and pesticides) from farmlands into water bodies should be considered a serious concern with respect to their impact on groundwater quality. In Bangladesh, between 1975 and 1976, fertilizer consumption was 0.36 kg/ha of agricultural land, whereas by 2007 it had increased to 298 kg/ha (Basak 2011). In the central-west region of Bangladesh, the shallow and deep groundwater nitrate concentrations range from <0.10 to 75.12 mg/L and <0.10 to 40.78 mg/L, respectively (Majumder et al. 2008). The WHO's maximum contaminant level (MCL) for nitrate is 50 mg/L. Nitrates are highly soluble, mobile, and not readily biodegradable. The source of both nitrate and ammonium-N in groundwaters of Bangladesh has been ascribed to excessive application of nitrogenous fertilizer (Kurosawa et al. 2008; Majumder et al. 2008).

Recent studies of pesticide in groundwaters of Bengal Basin have found a large area of the Ganges aquifers to be susceptible to pesticide pollution (e.g., Anwar and

Yunus 2013; Saha and Alam 2014). An investigation of the mobility and leaching potential of various pesticides in a shallow unconfined aquifer in northwest Bangladesh reported that topsoils are found to be vulnerable to organochlorine pesticide accumulation (Anwar and Yunus 2013). Additionally, low concentrations of heptachlor and dichlorodiphenyltrichloroethane (DDT) were detected in some parts of the country (Zahid and Ahmed 2006). Furthermore, Hossain (1997) reported higher concentration of ammonium and nitrate in shallow aquifers. Because of its solubility, excessive ammonia may infiltrate into deeper soils and ultimately reach groundwater.

13.21 Saltwater Intrusion

Most groundwater in Bangladesh is fresh, except in parts of the southern coastal region where salinity is the highest in groundwater due to ingress of seawater (Ahmed 1994; Ravenscroft 2003). In coastal plain aquifers of southern Bangladesh, a sequence of aquifer layers containing saline or brackish groundwater overlies deeper aquifers containing freshwater (DPHE-DANIDA 2001). During the dry season, moderate-to-strong saline groundwaters are encountered within 1–2 m below the soil surface at all locations (Datta and Biswas 2004; Rasel et al. 2013). The coastal communities in the southern region are particularly vulnerable to salinity intrusion due to increasingly shrinking quantities of freshwater (Rasel et al. 2013). Note that salinization of groundwater is a serious threat to aquifer sustainability as there is no natural attenuation mechanism (UNEP-DEWA 2003).

13.22 Consequences of Groundwater Overdraft

It is widely documented that during the last decade, long-term excessive exploitation of groundwater has led to substantial drawdown of aquifers (McArthur et al. 2001; Jahan et al. 2010; Shahid 2011). The worst-affected areas in terms of declining water table lie in the northwestern (i.e., Barind Tract) and northcentral (Madhupur Tract) regions (Shamsudduha et al. 2009). These are areas of *Boro* rice cultivation and intensive groundwater-fed irrigation in the dry season. An estimated 3,000–5,000 L of water is required to produce one kilogram of rice (Biswas and Mandal 1993). The irrigation water supply primarily comes from shallow aquifers. Bangladesh Agricultural Development Corporation (BADC 2003) reported that between 1979 and 2003, groundwater-fed irrigation for dry season rice cultivation has increased annually by around 875 million m^3. Numerous studies have reported that in the northwestern regions, water tables are declining steadily at a rate of 0.1–0.5 m/year (e.g., Shamsudduha et al. 2009; Dey et al. 2013). In contrast, rising groundwater levels (0.5–2.5 cm/year) are observed in the southern coastal region, albeit slow, a consequence of seawater intrusion (Shamsudduha et al. 2009;

Brammer 2014). Groundwater use in the coastal region remains unexploited due to salinity concerns in shallow and lower shallow aquifers (Qureshi et al. 2014).

Acknowledgements The author is deeply grateful to Mr. Mahbub Haque for all his help, support and valuable comments that greatly improved the manuscript. The author thanks Messrs. S. M. Habibullah, Md. Ahsanul Hoque, and Md. Alamgir for their assistance with the figures.

References

Acharyya SK, Lahiri S, Raymahashay BC, Bhowmik A (2000) Arsenic toxicity of groundwater in parts of the Bengal basin in India and Bangladesh: the role of Quaternary stratigraphy and Holocene sea-level fluctuation. Environ Geol 39(10):1127–1137

Acton QA (2013) Boron compounds—advances in research and application. Scholarly Edition, Georgia

Ahmed KM (1994) Hydrogeology of the Dupi Tila Aquifer of the Barind Tract, NW Bangladesh. Ph.D. thesis, University of London (Unpublished)

Ahmed KM, Hoque M, Hasan MK, Chowdhury LR (1998) Occurrence and origin of water well methane gas in Bangladesh. J Geol Soc India 51(5):697–708

Ahmed KM, Bhattacharya P, Hasan MA, Akhter SH, Alam SMM, Bhuyian MAH (2004) Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview. Appl Geochem 19(2):181–200

Alam A (2006) Groundwater zoning map and its application. A National Seminar of Bangladesh Agricultural Development Corporation Paper, Sech Bhaban, Dhaka, Bangladesh

Anawar HM, Akai J, Mihaljevič M, Sikder AM, Ahmed G, Tareq SM, Rahman MM (2011) Arsenic contamination in groundwater of Bangladesh: perspectives on geochemical, microbial and anthropogenic issues. Water 3:1050–1076. https://doi.org/10.3390/w3041050

Anwar AHMF, Yunus A (2013) Groundwater vulnerability to pesticides in Northwest Bangladesh. Environ Earth Sci 70:1971–1981. https://doi.org/10.1007/s12665-013-2708-1

Ball M, Landis ER, Woodside PR (1981) Geological assessment of fossil energy potential of Bangladesh. United States Department of the Interior Geological Survey, Project Report Bangladesh Investigation (IR) BG-6

BanDuDeltAS (2015) Water resources: Bangladesh Delta Plan 2100 formulation project, Baseline Study

BADC (Bangladesh Agriculture Development Cooperation) (2003) Survey report on irrigation equipment and irrigated area in Boro 2003 season. Survey and monitoring project for development of minor irrigation, Bangladesh Agricultural development Corporation, Sech Bhaban, Dhaka

BNDWQS (Bangladesh National Drinking Water Quality Survey) (2009) Bangladesh Bureau of Statistics, Planning Division, Ministry of Planning, Government of the People's Republic of Bangladesh

Bañuelos GS (2015) Coping with naturally-high levels of soil salinity and boron in the westside of central California. Perspect Sci 3(1–4):4–6

Basak J (2011) Future fertiliser demand for sustaining rice production in Bangladesh: a quantitative analysis. Unnayan Onneshan—The Innovators, Dhaka

BGS (British Geological Survey) and DPHE (Department of Public Health) (2001) Arsenic contamination of groundwater in Bangladesh. BGS Technical Report, WC/00/19. http://www.bgs.ac.uk/arsenic/bangladesh/, verified 24 Jan 2017

BGS and MML (Mott MacDonald Ltd) (1999) Groundwater studies for arsenic contamination in Bangladesh. Phase I: rapid investigation phase, Final Report in 4 volumes prepared for the Government of Bangladesh and the Department for International Development, UK

BGS and WaterAid (2001) Groundwater quality: Bangladesh. WaterAid, Bangladesh

Bhattacharya P, Jacks G, Ahmed KM, Khan AA (2002) Arsenic in groundwater of the Bengal Delta Plain Aquifers in Bangladesh. Bull Environ Contam Toxicol 69(4):538–545

Biswas MR, Mandal MAS (1993) Irrigation management for crop diversification in Bangladesh. Bangladesh Dev Stud 91:91–100

Bodrud-Doza M, Islam ARMT, Ahmed F, Das S, Saha N, Rahman MS (2016) Characterization of groundwater quality using water evaluation indices, multivariate statistics and geostatistics in central Bangladesh. Water Sci 30(1):19–40

Bouchard M, Laforest F, Vandelac L, Bellinger D, Mergler D (2007) Hair manganese and hyperactive behaviors: pilot study of school-age children exposed through tap water. Environ Health Perspect 115:122–127

Bouchard M, Sauvé S, Barbeau B, Legrand M, Brodeur M-È, Bouffard T (2011) Intellectual impairment in school-age children exposed to manganese from drinking water. Environ Health Perspect 119:138–143

Brammer H (2014) Bangladesh's dynamic coastal regions and sea-level rise. Clim Risk Manag 1:51–56

Burgess WG, Hoque MA, Michael HA, Voss CI, Breit GN, Ahmed KM (2010) Vulnerability of deep groundwater in the Bengal Aquifer System to contamination by arsenic. Nat Geosci 3: 83–87

BWDB (Bangladesh Water Development Board) (1994) Report on the compilation of aquifer test analysis results. Water Supply Paper 534, Ground Water Circle II, BWDB, Dhaka

Chakraborty M, Mukherjee A, Ahmed KM (2015) A review of groundwater arsenic in the Bengal Basin, Bangladesh and India: from source to sink. Curr Pollut Rep 1(4):220–247

Chakraborti D, Rahman MM, Paul K, Chowdhury UK, Sengupta MK, Lodh D, Chanda CR, Saha KC, Mukherjee SC (2002) Arsenic calamity in the Indian subcontinent—what lessons have been learned? Talanta 58(1):3–22

Chakraborti D, Mukherjee SC, Pati S, Sengupta MK, Rahman MM (2003) Arsenic groundwater contamination in Middle Ganga Plain, Bihar, India: a future danger? Environ Health Perspect 111:1194–1201

Chatterjee D, Nath B, Chakraborty S, Majumder S, Biswas A, Bhomick S, Halder D, Mondal P, Kundu A, Saha D, Barman S, Biswas U, Saha I, Das A, Sarkar S, Chatterjee D (2013) Groundwater Arsenic in the Fluvial Bengal plains: geochemistry and mitigation. Procedia Earth Planet Sci 7:143–146

Cheng Z, Van Geen A, Jing C, Meng X, Seddique A, Ahmed KM (2004) Performance of a household-level arsenic removal system during 4-month deployments in Bangladesh. Environ Sci Technol 38(12):3442–3448

Chouhan S, Flora SJS (2010) Arsenic and fluoride: two major ground water pollutants. Indian J Exp Biol 48:666–678

Datta DK, Biswas D (2004) Vulnerability of coastal aquifers: a case study from Khulna City Corporation, SW Bangladesh. Abstract of the Technical Program XI, Geological Conference, Bangladesh Geological Society

Datta S, Mailloux B, Jung H-B, Hoque MA, Stute M, Ahmed KM, Zheng Y (2009) Redox trapping of arsenic during groundwater discharge in sediments from the Meghna river-bank in Bangladesh. Proc Natl Acad Sci USA 106(40):16930–16935. https://doi.org/10.1073/pnas.0908168106

Department of Environment (1991) Environmental quality standards for Bangladesh. Government of the People's Republic of Bangladesh

Dey NC, Bala SK, Saiful Islam AKM, Rashid MA (2013) Sustainability of groundwater use for irrigation in northwest Bangladesh. Policy Report prepared under the National Food Policy Capacity Strengthening Programme (NFPCSP). Dhaka, Bangladesh, 89

Domenico PA, Schwartz FW (1998) Physical and chemical hydrogeology, 2nd edn. Wiley, New York

Dorsey ER, Constantinescu R, Thompson JP, Biglan KM, Holloway RG, Kieburtz K (2007) Projected number of people with Parkinson disease in the most populous nations, 2005 through 2030. Neurology 68:384–386

Dowling CB, Poreda RJ, Basu AR, Peters SL (2002) Geochemical study of arsenic release mechanisms in the Bengal Basin groundwater. Water Resour Res 38:1173. https://doi.org/10.1029/2001wr000968

DPHE/BGS/MML (1999) Groundwater studies for arsenic contamination in Bangladesh Phase I: rapid investigation phase. Main report and five supplementary volumes. Department of Public Health Engineering, Government of Bangladesh, British Geological Survey and Mott MacDonal Ltd (UK)

DPHE-DANIDA (2001) Urban water and sanitation project. Five districts water and sanitation group, Ministry of Foreign Affairs, Denmark

Edmunds WM, Ahmed KM, Whitehead PG (2015) A review of arsenic and its impact in groundwater of the Ganges-Bramhaputra—Meghna delta, Bangladesh. Environ Sci Process Impacts 17(6):1032–1046. https://doi.org/10.1039/c4em00673a

Ferri CP, Prince M, Brayne C, Brodaty H, Fratiglioni L, Ganguli M (2005) Global prevalence of dementia: a Delphi consensus study. Lancet 366:2112–2117

Frisbie SH, Mitchell EJ, Mastera LJ, Maynard DM, Yusuf AZ (2009) Public health strategies for Western Bangladesh that address arsenic, manganese, uranium, and other toxic elements in drinking water. Environ Health Perspect 117(3):410–416. https://doi.org/10.1289/ehp.11886

Goodbred SL Jr, Kuehl SA (2000) The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: late Quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta. Sed Geol 133(3–4):227–248

Haque SE, Johannesson KH (2006) Arsenic concentrations and speciation along a groundwater flow path: the Carrizo Sand aquifer, Texas, USA. Chem Geol 228(1):57–71

Haque S, Ji J, Johannesson KH (2008) Evaluating mobilization and transport of arsenic in sediments and groundwaters of Aquia aquifer, Maryland, USA. J Contam Hydrol 99(1–4):68–84. https://doi.org/10.1016/j.jconhyd.2008.03.003

Harvey CF (2001) Possible causes of high arsenic concentrations in the well water of Bangladesh. Environ Sci 8(5):491–504

Harvey CF, Swartz CH, Baruzzaman ABM, Keon-Blute N, Yu W, Ali MA, Jay J, Beckie R, Niedan V, Brabander D, Oates PM, Ashfaque KN, Islam S, Hemond HF, Ahmed MF (2002) Arsenic mobility and groundwater extraction in Bangladesh. Science 298(5598):1602–1606

Harvey CF, Swartz CH, Badruzzaman ABM, Keon-Blute N, Yu W, Ali MA, Jay J, Beckie R, Niedan V, Brabander D, Oates PM, Ashfaque KN, Islam S, Hemond HF, Ahmed MF (2005) Groundwater arsenic contamination on the ganges delta: biogeochemistry, hydrology, human perturbations, and human suffering on a large scale. C R Geosci 337(1–2):285–296

Harvey CF, Ashfaque KN, Yu W, BadruzzamanABM, Ali MA, Oates PM, Michael HA, Neumann RB, Beckie Islam RS, Ahmed MF (2006) Groundwater dynamics and arsenic contamination in Bangladesh. 228(1–3):112–136

Hasan S, Ali MA (2010) Occurrence of manganese in groundwater of Bangladesh and its implications on safe water supply. J Civ Eng 38(2):121–128

Hassan MQ, Rahman M, Islam MS, Shamsad SZKM (1998) Effects of salinity on the hydrogeo-environment of Khulna city and Mongla Port area of Bangladesh. Dhaka Univ J Biol Sci 7:113–127

Hoque B (1999) Biological contamination of tubewell water. In: 8th annual scientific conference, Dhaka, Bangladesh, ICDDR, B, Dhaka, Bangladesh

Hoque A (2006) Assessment of iron, manganese and arsenic removal efficiencies of conventional iron removal plants. Master's thesis, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

Hoque M, Hasan MK, Ravenscroft P (2001) Investigation of groundwater salinity and gas problems in Southeast Bangladesh. In: Rahman AA, Ravenscroft P (eds) Groundwater resources and development in Bangladesh. Bangladesh Centre for Advanced Studies, University Press, Dhaka

Hoque M, Hasan MK, Ravenscroft P (2003) Investigation of groundwater salinity and gas problems in Southeast Bangladesh. In: Rahman AA, Ravenscroft P (eds) Groundwater resources and development in Bangladesh—background to the arsenic crisis, agricultural potential and the environment, Bangladesh Centre for advanced studies. University Press, Dhaka

Hoque MA, Khan AA, Shamsudduha M, Hossain MS, Islam T, Chowdhury SH (2009) Near surface lithology and spatial variation of arsenic in the shallow groundwater: southeastern Bangladesh. Environ Geol 56(8):1687–1695

Hossain M (1997) Groundwater pollution by fertilizers and pesticides. In: Proceedings of workshop on groundwater and environment, Dhaka, September 6–8

Hossain MD, Huda MK (1997) Study of iron content in groundwater of Bangladesh. J Civ Eng Inst Eng Bangladesh CE 25(2)

Hussain MM, Abdullah SKM (2001) Geological setting of the areas of arsenic safe aquifers. Report of the ground water task force. Interim Report No. 1, Ministry of Local Government, Rural Development and Cooperatives, Local Government Division, Bangladesh

Islam MS, Siddika A, Khan MNH, Goldar MM, Sadique MA, Kabir ANMH, Huq A, Colwell RR (2001) Microbiological analysis of tube-well water in a rural area of Bangladesh. Appl Environ Microbiol 67:3328–3330

Islam ARMT, Rakib MA, Islam MS, Jahan K, Patwary MA (2015) Assessment of health hazard of metal concentration in groundwater of Bangladesh. Am Chem Sci J 5(1):41–49

Jahan CS, Mazumder QH, Akter N, Adham MI, Zaman MA (2010) Hydrogeological environment and groundwater occurrences in the plio-pleistocene aquifer in barind area, north-west Bangladesh. Bangladesh GeoSci J 16:23–37

Jakariya M, Choudhury M, Tareq MAH, Ahmed J (1998) BRAC: village health workers can test tubewell water for arsenic. Bangladesh Rural Advancement Committee

Kahlon MS, Lal R, Lubana PS (2012) Sustaining groundwater use in South Asia. In: Lal R, Stewart BA (eds) Advances in soil science: soil water and agronomic productivity. CRC Press, Florida, p 139

Kinniburgh DG, Smedley PL, Davies J, Milne CJ, Gaus I, Trafford JM (2003) The scale and causes of the groundwater arsenic problem in Bangladesh. In: Welch AH, Stollenwerk KG (eds) Arsenic in groundwater. Kluwer Academic Publishers; Boston, pp 211–257

Kondakis XG, Makris N, Leotsinidis M, Prino M, Papapetropoulos T (1989) Possible health effects of high manganese concentration in drinking water. Arch Environ Health: Int J 44: 175–178

Kurosawa K, Egashira K, Tani M, Jahiruddin M, Moslehuddin AZM, Rahman MZ (2008) Variation in arsenic concentration relative to ammonium nitrogen and oxidation reduction potential in surface and groundwater. Comm Soil Sci Plant Analysis 39(9–10)

Lindsay JF, Holiday DW, Hulbert AG (1991) Sequence stratigraphy and the evolution of the Ganges-Brahmaputra complex. Am Asso Petrol Geol Bull 75:1233–1254

Luby S, Islam MS, Johnston R (2006) Chlorine spot treatment of flooded tube wells, an efficacy trial. J Appl Microbiol 100(5):1154–1158

Mainuddin M (2002) Groundwater irrigation in Bangladesh: tool for poverty alleviation or cause of mass poisoning? In: Proceedings of the symposium on intensive use of groundwater: challenges and opportunities, Valencia, Spain

Majumder RK (2014) Uranium exploration status in Bangladesh: conceptual study. IAEA: Technical Meeting on Uranium from Unconventional Resources Vienna, Austria

Majumder RK, Hasnat MA, Hossain S, Ikeue K, Machida M (2008) An exploration of nitrate concentrations in groundwater aquifers of central-west region of Bangladesh. J Hazard Mater 159(2–3):536–543

McArthur JM, Ravenscroft P, Safiullah S, Thirlwall MF (2001) Arsenic in Groundwater: testing pollution mechanisms for sedimentary aquifers in Bangladesh. Water Resour Res 37(1): 109–117

McBean E, deJong A, Gharabaghi B (2011) Groundwater in Bangladesh: implications in a climate-changing world. Water Res Manag 1(3):3–8. UDK: 551.583:556.32(549.3)

Michael H, Voss CI (2009) Estimation of regional-scale groundwater flow properties in the Bengal Basin of India and Bangladesh. Hydrogeol J 17(6):1329–1346

Morgan JP, McIntire WG (1959) Quaternary geology of the Bengal Basin, East Pakistan and India. Geol Soc Am Bull 70:319–342

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Mukherjee AB, Bhattacharya P (2001) Arsenic in groundwater in the Bengal Delta Plain: slow poisoning in Bangladesh. Environ Rev 9(3):189–220. https://doi.org/10.1139/cr-9-3-189

Mukherjee A, Fryar AE, Thomas WA (2009) Geologic, geomorphic and hydrologic framework and evolution of the Bengal basin, India. J Asian Earth Sci 34(3):227–244

Mukherjee A, Saha D, Harvey CF, Taylor RG, Ahmed KM, Bhanja SN (2015) Groundwater systems of the Indian Sub-Continent. J Hydrol Reg Stud 4(A):1–14

Nandy DR (2001) Geodynamics of Northeastern India and Adjoining Region. ACB Publications, Kolkata, p 209

Nickson RT, McArthur JM, Ravenscroft P, Burgress WG, Ahmed KM (2000) Mechanism of arsenic release to groundwater, Bangladesh and West Bengal. Appl Geochem 15(4):403–413

Nordstrom DK (2002) Worldwide occurrences of arsenic in ground water. Science 296:2143–2145

Parvez MAK, Marzan M, Liza SM, Ahmed ZU (2014) Levels of reactive nitrogen in surface and ground water samples obtained from difference parts of Bangladesh. J Bangladesh Acad Sci 38(1):75–82

Qureshi AS, Ahmed Z, Krupnik TJ (2014) Groundwater management in Bangladesh: an analysis of problems and opportunities. Cereal Systems Initiative for South Asia Mechanization and Irrigation (CSISAMI) Project, Research Report 2, Dhaka, Bangladesh: CIMMYT

Rahman M, Hassan MQ, Islam MS, Shamsad SZKM (2000) Environmental impact assessment on water quality deterioration caused by the decreased Ganges outflow and saline water intrusion in south-western Bangladesh. Environ Geol 40(1):31–40

Rajappa B, Manjappa S, Puttaiah ET (2010) Monitoring of heavy metal concentration in groundwater of Hakinaka Taluk, India. Contemp Eng Sci 3(4):183–190

Rajmohan N, Prathapar SA (2013) Hydrogeology of the eastern ganges basin: an overview. IWMI Working Paper 157. https://doi.org/10.5337/2013.216

Rasul MT, Jahan MS, (2010) Quality of ground and surface water of Rajshahi City Area for sustainable drinking water source. J Sci Res 2(3)

Rasel HM, Hasan MR, Ahmed B, Miah MSU (2013) Investigation of soil and water salinity, its effect on crop production and adaptation strategy. Int J Water Resour Environ Eng 5(8): 475–481. https://doi.org/10.5897/ijwree2013.0400

Ravenscroft P (2003) Overview of the hydrogeology of Bangladesh. In: Rahman AA, Ravenscroft P (eds) Groundwater resources and development in Bangladesh—background to the arsenic crisis, agricultural potential and the environment. The University Press Ltd, pp 43–86

Ravenscroft P, Burgess WG, Ahmed KM, Burren M, Perrin J (2005) Arsenic in groundwater of the Bengal Basin, Bangladesh: distribution, field relations, and hydrogeological setting. Hydrogeol J 13:727–751

Ravenscroft P, McArthur JM, Hoque MA (2013) Stable groundwater quality in deep aquifers of Southern Bangladesh: the case against sustainable abstraction. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2013.02.071

Sack J, Kaiserman I, Tulchinsky T, Harel G, Gutekunst R (2000) Geographic variation in groundwater iodine and iodine deficiency in Israel, The West Bank and Gaza. J Pediatr Endocrinol Metab 13(2):185–190

Saha KC (1995) Chronic arsenic dermatoses from tube-well water in West Bengal during 1983–1987. Indian J Dermatol 40:1–11

Saha D, Alam F (2014) Groundwater vulnerability assessment using DRASTIC and Pesticide DRASTIC models in intense agriculture area of the Gangetic plains, India. Environ Monit Assess 186(12):8741–8763. https://doi.org/10.1007/s10661-014-404-x

Scott CA, Sharma B (2009) Energy supply and the expansion of groundwater irrigation in the Indus-Ganges Basin. Int J River Basin Manag 7:1–6

Shahid S (2011) Impact of climate change on irrigation water demand of dry season Boro rice northwest Bangladesh. Clim Change 105:433–453

Shahid S, Wang X-J, Rahman MM, Hasan R, Harun SB, Shamsudin S (2015) Spatial assessment of groundwater over-exploitation in northwestern districts of Bangladesh. J Geol Soc India 85(4):463–470

Shamsudduha M, Uddin A (2007) Quaternary shoreline shifting and hydrogeologic influence on the distribution of groundwater arsenic in aquifers of the Bengal basin. J Asian Earth Sci 31:177–194. https://doi.org/10.1016/j.jseaes.2007.07.001

Shamsudduha M, Chandler RE, Taylor R, Ahmed KM (2009) Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. Hydrol Earth Syst Sci 13:2373–2385

Shamsudduha M, Taylor RG, Ahmed KM, Zahid A (2011) Hydrogeol J 19(4):901–916

Smedley PL, Kinniburgh DG (2002) A review of the source, behaviour and distribution of arsenic in natural waters. Appl Geochem 17(5):517–568

Smith AH, Lingas EO, Rahman M (2000) Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. Bull World Health Organ 78(9):1093–1103

Sumiya NN, Khatun H (2016) Groundwater variability in Bangladesh: assessment based on rainfall variation and use of water irrigation. J Asiatic Soc Bangladesh (Science), 42(2)

Sultana J, Biswas SK, Uddin MR (2014) Uranium concentration in ground water of Bangladesh. Natl Univ J Sci 1(1)

Uddin A, Lundberg N (1998a) Cenozoic history of the Himalayan–Bengal system: sand composition in the Bengal basin, Bangladesh. Geol Soc Am Bull 110:497–511

Uddin A, Lundberg N (1998b) Unroofing history of the eastern Himalaya and the Indo–Burman ranges: heavy mineral study of the Cenozoic sediments from the Bengal basin, Bangladesh. J Sed Res 68:465–472

Uddin MN, Abdullah SKM (2003) Quaternary geology and aquifer systems in the Ganges–Brahmaputra–Meghna delta complex, Bangladesh. In: Proceedings of GEOSAS-IV, Geological Survey of India, pp 400–416

Umitsu M (1993) Late Quaternary sedimentary environments and landforms in the Ganges Delta. Sed Geol 83:177–186

UNDP (United Nation Development Programme) (1982) Groundwater survey: the hydrogeological conditions of Bangladesh. Technical Report DP/UN/BGD-74-009/1, New York

UNICEF (United Nations Children's Fund) (2011) Bangladesh national drinking water quality survey of 2009. https://www.unicef.org/bangladesh/knowledgecentre_6868.htm, verified 24 Jan 2017

United Nations Environment Programme's Division of Early Warning and Assessment (UNEP-DEWA) (2003) Groundwater and its susceptibility to degradation: a global assessment of the problem and options for management. Early warning and assessment report series, RS. 03-3

Margat J, Van der Gun J (2013) Groundwater around the world: a geographic synopsis. CRC Press

van Geen A, Zheng Y, Versteeg R, Stute M, Horneman A, Dhar R, Steckler M, Gelman A, Small C, Ahsan H, Graziano JH, Hussain I, Ahmed KM (2003) Spatial variability of arsenic in 6000 tube wells in a 25 km^2 area of Bangladesh. Water Resour Res 39(5):1140. https://doi.org/10.1029/2002WR001617

van Geen A, Ahmed KM, Akita Y, Alam MJ, Culligan PJ, Emch M, Escamilla V, Feighery J, Ferguson AS, Knappett P, Layton AC, Mailloux BJ, McKay LD, Mey JL, Serre ML, Streatfield PK, Wu J, Yunus M (2011) Fecal contamination of shallow tube-wells in Bangladesh inversely related to arsenic. Environ Sci Technol 45(4):1199–1205

Wasserman GA, Liu X, Parvez F, Ahsan H, Levy D, Factor-Litvak P (2006) Water manganese exposure and children's intellectual function in Araihazar, Bangladesh. Environ Health Perspect 114:124–129

Whiticar MJ, Schoell M (1986) Biogenic methane formation in marine and freshwater environments: CO_2 reduction vs. acetate fermentation-Isotope evidence. Geochimica et Cosmochimica Acta 50(5):693–709

WHO (World Health Organization) (1996a) Iron in drinking-water. Background document for development of WHO Guidelines for drinking-water quality, vol 2, 2nd edn. Health criteria and other supporting information. WHO/SDE/WSH/03.04/08

WHO (1996b) Ammonia in drinking-water. Background document for development of WHO Guidelines for drinking-water quality. WHO/SDE/WSH/03.04/01

WHO (2004) Barium in drinking water. Background document for development of WHO Guidelines for drinking-water quality. WHO/SDE/WSH/03.04/76

WHO (2011) Guidelines for drinking-water quality, 4th edn

Zahid A, Ahmed SR (2006) Groundwater research and management: integrating science into management decisions. In: Sharma BR, Villholth K, Sharma KD (eds) Groundwater research and management integrating science into management decisions. Proceedings of IWMI-ITP-NH International workshop on creating synergy between groundwater research and management in South and Southeast Asia, India, pp 27–46

Zahid A, Hossain A, Uddin ME, Deeba F (2004) Groundwater level declining trend in Dhaka city aquifer. In: Proceeding of the international workshop on water resources management and development in Dhaka City, p 133

Chapter 14
Isotope Tracer Applications in Groundwater Hydrology: A Review of Indian Scenario

R. D. Deshpande

Abstract Applications of stable and radioactive isotopes in groundwater hydrology have a legacy of over five decades in India. Isotope hydrology began in India around 1973, concurrently with the worldwide programme of the International Hydrological Decade (1965–1974) launched by UNESCO. The main thrust of isotope applications initially was the groundwater age estimation and understanding recharge process in alluvial terrain assuming piston-flow approach, followed by, in hard rock terrain, to understand the preferential flow for groundwater recharge. It began with application of environmental and injected tritium but gradually a suite of other radioactive and stable isotopes were employed in groundwater hydrology. Actually, it encompassed examination of the entire hydrological continuum from atmosphere to surface to subsurface components of hydrological cycle rather than just the groundwater age estimation and groundwater recharge processes. Initially, the isotope analyses capabilities were restricted only to a few national laboratories but a few other research and academic institutions also developed these capabilities and initiated isotope hydrology programme. The acquisition of correct basic temporal and spatial data is of paramount importance in preparing groundwater resource management policies and development projects of widely different kinds. This can be achieved only when isotope expertise is transported from leading research institutions to numerous state and central water resource agencies and academic institutions. This is essential for India so that demonstrated potentials of isotope applications in hydrology can be effectively used to mitigate water resource scenario in the country. This paper aims to provide a snapshot review of evolution of groundwater isotope hydrology in India over the past five decades.

R. D. Deshpande (✉)
Geosciences Division, Physical Research Laboratory,
Navrangpura 380009, Ahmedabad, India
e-mail: desh@prl.res.in

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_14

14.1 Introduction

Applications of stable and radioactive isotopes in groundwater hydrology have a legacy of over five decades in India. One of the earliest applications of isotopes in India began with use of environmental tritium to evaluate the groundwater recharge in the semi-arid western India (Sukhija and Rama 1973) and in western Uttar Pradesh (Datta et al. 1973). This was followed by some other studies (Sukhija and Shah 1976; Gupta and Sharma 1984; Athavale and Rangarajan 1988; Sukhija et al. 1996a, b) in which environmental or injected tritium was used to estimate groundwater recharge and to understand recharge processes in arid and semi-arid regions of India. These studies were based on piston-flow approach invoking downward movement of soil moisture in homogeneous soil without any preferential migratory pathways in terms of fractures and fissures, resulting in movement of water from unsaturated to saturated zone in the form of sequential layers. The validity of this piston-flow model in the non-homogeneous environment was examined subsequently by studying the natural recharge processes in consolidated fractured granites, semi-consolidated sandstones and unconsolidated alluvial formations, using isotopic and geochemical tracers. These studies demonstrated a significant contribution from the preferential flow recharge process, especially in the fractured granites (75% of total recharge) and semi-consolidated sandstones (an average of 33% of total recharge) (Sukhija et al. 2003; Sukhija et al. 2000). Using injected tritium Athavale et al. (1992) measured natural recharge across the country, whereas Rangarajan and Athavale (2000) estimated annual replenishable groundwater otential for India.

In addition to the use of environmental and injected tritium to understand groundwater recharge processes, the uranium series isotopes and radiocarbon were also used to understand river–groundwater interaction, groundwater age determination and estimating horizontal flow velocities (Borole et al. 1979; Bhandari et al. 1986). For estimating vertical leakage across semi-permeable aquitard layers, a dual tracer (^{32}Si and ^{14}C) dating method was also used (Gupta et al. 1981).

In addition to radiocarbon and uranium series methods, helium accumulation and ^{4}He/^{222}Rn methods have also been used for groundwater age determination and to understand the hydrothermal circulation along the major fault systems (Gupta and Deshpande 2003a, b, c; Agrawal et al. 2006; Deshpande 2006; Deshpande and Gupta 2013).

The isotope tracers have also been used to understand origin, movement and mixing of natural contaminants like Fluoride (Gupta and Deshpande 2003a, b, c; Gupta et al. 2005a) and Arsenic (Mukherjee et al. 2007). Isotopic composition in conjunction with geochemical properties has also been used to understand climatic signatures in the groundwater and to understand climatic controls on observed geochemical properties of groundwater (Navada et al. 1993; Sukhija et al. 1998; Gupta et al. 2005a, b).

Oxygen and hydrogen isotopes have turned out to be the most adoptable isotope tracers in hydrology simply because they constitute the water molecule itself and provide a tool to understand the water from within, instead of measuring something dissolved in water. Also in terms of sampling and analytical protocols measuring oxygen and hydrogen isotopic composition is far simpler than many other isotopes. A significant contribution of oxygen and hydrogen isotopic application to groundwater hydrology in India has come from research group at Physical Research Laboratory (PRL), India (e.g. Bhattacharya et al. 1985; Krishnamurthy and Bhattacharya 1991; Ramesh and Sarin 1992; Deshpande et al. 2003, Gupta et al. 2005a, b; Deshpande 2006; Deshpande and Gupta 2013). There are other important research groups in India who have also contributed significantly to isotope applications in groundwater. A detailed discussion of oxygen and hydrogen isotopic investigations by various other research groups in India has been exhaustively compiled by Gupta and Deshpande (2005).

Among various isotopes, stable isotopes of oxygen and hydrogen have been most widely adopted by various research groups in India to understand groundwater hydrological processes (Hameed et al. 2015; Jeelani et al. 2015). A big push towards understanding the hydrological cycle was given by the launch of a multi-institutional collaborative national research programme on isotope fingerprinting of waters of India (IWIN) (Deshpande and Gupta 2008, 2012). One of the major outcomes of the IWIN programme in terms of groundwater hydrology was that isotope application in groundwater became a familiar tool in central groundwater agency in India. Interpretation of IWIN groundwater isotope data is still currently underway as the required geohydrological data essential for isotope interpretation is obtained from various government agencies.

In spite of numerous research studies successfully undertaken over more than five decades in India, the analytical capabilities for variety of isotope systematics and its application in groundwater hydrology have been a privilege of only a few central laboratories and academic institutions. Intensive teaching of isotope applications in groundwater hydrology in various academic institutions and universities, and building of their own analytical facilities by concerned groundwater departments seems to be the most urgent priority if isotope techniques are to be effectively used to address various region-specific hydrological problems and to mitigate water resource scenario in the country.

Some of the salient points of groundwater isotope hydrology legacy in India are discussed in the following after a brief inventory of stable and radioactive isotopes relevant to groundwater hydrology.

14.2 Isotope Tracers for Groundwater Hydrology

Any isotopic species that tag water and can be measured with high analytical precision can be used to trace a water molecule in the hydrological cycle because of uniqueness of isotopes in a given hydrologic system. The isotope tracers can be broadly classified into environmental and artificial tracers. Environmental isotope tracers are those already present in the system naturally or introduced inadvertently.

These environmental tracers provide new insights into the age, origin and pathways of water movement. Isotope tracers can be further classified broadly into stable (e.g. ^{2}H, ^{18}O, ^{13}C, ^{34}S, ^{4}He and ^{15}N) and radioactive isotopes (e.g. ^{3}H; $T_{1/2}$ = 12.43 year, ^{14}C; $T_{1/2}$ = 5730 year, ^{32}Si; $T_{1/2} \cong$ 100 year, ^{36}Cl; $T_{1/2}$ = 306,000 year, ^{39}Ar; $T_{1/2}$ = 269 year, ^{81}Kr; $T_{1/2}$ = 210,000 year, ^{85}Kr; $T_{1/2}$ = 10.8 year, ^{234}U; $T_{1/2}$ = 250,000 year). Artificial isotopic tracers are the ones which are introduced into the system in a certain known quantity before start of the tracer study.

Interaction with cosmic rays in the upper atmosphere produces a variety of radioactive isotopes, among which the three isotopes, namely ^{3}H, ^{14}C and ^{36}Cl are of special interest in groundwater hydrology because they get incorporated from atmosphere into groundwater and decay in the saturated zone providing three radiometric dating tools applicable over a wide range from a few decades to million years. These three isotopes have also been produced during testing of thermonuclear devices, which provide additional handle to understand groundwater hydrological processes in the post-nuclear era.

Radioactive decay of uranium and thorium present in small concentrations in aquifer material produces radiogenic ^{4}He which dissolves and accumulates in groundwater. Accumulated ^{4}He in groundwater, in excess of that dissolved from atmospheric equilibration, provides another dating method for old groundwater in the range of 10^{4}–10^{8} years.

Oxygen and hydrogen isotopic ratios ($^{18/16}O$ and $^{2}H/^{1}H$) of groundwater are principally inherited from long-term average isotopic composition of the precipitation recharging the concerned groundwater aquifer. Any significant deviation of isotopic characteristics of groundwater from that of long-term average precipitation actually provides a tool to understand the underlying processes affecting the groundwater. Some of the applications of stable oxygen and hydrogen isotopes are to understand preferential recharge from particular source water, seepage/leakage from reservoir, base flow contribution, admixture of different water masses and seasonal variation in source water recharging the aquifer, surface water–groundwater interaction.

14.3 Isotope Applications in Groundwater

Various stable and radioactive isotopes can be used individually or in combination, and in conjunction with other geochemical parameters to study different hydrological problems. Application of stable and radioactive isotopes in groundwater hydrology can be broadly grouped in the following categories: (1) groundwater age determination; (2) groundwater recharge estimation; (3) understanding surface water–groundwater interaction; (4) origin and propagation of natural contaminants; (5) hydrothermal circulation and tectonic fabric; (6) palaeo-climatic imprints.

Some of the representative case studies in each of the above categories is described in the following. *However, it must be noted clearly that these are not the* *only case studies in India. There are several other studies in each of these categories but describing them all is beyond the scope of this review.*

14.4 Groundwater Age Determination

Groundwater age evolution during its passage from the recharge area in the hard rock alluvium boundary, through a multi-layered regional alluvial aquifer system of North Gujarat in western India, has been studied (Deshpande 2006; Agarwal et al. 2006). The ^{14}C, ^{4}He and ^{4}He/^{222}Rn dating methods have been used to determine the age of groundwater. The U and Th concentrations were measured in the sediments from a drill core to estimate the production rate of ^{4}He and ^{222}Rn in order to estimate the age of groundwater age. Additionally, the controlling factors for distribution of ^{222}Rn, ^{4}He and temperature anomalies in groundwater, in the context of the tectonic framework and lithology, were also examined. This study revealed comparable groundwater age estimates by the three different methods. The groundwater radiocarbon ages increased, progressively, in the groundwater flow direction: from the foothills of Aravalli Mountains in the east, and reached a value of $\sim$35 ka towards the region of lowest elevation, linking Little Rann of Kachchh—Nalsarovar—Gulf of Khambhat in the western part of the study area. Within the Cambay Basin, ^{14}C age contours were found to be nearly parallel to each other and the horizontal distance between successive 5 ka contours was nearly constant giving a regional flow velocity in the range 2.5–3.5 m a^{-1} for a natural hydrostatic gradient of 1 in 2000 (Gujarat Water Resources Development Corporation, Unpublished data), which is comparable to an earlier estimate of $\sim$6 m a^{-1} (Borole et al. 1979) for the small part of the Vatrak–Shedi sub-basin.

The groundwater from the free-flowing thermal wells and springs in this region is estimated to be up to million years old based on ^{4}He and ^{4}He/^{222}Rn methods. Such anomalous age estimation was ascribed to enhanced mobilization and migration of ‘excess helium’ from hydrothermal circulation vents along deep-seated faults. Barring such anomalous cases and considering all uncertainties, there is a reasonable agreement between the groundwater ages in the Cambay Basin, based on ^{4}He and ^{4}He/^{222}Rn methods for a helium release factor of 0.4 ± 0.3, and the ^{14}C method. The ^{4}He method also indicated progressive increase in groundwater ages in the west-southwards direction up to $\sim$100 ka beyond the Cambay Basin.

Large ‘excess helium’ concentrations were associated in general with anomalous groundwater temperatures (>35 °C) and found to overlie some of the basement faults in the study area, particularly along the east and the west flanks of the Cambay Basin. Groundwater ^{222}Rn activities in most of the study area are reported to be 800 ± 400 dpm/l, with the highest value of $\sim$63,000 dpm/l recorded in one of the thermal springs at Tuwa on the east flank of the Cambay Basin, having granitic basement at shallow depth.

14.5 Groundwater Recharge Estimation

In one of the earliest isotope applications in groundwater, distribution of environmental tritium in soil moisture was used for the estimation of natural groundwater recharge in North Gujarat (Sukhija and Rama 1973). The method depended on estimating the total inventory of tritium as fraction of fallout at a given location, produced during late fifties–early sixties due to atmospheric testing of nuclear weapons (Bomb Tritium). It was shown that within the soil profile, each year's rainfall could be identified as a downward moving layer (Sukhija et al. 1996a, b). This study indicated that water from a given year's rainfall took several years before reaching the water table despite a quick rise in water table observed following monsoon rains every year. This is due to pushing down of successive moisture layers from several previous years by the downward moving uppermost soil moisture from current year's rainwater, very much like a piston. Post-monsoon groundwater level rise is further facilitated by cessation of heavy pumping prevalent during the pre-monsoon period. Using the natural tritium method of tracing the soil moisture layers, natural recharge of groundwater in North Gujarat was estimated ~10% of the rainfall, significantly lower than conventional estimates of 15–25%. This study was followed by tracing of soil moisture using artificially injected tritium in Ganga (Datta et al. 1973) and Sabarmati basins (Gupta and Sharma 1984; Bhandari et al. 1986) and at several locations in Peninsular India (Athavale et al. 1992; Rangarajan and Athavale 2000). In this latter method, the amount of soil moisture deposited above a downward moving tritiated layer was estimated as a fraction of precipitation plus irrigation since the time of tracer injection. Based on several of these measurements, a composite estimate of natural groundwater recharge (as fraction of total water input) has been made at various locations within the country (Gupta and Deshpande 2004). The estimated average annual recharge for the country as a whole, based on this data, is 11.5 ± 3.6% of local water input. While groundwater fractional recharge values higher than average are estimated in the Indo-Gangetic plains, lower values are estimated in parts of Gujarat, Rajasthan and Peninsular India (Gupta and Deshpande 2004). These regions are characterized by relatively low rainfall and high potential evaporation (Gupta and Deshpande 2005).

Some of these studies (Sukhija and Rama 1973; Gupta and Sharma 1984; Sukhija et al. 1996a, b; Gupta and Deshpande 2004) also indicated that within the soil zone in alluvial areas, the movement of soil moisture largely followed a piston-flow model but with increasing dispersion of the tracer concentration of the moisture layer towards the water table. However, in highly heterogeneous soils as found mostly in hard rock areas, instances of non-piston type of flow could also be identified (Sukhija et al. 2003). The studies also showed that a nonlinear relationship existed between the rainfall and the fraction recharged, and a certain minimum value of rainfall was required at a given location for affecting groundwater recharge. The minimum value, however, depended on climate, geography and soil type of the location (Datta et al. 1973).

14.6 Understanding Surface Water–Groundwater Interaction

Oxygen and hydrogen isotopic composition of groundwater and river water samples from the southern part of India (8–16°N) was studied to understand the interaction between the groundwater and the surface water (rivers and rain) and to relate it with the vapour sources for rain contributing to groundwater (Deshpande et al. 2003). This study showed that the regions dominated by NE monsoon have lower $\delta^{18}O$ and δD values of groundwater compared to those dominated by SW monsoon. The $\delta^{18}O$-δD regression line slope (~ 6) in the east coast region is lower than that expected for local precipitation suggesting secondary evaporation. The altitude of the Western Ghats hill ranges significantly controls the isotopic distribution along the west coast region. The low d-excess ($=\delta D - 8 \times \delta^{18}O$) values in most parts of southern Indian peninsula indicate secondary evaporation. The high d-excess values over the Deccan Plateau region suggest admixture of recycled moisture with the inflowing oceanic vapour. In the second part of this study, Gupta et al. (2005a, b) related the groundwater isotopic composition in the central Indian peninsula (16–24°N) with vapour derived from Arabian Sea and the Bay of Bengal branches of summer monsoon.

Temporal variation of $\delta^{18}O$ in groundwater and river water samples along River Ganga (Hardwar–Narora sector) was studied by Navada and Rao (1991) to showcase the spatially variable interaction between River Ganga and the adjoining groundwater aquifers. This study showed that seasonal average isotopic composition of groundwater at a given location does not change much with time, in contrast to the rivers which change their seasonal isotope character in such a way that during monsoon spatial distributions tend to disappear and in post-monsoon season they progressively tend to acquire the isotope character of the local groundwater indicating effluent discharge of groundwater. In the context of temporal variation of $\delta^{18}O$, it is also observed in some groundwater samples in Delhi region (Datta 1997) that the average isotopic character of groundwater varies with location but does not change much with time. However, in divergence from these two observations of temporal invariance of isotopic composition of groundwater, significant temporal variation has also been reported in isotope character of groundwater in the state of Karnataka. This is inferred as due to fast recharge following a storm event facilitated by secondary porosity from fracture and fissures in hard rock terrain and a thin soil cover in the study area of Kolar District (Shivanna et al. 2004).

Gupta and Deshpande (2005) have compiled all available oxygen and hydrogen isotope data of groundwater from India and tried to relate the observed geographical variation with rainfall, potential evapotranspiration, physiography and soil cover. This compilation also includes an exhaustive list of references of all Indian case studies of groundwater isotope investigation, which could not be discussed here due to space constraints.

Mukherjee et al. (2007) have studied interaction of groundwater with Rivers Ganges and Bhagirathi-Hoogly and interpreted observed differences in the isotopic composition of the two river systems and ground waters in terms of the origin of water masses in these rivers.

Hameed et al. (2015) carried out oxygen isotopic characterization and mass balance in the mountainous Chaliyar River basin, Kerala, India, to understand the river water–groundwater interaction and the recharge pattern and to estimate the groundwater recharge through river. Based on the spatio-temporal variation in ^{18}O values of river and groundwater and fluctuations in groundwater levels, the river water contribution to post-monsoon groundwater recharge was estimated to be $\sim 16\%$ in the lowland coastal area of the Chaliyar River basin and 29% in the midland region. It was also inferred that northeast winter monsoon rains contribute to the groundwater of Chaliyar River basin only in an insignificant manner and with a delayed response. An inverse altitude gradient in $\delta^{18}O$ was also detected in the Chaliyar basin which has been explained as quick flowing down of isotopically depleted rainwater from high altitude and slow groundwater recharge in high altitude by evaporated residual water.

14.7 Origin and Propagation of Natural Contaminants

Isotopic studies of groundwater have also helped in identifying origin of the natural and/or anthropogenic contaminants such as excessive fluoride (Deshpande 2006; Gupta and Deshpande 2003a, b, c; Gupta et al. 2005a, b) observed in groundwater in North Gujarat-Cambay region. Based on the ^{14}C age determinations of groundwater of North Gujarat, it has been shown that the groundwater in the high fluoride belts was recharged during 15–25 ka B.P., i.e. around the period of last glacial maxima (LGM). During this period, other independent evidence indicated that the climate of the region was more arid than during the preceding and the succeeding time periods. The $\delta^{18}O$ values of groundwater from North Gujarat also indicated enrichment of heavier oxygen isotope, consistent with the fact that the groundwater recharge during this period could have undergone a significant evaporation during passage through the capillary fringe zone. Similarly, radiocarbon dating of groundwater and its stable isotopic composition from the Neyveli Basin showed that groundwater recharged during the period of LGM had distinct imprints of relatively more arid climate (Sukhija et al. 1998). Thus, similar climatic inferences are drawn from groundwater isotopic studies in two regions geographically far apart. Older ground waters have also been shown to have different isotopic composition compared to contemporary groundwater in Rajasthan (Navada et al. 1993; Nair et al. 1999) indicating a different climatic regime during which groundwater recharge was affected for this older groundwater.

14.8 Hydrothermal Circulation and Tectonic Fabric

Natural helium in soil–gas and groundwater was studied in the Cambay Basin region of Gujarat which is known for its high heat flow and major fault system with successive down faulting along sympathetic faults parallel or orthogonal to major fault line (Gupta and Deshpande 2003a, b, c; Deshpande 2006). Anomalous helium concentration (higher than atmospheric equilibration concentration) was observed in several wells. These wells, with high than average groundwater temperature, were broadly located along basement faults, particularly on both eastern and western flanks of the Cambay Basin. Groundwater helium anomalies were explained in this investigation through a conceptual model as originating largely from within the crystalline basement, through radioactive decay in the form of plumes localized by the major faults and fractures. A shallow depth (~ 1 to 2 km) convective circulation along major faults is inferred that facilitate both downward and upward migration of groundwater and result in increased temperature of groundwater. Because of the dispersion that takes place in sedimentary cover, no significant helium anomalies are seen within the Cambay graben that has more than 3-km-thick sedimentary cover. Even though higher helium and higher groundwater temperature originate by difference mechanisms, the faults and fractures in the crust provide preferred migratory pathways for water from the depth (with high temperature and high helium) to come up near the surface by establishing a convective hydrothermal circulation of groundwater.

Deshpande and Gupta (2013) carried out a field investigation of dissolved helium, fluoride and electrical conductivity in groundwater from across the main stem of the Narmada River, between Bharuch (21.71°N, 72.99°E) in the west and Amarkantak (22.68°N, 81.75°E) in the east, to identify active tectonic regions, based on the locations of high helium concentrations in groundwater. Anomalous helium in groundwater, in excess of atmospheric equilibration value, was interpreted as indicative of upward migration of deep fluids. Existence of deep fluids in this region has been hypothesized earlier based on various geophysical studies in the Narmada Rift Basin—a major tectonic feature in central India. However, geochemical and isotopic imprints of deep fluids were offered for the first time by this isotope-based study. Samples with high helium concentration were found to be clustered in two broad regions with known intersecting faults, indicating the possibility of plumes with high helium concentration being injected into shallower groundwater in these regions, facilitated by these faults and fractures. Locations of groundwater samples having excess fluoride remarkably corresponded to these two clusters of excess helium. This also suggested a possible commonality between the causal factor of excess helium and higher fluoride in groundwater.

14.9 Paleoclimatic Imprints

Some of the earlier investigations in Sabarmati basin (Bhandari et al. 1986) indicated that under natural gradients, the horizontal velocity of groundwater is very low (<10 m/year) in alluvial aquifers. The dispersion is not able to obliterate the low frequency (thousands of years' time scale) change in isotopic composition (e.g. due to climatic change) of the input rainwater. Therefore, under suitable conditions, e.g. in confined to semi-confined aquifers, where piston-flow model is still applicable, one cannot only see an age progression from recharge to discharge area but also climatically induced isotopic and geochemical signals in groundwater. In such cases, radiometric age determination of groundwater can also be used to identify groundwater recharged under different past climatic regimes.

Two important studies from different parts of India, employing radiocarbon dating of groundwater showed that in multi-layered regional alluvial aquifer systems, groundwater flow velocities away from the recharge area are very low (<10 m/year). It is noteworthy that isotopic and geochemical imprints of climatic condition or geohydrological set-up, imparted during recharge, are preserved even after mixing and dispersion during its passage underground and away from recharge area for tens to hundreds of kilometres.

The difference between the present-day climatic conditions and that prevalent during the last glacial maxima ($\sim$20 K year ago) has been identified in terms of the corresponding isotopic and geochemical signatures in the groundwater of Neyveli region in southern India and North Gujarat in western India (Sukhija et al. 1998; Gupta et al. 2005a, b; Deshpande 2006).

14.10 IWIN National Programme

In the above backdrop of isotope applications in India, a big push towards understanding the hydrological cycle was given by the launch of a multi-institutional collaborative national research programme on isotope fingerprinting of waters of India (IWIN) (Deshpande and Gupta 2008, 2012). In this programme, 14 leading research institutions and central agencies collaborated with the Physical Research Laboratory (PRL) as the nodal agency for implementation. The Central Ground Water Board (CGWB) was the main collaborator for the groundwater component of IWIN programme under which 6000 groundwater samples (pre-monsoon and post-monsoon) from across the country were collected by CGWB and analysed by PRL for their oxygen and hydrogen isotopic composition. Interpretation of this immensely valuable groundwater isotope dataset is currently underway jointly by PRL and CGWB.

Unlike annual precipitation which is isotopically homogeneous over large geographical areas, the groundwater has considerable geographical variation even on a smaller ($\sim$100 km) spatial scale (Deshpande et al. 2011; Deshpande and

Gupta 2012). Since groundwater is affected by local precipitation, surface water sources (river, lake, irrigation return flow, etc.) and soil and geomorphic factors, significant variation on a smaller spatial scale is to be expected. Therefore, the area-specific factors for observed variations in isotopic composition of groundwater are being examined in the light of geohydrological data and in field features. In terms of isotope applications in groundwater, IWIN programme is one of the biggest collaborative research initiatives.

14.11 Epilogue

Isotope studies in groundwater hydrology in India undertaken during more than five decades have demonstrated how various stable and radioactive isotopes can be used to obtain new insights about a particular groundwater aquifer. In particular, it is possible to obtain from isotope studies that information which cannot be derived from conventional measurements of pre-monsoon and post-monsoon groundwater levels. However, all of these studies were undertaken by research and academic institutes which are not directly responsible for groundwater resource development and management. Therefore, it is essential that isotope tracer techniques are routinely adopted by concerned central and state agencies managing the groundwater of the country, and they develop their own isotope analytical facilities. On their part, research and academic institutions already possessing expertise in the field of isotope applications have to extend their cooperation to any water resource agency desirous of building their own isotope analytical facilities.

Acknowledgements Several isotope hydrologists of India who provided their valuable inputs during several rounds of telephonic discussions regarding the subject matter of this manuscript. I remember and thank them all though individually naming them is not possible. I wish to place on records my sincere gratitude for Dr. S. K. Gupta my teacher and the closest professional colleague during last ~3 decades.

References

Agarwal M, Gupta SK, Deshpande RD, Yadava MG (2006) Helium, radon and radiocarbon studies on a regional aquifer system of the North Gujarat-Cambay region, India. Chemical Geology 228(4):209–232

Athavale RN, Rangarajan R (1988) Natural recharge measurements in the hard rock regions semi-arid India using tritium injection—a review. In: Simmers I (ed) Estimation of natural recharge of groundwater. North Atlantic Treaty Organisation, Advanced Science Institute Series 222:175–194

Athavale RN, Rangarajan R, Muralidharan D (1992) Measurement of natural recharge in India. J Geological Society India 39:235–244

Bhandari N et al (1986) Hydrogeological investigations in Sabarmati and Mahi Basins and coastal Saurashtra using radio-isotopic and chemical tracers. High Level Technical Committee on Hydrology (Ministry of Water Resources, Govt. of India), NIH Roorkee, 115 p

Bhattacharya SK, Gupta SK, Krishnamurthy RV (1985) Oxygen and hydrogen isotopic ratios in groundwaters and river waters from India. Proceedings of Indian academy of sciences (earth and planetary science) 94(3):283–295

Borole DV, Gupta SK, Krishnaswami S, Datta PS, Desai BI (1979) Uranium isotopic investigations and radiocarbon measurement of river-groundwater systems, Sabarmati Basin, Gujarat, India. Isotopic hydrology, 1. IAEA, Vienna, pp 181–201

Datta PS (1997) Stable isotopic investigations for groundwater management and sustainable environment (search for alternatives). Nuclear Research Laboratory, IARI, New Delhi, p 100

Datta PS, Goel PS, Sangal SP (1973) Groundwater recharge in western Uttar Pradesh. In: Proceedings of Indian academy of sciences, vol LXXVII(A.I), pp 1–12

Deshpande RD (2006) Groundwater in and around Cambay Basin, Gujarat: some geochemical and isotopic investigations, Ph.D. thesis, 158 p. M.S. University of Baroda, Vadodara, India

Deshpande RD, Gupta SK (2008) National programme on isotope fingerprinting of waters of India. In: Singhvi AK, Bhattacharya A, Guha S (eds) Glimpses of geosciences research in India, the Indian report to IUGS. Indian National Science Academy, INSA, New Delhi, pp 10–16

Deshpande RD, Gupta SK (2012) Oxygen and hydrogen isotopes in hydrological cycle: new data from IWIN national programme. Proceedings of Indian National Science Academy 78(3):321–331

Deshpande RD, Gupta SK (2013) Groundwater helium: an indicator of active tectonic regions along Narmada River, central India. Chem Geol 344:42–49

Deshpande RD, Bhattacharya SK, Jani RA, Gupta SK (2003) Distribution of oxygen and hydrogen isotopes in shallow groundwaters from Southern India: influence of a dual monsoon system. J Hydrol 271(1–4):226–239

Deshpande RD, Dave M, Laxmi SR, Gupta SK (2011) IWIN national programme: new hydrological insights. In: Aggarwal SK, Jaison PG, Sarkar A (eds) Fourteenth ISMAS symposium cum workshop on mass spectrometry: Munnar. Indian Society for Mass Spectrometry, India, pp 95–108

Gupta SK, Deshpande RD (2003a) High fluoride in groundwater of North Gujarat-Cambay Region: origin, community perception and remediation. In Singh VP, Yadav RN (eds) Proceedings of the international conference on water and environment: ground water pollution, pp 368–388. Allied Publishers Pvt. Ltd., New Delhi, Bhopal, India, 16–18 Dec 2003

Gupta SK, Deshpande RD (2003b) Origin of groundwater helium and temperature anomalies in the Cambay region of Gujarat, India. Chem Geol 198(1–2):33–46

Gupta SK, Deshpande RD (2003c) Dissolved helium and TDS in groundwater from Bhavnagar in Gujarat: unrelated to seismic events between August 2000 and January 2001. Proc Indian Acad Sci (Earth and Planet Sci) 112(1):51–60

Gupta SK, Deshpande RD (2004) Isotopes for water resource management in India. Himalayan Geol 26(1):211–222

Gupta SK, Deshpande RD (2005) Groundwater Isotopic Investigations in India: what has been learned? Curr Sci 89(5):825–835

Gupta SK, Sharma P (1984) Soil moisture transport through unsaturated zone: tritium tagging studies in Sabarmati Basin, Western India. Hydrological Sciences J 29(2):177–189

Gupta SK, Lal D, Sharma P (1981) An approach to determining pathways and residence time of ground waters: dual radiotracer dating. J Geophys Res 86(C6):5292–5300

Gupta SK, Deshpande RD, Agarwal M, Raval BR (2005a) Origin of high fluoride in groundwater in the North Gujarat-Cambay region, India. Hydrogeol J 13:596–605

Gupta SK, Deshpande RD, Bhattacharya SK, Jani RA (2005b) Groundwater $\delta^{18}O$ and δD from Central Indian Peninsula: influence of the Arabian Sea and the Bay of Bengal branches of the summer monsoon. J Hydrol 303:38–55

Hameed AS, Resmi TR, Suraj S, Warrier CU, Sudheesh M, Deshpande RD (2015) Isotopic characterization and mass balance reveals groundwater recharge pattern in Chaliyar river basin, Kerala, India. J Hydrol Reg Stud 4:48–58

Jeelani G, Saravana Kumar U, Bhat NA, Sharma S, Kumar B (2015) Variation of δ 18O, δ D and 3H in karst springs of south Kashmir, western Himalayas (India) Hydrol. Process 29

Krishnamurthy RV, Bhattacharya SK (1991) Stable oxygen and hydrogen isotope ratios in shallow groundwaters from India and a study of the role of evapotranspiration in the Indian monsoon, edited, The Geochemical Society, pp 187–193

Mukherjee A, Fryar AE, Rowe HD (2007) Regional-scale stable isotopic signatures of recharge and deep groundwater in the arsenic affected areas of West Bengal, India. J Hydrol 334: 151–161

Nair AR, Navada SV, Rao SM (1999) Isotope study to investigate the origin and age of groundwater along Palaeochannels in Jaisalmer and Ganganagar Districts of Rajasthan. Memmoir Geol Soc India 42:315–319

Navada SV, Rao SM (1991) Study of Ganga river–groundwater interaction using environmental ^{18}O. Isotopenpraxis 27(8):380–384

Navada SV, Nair AR, Rao SM, Paliwall BL, Dashy CS (1993) Groundwater recharge studies in arid region of Jalore, Rajasthan using isotope techniques. J Arid Environ 24:125–133

Ramesh R, Sarin MM (1992) Stable isotope study of Ganga (Ganges) River system. J Hydrol 139:49–62

Rangarajan R, Athavale RN (2000) Annual replenishable groundwater potential of India—an estimate based on injected tritium studies. J Hydrol 234:38–53

Shivanna K, Kulkarni UP, Joseph TB, Navada SV (2004) Contribution of storm to groundwater in semi-arid regions of Karnataka India. Hydrol Proc 18(3):473–485

Sukhija BS, Rama (1973) Evaluation of groundwater recharge in the semi-arid region of India using the environmental tritium. Proc Indian Acad Sci 77(6):279–292

Sukhija BS, Shah CR (1976) Conformity of groundwater recharge rate by tritium method and mathematical modelling. J Hydrol 30:167–178

Sukhija BS, Nagabhushanam P, Reddy DV (1996a) Groundwater recharge in semi-arid regions of India: an over view of results obtained using tracers. Hydrogeol J 4(3):50–71

Sukhija BS, Reddy DV, Nagabhushanam P, Hussain Syed, Giri VY, Patil DJ (1996b) Environmental and injected tracers methodology to estimate direct precipitation recharge to a confined aquifer. J Hydrol 174:77–97

Sukhija BS, Reddy DV, Nagabhushanam P (1998) Isotopic fingerprint of palaeoclimates during the last 30,000 years in deep confined groundwaters of Southern India. Quat Res 50:252–260

Sukhija BS, Reddy DV, Nagabhushanam P, Hussain S (2000) Natural groundwater recharge assessment: role of preferential flow in semi-arid fractured aquifers. In: Sililo et al. (ed) Proceedings of groundwater: achievements in the past and challenges for the future. Balkema, Rotterdam, pp 331–336

Sukhija BS, Reddy DV, Nagabhushanam P, Hussain S (2003) Recharge processes: piston flow vs preferential flow in semi-arid aquifers of India, Hydrogeol J 11(3):387–395

Chapter 15
An Overview of Agricultural Pollutants and Organic Contaminants in Groundwater of India

Srimanti Dutta Gupta, Abhijit Mukherjee, Jayanta Bhattacharya and Animesh Bhattacharya

Abstract Major part of Indian population depends on groundwater for drinking purpose. Recent reports of detection of trace quantities of agricultural pollutants and organic contaminants in groundwater have raised serious public health concern. Organic contaminants can enter into groundwater system both through infiltration and through interaction of surface water and groundwater. In addition, problems also arise from the disposal of large amounts of manure and slurries from the increasing numbers of animal rearing units. A series of problems emerge gradually with the utilization of contaminated groundwater. Groundwater wells in Ganges basin which occasionally has very high level of organic contaminants require careful monitoring. The detection of a number of pesticides in groundwater in recent years has been made possible due to development of analytical methods capable of measuring concentrations in parts per billion (ppb) or even lower. It has been found that mostly two herbicides, Alachlor and Atrazine, and one insecticide, Malathion, are found in significant levels in groundwater of India. In lower Ganges basin, Malathion concentration is much higher than the permissible limit. Significant amount of nitrate and phosphate fertilizers has also been detected in

---

S. Dutta Gupta · A. Mukherjee (✉) · J. Bhattacharya · A. Bhattacharya
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: amukh2@gmail.com; abhijit@gg.iitkgp.ernet.in

A. Mukherjee
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee
Applied Policy Advisory to Hydrogeosciences, Indian Institute
of Technology Kharagpur, Kharagpur 721302, West Bengal, India

J. Bhattacharya
Department of Mining Engineering, Indian Institute of Technology Kharagpur,
Kharagpur 721302, West Bengal, India

A. Bhattacharya
Water Supply Sanitation Organization, Public Health Engineering Department,
Shuklalpur, West Bengal, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_15

groundwater systems of India. Research on pesticide and fertilizer contamination and their dissemination in groundwater system is being studied. Adverse effect of these contaminants on human health in India is yet to be established, but research on such fields is been undertaken by different scientific communities.

Keywords Groundwater · Organic pollution · Pesticides · Chemical fertilizers Malathion

15.1 Introduction

Groundwater sources comprise of seepage from the surface water mainly from river water, rainwater, lakes, and streams. Entire human population depends on 6% of the aggregate water on Earth which is freshwater of which majority is in the form of ice caps and ice masses. If these sources are deducted from the total freshwater content, only 0.3% of the water on Earth is accessible for drinking purposes of which majority is groundwater (USEPA 1992). Since significant part of the population in the developing countries relies entirely on groundwater for drinking purpose, groundwater pollution may cause serious health concerns (APHA 1995). Groundwater pollution can be broadly categorized into two types: natural geogenic pollution and anthropogenic pollution. Anthropogenic pollution has more impact than geogenic pollution in the shallow dug which is mainly used by people for drinking purpose. Anthropogenic pollution in groundwater can be broadly clustered into four groups: municipal, industrial, agricultural, and individual domestic sources. Contamination of municipal sources includes open dumpsites, inadequately constructed latrines, and other waste places. Each of these can contain a huge number of pathogens and also high metal concentration that can infiltrate to the groundwater aquifers. Mining activities effect groundwater contamination through draining of mine tailing piles. Another major source of groundwater pollution is agricultural contamination which essentially comes from use of pesticides and fertilizers which can later infiltrate to the groundwater system. Contamination in India's groundwater has long been a natural concern and focus of global environmental concern. Since there are very few studies on the agricultural contaminants in groundwater, this chapter deals with the general assessments of agricultural contaminants with special reference to pesticides and fertilizers present in Indian groundwater.

Groundwater contamination differs from surface water contamination in several points of views. During late nineteen, the quality of groundwater has been degraded and presence of hazardous waste in groundwater was reported. Later, a considerable effort was applied to protect and clean the surface water where pollution was readily visible. During 80s, widespread reports on presence organic pollutants in trace quantity in groundwater shifted the focus from surface water to groundwater protection, resulting in the change of drinking water regulation. Groundwater contamination has been called the problem of the 1980s. Arsenic pollution in groundwater was first reported during this time.

This chapter is intended to provide an overview of the organic pollution in Indian groundwater and health effects of contaminated groundwater (Chap. 1, Fig. 1.4). Organic pollutants from surface water can seep into groundwater from any place (Winter 1983). Quality of groundwater also degrades due to contact with sediments. In recent studies, it has been observed that excessive use of agricultural fertilizers increases the nitrate and phosphate contents in groundwater.

Punjab and Haryana are one of the most agriculturally productive lands in India. These two places are rich in natural resources which include nutrient-rich soil and a satisfactory amount of water supply and favorable climate conditions for agriculture. As a result, two or more types of crop in a year have been obtained from this land. During the 1970s and 1980s, green revolution was held to expand the irrigated areas by the development of surface water and groundwater resources. Increased use of fertilizers and pesticides improved the quality of the crop and food (Avtar et al. 2013). Subsequently, groundwater of these places becomes vulnerable to organic pollution, and drinking water supply was threatened. A series of difficulties developed eventually with the application of pesticides and organic fertilizers which seeped into groundwater.

River water has been over-exploited and polluted in many parts of the world, so have groundwater. During 1978, the presence of dioxins in Love Canal is one of the exemplars which cause carcinogenic effects and an alarming number of neonatal deformities. Similar event persists in the present world. Well, documentation of nature and pollution mechanism of the organic contaminants in the groundwater has been done after years of researches. The present study focuses on the types of organic contaminants in groundwater, sources of it along with the present scenario of contaminants in groundwater system in India. More related information regarding groundwater of South Asia is available in (Mukherjee 2018).

15.2 Present Scenario of Agricultural Pollution in Groundwater in India

Water passing through an aquifer is naturally filtered, either by the natural degradation of contaminants or through surface adsorption. Groundwater often serves safe and clear drinking water. Water from shallow aquifer is safer than deep aquifer in respect of natural geogenic pollution such as arsenic. But anthropogenic activities are the major cause of pollution in shallow groundwater. As of 2011, India is the second largest country in the agricultural sector. About 40% of the total land use is covered by agricultural field. Since India is the largest user of groundwater, groundwater pollution is a major concern in India. Sometimes organic compounds are stable and also soluble in water. Surface adsorption also depends on the soil properties and residence time. During 1948–49, use of organic pesticides started with DDT (Dichlorodiphenyltrichloroethane) and BHC (benzene hexachloride). During the 1970s, the green revolution had been aimed to increase the crop productivity, and organic pesticides and agricultural fertilizers have been applied in the agricultural field. Indian pesticide market comprises more than 550 pesticides (Gupta 2004).

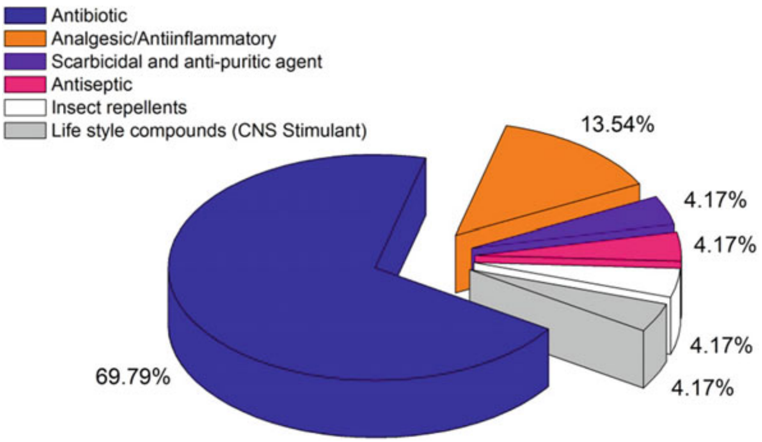


Fig. 15.1 Occurrence (%) of organic compounds detected in groundwater in Asiatic countries. *Data source* Ministry of chemicals and petrochemicals; number of compound identified = 24

Twenty-four pharmaceutical compounds are present in the groundwater of Asian countries, among them 23 are pharmaceuticals antibiotics and another one is Caffeine (Hu et al. 2010; Zhou et al. 2013; Yao et al. 2014). There is very few literature which reports occurrence of pesticides and other agricultural pollutants in groundwater. Antibiotics, analgesic/anti-inflammatory, anticonvulsant, herbicidal, and anti-puritic agents, antiseptics, insect repellents, and lifestyle compounds (Central Nervous System Stimulant) are mostly reported and identified compounds in groundwater of Asian countries (Fig. 15.1). Two most common identified compounds include two antibiotics, namely sulfamethoxazole and tetracycline (Hu et al. 2010).

Most of the countries in Southeast Asia are trying to find their gateway in the global market as a supplier of varieties of fresh fruits and vegetables. The recent agricultural practice involves a use of pesticides and fertilizers which gradually infiltrates into groundwater resulting drinking water pollution. Report from a study in Hanoi, in the Red River Delta, showed that proper guideline was followed by only 25% farmers and 58% followed their own experience and 17% were unskilled (Jaeken et al. 2005). In developing countries, after applying the pesticides on the fields, farmers dispose of the remaining spray in the surface water and the spraying equipment is cleaned in canal and ditches. Unaware about the proper disposal procedure, remaining part is sprayed on other plants (Castillo et al. 2007). Due to this kind of agricultural practices, infiltration of contaminants in groundwater pollution increases.

According to Pakistan Council of Research in Water Resources, by-products of various industries such as textile, metal, dyes, fertilizers, pesticides, cement, and petrochemical industries are the primary contributors of the organic pollution in groundwater (PCRWR 2010). Between July and December 2002, the Pollution Monitoring Laboratory of the New Delhi-based Center for Science and Environment (CSE) examined 17 brands of bottled water. Among them, six bottled water plants showed the frequent presence of beta-Hexachlorocyclohexane (HCH), Dichlorodiphenyltrichloroethane (DDT), Malathion, and Chlorpyrifos. Some raw water samples also showed the presence of Endosulfan, Dieldrin, Dimethoate, and Methyl parathion which was more than the permissible limit.

In 2008, a study was directed to scrutinize the ecological exposure of natural water pollution distant mountainous areas of northern Vietnam. The study observed the fate of four groups of pesticides, namely imidacloprid, fenitrothion, fenobucarb, and dichlorvos, from paddy field to a stream on the watershed scale and computed groundwater pollution. Maximum measured concentration was 0.47, 0.22, 0.17, and 0.07 ppb for fenitrothion, imidacloprid, fenobucarb, and dichlorvos, respectively. The report suggests that present agricultural use of pesticide in the paddy field causes a serious ecological concern in the region (Lamers et al. 2011).

Pesticide includes a wide variety of compounds which contain insecticides, fungicides, herbicides, and plant growth regulators. Approximately, in India, 76.3% of the pesticide used is insecticide, and use of herbicides and fungicides is comparatively less. This chapter contains the yearly variation of use of pesticides in India since 2000 (Fig. 15.2). The pesticide consumption in India during 1954 to 2000 has been increased from 434 to 46,195.16 Metric Tonne. The increase in use of pesticides supports the increase in residual pesticide concentration in groundwater and surface water by percolation and surface runoff, respectively.

The discovery of a numerous number of pesticides in groundwater in past few decades has been made feasible by the improvement of new cutting-edge technologies which are capable of determining concentrations in the parts per billion (ppb) ranges or even less than that. Distribution of different classes of pesticides applied on agricultural fields in India has been shown in Fig. 15.3.

Central Pollution Control Board (CPCB) has detected the pesticides in groundwater. It has found that mostly two herbicides such as Alachlor and Atrazine and two pesticides such as Lindane and Chlorpyrifos are found in groundwater in India. Pesticide concentrations in groundwater in recent years have been monitored

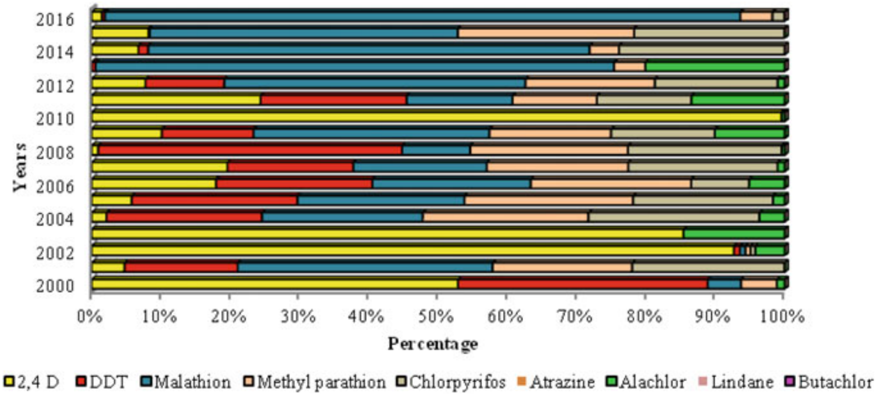


Fig. 15.2 Use of pesticides during 2000–2016 in India. *Data source* Central Pollution Control Board

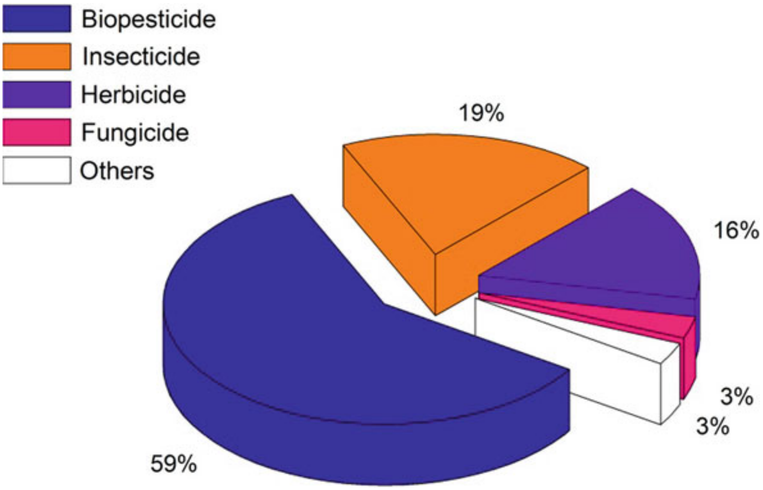


Fig. 15.3 Distribution of different classes of pesticides used in India. *Data source* State Pollution Control Board

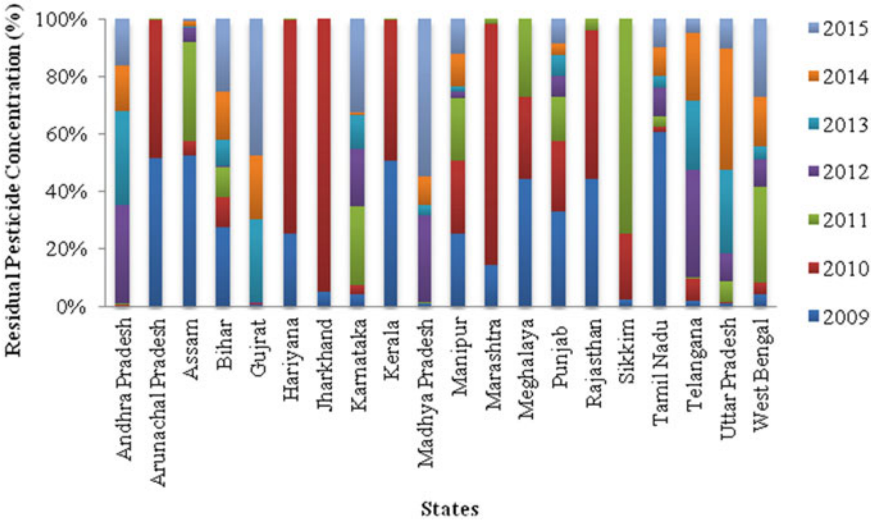


Fig. 15.4 Overall pesticide concentration in groundwater for different states in recent years

by state pollution control board (Fig. 15.4). Three states Haryana, Punjab, and West Bengal found to be most susceptible area to pesticide pollution in groundwater (Fig. 15.5). This figure depicts locations having the high amount of residual pesticide concentration in groundwater. These areas are agricultural dependent land, and people are also dependent on groundwater from private wells those are situated

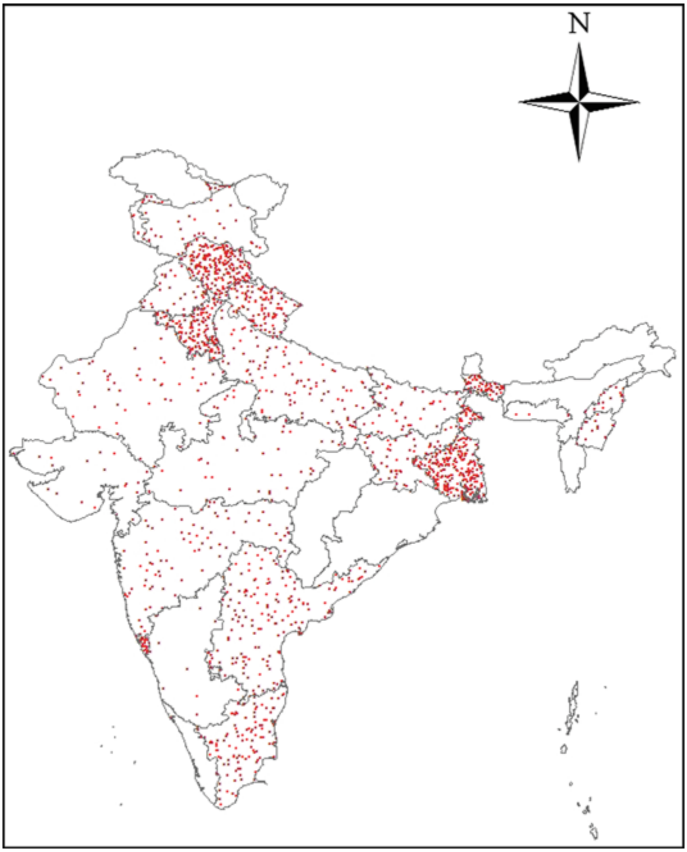


Fig. 15.5 Distribution of residual pesticide in different locations of each state in Indian groundwater

just beside the pesticide-applied agricultural field. Pesticides have been detected in private wells and even in public shallow wells adjacent to the pesticide-treated field. Twelve pesticides have been detected which showed higher than permissible limit as per Environment Protection Agency (EPA) in drinking water wells under specific conditions from the limited monitoring sites.

Most of the pesticides listed are applied to the surface of the soil or are fused with the soil, as opposed to being sprayed onto growing crops. Discontinuation of use of pesticide in affected area may be obtained if the concentration of pesticide in groundwater reaches the permissible limit. The higher amount of aldrine has been found in groundwater in rural areas of Uttar Pradesh. Approximately 62% of the total area of West Bengal has cultivated the land. According to West Bengal pollution control board, lower Ganges basin showed the higher amount of Malathion concentration which is three times more than the permissible limit. Ecological cautions on pesticide concentrations should always be noticed. Activated carbon filter is an

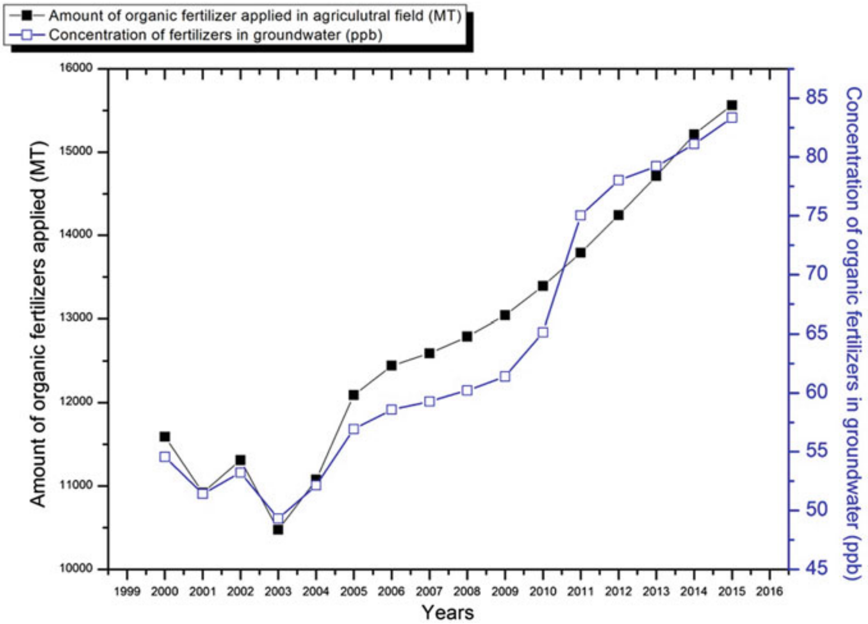


Fig. 15.6 Use of organic fertilizer in agricultural field and concentration of organic fertilizer in groundwater. *Data source* Department of Fertilizer and Public Health Engineering Department, Govt. of India

effective remediation technology to reduce the concentration of pesticides in drinking water. Use of ultraviolet light to decompose the pesticide residues can be an alternative way to get rid of pesticide pollution. Regular monitoring of groundwater must be observed at monthly intervals to regulate the concentration. Research on organic pollution is continuing for many organic compounds.

Chemical fertilizers are widely used in the agricultural sector of India. It has been observed that nitrate and phosphate concentration has been increased during last few decades. Since potassium having limited mobility and phosphorus being virtually immobile, neither is leached out very easily and does not appear to have any adverse effects on the natural water. On the contrary, nitrogen fertilizers are readily converted to nitrates which are soluble, thus posing more serious problems. Studies show, however, that a proportion of the nitrate is contributed by nitrogen-fixing bacteria found in all fertile soils. Reports also suggest that nitrate is also contributed by rainwater and sewage effluents. Groundwater wells associated with Ganges basin which occasionally have very high levels of fertilizers do require careful monitoring. In current years, there has been alarm about environmental pollution and it has been frequently stated that chemical fertilizer usage has added to this pollution by increasing the fertilizer concentration in groundwater. The tonnages of manufactured fertilizer nutrients such as nitrate used in India in recent years are given in Fig. 15.6.

These data, which are readily obtainable from Department of Fertilizer, Govt. of India, shows that the use of nitrate fertilizer has been increased in last 16 years. The concentration of nitrate in groundwater showed the same result over the last 16 years. Although the fertilizer loss is important economically to the farmer, the more important concern is its effect on the environment. Two major problems contributed by high nutrient levels are algal blooms which have been attributed to soluble nitrates and phosphates in water and adverse effect on young babies up to the age of about three months, which is due to the presence of excessive levels of nitrate in drinking water. Algal growths which have been known for centuries are incompletely understood, but the levels of nutrients which it is claimed to limit algal growth are below 0.3 ppm nitrate and 0.01 ppm phosphates, respectively. It is thought that factors such as water temperature, carbon dioxide concentrations, and the presence of organic matter are important, and in general, it seems unlikely that marginal increase in nitrate levels would initiate algal growth.

References

APHA (American Public Health Association) (1995) American Water Works Association and Water Pollution Control Federation, Standard methods of examination of water and waste water, 19th edn, New York, USA

Avtar R, Kumar P, Singh CK, Sahu N, Verma RL, Thakur JK, Mukherjee S (2013) Hydrogeochemical assessment of groundwater quality of Bundelkhand, India using statistical approach. Expos Health 5(3):t05–I15

Castillo MDP, Torstensson L (2007) Effect of biobed composition moisture, and temperature on the degradation of pesticides. J Agric Food Chem 55:5725–5733

Gupta PK (2004) Pesticide exposure—Indian scene. Toxicol 198:83–90

Hu G, Dai J, Mai B, Luo X, Cao H, Wang J, Li F, Xu M (2010) Concentrations and accumulation features of organochlorine pesticides in the Baiyangdian Lake freshwater food web of North China. Arch Environ Contam Toxicol 58

Jaeken P, Debaer C (2005) Risk of water contamination by plant protection products (PPP) during pre- and post-treatment operations. Annu Rev Agric Eng 4(1):93–114

Lamers M, Anyusheva M, La N, Nguyen VV, Streck T (2011) Pesticide pollution in surface-and groundwater by paddy rice cultivation: a case study from Northern Vietnam. Clean Soil Air Water 39(4):356–361

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore (ISBN 978-981-10-3888-4)

PCRWR (2010) Water quality status in rural areas of Pakistan, Pakistan Council of Research in Water Resources, Islamabad, Pakistan

United States Environmental Protect ion Agency (1992) Pesticide industry sales and usage, 1990 and 1991 market estimates. United States Environmental Protection Agency Publishing, Washington, D.C.

Winter TC (1983) The interaction of lakes with variably saturated porous media. Water Resour Res 19(5):1203–1218

Yao LQ, Huo ZL, Feng SY, Mao XM, Kang SZ, Chen J, Xu JJ, Steenhuis TS (2014) Evaluation of spatial interpolation methods for groundwater level in an arid inland oasis, northwest China. Environ Earth Sci 71(4):1911–1924

Zhou F, Guo HC, Liu Y, Jiang YM (2013) Chemometrics data analysis of marine water quality and source identification of Southern Hong Kong. Mar Pollut Bull 54(6):745–756

Chapter 16
A Comparative Analysis of Fluoride Contamination in a Part of Western India and Indus River Basin

Shubhangi, Anand Kumar, Akanksha Balha, Sonal Bindal and Chander Kumar Singh

Abstract Fast-growing population, water demand, and the presence of inorganic contaminants in groundwater of arid and semiarid region have created a need for quality assurance before the domestic water supply. Altogether, 30 water samples were collected from Jaisalmer (10 samples each from Jaisalmer and Pokhran blocks) and Bhatinda (10 samples) districts of Rajasthan and Punjab, respectively, and analyzed for major ions and water quality parameters. Results suggest that most of the groundwater samples are alkaline in nature with high electrical conductivity. Based on the mean value, most of the ions such as Na^+, $SO_4{}^{2-}$, Cl^-, $NO_3{}^-$, and F^- are found to be above the WHO guideline for drinking water. Geochemical modeling and conventional graphical plots are used to decipher the groundwater chemistry. Mg–HCO_3 is found as the most dominant water type followed by Na–HCO_3 and Na–Cl in Bhatinda, while in Jaisalmer and Pokhran Na–Cl is found as the most dominant water type except one sample which shows water facies of Na–HCO_3 type. Fluoride is found as the major contaminant in all the three regions as F varied from 1.9 to 4.5 mg/L in Jaisalmer, while in Pokhran and Bhatinda it has varied between 1.1 and 6.1 mg/L and 0.8 and 4.0 mg/L, respectively. About 60% of the samples from Bhatinda, 100% samples in Jaisalmer, and 90% of the samples from Pokhran contain $F > 1.5$ mg/L. Most of the samples are undersaturated with fluorite and gypsum while oversaturated with calcite and dolomite suggesting dissolution of fluorite as a major contributor for high F^- in groundwater of the study areas.

Keywords Fluoride · Groundwater · Arid and semiarid regions

Shubhangi · A. Kumar · A. Balha · S. Bindal · C. K. Singh (✉)
Department of Energy and Environment, TERI School of Advanced Studies,
New Delhi 110070, India
e-mail: chanderkumarsingh@gmail.com

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_16

16.1 Introduction

The occurrence of fluorine, a naturally found element in earth's crust as fluoride (F^-) ions in groundwater, has become a global public health concern. Due to high electronegativity and reactivity, fluorine is mostly found as fluoride mineral complexes and under favorable conditions this moves from aquifer minerals to groundwater. Fluoride is an essential part of human diet as a daily dose of 0.5–1.0 ppm is required for proper development and mineralization of bones and enamels of teeth. Consumption of fluoride through groundwater is reported as the tow edge knife as both low and high fluorides affect human health adversely (Hussain et al. 2002, 2004). It has been found that the deficiency of fluoride leads to dental caries, formation of enamel, and bone fragility (Cao et al. 2000; Ayenew 2008), while the high concentration of fluoride (>1.5 ppm) is also toxic as its prolonged consumption causes lack of enamel formation, molting of teeth, bone fragility, and at the severe stage it may cause bilateral lameness and stiffness of gait depending on the level and period of exposure (Edmunds and Smedley 2005; Singh et al. 2011, 2013).

Fluoride is widely distributed in several naturally occurring minerals, such as fluorite (CaF_2), cryolite (Na_3AlF_6), topaz, tourmaline, and micas, where it is found in combination with silicates, but particularly in association with phosphorus as fluorapatite [$Ca_5(PO_4)_3F$]. Human interference in groundwater is almost negligible; therefore, hydrogeochemical process including mineral weathering, precipitation, dissolution, ion-exchange, oxidation, reduction, and residence time determines the extent of fluoride contamination (Barbecot et al. 2000; Reghunathet al. 2002; Singh et al. 2011; Rina et al. 2012; Kumar et al. 2015). The concentration of fluoride in groundwater depends on the various factors including types of aquifer minerals, interaction between groundwater and aquifer minerals, climatic condition, chemistry in recharge area, and intermixing of water.

In India (Chap. 1, Fig. 1.6), the problem is acute in states of Andhra Pradesh, Bihar, Gujarat, Madhya Pradesh, Punjab, Rajasthan, Tamil Nadu, Assam, and Uttar Pradesh (Godfrey et al. 2006; Ayoob and Gupta 2006; Sharma et al. 2007; Khaiwal and Garg 2007; SIHFW 2008; Hussain et al. 2012; Singh and Mukherjee 2015). The effect of fluoride on human health is more severe in semiarid and arid regions because of extreme climatic conditions favor the dissolution of fluorite in groundwater. It has been reported that 30 districts of Rajasthan and 11 districts of Punjab are fluoride affected (CGWB 2009). Several methods including multivariate statistical analysis, geochemical modeling, inverse geochemical modeling, conventional plots (Yidana and Yidana 2010; Singh et al. 2011; Machiwal and Jha 2015), geochemical modeling (Yidana et al. 2008), stable isotopes (Barbieri et al. 2005; Carucci et al. 2012), redox indicator, and structural equation modeling (Belkhiri and Narany 2015) are widely used to investigate the geochemical evolution and hydrochemical processes controlling the chemical characteristics and fluoride contamination in groundwater. With the above background, this study is an attempt to compare the major hydrogeochemical process responsible for fluoride enrichment in groundwater of the study area. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

16.2 Materials and Methods

16.2.1 Study Area

The study area is situated in the northwestern region of India and includes Bhatinda district of Punjab state and two administrative blocks of the Jaisalmer district of Rajasthan state, namely Jaisalmer and Pokhran (Fig. 16.1)

The Jaisalmer block is located between 70.80°E and 71.58°E longitudes and between 26.41°N and 27.20°N latitudes, covering approximately an area of 3850 km^2. The Pokhran block is located between 71.39°E and 72.09°E longitudes and between 26.32°N and 27.54°N latitudes, covering an area of approximately 6000 km^2 amid the Thar Desert, while Bhatinda lies between 29.55° and 30.6°north latitude and 74.63° to 75.76°east longitudes in Punjab very close to the Thar Desert. The Jaisalmer district lies in the arid region as the annual rainfall varies from 450 mm at the eastern margin to 100 mm at the western margin of the district.

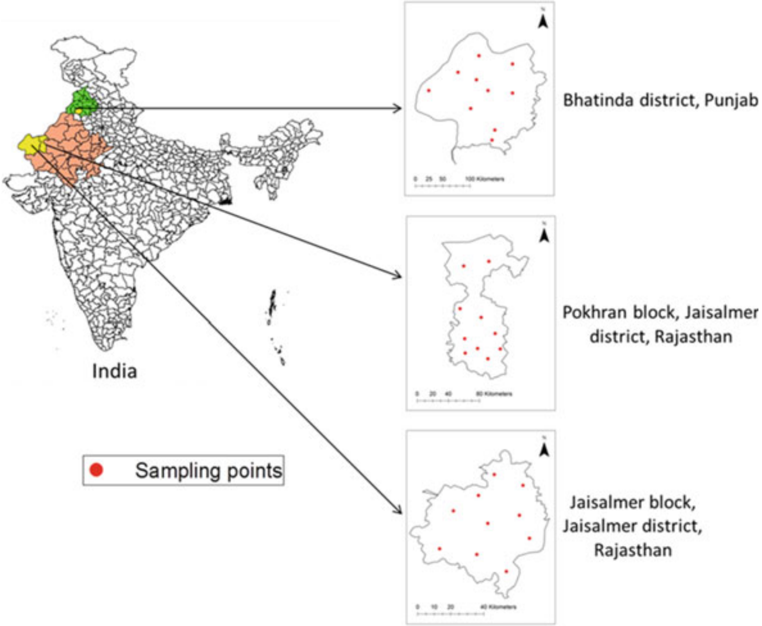


Fig. 16.1 Study area with sampling location

The mean maximum temperature varies from 40 to 45 °C and minimum temperature varies from 3 to 10 °C. The evapotranspiration rate is very high, i.e., approximately 3–20 times higher than precipitation. Bhatinda district also lies in the semiarid climatic zone with the annual rainfall of around 450 mm.

Geologically, Pokhran and Jaisalmer are overlaid by the vast blanket of young unconsolidated alluvium including blown sand of the Thar Desert of western Rajasthan. The important lithological formations in the region are sedimentary rocks comprising of sandstone, limestone, and shales. Carbonate rocks such as limestone, marble, and dolomite are dominant rocks in the region. The various geological formations of Jaisalmer and Pokhran are consolidated, semiconsolidated, and unconsolidated, while Bhatinda has both unconfined and confined aquifers covered with Indo-Gangetic alluvial plain of Quaternary age.

16.2.2 Sample Collection and Analysis

A random sampling plan was adopted, and altogether 30 samples, out of which 20 from Jaisalmer and Pokhran blocks of Jaisalmer district of Rajasthan and 10 from the Bhatinda district of Punjab, have been collected. The tube wells were pumped for 3–5 min to avoid any interference of iron cast pipes, the samples were collected in polypropylene bottles, and the location was geocoded using global positioning system (Garmin GPS). Samples are mostly collected from the tube wells and deep to shallow hand pumps which are the major source of drinking water. The pH, total dissolved solid (TDS), and electrical conductivity (EC) of the water samples were measured at sampling sites with the help of portable pH, TDS, and EC electrodes (Oakton Probe).

The water samples were collected in the 100 mL bottles, one of them was acidified using HNO_3 for cation analysis, and the other unacidified bottle was also filled with the sample for anion analysis. The samples were stored in an icebox, carried to the laboratory, and kept at 4 °C for further chemical analysis. Immediately after the water samples were transported to the laboratory, the major cations were (Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}) analyzed using an atomic absorption spectrometer Thermo Fisher Scientific M series AAS graphite furnace (GFAAS), and the major anions $\left(F^{-}, Cl^{-}, SO_4{}^{2-}, NO_3{}^{-}\right)$ were analyzed using an ion chromatograph (Dionex). Bicarbonate ($HCO_3{}^{-}$) was determined by titration using standard procedures as described in standard methods for the examination of water and wastewater (APHA 2007). The analytical precision of the ions analyzed was determined by calculating the normalized ionic charge balance error, which varied within ±5%. Saturation index and major water types have been calculated using PHREEQC. Saturation index was calculated using the following formula:

$$\mathrm{SI} = \log \_\mathrm{IAP}/K_t \tag{16.1}$$

where IAP is the ion activity product of dissociation of the mineral in the aqueous solution, and K_t is the equilibrium solubility product of the mineral.

16.3 Result and Discussion

16.3.1 Distribution of Major Ions

Water quality parameters with the basic statistics have been summarized in Table 16.1. pH of all the water samples indicates alkaline condition in the study area. pH of the water samples in Jaisalmer varied from 7.7 to 8.2 with the mean value of 8.0, while in Pokhran and Bhatinda it varied from 7.6 to 8.5 and 8.2 to 8.9 with the mean value of 7.9 and 8.6, respectively. Based on the mean value of pH, highest pH has been observed in Bhatinda. High concentration of pH in groundwater suggests high interaction between rainwater and the soil in the region. Enhanced dissolution imparts alkalinity in the aquifer system.

Large variation in EC concentration has been observed in all three regions. In Jaisalmer, the concentration of EC varied from 1600 to 3600 µS/cm with the mean value of 2460 µS/cm. The EC in Pokhran varied from 1790 to 12,000 µS/cm, and in Bhatinda, it varied from 280 to 2410 µS/cm with the mean value of 3919 and 1479 µS/cm, respectively. The high EC and TDS value indicates high salinity in groundwater. The study area lies in arid to semiarid region where evaporation is very high thus results in increased salt concentration. Wide variation in water quality parameters suggests that the hydrogeochemistry of the area is not homogenous, and it has been affected by the climatic factors including rock–water interaction as well as anthropogenic inputs. Only four samples (all from Bhatinda) out of 30 collected have EC value <1500 which falls within the WHO prescribed limit for drinking water (WHO 2009).

Na^+ is found as the most dominant cation in all three sampled areas followed by Ca^{2+}, $Mg^{2\,+}$, and K^+ in Pokhran and Jaisalmer and K^+, $Mg^{2\,+}$, and Ca^{2+} in Bhatinda. The concentration of Na^+ in Jaisalmer varied from 239 to 670 mg/L with mean value 416.4 mg/L. The concentration of Na in Pokhran varied from 215 to 1068 mg/L, while in Bhatinda it varied from 34 to 312 mg/L with the mean value 588.1 and 129.2 mg/L, respectively. Na^+ is considered as conservative in nature, and it binds with the clay minerals (Subramanian and Saxena 1983). Concentration of Ca^{2+} in Jaisalmer varied from 40 to 108 mg/L with an average value of 70.3 mg/L, while in Pokhran and Bhatinda the values ranged between 30–125 and 12–88 mg/L with an average of 84.1 and 38.6 mg/L, respectively. The highest concentration of Ca^{2+} is found in Pokhran and the lowest is observed in Bhatinda. The concentration of Mg^{2+} in the groundwater varied from 23 to 48.6 mg/L in Jaisalmer, while in Pokhran and Bhatinda it varied from 12.1 to 68.6 mg/L and 21.0 to 113.0 mg/L, respectively.

Table 16.1 Descriptive statistics of the samples from study area with WHO (2009) guideline

Variable	Pokhran				Jaisalmer				Bhatinda				WHO (2009)
	Min	Max	Mean	Std. deviation	Min	Max	Mean	Std. deviation	Min	Max	Mean	Std. deviation	
pH	7.6	8.5	8.0	0.2	7.7	8.2	7.9	0.1	8.2	8.9	8.6	0.2	6.5–8
EC	1790.0	12000.0	3919.0	3080.6	1600.0	3600.0	2460.0	826.2	280.0	2410.0	1479.0	854.0	–
TDS	1206.0	3118.0	1959.6	654.2	810.0	2211.0	1414.1	537.4	80.0	2100.0	713.0	665.1	500
Na	215.0	1068.0	588.1	325.7	239.0	670.0	416.4	169.1	34.0	312.0	129.2	109.3	200
K	6.6	54.8	22.5	15.0	6.0	17.8	12.6	3.4	8.0	150.0	56.0	53.8	30
Ca	30.0	125.0	84.1	26.6	40.0	108.0	70.3	18.5	12.0	88.0	38.6	28.5	200
Mg	12.1	68.6	37.9	17.6	23.0	48.6	34.0	8.2	21.0	113.0	44.0	29.9	150
Cl	368.0	1395.0	635.6	324.0	172.0	652.0	428.6	156.4	45.0	593.0	259.1	205.1	250
SO_4	81.0	374.0	188.0	89.7	93.0	417.0	184.8	97.6	0.05	0.4	0.2	0.1	250
HCO_3	183.0	1220.0	544.7	332.4	242.0	610.0	409.1	109.8	379.0	654.0	553.4	105.4	600
NO_3	29.7	304.4	170.2	103.5	5.00	360.2	86.2	135.4	1.1	7.9	4.7	2.5	50
F	1.1	6.1	4.0	1.5	1.9	4.5	2.7	0.8	0.8	4.0	1.8	1.0	1.5

Ca^{2+} and Mg^{2+} along with HCO_3^- determine the hardness of the groundwater. At soil zone, precipitation of Ca^{2+} and Mg^{2+} occurs due to temporary hardness, and these precipitated salts might get leached from the soil zone with rainwater or irrigation water and contribute high concentration of these ions in groundwater. K^+ concentration in Jaisalmer varied from 6 to 17.8 mg/L with an average of 12.6 mg/L, while in Pokhran and Bhatinda the values range between 6.6–54.8 and 8–150 mg/L with average values of 22.5 and 56 mg/L, respectively. The highest concentration of K^+ was found in Bhatinda. Weathering of K^+ bearing minerals, i.e., K-feldspar might be responsible for the K^+ concentration in groundwater. Anthropogenic activities as use of synthetic fertilizers might also contribute K^+ in groundwater.

Among anions the Cl^- is the most dominant based on the mean values in Jaisalmer and Pokhran followed by $HCO_3^-, SO_4^{2-}, NO_3^-$ and F^-, while in Bhatinda HCO_3^- is the most dominant anion followed by Cl^-, NO_3^-, F^-, and SO_4^{2-}. The concentration of Cl^- in Jaisalmer varied from 172 to 652 mg/L with an average of 428.6 mg/L, while in Pokhran and Bhatinda the concentration varied from 368–1395 and 45–593 mg/L with an average of 635.6 and 205.1 mg/L, respectively. The maximum Cl^- concentration is found in the Pokhran and Jaisalmer where the temperature is found to be high during most of the time in year compared to Bhatinda, high concentration of Cl^- might be due to high evaporation rate in these regions. HCO_3^- concentration varied from 242 to 610 mg/L with an average value of 409.1 mg/L in Jaisalmer, while in the Pokhran and Bhatinda it varied from 183 to 1220 mg/L and 379–654 mg/L with average values of 544.7 and 553.4 mg/L. High HCO_3^- concentration indicates the presence of carbonate minerals. Weathering of silicate and carbonate minerals along with degradation of organic matter might contribute high concentration of HCO_3^- ions in groundwater (Rina et al. 2012). The concentration of NO_3^- is found highest in groundwater samples collected from Pokhran as the concentration ranges from 29.7 to 304.4 mg/L with an average of 170.2 mg/L, while in Jaisalmer and Bhatinda the concentration of NO_3^- varied from 5 to 360 mg/L and 1.1 to 7.9 mg/L with an average of 4.7 mg/L. Very low concentration of SO_4^{2-} is observed in Bhatinda where the concentration of SO_4^{2-} varied from 0.05 to 0.4 mg/L, while in Pokhran and Jaisalmer the concentration of SO_4^{2-} is comparatively high as the concentration varied from 81.37 mg/L in Pokhran and 93–417 mg/L in Jaisalmer, respectively. Dissolution of minerals such as gypsum and anhydrite might contribute SO_4^{2-} in groundwater, while anthropogenic activities as use of fertilizers and leaching of municipal waste or agricultural runoff might contribute high concentration of NO_3^- in groundwater, whereas the anthropogenic inputs in desertic regions are very less, however, the high NO_3^- can be observed as it has accumulation over the long periods of climatic phenomena of lightening and rainfall (Walvoord et al. 2003).

Fluoride is found as the major contaminant with severe health risk in all three regions as the concentration of F varied from 1.9 to 4.5 mg/L in Jaisalmer, while in Pokhran and Bhatinda it has been found to vary between 1.1–6.1 and 0.8–4.0 mg/L, respectively. In semiarid and arid regions, the weathering of fluoride-containing rocks (fluorite) is the major source of F^- in groundwater. However, high pH along with high HCO_3^- favors the dissolution of fluorite-bearing minerals.

16.3.2 Correlation Between Major Ions

The correlation matrix ($p < 0.05$) for all the water quality parameters has been analyzed to decipher the relationship among the major ions present in the study area (Table 16.2). Correlation between water quality variables gives an insight of the major hydrogeochemical process which controls the chemical characteristics of the groundwater. In Pokhran, pH is strongly correlated with K^+, while Na^+ shows strong correlation with Cl^- and moderate correlation with SO_4^{2-}, HCO_3^-, and NO_3^-. K^+ shows moderate positive correlation with NO_3^-. In Jaisalmer, pH is strongly correlated with Ca^{2+}, while Na^+ is strongly correlated with Cl^-, SO_4^{2-}, and HCO_3^-. Positive correlation between Cl^- and Na^+ with EC shows that dissolution of ions from rocks is a major controlling factor of EC. In Bhatinda, Na^+ shows strong and positive correlation with K^+ and Cl^- and moderate correlation with Mg^{2+}, Ca^{2+}, and HCO_3^-. A strong correlation among SO_4^{2-} and NO_3^- in Bhatinda indicates agricultural activities and seepages from the drainage as major contributor of these ions in groundwater.

16.3.3 Hydrogeochemical Processes

16.3.3.1 Weathering and Dissolution

Plot between Ca^{2+}/Na^+ and $HCO_3^-Na^+$, i.e., Na^+ normalized Ca^{2+} versus HCO_3^- graph, is used to identify the dominance of hydrogeochemical process, i.e., influence of silicate weathering, evaporate dissolution, or carbonate weathering on groundwater chemistry. Figure 16.2a indicates that chemical characteristics of most of the water samples from all three locations have been influenced by the evaporate dissolution. In Fig. 16.2b, Na^+ normalized Ca^{2+} versus Mg^{2+} graph indicates that most of the Mg^{2+} is derived due to evaporate dissolution. The scatter plot between $Ca^{2+} + Mg^{2+}$ and $SO_4^{2-} + HCO_3^-$ identifies the ion-exchange is the dominant process. The samples close to equiline (1:1 line) indicate the dissolution of dolomite, calcite, or gypsum as the dominant process in the aquifer (Fig. 16.2c). If ion-exchange is the major process, then it will shift the points away from the equiline, i.e., toward right while if reverse ion-exchange is dominant, then it tends to shift the points left to equiline due to excess of $Ca^{2+} + Mg^{2+}$ ions (Singh et al. 2013). The scatter plot between $Ca^{2+} + Mg^{2+}$ and $SO_4^{2-} + HCO_3^-$ indicates that most of the water samples of Bhatinda are below equiline which indicates

Table 16.2 Correlation analysis of physicochemical parameters from different regions

	pH	EC	TDS	Na	K	Ca	Mg	Cl	SO_4	HCO_3	NO_3	F
Bhatinda												
pH	**1**											
EC	−0.053	**1**										
TDS	0.239	**0.792**	**1**									
Na	−0.232	**0.804**	**0.730**	**1**								
K	−0.159	**0.843**	**0.755**	**0.911**	**1**							
Ca	−0.193	**0.678**	0.232	0.380	**0.554**	**1**						
Mg	**−0.681**	0.460	0.085	**0.690**	**0.532**	0.428	**1**					
Cl	−0.135	**0.881**	**0.729**	**0.962**	**0.943**	**0.549**	**0.619**	**1**				
SO_4	0.290	−0.124	−0.393	−0.140	−0.160	0.199	0.132	−0.076	**1**			
HCO_3	0.394	**0.608**	**0.620**	0.390	**0.528**	0.429	0.048	0.439	0.319	**1**		
NO_3	0.407	−0.323	**−0.561**	**−0.581**	**−0.547**	0.142	−0.209	−0.474	**0.746**	0.076	**1**	
F	**0.541**	0.210	0.053	−0.287	−0.001	0.368	−0.409	−0.084	0.344	**0.523**	**0.536**	**1**
Pokhran												
pH	**1**											
EC	**−0.083**	**1**										
TDS	**0.410**	**−0.060**	**1**									
Na	**0.174**	**0.790**	**0.450**	**1**								
K	**0.713**	**−0.134**	**0.266**	**−0.078**	**1**							
Ca	**0.192**	**−0.027**	**0.474**	**−0.052**	**0.405**	**1**						
Mg	**−0.299**	**−0.081**	**−0.005**	**−0.341**	**−0.174**	**0.487**	**1**					
Cl	**−0.068**	**0.962**	**0.073**	**0.809**	**−0.073**	**0.061**	**0.006**	**1**				
SO_4	**0.451**	**0.166**	**0.639**	**0.510**	**−0.001**	**0.290**	**0.113**	**0.314**	**1**			
HCO_3	**0.323**	**0.162**	**0.753**	**0.649**	**−0.068**	**0.065**	**−0.318**	**0.136**	**0.456**	**1**		

(continued)

Table 16.2 (continued)

	pH	EC	TDS	Na	K	Ca	Mg	Cl	SO_4	HCO_3	NO_3	F
NO_3	**0.470**	**0.247**	**0.653**	**0.559**	**0.586**	**0.264**	**−0.421**	**0.321**	**0.280**	**0.452**	**1**	
F	**0.140**	**−0.023**	**0.596**	**0.242**	**0.324**	**0.441**	**−0.211**	**−0.060**	**−0.079**	**0.584**	**0.669**	**1**
Jaisalmer												
pH	**1**											
EC	−0.115	**1**										
TDS	−0.012	**0.974**	**1**									
Na	−0.176	**0.993**	**0.978**	**1**								
K	0.179	0.316	0.268	0.261	**1**							
Ca	**0.707**	−0.048	0.032	−0.090	−0.203	**1**						
Mg	−0.129	**0.550**	**0.645**	**0.583**	0.209	−0.079	**1**					
Cl	−0.232	**0.926**	**0.869**	**0.918**	0.235	−0.086	**0.530**	**1**				
SO4	0.037	**0.696**	**0.738**	**0.722**	0.362	−0.072	0.285	**0.565**	**1**			
HCO3	−0.245	**0.763**	**0.677**	**0.753**	0.146	0.085	0.199	**0.629**	0.455	**1**		
NO3	0.329	**0.512**	**0.657**	**0.526**	0.012	0.167	**0.718**	0.341	0.284	0.146	**1**	
F	−0.289	0.393	0.360	0.430	0.462	−0.477	0.059	0.358	**0.753**	0.220	−0.143	**1**

Bold shows moderate to good correlation

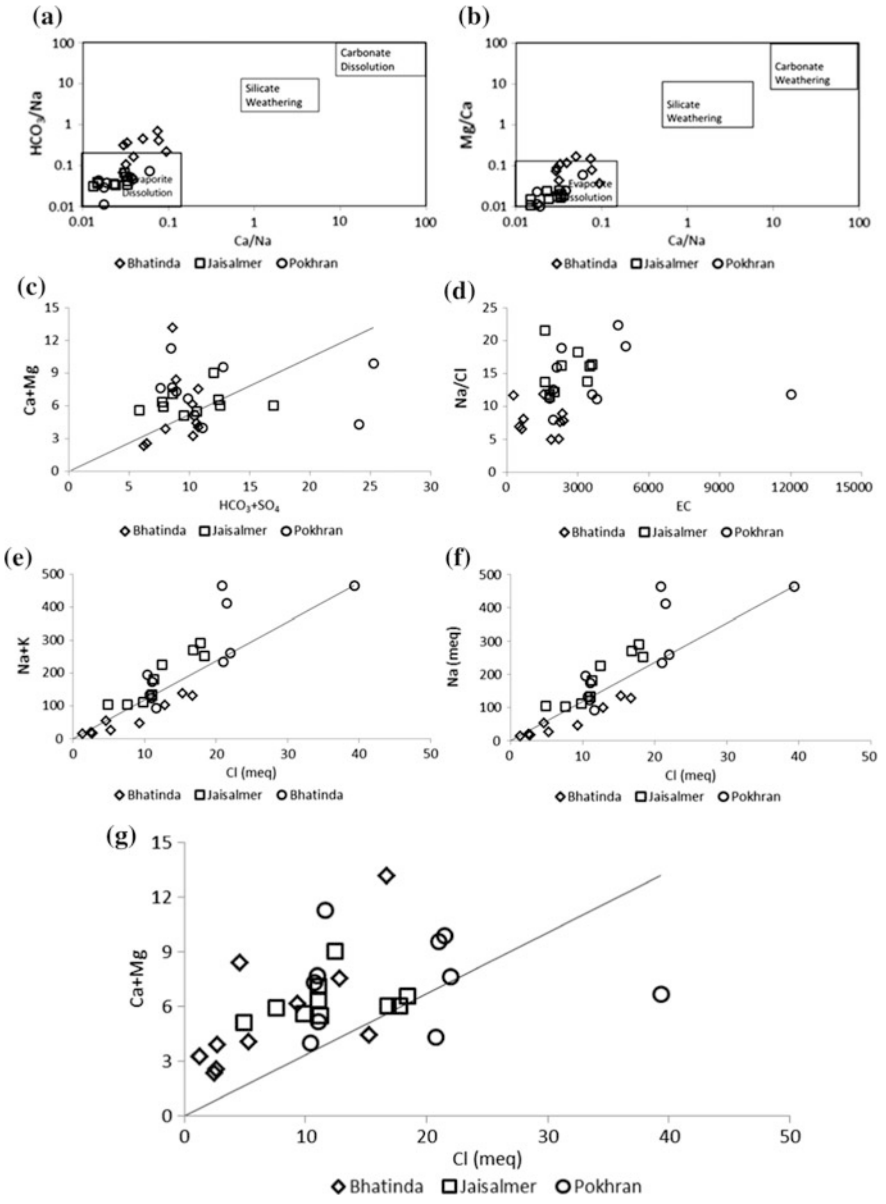


Fig. 16.2 **a** Na^+ normalized Ca^{2+} versus HCO_3^- scatter plot; **b** Na^+ normalized Ca^{2+} versus Mg^{2+} scatter plot; **c** $Ca^{2+} + Mg^{2+}$ versus $SO_4^{2-} + HCO_3^-$ scatter plot; **d** Na+/Cl^- versus EC scatter plot; **e** scatter plot between Na^+ versus Cl^-; **f** scatter plot between Na^++K^+ versus Cl^-; **g**. scatter plot between $Ca^{2+} + Mg^{2+}$ versus Cl^-

ion-exchange as a major process in this region, while the samples from Pokhran show reverse ion-exchange as a major process.

Ratio of Ca^{2+} and Mg^{2+} determines the dissolution of calcite and dolomite; if the value of Ca/Mg is below 1, it indicates dissolution of dolomite and values >1 indicates dissolution of calcite. In this study, most of the water samples collected from Bhatinda show Ca/Mg value < 1 indicating dissolution of dolomite while in Jaisalmer and Pokhran the value of Ca/Mg > 1 indicating calcite dissolution.

16.3.3.2 Evaporation

Evaporation plays an important role in determining the concentration of ions in groundwater system. Na^+/Cl^- versus EC plot is the effective indicator of evaporation (Fig. 16.2d). If halite dissolution is the dominant process, then in that case the value of Na^+/Cl^- ratio will be 1. High value of Na/Cl indicates Na^+ might be released from the silicate weathering. The scatter plot between $Na^+ + K^+$ versus Cl^- indicates the dominance of silicate weathering; samples above 1:1 lines indicate excess of cations due to weathering of silicate minerals. The plot between $(Na^+ + K^+)$ versus Cl^- indicates that most of the water samples from Bhatinda are below equiline, while the samples from Pokhran and Jaisalmer are above the equiline. It suggests that that the groundwater quality in Jaisalmer and Pokhran is influenced by the silicate weathering or the excess of cations might be due to the presence of saline soil. In Jaisalmer and Pokhran, high concentration of Na^+ is observed while low K^+ which might be because of resistance of potassium to chemical weathering.

16.3.3.3 Ion-Exchange

The Na^+ versus Cl^- scatter plot indicates that most of the samples from Bhatinda are below the equiline suggesting evaporation as a dominant process, while the samples from the Jaisalmer and Pokhran are above the equiline suggesting that the silicate weathering might be contributing the excess of cation in groundwater. Exchange of cations might also act as an alternative source of excess of Na^+ as the area is in arid region where alkaline soil is common. The scatter plot between $Ca^{2+} + aMg^{2+}$ versus Cl^- indicates ion-exchange as most of the samples from all the regions are above equiline.

16.4 Geochemical Modeling

16.4.1 Hydrochemical Facies

Hydrochemical facies are used to identify the overall chemical characteristics of the aquifer. It indicates the effects of interaction between the water and aquifer minerals within the lithological framework. Na–Cl is found as the most dominant hydrochemical facies in Jaisalmer and Pokhran area, while in Bhatinda Na–HCO_3 and Mg–HCO_3 are the most dominant facies (Fig. 16.3 and Table 16.3). The flow path of groundwater, residence time, interaction between groundwater and aquifer minerals, and chemical process within the aquifer system determine the type of the water. Piper trilinear diagram also suggests Na^+ and Ca^{2+} as dominant cationic species and Cl^- and $HCO_3{}^-$ as dominant anionic species. The low concentration of Ca^{2+} might be due to the precipitation of Ca^{2+} as carbonate (Gaciri and Davis 1993). Ion-exchange between Ca^{2+} and Na^+ due to the movement of groundwater in the weathering zone may also result in high F^- associated with high Na^+ and low Ca^{2+} concentration (Tamta 1994).

16.4.2 Saturation Indices

Saturation indices are used to determine the reactivity of the minerals in groundwater. Positive value of saturation indices (SI) indicates oversaturation of the minerals, while the negative value of SI indicates undersaturation. When the solution will be undersaturated in terms of any minerals, it will tend to dissolve; while if the solution is oversaturated, that mineral will precipitate. In this study, all the samples from Bhatinda are found to be undersaturated with fluorite and gypsum while oversaturated with dolomite and calcite, whereas in Jaisalmer all except one sample is undersaturated with fluorite and oversaturated with dolomite and calcite. In Pokhran, most of the water samples, 7 out of 10, are oversaturated with fluorite and all samples are oversaturated with respect to dolomite and calcite. This region lies in the arid climatic zone with high temperature and less rainfall which is responsible for the precipitation of these minerals in groundwater. It also indicates that the water has enough residence time to reach up to mineral equilibrium. The samples with high F^- are undersaturated with fluorite and indicate dissolution of fluorite as a major source of fluoride in groundwater. Oversaturation of calcite and therefore precipitation of Ca in alkaline environment favor the dissolution of fluorite (Adriano 1986). Increase in concentration of HCO_3 ions, pH, and temperature can result in the precipitation of calcite (Hounslow 1995).

16.5 Fluoride Enrichment

Fluoride is an essential element for formation of bone and enamel of teeth; a daily intake of 0.5 mg of F^- is essential for healthy diet, but once the concentration increases above 1.5 mg/L it adversely affects the human health. In present study out of total 30 collected samples from three areas, only five samples are having $F < 1.5$ mg/L, which indicates sever health implications. It has been reported that lower pH value prevents the dissolution of fluorite minerals, while the high pH value favors the dissolution of fluorite (Adriano 1986). In arid and semiarid regions, less rain and high evaporation play an important role in dissolution of fluorite in groundwater (Farooqi et al. 2007; Singh and Mukherjee 2015). In alkaline environment, hydroxyl ions replace F^- from fluorite-bearing minerals, and high TDS enhances the ionic strength of the solution which favors the dissolution of fluorite. In granitic or sandstone dominant aquifers, dissolution of fluorite can be a possible reason for the presence of fluoride in groundwater. The hydrolysis of aluminosilicate in aquifers produces bicarbonate ion, which might enhance the dissolution of fluorite in groundwater.

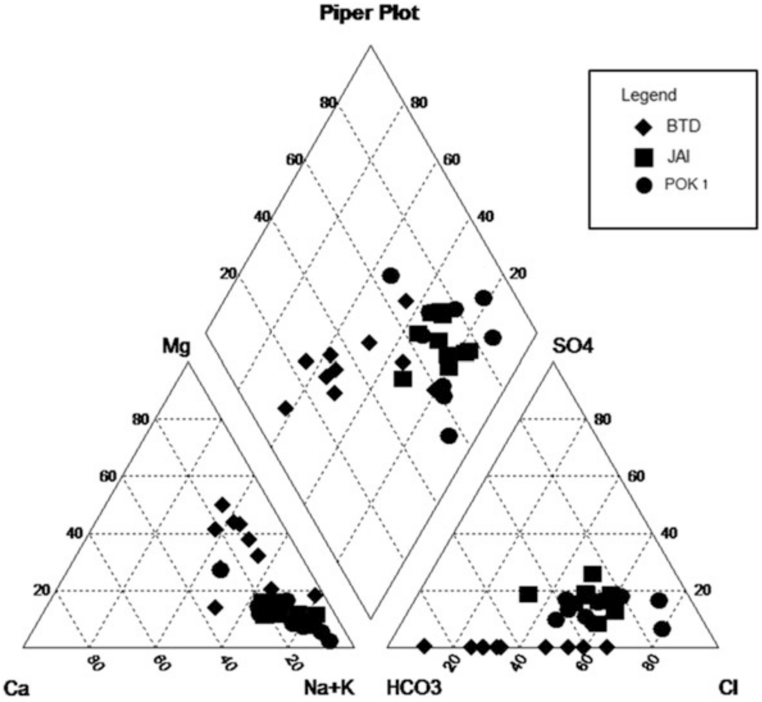


Fig. 16.3 Piper plot of Bhatinda, Jaisalmer, and Pokhran

Table 16.3 Major water facies and their distribution

Water type	Total no of sample	Jaisalmer	Pokhran	Bhatinda
Mg–Na–HCO_3–Cl	3	0	0	3
Na–Cl–HCO_3	12	5	5	2
Mg–HCO_3	1	0	0	1
Na–HCO_3–Cl	1	0	0	1
Na–Ca–HCO_3–Cl	2	1	0	1
Na–Mg–Cl–HCO_3	1	0	0	1
Na–Cl–SO_4–HCO_3	1	1	0	0
Na–Ca–Cl–HCO_3	1	3	2	0
Na–Cl	5	0	2	0
Na–Mg–Ca–Cl–HCO_3	2	0	1	0
Na–Mg–HCO_3–Cl	1	0	0	1

$$CaF_2 + 2HCO_3^- \rightarrow CaCO_3 + 2F^- + H_2O + CO_2 \tag{2}$$

$$CaF_2 + Na_2CO_3 \rightarrow CaCO_3 + 2Na^+ + 2F^- \tag{3}$$

Along with high pH, Na^+ and HCO_3^- are found making it favorable for dissolution of fluorite (Singh et al. 2013). However, other minerals and ionic constituents of water may influence the dissolution of fluorite in groundwater (Table 16.4).

16.6 Conclusion

The conventional graphical plot along with the geochemical modeling helps in understanding the geochemical process leading to fluoride enrichment in groundwater of the study area. Groundwater is the only source of portable water supply in arid and semiarid regions of India. High concentration of fluoride in the well water is a severe public health concern. The anthropogenic influence of fluoride in groundwater is not much possible in these regions thus the high fluoride in groundwater is mostly of geogenic nature. The study suggests that water samples from Bhatinda are less saline in comparison with the Jaisalmer and Pokhran.

Table 16.4 Saturation indices of water samples

Sample no	SI (Calcite)	SI (Dolomite)	SI (Gypsum)	SI (Fluorite)
BTD 1	0.8409	2.2897	−5.1374	−1.3318
BTD 2	0.9099	2.423	−5.026	−1.0761
BTD 3	1.2503	2.8901	−4.5678	−0.9933
BTD 4	1.5672	3.2515	−4.4698	−0.1366
BTD 5	0.8996	2.3508	−4.7714	−1.4558
BTD 6	1.855	3.4058	−4.3443	−0.1066
BTD 7	0.3954	1.3264	−5.5443	−1.8284
BTD 8	1.2994	2.808	−5.1591	−0.4183
BTD 9	1.0653	2.5981	−4.341	−1.0246
BTD 10	0.9843	2.8721	−5.4883	−2.0074
JAI 1	0.78	1.4536	−1.295	0.0842
JAI 2	0.3381	0.7609	−1.6484	−0.1166
JAI 3	0.2573	0.8883	−1.7564	−0.5195
JAI 4	0.6765	1.1948	−1.6705	−0.5045
JAI 5	0.6886	1.3476	−1.7254	−0.2034
JAI 6	0.6824	1.1464	−1.7646	−0.4029
JAI 7	0.6863	1.2332	−1.5207	−0.4481
JAI 8	1.1026	2.1054	−1.4141	−0.4811
JAI 9	0.4746	1.0387	−1.6681	−0.3009
JAI 10	0.7229	1.3928	−1.7638	−0.4952
POK 1	1.1512	1.8648	−1.7407	0.2395
POK 2	0.4499	0.7862	−1.4516	0.0748
POK 3	1.6229	3.0907	−1.2511	0.4148
POK 4	1.2482	2.3845	−1.568	0.151
POK 5	0.6317	1.0639	−1.5646	−0.3054
POK 6	0.7676	1.7277	−1.401	−1.0869
POK 7	0.6049	1.1655	−1.7915	−0.1531
POK 8	0.4686	1.2319	−2.0574	−0.5088
POK 9	0.9947	1.754	−1.6971	0.3371
POK 10	0.5732	1.2197	−1.7376	0.5254

Extreme climate along with the geochemical process is the main controlling factor governing the fluoride concentration in groundwater in both of these regions. Weathering of silicate minerals along with evaporate dissolution is the major hydrogeological process in Bhatinda, while in Jaisalmer and Pokhran the chemical characteristics of groundwater are evolved mainly because of evaporate dissolution. High-temperature low precipitation, ion-exchange, and highly alkaline condition along with weathering and dissolution of fluoride-containing minerals are responsible for fluoride contamination in groundwater.

References

Adriano DC (1986) Trace elements in the terrestrial environment. Springer, New York, p 533

American Public Health Association (APHA) (2007) Standard methods for the examination of water and waste water, 21st edn. American Public Health Association, Washington DC

Ayenew T (2008) The distribution and hydrogeological controls of fluoride in the groundwater of central Ethiopian rift and adjacent highlands. Environ Geol 54:1313–1324

Ayoob S, Gupta AK (2006) Fluoride in drinking water: a review on the status and stress effects. Crit Rev Environ Sci Technol 36(6):433–487

Barbecot F, Marlin C, Gibert E, Dever L (2000) Hydrochemical and isotopic characterisation of the Bathonian and Bajocian coastal aquifer of the Caen area (northern France). Appl Geochem 15(6):791–805

Barbieri M, Boschetti T, Petitta M, Tallini M (2005) Stable isotopes (2H, 18O and 87Sr/86Sr) and hydrochemistry monitoring or groundwater hydrodynamics analysis in a karst aquifer (Gran Sasso, Central Italy). Appl Geochem 20:2063–2081

Belkhiri L, Narany TS (2015) Using multivariate statistical analysis, geostatistical techniques and structural equation modeling to identify spatial variability of groundwater quality. Water Resour Manag 29:2073–2089

Cao J, Zhao Y, Lin JW, Xirao RD, Danzeng SB (2000) Environmental fluoride content in Tibet. Environ Res 83:333–337

Carucci V, Petitta M, Aravena R (2012) Interaction between shallow and deep aquifers in the Tivoli Plain (Central Italy) enhanced by groundwater extraction: a multi-isotope approach and geochemical modeling. Appl Geochem 27:266–280

CGWB (2009) Groundwater year book. Central Ground Water Board, Rajasthan

Edmunds M, Smedley P (2005) Fluoride in natural waters. In: Selnius O, Alloway B, Centeno JA, Finkleman RB, Fuge R, Lindh U, Smedley P (eds) Essentials of medical geology-impacts of natural environment on public health. Academic Press, Amsterdam

Farooqi A, Masuda H, Firdous N (2007) Toxic fluoride and arsenic contaminated groundwater in the Lahore and Kasur districts, Punjab, Pakistan and possible contaminant sources. Environ Pol 145(3):839–849

Gaciri SJ, Davis TC (1993) The occurrence and geochemistry of fluoride in some natural waters of Kenya. J Hydrol 143:395–412

Godfrey S, Wate S, Kumar P, Swami A, Rayalu S, Rooney R (2006) Health-based risk targets for fluorosis in tribal children of rural Madhya Pradesh. In: India 32nd WEDC international conference, Colombo, Sri Lanka

Hounslow A (1995) Water quality data: analysis and interpretation. CRC press.

Hussain I, Arif M, Hussain J (2012) Fluoride contamination in drinking water in rural habitations of central Rajasthan, India. Environ mon asses 184(8):5151–5158

Hussain I, Hussain J, Sharma KC, Ojha KG (2002) Fluoride in drinking water and health hazardous: some observations on fluoride distribution Rajasthan. In: Environmental scenario of 21st century, pp 355–374

Hussain J, Sharma KC, Hussain I (2004) Fluoride in drinking water and its ill effects on Human Health. J Tissue Res 4(2):263–273

Khaiwal R, Garg VK (2007) Hydro-chemical survey of groundwater of Hisar city and assessment of defluoridation methods used in India. Environ Monit Assess 132(1):33–43

Kumar A, Singh CK (2015) Characterization of hydrogeochemical processes and fluoride enrichment in groundwater of south-western Punjab. Water Qual Expo Health 7(3):373–387

Machiwal D, Jha MK (2015) Identifying sources of groundwater contamination in a hard-rock aquifer system using multivariate statistical analyses and GIS-based geostatistical modeling techniques. J Hydrol Region Stud 4:80–110

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore (ISBN 978-981-10-3888-4)

Reghunath R, Murthy TRS, Raghavan BR (2002) The utility of multivariate statistical techniques in hydrogeochemical studies: an example from Karnataka, India. J Water Resour 36:2437–2442

Rina K, Datta PS, Singh CK, Mukherjee S (2012) Characterization and evaluation of processes governing the groundwater quality in parts of the Sabarmati basin, Gujarat using hydrochemistry integrated with GIS. Hydrol Process 26(10):1538–1551

Sharma KC, Arif M, Hussain I, Hussain J (2007) Observation on fluoride contamination in groundwater of district Bhilwara, Rajasthan and a proposal for a low cost defluoridation technique. In: The XXVIITH conference of the international society for fluoride research (ISFR XXVII), pp 9–12

SIHFW (2008) Community based planning and monitoring of health services, June 18

Singh CK, Kumari R, Singh RP, Shashtri S, Kamal V, Mukherjee S (2011) Geochemical modeling of high fluoride concentration in groundwater of Pokhran area of Rajasthan, India. Bull Environ Contam Toxicol 86(2):152–158

Singh CK, Kumari R, Singh N, Mallik J, Mukherjee S (2013) Fluoride enrichment in aquifers of the Thar Desert: controlling factors and its geochemical modeling. Hydrol Process 27:2462–2474

Singh CK, Mukherjee S (2015) Aqueous geochemistry of fluoride enriched groundwater in arid part of Western India. Environ Sci Pollut Res 22(4):2668–2678

Subramanian V, Saxena K (1983) Hydro-geochemistry of groundwater in the Delhi region of India, relation of water quality and quantity. In: Proceedings of the Hamberg symposium IAHS publication no. 146, pp 307–316

Tamta SK (1994) Possible mechanism for concentration of fluoride in groundwater. Bhujal News 6:11

World Health Organization (WHO) (2009) Guidelines for drinking water quality. World Health Organization, Geneva

Yidana SM, Ophori D, Yakubo BB (2008) Hydrochemical evaluation of the Voltaian system—the Afram Plains area, Ghana. J Environ Manag 88:697–707

Yidana SM, Yidana A (2010) Assessing water quality using water quality index and multivariate analysis. Environ Earth Sci 59(7):1461–1473

Walvoord MA, Phillips FM, Stonestrom DA, Evans RD, Hartsough PC, Newman BD, Striegl RG (2003) A reservoir of nitrate beneath desert soils. Science 302(5647):1021–1024

Chapter 17
Groundwater Chemistry and Arsenic Enrichment of the Ganges River Basin Aquifer Systems

Abhijit Mukherjee

Abstract The Ganges river basin aquifers provide one of the most prolific groundwater reservoirs of the South Asia, specifically northern India and Bangladesh. The thick aquifers serve as a perennial source for fresh, potable groundwater and stretch from the Himalayan foothills (of the north-central India) up to the Bay of Bengal (to the east), and are confined along the Himalayan foredeep between the Main Frontal Thrust (MFT) to the north and the cratonic outcrops to the south. The basin is underlain by a main shallow semi-confined (yet interconnected) aquifer system, hosting hydrochemically heterogeneous groundwater facies, along with the existence of deeper isolated aquifers. In the central Gangetic basin (CGB), the aquifers can be classified to be of Pre-Cenozoic (PC) lithology, piedmont deposit (PD), younger alluvial (YA), and older alluvium (OA). The lower Gangetic basin (LGB) is predominantly composed of YA and OA, which also forms the most extensive and prolific aquifers. Recharge of groundwater in these aquifers has taken place from meteoric inflow or partially evaporated surface water. However, in recent times, irrigational return flow also acts as major source of recharge. The groundwaters' composition is predominated by recent-aged, Ca–HCO_3 facies, with some aquifers hosting varied hydrochemical facies, ranging from Ca–Na–HCO_3^-–Cl to Na–HCO_3^- types, indicating hydrogeochemical evolution through longer water–rock interaction. While most of the solutes for the YA groundwater are derived from weathering of young, Himalayan carbonate dissolution, many of the PD, PC, and OA in CGB and LGB groundwater have evolved by silicate weathering of silicate-rich other lithotypes and temporally longer

---

A. Mukherjee (✉)
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in; amukh2@gmail.com

A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur, India

A. Mukherjee
Applied Policy Advisory to Hydrogeosciences Group, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_17

evolutionary processes. Groundwater redox ranges from oxic to methanic, with indefinite spatial and depth variance, and is dominated by metal-reducing conditions. The coexisting redox-sensitive solutes, e.g., As(III), Fe(II), $NH_{3(dis)}$, elevated HS^- indicate disequilibrium in an overall reducing, post-oxic condition, with overlapped redox zones. More than 75% of groundwater for the YA and PD, north of the 22.75° latitude, are found to have dissolved As ≥ 0.01 mg/L, with negligibly elevated concentrations recorded in the OA and PC groundwater. Dissolution/mobilization of arsenic can be caused by reduction of Fe(III), as a consequence of the coupled Fe–S redox cycles, and this mechanism is regarded as the dominant process of As release in the basin groundwater. However, processes like ion exchange or replacement, driven by competitive anions, introduced from active water–rock interactions, or from nutrients sourced from agricultural practices, can also act as potential triggers for As mobilization in groundwater.

17.1 Introduction

The Ganges (Ganga) river basin (GRB), situated in central and eastern parts of India and in western parts of Bangladesh (Figs. 1.1, 1.3), is regarded as one of the largest fluvio-deltaic systems and most populous regions of the world. The GRB also hosts some of the most prolific groundwater reservoirs of the South Asia. In India, the GRB forms most of north India, mostly occupying parts of the Indian states of Uttar Pradesh (UP), Bihar, and West Bengal, along with some parts of the states of Uttarakhand, Madhya Pradesh, and Jharkhand (Fig. 17.1). The plains of GRB are extremely fertile for agricultural practices and are rich in freshwater resources, thus providing favorable conditions for sustaining agrarian village communities, and numerous population centers and urban sprawls like Patna, Kanpur, and Varanasi for last several thousand years. The present-day megacities like Kolkata (Calcutta) also have grown in this basin. But recent studies have found that the Gangetic aquifers are stressed with major quality and quantity concerns, because pollution by geogenic and anthropogenic contaminants as well as pressing demand for high-yielding, year-long food production resulted in extensive exploitation of groundwater resources. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

The aquifers extend for more than 1500 km in length, extending from northern India to the Bay of Bengal. From north to south, the aquifers are confined along the Himalayan foredeep between the Main Frontal Thrust (MFT) to the north and the cratonic outcrops to the south (Fig. 17.1). The thicknesses of the aquifers are undetermined in most places, with possibilities of extension to more than 1000 s of meters at places. However, the first couple of hundred of meters of the unconsolidated, porous aquifer are of main interest for groundwater exploitation because of the perennial, shallow fresh potable groundwater availability.

From the early 1980s, epidemiological symptoms of chronic arsenic (As) poisoning from prolonged consumption, leading to arsenicosis and

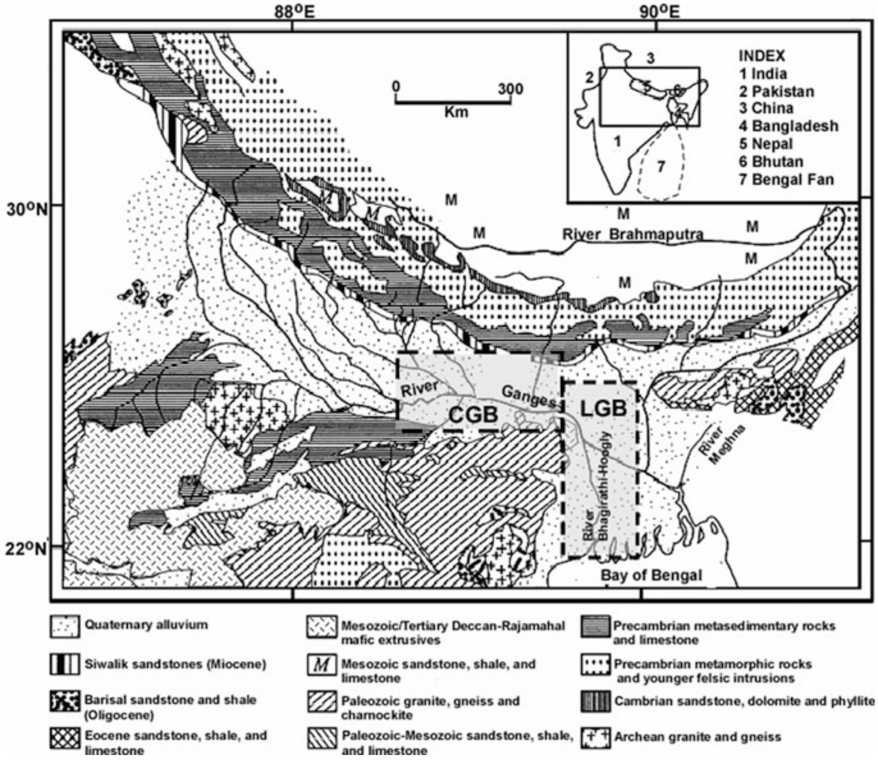


Fig. 17.1 Geological map of parts of eastern South Asia, showing the locations of the central Gangetic basin (CGB) and lower Gangetic basin (LGB). Lines 1 and 2 represent the locations of the hydrostratigraphic cross sections shown in Fig. 17.2

malignancies, were observed in residents of the lower Gangetic plains in West Bengal and adjoining Bangladesh. It was regarded for a long time that the As-enriched groundwater is mostly hosted by the aquifers of the lower Gangetic flood and delta plains in West Bengal and adjoining Bangladesh. However, in the last few years, reports of widespread groundwater As in different parts of the aquifers of the central Gangetic plains, upstream of West Bengal, in Bihar, Jharkhand, and eastern U.P. have been published in many scientific and social reports (Mukherjee et al. 2009a, 2012). Subsequent surveys found that arsenic-enriched groundwater (>0.01 mg/L) is widely used for drinking and irrigational purposes, and as many as 15 million residents in West Bengal and 10 million residents in central Gangetic plain (Mukherjee et al. 2009a) are at risk of arsenic poisoning from exposure to arsenic levels above the permissible limit. A larger number of people are under threat from As pollution in Bangladesh. However, till date, most of the hydrogeologic studies have been undertaken in lower Gangetic plain and delta aquifers (mostly in Bangladesh and some in West Bengal) for identification of the source and transport of the contaminant (e.g., Bhattacharya et al. 1997; BGS/DPHE/MML 2001; Harvey et al. 2002; Van Geen et al. 2004; Zhang et al. 2004, 2005; Mukherjee et al. 2007a, b, c, 2008a, 2011). It was found that the regional distribution of As in groundwater is heterogeneous, which may reflect both assorted distribution of sediment properties and aquifer hydraulics, along with variable well depths. It is believed that the geogenic As in sediments tends to be adsorbed onto Fe oxides and oxyhydroxides, and As may be desorbed by reductive dissolution of metal oxides/hydroxides.

17.2 Upper and Central Gangetic Basin Aquifers

17.2.1 *The Aquifers*

The aquifers in these parts of the GRB are mostly present in the northern bank, being predominantly sourced from the Himalayan sediments (Figs. 17.1 and 17.2). The southern bank aquifers are not that well developed, excluding areas very close to the river channel, and they mostly have their sedimentary provenance in the adjoining Indian cratonic rocks. Accordingly, the aquifers range from Pre-Cenozoic (PC) lithology, piedmont deposit (PD), younger alluvial (YA), and older alluvial deposits (OA). The alluvial aquifers are composed of thick sequences of unconsolidated Quaternary-aged alluvium of 300–400 m thickness (Fig. 17.2), with several cycles of fining-upward sequence. In the northernmost part of the GRB, mostly the alluvial fan deposits at the foothills of the Himalayas dominate the

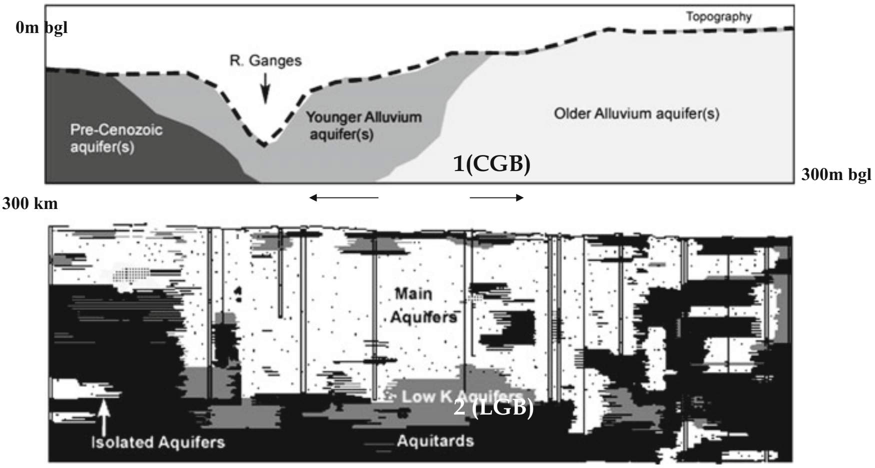
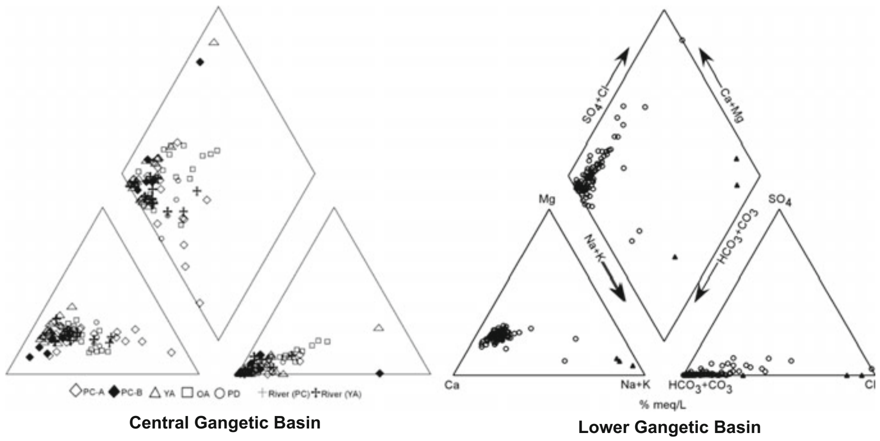


Fig. 17.2 **a** Hydrostratigraphic cross section of the aquifer types present along line 1 in Fig. 17.1; **b** the groundwater levels from 1976 to 1997 in surficial aquifers of the MRBA

stratigraphy. These beds are within 100 m depth and are steeply dipping toward south. The aquifers are dominantly composed of pebbles and coarse-grained sands, along with localized, interbedded clay layers. In the more distal areas of the north bank, closer to the main channel of the Ganges, the sedimentary beds gently dip toward the south (Kumar et al. 2006; Saha et al. 2010). From northern parts to south, up to the river, the aquifers are laterally continuous and can be traced to depths of >300 m, and are suspected to be up to 1-km-deep below ground level (bgl). The aquifers are made up of coarse-to-medium-grained sediment sequences of sands and gravels, along with floodplain mud deposits. The water levels observed during pre-monsoon ranged from 2.5 to 7.8 m bgl (mean ~4.2 m bgl) in most of the areas. During late monsoon, the mean water level is near surface (<1.5 m bgl), eventually saturating the whole aquifer and resulting in wide-scale flood in most years, thus leading to huge volume of rejected recharge (CGWB/GWD 2007; Saha et al. 2010, 2011). Mean water level rise from monsoon precipitation is ~3 m per year; however, ~40% of the recharged water is estimated to be flowing out as base flow to Ganges and its tributaries.

17.2.2 Hydrochemical Studies

The hydrogeochemistry of the GRB aquifers is believed to be influenced by the interaction of groundwater with carbonate minerals, silicate composition, and the oxidation of sulfides (Galy and France-Lanord 1999; Mukherjee and Fryar 2008). Alkali and alkaline earth cations, Fe, Al, and Si are leached by reaction of groundwater of proton-rich, cation-poor solutions (e.g., organic and carbonic acids) on rocks containing cation-rich silicate minerals. The bulk chemistry and mineralogical composition of the minerals and clays in the source rock or soil control the extent of weathering. The groundwater chemistry of the YA is mostly derived from weathering of detrital carbonates leading to dominance of Ca–HCO_3 water (Fig. 17.3) (Dowling et al. 2003; Mukherjee and Fryar 2008; Mukherjee et al. 2007a, b, c, 2012). However, much of the OA groundwaters are indicative of silicate weathering, possibly resulted from hydrochemical evolution through the prolonged interaction of the silt-dominated sediments in the Himalayan foreland basin of which GRB is a part (Mukherjee et al. 2012), from the rising Himalayas (Burbank 1992; Derry and France-Lanord 1996; Galy and France-Lanord 1999). Leaching of Na and K feldspars from the Himalayan silicates, where plagioclases are less dominant, results to dissolution of Na and K, which act as dominant cations in the groundwater. Leaching of secondary minerals like hydrobiotite, smectitie, and vermiculite (Baumler and Zech 1994; Grout 1995), that are in turn weathered from primary micas (like biotite), in the Himalayan sediments, results to the introduction of Mg in the GRB groundwater (Galy and France-Lanord 1999). However, the ubiquitous presence of high HCO_3 is possibly linked to high rate of H_2CO_3 liberation, by microbially mediated degradation of organic matter. Also, sulfide oxidation leads to H_2SO_4 generation, which results in weathering of some


Central Gangetic Basin

Lower Gangetic Basin

Fig. 17.3 Piper plot of the hydrogeochemical facies as identified in the MRBA

silicates and enhanced levels of SO_4 in the groundwater. The PC groundwater composition demonstrates signatures of cation exchange reactions, which possibly has large influence on the water chemistry of these aquifers. This observation is also in agreement with the possible long residence time of the groundwater in the aquifers of the PC terrain. The groundwater of OA, YA, and PD that have relatively lower residence time suggests minimal indication of cation exchange in their groundwater composition (Fig. 17.3) (Mukherjee et al. 2007a, b, c, 2012).

The groundwater $\delta^{18}O$ ranges from −2.3 to −10.3‰, with a median of −6.1‰ VSMOW. The bivariate of $\delta^{18}O$ and δ^2H for the groundwater trends [$\delta^2H = 5.5\ \delta^{18}O - (8 \pm 2)$] plots on global meteoric water line (GMWL), suggesting that the recharge from meteoric water might have undergone only limited evaporation. The δ18O for the YA groundwater ranges from −2.3 to −8.5‰ and that for the OA groundwater ranges between −5.5 and −10.3‰. The OA samples seem to be in equilibrium with the precipitation water ($\delta^2H = 8.2\ \delta^{18}O + 10.1$). The $\delta^{18}O$ values of the Pre-Cenozoic aquifer and Himalayan foothill groundwater range from −5 to −7‰ (Fig. 17.4).

Redox environments of groundwater in the central Gangetic plain aquifers are spatially variable (oxic to methanic, dominated by metal reduction), with no systematic depth variation. Coexistence of As(III), Fe(II), $NH_{3(dis)}$, elevated HS^- and other redox-sensitive parameters suggest a reducing, post-oxic condition (Mukherjee et al. 2007a, b, c, 2012), with median E_H in all of the terrain aquifers, ranging between 2 and 3.5 (metal-reducing zone). The Eh ranges in the older aquifers are 0.12–0.7 V, which suggest an oxic to slightly anoxic, metal-reducing conditions (Fig. 17.5). The older aquifers have high NO_3^- (<1–120 mg/L) and SO_4^{2-} (15–379 mg/L) concentrations, which are not a typical of the younger aquifers, indicating that this groundwater has developed in a much different redox system. Thus, such a mildly reducing redox condition indicates only limited

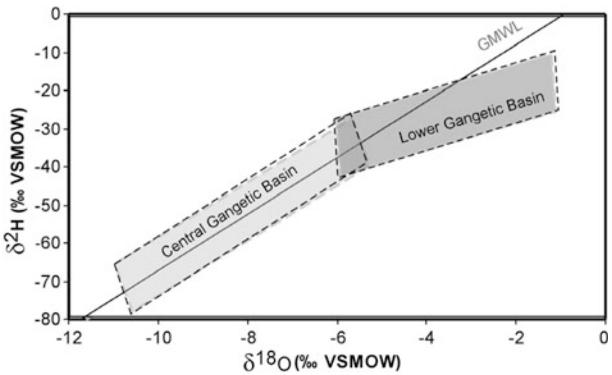


Fig. 17.4 Plot of concentrations (in µM) of selected groundwater solutes in the various aquifers of MRBA, along depth. bgl: below ground level

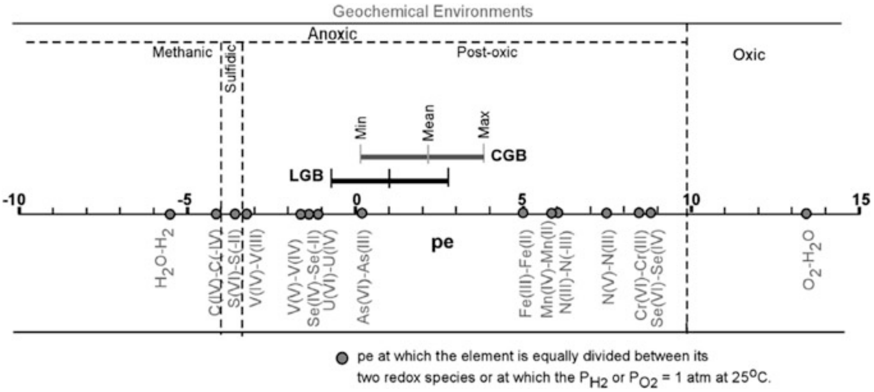


Fig. 17.5 The range of groundwater redox conditions encountered in the aquifers of MRBA are plotted against the equilibrated pe of various redox couples. The plot is modified after Mukherjee et al. (2008a, b)

reduction of NO_3^-, SO_4^{2-}, and Fe(III), which is also evident from the solute chemistry. Fe(III) and Al generally tend to be extremely insoluble under oxidizing conditions at near-neutral pH. Consequentially, redox-sensitive parameters indicating oxidizing conditions, like DO (median range 0.2–0.7 mg/L) and NO_3 (median range <0.05–0.25 mg/L as NO_3–N), are present in low concentrations in all terrains.

The enhanced reducing conditions in the younger aquifers are suggested by reduction indicators like NH_3 that are detected in the groundwater (median range 0.1–1.0 mg/L) in most places. However, based on the relative concentrations, the YA and PD groundwater samples are expected to be somewhat influenced by agricultural recirculated water. Elevated levels of ortho-PO_4 (median > 2 mg/L) are found in YA and PD groundwater, in contrast to the groundwater from PC and OA (median < 1 mg/L). Elevated concentrations of dissolved Fe (predominantly in the ferrous [Fe(II)] form) and As (mostly in the [As(III)] form) is found in almost all terrains of the basin. Some of the younger aquifers have groundwater with detectable H_2S, indicating active SO_4 reduction. Many of the wells in these aquifers are also identified to have elevated CH_4 concentrations (Mukherjee et al. 2012).

17.2.3 Arsenic Distribution

The upper and central GRB has more localized groundwater As distribution, in contrast to the lower GRB aquifers (Acharya and Shah 2004; Chauhan et la. 2009; Bhattacharya et al. 2011). The groundwater in the aquifers of YA and PD is most extensively polluted than only limited or no As pollution in the PC and OA aquifers (Mukherjee et al. 2012). A blanket survey of dissolved As concentration along a 10-km zone across the present channel of the Ganges has indicated wide-scale presence of elevated dissolved As (Ghosh 2005). Enriched samples range from 40 to 60% of the total sampled wells, with a maximum of 1.86 mg/L. Most of the affected areas were in and around the present or recently abandoned channels of the River Ganges. Elevated levels of As concentrations have been identified in various districts in the these parts of the GRB, which from east to west are Sahibganj district in Jharkhand, Bhagalpur, and Patna districts of Bihar, and Ballia, Varanasi, and Gazipur districts in UP. The Sahibganj district of Jharkhand was found to have 33% wells containing ≥ 0.01 mg/L of As and 25% with concentrations even ≥ 0.05 mg/L (Chakraborti et al. 2004). In the state of Bihar (north of Jharkhand and immediate upstream of the Ganges from the lower GRB), elevated As was first reported at the Semria Ojha Patti village of Bhojpur (Chakraborti 2003). About 80% of the wells in the village were found to be As-enriched, with $\sim 60\%$ having ≥ 0.05 mg/L As (maximum: 1.65 mg/L As). Further upstream, in the upper Ganges plains of UP, widespread As-enriched groundwater has been found in the last few years, with $\sim 50\%$ of the drinking water wells in areas adjoining the channel of River Ganges as having ≥ 0.01 mg/L of As (Ahamed et al. 2006). Dissolved As concentrations between the shallow (<35 m) and the deep (>50 m) wells are highly variable, and the most plausible and dominant mechanism of As mobilization is reductive dissolution of FeOOH in the YA aquifers (Ramanathan et al. 2006). The differences in patterns of the As distribution in the OA, YA, and PD aquifers suggest that As is mobilized by multiple processes, in situ or along the flow path. The enrichment processes in the YA and PD might be influenced by considerably different mechanisms. While in YA, which is located mostly at the discharge zones of the flow paths, mobilization by metal-reductive dissolution is a potential dominant mechanism, enrichment in the recharge areas, i.e., PD, might be more influenced by competitive anion exchange between adsorbed As and anions derived from active water–rock interaction processes or by nutrients introduced by agricultural processes (e.g., ortho-PO_4). The infiltrating rainfall introduces organic matter from the recently accumulated biomass deposited in the young alluvial deposits, which catalyzes the mobilization of the As from solid phase (Saha et al. 2008, 2010, 2011).

17.3 Lower Gangetic Basin Aquifers

17.3.1 The Aquifers

The aquifer–aquitard characterization up to a depth of 300 m of the lower Gangetic basin, also forming most of the Bengal basin, has demonstrated the presence of two major types of aquifers (Mukherjee et al. 2007a, b, c; Mukherjee and Fryar 2008). The extensive shallow aquifer system is continuous and semi-confined, mostly composed of sand and silt, and is used for groundwater exploitation in the area. This aquifer is composed by both YA and OA. The other types aquifers are mostly confined and limited in size and embedded and isolated within the main aquifer or the underlying aquitard and are all of OA composition. Thereby, these isolated aquifers are hydraulically disconnected from the main aquifer and mostly exist at deeper depths (~200–300 m) (Figs. 17.1 and 17.2). The main aquifer deepens from a maximum of ~50–80 m to the north to ~180 to >200 m bgl in the south. This aquifer varies hydrostratigraphically in local scales to form locally heterogeneous aquifers, which however are found to homogeneous in a regional scale, with a hydraulic conductivity similar to fine-to-medium sand and anisotropy ratio varying from 0.1 to 0.0001 (Michael and Voss 2008, 2009a, b). The aquifer thickens toward south and east, following the direction of Ganges delta progradation (Fig. 17.2). In the southern part, discontinuous clay–silt aquitards locally divide the thick continuous aquifer into several deeper, multi-tiered confined aquifers. There are also some deep parts of this main aquifer that are partially isolated and have chemical characters between those of the upper main and the isolated aquifers. A basin-wide aquitard has been observed at a depth of ~300 m below mean sea level, thereby segregating the shallower, freshwater aquifers from deeper, brackish water aquifers that are not typically used from domestic or irrigational purposes (Fig. 17.2).

17.3.2 Hydrogeochemistry

The Gangetic basin sediments, in general, are regarded to be sourced to the Himalayan lithology, but the sediments in the lower GRB may not have been derived solely from the eastern Himalayas. During the different stages of development of the Bengal basin, sediments from the Himalayas in the north as well as from cratonic India in the west were transported and deposited (Mukherjee et al. 2009b). Thus, the sediments of the lower GRB and their mineralogy and bulk chemistry may have also been influenced by weathering and deposition of the Precambrian gneiss, schist, and basalts from the adjoining Indian craton by the west-bank tributary systems of the River Bhagirathi-Hoogly (e.g., River Damodar). This contribution would be more subdued moving toward the central part of the basin in Bangladesh.

Both the YA and OA of the lower GRB aquifers are predominated by Ca–HCO_3 water, with Ca^{2+} and HCO^{3-} as the predominant ions in most of the groundwaters of the main aquifers (Fig. 17.3), with average Ca^{2+}: ~110 mg/L, Na^{+}: ~60 mg/L, HCO^{3-}: ~460 mg/L, and Cl^{-}: ~65 mg/L. However, deeper parts of the main aquifer (>200 m), which are believed to be representing semi-isolated conditions, have much higher concentrations of Na^{+} than Ca^{2+}, which are in contrast to other parts of the main aquifer. The aforesaid, hydraulically isolated, confined aquifers are also found to be hydrogeochemically distinct, with Na^{+} and Cl^{-} being present as the primary solutes (average Na^{+}: ~1130 mg/L, Ca^{2+}: ~33.9 mg/L, Cl^{-}: ~1620 mg/L, and $HCO3^{-}$: ~570 mg/L). The groundwater in the main aquifer is believed to have evolved from relatively young, meteorically surface-recharged groundwater by water–sediment interactions along flow path, with relatively less residence time. The $\delta^{18}O$ of the main aquifer groundwaters (~−3 to −6‰ VSMOW) suggest that the pore water has been modified by meteoric digenesis and evaporation, prior to recharge (Fig. 17.4). A Piper plot suggests that the lower GRB can be broadly classified into seven hydrochemical facies, varying from Ca^{2+}–HCO_3^{-} to Na^{+}–Cl^{-}. The facies show a systematic distribution depending on its distance from the Bay of Bengal (Fig. 17.3), such that most of the northern samples belong to Ca^{2+}–HCO^{3-} facies. In the southern districts like 24 Parganas, most of the groundwater is moderately to highly brackish, indicating the presence of chemically distinctive water bodies nearer to the Bay of Bengal. The isolated aquifers have been suggested to contain connate waters from paleo-Bay of Bengal (Figs. 17.2 and 17.3), which got trapped in the prograding delta aquifers. The connate waters subsequently evolved under limited interaction with the dispersive modern groundwater leakage, thereby suggesting very long residence time for these groundwaters. However, in some extremely isolated aquifers, very high HCO^{3-} (1470 mg/L) concentrations have also been noted, possibly suggesting microbially mediated evolution. These isolated aquifer waters and partially confined main aquifer groundwater (~−3 to −5‰) indicate mixed marine-and-terrestrial sourced water (Mukherjee et al. 2007a, b, c; Mukherjee and Fryar 2008) (Figs. 17.2 and 17.4).

The numerous studies of groundwater chemistry of the lower GRB have unequivocally referred the trace element cycling in the aquifers influenced by depth-dependent redox processes in the aquifers that are largely controlled by metal (Fe/Mn/Al) oxide/hydroxide reduction as an effect of microbially mediated oxidation of natural organic matter (NOM) (Bhattacharya et al. 1997; Harvey et al. 2002, 2005; Zheng et al. 2004; Stuben et al. 2003; Mukherjee et al. 2008a, b) and sequestration by authigenic sulfide formation (Lowers et al. 2007) (Fig. 17.5). The identification of dissolved redox couples in the groundwater of the lower GRB

(O, N, Fe, As, and C) with the observed EH values (310 to −40 mV) suggests that the groundwater generally has redox conditions varying from Fe(II)/Fe(III) to As (III)/As(V). Thus, in spite of the presence of several redox-sensitive solutes, Fe(III) reduction to Fe(II) is the prominent redox process in groundwater of the lower GRB aquifers. However, the simultaneous coexistence of various redox solutes in the same environment (e.g., $NH_4{}^+$, Fe(II), As(III), V, $SO_4{}^{2-}$, and CH_4) suggests that the groundwater does not exhibit redox equilibrium (Fig. 17.5) and indicates strong redox overlapping, resulting to leaching cycles of labile trace elements including As, by transient reactive transport within the groundwater, in the presence of microbial electron shuttling, promoted by availability of the NOMs. While these NOMs are available as dissolved organic carbon or peat layers in some areas (Ravenscroft et al. 2001; McArthur et al. 2004), in most other parts of the aquifers, they are available as dispersed phases that result to the high concentrations of microbially sourced $HCO_3{}^-$ in these aquifers. The groundwater has been found to be anoxic (Zheng et al. 2004; Mukherjee et al. 2008a, b), with sparse presence of HS^- and CH_4 (e.g., Mukherjee et al. 2008a, b) and very little dissolved O_2.

17.3.3 Groundwater Arsenic

In spite of its relatively smaller aerial extent, the lower Gangetic basin aquifers have attained the maximum attention for their high enrichment of groundwater arsenic, resulting in an extensive epidemiological impact on the ~50–60 million residents, which has been declared to be under active arsenicosis risk. Based on dose-response data (Garai et al. 1984), at least a million residents are possibly estimated to be suffering from arsenicosis, (Bhattacharya et al. 2011), thus terming the contamination as the greatest mass poisoning in human history (Smith et al. 2000). Only in Bangladesh, more than 35 million people are residing in areas with As concentrations more than 0.05 mg/L along with at least 15 million more in West Bengal (Mukherjee et al. 2009a). The YA and OA aquifers in the lower GRB are not very distinguishable, but, yet where possible, the YA aquifers are found to be more enriched with groundwater As, while the OA aquifers are more enriched with solid-phase As. In the floodplains of eastern parts of the lower GRB in Bangladesh, it is believed that below at depth of ~150 m, the gray-colored Holocene YA sediments are underlain by brown-colored Pleistocene OA aquifers, characterized by lower As concentrations (e.g., BGS/DPHE 2001; van Geen et al. 2003, 2008), and sometime with more oxygen content (Zheng et al. 2004), indicating a different geochemical environment in contrast to the YA. However, such basin-scale variability is not observed in the western parts of the basin, and significant spatial and temporal heterogeneity exists in the dissolved As, both horizontally and with depth. Groundwater with extremely high and negligible As concentration can exist within distance of few meters of each other (Mukherjee et al. 2009a). Similarly, As-enriched groundwater varies significantly with depth, increasing from almost negligible concentrations in surficial depths to >0.5 mg/L at depth of 40–50 m. Thus, the shallow dug wells are believed to be safe (<10 µg/L) from As contamination (Chakraborti et al. 2001). However, Bhattacharya et al. (2011) suggested that the low concentrations of As in the dug well are caused by interaction of resident groundwater with recently meteoric-recharged groundwater that induces oxygenation to the open waters in the dug wells, leading to oxidation and coprecipitation of As-enriched metal oxides. The As is believed to liberate from solid phase by a complex interplay of Fe–S–C cycle (Mukherjee and Fryar 2008; Mukherjee et al. 2008a, b), thereby reducing metal oxides and hydroxides (Bhattacharya et al. 1997) in biogeochemically active environment (Islam et al. 2004). It has been widely proclaimed that most of the As-enriched groundwater is present within a depth of 80–100 m (e.g., Harvey et al. 2002; Chakraborti 2003), and the number of polluted wells tapping groundwater from deeper levels (below 100–150 m bgl) is insignificant. The depth of maximum pollution has been suggested to be between 15 and 40 m, possibly being the zone of major geochemical interaction between the resident, polluted and recently recharged, non-polluted waters (Harvey et al. 2002; Klump et al. 2006). Studies by West Bengal and Bangladesh government agencies, as well as the BGS/DPHE (2001), report that only a very few deeper wells have As-enriched groundwater. Hence, several workers (e.g., JICA 2002; van Geen et al. 2003; Zheng et al. 2005) had recommended the groundwater from deeper aquifers as a safe and sustainable, As-free drinking water source. However, based on differential hydrostratigraphic and sedimentological evolution of the delta lobes of the lower GRB, such universal homogeneity is not observed in all parts of the basin, and much extensive deeper groundwater pollution exists in the main aquifer of the western parts of the basin. More than 80% of the deeper groundwater in hydraulically connected part of these aquifers are enriched with dissolved As, which are possibly promoted by a combination of hydrostratigraphic connectivity, geochemical cycling with redox disequilibria, and active groundwater exploitation scenario by extensive multi-depth abstraction (Mukherjee et al. 2011).

References

Acharyya SK, Shah BA (2004) Risk of arsenic contamination in groundwater affecting the Ganga Alluvial Plain, India. Environ Health Perspect 112(1):A19–A20

Ahamed S, Sengupta K, Mukherjee M, Hossain AM, Das B, Nayak B, Pal B, Mukherjee AC, Pati S, Dutta S (2006) Arsenic groundwater contamination and its health effects in the state of Uttar Pradesh (UP) in upper and middle Ganga plain, India: a severe danger. Sci Total Environ 338(3):189–200

Baumler R, Zech W (1994) Soils of the high mountain region of Eastern Nepal: classification, distribution and soil forming processes. CATENA 22:85–103

BGS/DPHE/MML (2001) Arsenic contamination of groundwater in Bangladesh. Technical Report WC/00/19, British Geological Survey, Keyworth

Bhattacharya P, Mukherjee A, Mukherjee AB (2011) Arsenic contaminated groundwater of India. In: Nriagu J (ed) Encyclopedia of environmental health. Elsevier B.V., Netherlands, pp 150–164

Bhattacharya P, Chatterjee D, Jacks G (1997) Occurrence of arsenic-contaminated groundwater in alluvial aquifers from the Bengal Delta Plain, Eastern India: options for a safe drinking water supply. Water Resour Dev 13:79–92

Burbank DW (1992) Causes of recent Himalayan uplift deduced from deposited patterns in the Ganges basin. Nature 357:680–683

CGWB/GWD (2007) Dynamic Groundwater Resources of Bihar State as on 31st March 2004. Central Groundwater Board, Government of India and Ground Water Investigation Directorate, Government of Bihar, Patna

Chakraborti D, Basu GK, Biswas BK, Chowdhury UK, Rahman MM, Paul K, Chowdhury TR, Chanda CR, Lodh D, Ray SL (2001) Characterization of arsenic-bearing sediments in the Gangetic delta of West Bengal, India. In: Chappell WR, Abernathy CO, Calderon RL (eds) Arsenic exposure and health effects IV. Elsevier Science Ltd., Oxford, pp 27–52

Chakraborti D (2003) Arsenic poisoning suspected throughout Indo-Gangetic Plain. Trac-Trends in Analytical Chemistry, 22(4):III–IV

Chakraborti D, Sengupta MK, Rahman MM, Ahamed S, Chowdhury UK, Mukherjee SC (2004) Groundwater arsenic contamination and its health effects in the Ganga-Meghna-Brahmaputra plain. J Environ Monit 6(6):74 N–83 N

Chauhan VS, Nickson RT, Chauhan D, Iyenger L, Sankaramkrishanan N (2009) Ground water geochemistry of Ballia district, Uttar Pradesh, India and mechanisms of arsenic release. Chemosphere 75:83–91

Derry LA, France-Lanord C (1996) Neogene Himalayan weathering history and river ^{87}Sr/^{86}Sr: impact on the marine Sr record. Earth Planet Sci Lett 142:59–74

Dowling CB, Poreda RJ, Basu AR (2003) The groundwater geochemistry of the Bengal Basin: weathering, chemsorption, and trace metal flux to the oceans. Geochim Cosmochim Acta 67(12):2117–2136

Galy A, France-Lanord C (1999) Weathering processes in the Ganges-Brahmaputra basin and the riverine alkalinity budget. Chem Geol 159:31–60

Garai R, Chakraborty AK, Dey SB, Saha KC (1984) Chronic arsenic poisoning from tube-well water. J Indian Med Assoc 82:32–35

Ghosh A (2005) Arsenic hot spots detected in the State of Bihar (India) a serious health hazard for estimated human population of 5.5 Lakhs. In: International conference on environmental management, Hyderabad, India

Grout H (1995) Characterization physique, mineralogique, chimique et signification de la charge particulaire et colloýdale derivieres de la zone subtropicale. Unpublished Ph.D. Thesis, Aix-Marseille, France

Harvey CF, Swartz CH, Badruzzaman ABM, Keon-Blute N, Yu W, Ali MA, Jay J, Beckie R, Niedan V, Brabander D, Oates PM, Ashfaque KN, Islam S, Hemond HF, Ahmed MF (2002) Arsenic mobility and groundwater extraction in Bangladesh. Science 298:1602–1606

Harvey CF, Swartz CH, Badruzzaman ABM, Keon-Blute N, Yu W, Ali MA, Jay J, Beckie R, Niedan V, Brabander D, Oates PM, Ashfaque KN, Islam S, Hemond HF, Ahmed MF (2005) Groundwater arsenic contamination on the Ganges Delta: biogeochemistry, hydrology, human perturbations, and human suffering on a large scale. External Geophysics, Clim Environ 337 (1–2):285–296

Islam FS, Gault AG, Boothman C, Polya DA, Charnock JM, Chatterjee D, Lloyd JR (2004) Role of metal-reducing bacteria in arsenic release from Bengal delta sediments. Nature 430:68–71

JICA (2002) The study on the ground water development of deep aquifers for safe drinking water supply to arsenic affected areas in western Bangladesh. Draft final report, book 1–3. Japan International Cooperation Agency, Kokusai Kogyo Co. Ltd. and Mitsui Mineral Development Engineering Co. Ltd.

Klump S, Kipfer R, Olaf AC, Harvey CF, Brennwald MS, Khandkar NA, Badruzzaman ABM, Hug S, Imboden DM (2006) Groundwater dynamics and arsenic mobilization in Bangladesh assessed using noble gases and tritium. Environ Sci Technol 40:243–250

Kumar K, Ramanathan A, Rao MS, Kumar B (2006) Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi, India. Environ Geol 50:1025–1039

Lowers HA, Breit GN, Foster AL, Whitney J, Yount J, Uddin MN, Muneem AA (2007) Arsenic incorporation into authigenic pyrite, Bengal Basin sediment, Bangladesh. Geochim Cosmochim Acta 71:2699–2717

McArthur JM, Banerjee DM, Hudson-Edwards KA, Mishra R, Purohit R, Ravenscroft P, Cronin A, Howarth RJ, Chatterjee A, Talukder T, Lowry D, Houghton S, Chadha D (2004) Natural organic matter in sedimentary basins and its relation to arsenic in anoxic groundwater: the example of West Bengal and its worldwide implications. Appl Geochem 19:1255–1293

Mukherjee A, Fryar AE (2008) Deeper groundwater chemistry and geochemical modeling of the arsenic affected western Bengal basin, West Bengal, India. Appl Geochem 23:863–892

Mukherjee A, Fryar AE, Howell P (2007a) Regional hydrostratigraphy and groundwater flow modeling of the arsenic contaminated aquifers of the western Bengal basin, West Bengal, India. Hydrogeol J 15:1397–1418

Mukherjee A, Fryar AE, Rowe HD (2007b) Regional scale stable isotopic signature and recharge of the deep water of the arsenic affected areas of West Bengal, India. J Hydrol 334:151–161

Mukherjee A, Scanlon BR, Chaudhary S, Misra R, Ghosh A, Fryar AE, Ramanathan AL (2007c) Regional hydrogeochemical study of groundwater arsenic contamination along transects from the Himalayan alluvial deposits to the Indian shield, Central Gangetic Basin, India. Geol Soc Am Abstracts Programs 39(6):519

Mukherjee A, Bhattacharya P, Savage K, Foster A, Bundschuh J (2008a) Distribution of geogenic arsenic in hydrologic systems: controls and challenges. J Contam Hydrol 99:1–7

Mukherjee A, von Brömssen M, Scanlon BR, Bhattacharya P, Fryar AE, Hasan MA, Ahmed KM, Jacks G, Chatterjee D, Sracek O (2008b) Hydrogeochemical comparison and effects of overlapping redox zones on groundwater arsenic near the western (Bhagirathi sub-basin, India) and eastern (Meghna sub-basin, Bangladesh) of the Bengal basin. J Contam Hydrol 99:31–48

Mukherjee A, Fryar AE, O’Shea BM (2009a) Major occurrences of elevated arsenic in groundwater and other natural waters. In: Henke KR (ed) Arsenic—environmental chemistry, health threats and waste treatment. Wiley, Chichester, U.K., pp 303–350

Mukherjee A, Bhattacharya P, Shi F, Fryar AE, Mukherjee AB, Xie ZM, Sracek O, Jacks G, Bundschuh J (2009b) Chemical evolution in high arsenic groundwater in Huhhot basin, Inner Mongolia, P.R. China and its difference from Western Bengal basin, India. Appl Geochem 24:1835–1851

Mukherjee A, Scanlon BR, Fryar AE, Saha D, Ghosh A, Chowdhuri S, Mishra R (2012) Solute chemistry and arsenic fate in aquifers between the Himalayan foothills and Indian craton (including central Gangetic plain). Influence Geol Geomorphology 90:283–302

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore, ISBN 978-981-10-3888-4

Michael HA, Voss CI (2008) Evaluation of the sustainability of deep groundwater as arsenic-safe resources in the Bengal Basin. PNAS 105:8531–8536

Michael HA, Voss CI (2009a) Estimation of regional-scale groundwater flow properties in the Bengal Basin of India and Bangladesh. Hydrogeol J 17:1329–1346

Michael HA, Voss CI (2009b) Control on groundwater flow in the Bengal Basin of India and Bangladesh: regional modeling analysis. Hydrogeol J. https://doi.org/10.1007/s10040-008-0429-4

Mukherjee A, Fryar AE, Scanlon BR, Bhattacharya P, Bhattacharya A (2011) Elevated arsenic in deeper groundwater of western Bengal basin, India: extents and controls from regional to local-scale. Appl Geochem 26:600–613

Ramanathan A, Bhattacharya P, Tripathi P (2006) Arsenic in groundwater of the aquifers of the central Gangetic plain of Uttar Pradesh, India. Geol Soc Am Program Abstracts 38(7):241

Ravenscroft P, McArthur JM, Hoque B (2001) Geochemical and palaeohydrological controls on pollution of groundwater by arsenic. In: Chappell WR, Abernathy CO, Calderon RL (eds) Arsenic exposure and health effects IV. Elsevier Science, Oxford, pp 53–77

Saha D, Dhar YR, Sikdar PK (2008) Geochemical evolution of groundwater in the Pleistocene aquifers of South Ganga Plain Bihar. J Geol Soc India 71:473–482

Saha D, Sarangam SS, Dwivedi SN, Bhartariya KG (2010) Evaluation of hydrogeochemical processes in arsenic-contaminated alluvial aquifers in parts of Mid-Ganga Basin, Bihar, Eastern India. Environ Earth Sci 61:799–811

Saha D, Sinha UK, Dwivedi SN (2011) Characterization of recharge processes in shallow and deeper aquifers using isotopic signatures and geochemical behavior of groundwater in an arsenic-enriched part of the Ganga Plain. Appl Geochem 26:432–443

Smith AH, Lingas EO, Rahman M (2000) Contamination of drinking water by arsenic in Bangladesh: a public health emergency. Bull. World Health Org. 78(9):1093–1103

Stüben D, Berner Z, Chandrasekharam D, Karmakar J (2003) Arsenic enrichment in groundwater of West Bengal, India: geochemical evidence for mobilization of As under reducing conditions. Appl Geochem 18(9):1417–1434

van Geen A, Ahmed KM, Seddique AA, Shamsudduha M (2003) Community wells to mitigate the arsenic crisis in Bangladesh. Bull WHO 81:632–638

van Geen A, Rose J, Thoral S, Garnier JM, Zheng Y, Bottero JY (2004) Decoupling of As and Fe release to Bangladesh groundwater under reducing conditions. Part II: evidence from sediment incubations. Geochim Cosmochim Acta 68:3475–3486

van Geen A, Radloff K, Aziz Z, Cheng Z, Huq MR, Ahmed KM, Weinmann B, Goodbred S, Jung HB, Zheng Y, Berg M, Trang PTK, Charlet L, Metral J, Tisserand D, Gulliot S, Chakraborty S, Gajurel AP, Upreti BN (2008) Comparison of arsenic concentrations in simultaneously-collected groundwater and aquifer particles from Bangladesh, India, Vietnam, and Nepal. Appl Geochem 23:3244–3325

Zheng Y, Stute M, van Geen A, Gavrieli I, Dhar R, Simpson HJ, Schlosser P, Ahmed KM (2004) Redox control of arsenic mobilization in Bangladesh groundwater. Appl Geochem 19:201–214

Zheng Y, van Geen A, Stute M, Dhar R, Mo Z, Cheng Z, Horneman A, Gavrieli A, Simpson HJ, Versteeg R, Steckler M, Grazioli-Venier A, Goodbred S, Shanewaz M, Shamsudduha M, Hoque M, Ahmed KM (2005) Geochemical and hydrogeological contrasts between shallow and deeper aquifers in two villages of Araihazar, Bangladesh: Implications for deeper aquifers as drinking water sources. Geochim Cosmochim Acta 69:5203–5218

Chapter 18
Groundwater Quality, Contamination, and Processes in Brahmaputra River Basin Aquifers

Swati Verma and Abhijit Mukherjee

Abstract The present study addresses the groundwater solute chemistry, hydrogeochemical evolution, aquifer sediments provenance, and geochemical processes that influences the fate of groundwater arsenic (As) in aquifers of three district tectono-morphic regions of Brahmaputra river basin (BRB). These regions are located in northwestern (NW), northern (N), and southern (S) site of Brahmaputra river along two distinct orogenic belts, i.e., Eastern Himalayas (NW and N) and Indo-Burma Range or Naga Hills (S) in Upper Assam, India. Stable isotopic composition (δ^2H and δ^{18}O) in groundwater suggests that the groundwater composition of BRB is influenced by slight evaporation through recharging water. Groundwater composition of S-region is dominated by Na–Ca–HCO_3 hydrogeochemical facies, whereas groundwater samples from NW- and N-regions vary between Ca–HCO_3 and Ca–Na–HCO_3 in BRB. The distribution of dissolved As concentrations shows huge variation among all studied regions in the Brahmaputra Basin. The groundwater of S-region is much enriched in groundwater As (bdl to 5.53 μM or 415 μg/L, mean 1.77 μM) compared to NW- and N-regions (bdl to 1.8 μM or 134 μg/L, mean 0.28 μM; bdl to 2.45 μM or 184 μg/L, mean 0.68 μM, respectively). Almost 92% collected groundwater sample from S-site is contaminated with dissolved As. This huge As variation might be caused by the differences in the geology, tectonic evolution, and the distance of the two regions from their provenances. Reductive dissolution of minerals, i.e., Fe/Mn oxides/hydroxides, is the most plausible mechanism for arsenic release into the groundwater of the NW and N part in BRB. However, As mobilization in groundwater of S-regions possibly controlled multiple

---

S. Verma · A. Mukherjee
Department of Geology and Geophysics, Indian Institute of Technology
(IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee (✉)
School of Environmental Science and Engineering, Indian Institute of Technology
(IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

A. Mukherjee
Applied Policy Advisory To Hydrogeosciences Group, Indian
Institute of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

© Springer Nature Singapore Pte Ltd. 2018
A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_18

hydrogeochemical processes and the groundwater As enrichment cannot be influenced by one single mechanism in S-aquifer. Thus, hydrogeochemical evolution and high variation in dissolved As enrichment (or distribution) might be explained in terms of geology and rock type of sediment provenance in BRB.

Keywords Groundwater · Arsenic · Hydrogeochemistry · Brahmaputra river basin

18.1 Introduction

Elevated arsenic (As) concentration in groundwater exceeding the World Health Organization (WHO) drinking water standards (i.e., >10 μg/L) has been reported from many parts of the world, where the groundwater serves as the major source of drinking water. Approximately, 100 million of the rural population affected by toxic levels of groundwater As in Southeast Asia including India, Nepal, Myanmar, Pakistan, Vietnam, and Cambodia (Smedley 2005; Charlet and Polya 2006; Fendorf et al. 2010; Mukherjee et al. 2009; Nriagu et al. 2007; Smedley and Kinniburgh 2002, Bhattacharya et al. 2007). Geographically, the arsenic contaminated aquifer systems mostly lie within a foreland basin of large orogens (Saunders et al. 2005; Guillot and Charlet 2007; Ravenscroft et al. 2009; Mukherjee et al. 2014). In most of these areas, the As-enriched aquifer sediments are of Quaternary age (Bhattacharya et al. 2001; Ahmed et al. 2004; Guillot et al. 2015). Many workers emphasized on the chemistry of the recharging water (meteoric/surficial), water–rock interaction, residence time of groundwater within the basin aquifers, and the occurrence of organic carbon in the system, etc., as the controlling factors of groundwater chemistry (Drever 1997; Faure 1998; Mukherjee et al. 2009, 2012; Verma et al. 2015, 2016). Saunders et al. (2005), Zheng (2006), and Nordstrom (2009) argued that arsenic enrichment in the groundwater is a function of the geochemical and biogeochemical processes and their interactions and proposed a link between As contamination and crustal evolution. The As enrichment scenario in the Ganges river system covering the Indian states and Bangladesh has been extensively studied and scrutinized in last three decades (Chapter 1, Fig. 1.6). So far, As enrichment in the aquifers of the Brahmaputra river basin (BRB), mostly located in Assam (India), is still largely unexplored and unreported in science. However, some studies (Bhattacharya et al. 2011; Chetia et al. 2011; Mahanta et al. 2015; Verma et al. 2015, 2016) have studied the extent of As in the groundwater, along with groundwater and aquifer sediment chemistry in the BRB. Additionally, Verma et al. 2015, 2016 undertook a detailed study to understand the geologic, geomorphic, and geochemical controls on the hydrogeochemistry of the groundwater, its evolution, and As fate in BRB.

The present study discusses the groundwater solute chemistry, hydrogeochemical evolution, and As enrichment within the aquifers of BRB. To investigate these processes, we selected three different tectono-morphic alluvial terrains located at the northern and southern site of Brahmaputra main river channel. Theses studied sites are situated along two distinct orogenic belts, i.e., Eastern Himalaya (northern site)

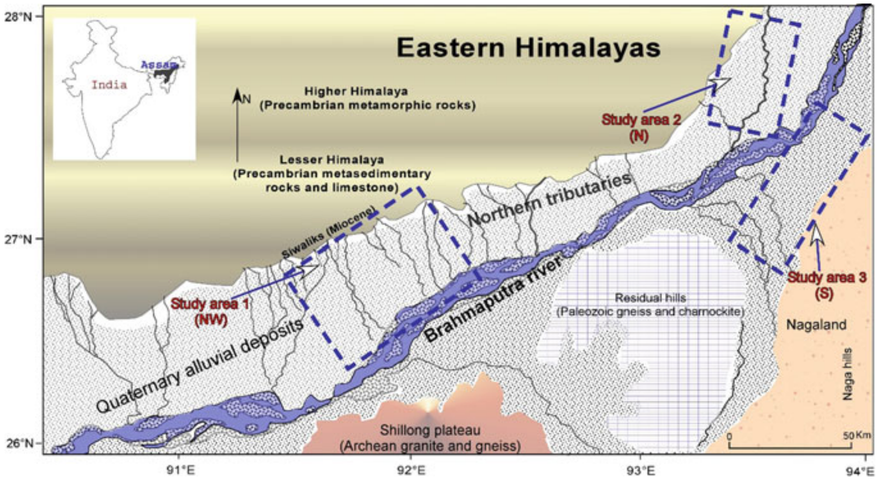


Fig. 18.1 Map of the study area showing three different tectono-morphic provenances in the BRB; classified as northwestern (NW) and northern (N) provenance along the Eastern Himalayas and the southern part (S) situated close to Naga thrust belt (modified from Verma et al. 2015, 2016)

and Indo-Burmese Range (southern site) in Upper Assam, India (Fig. 18.1). A detailed study about aquifers characterization, source of solutes in groundwater, hydrogeochemical evolution, and dissolved As enrichment (or distribution) in Brahmaputra Basin has been described in Verma et al. (2016). This study discusses the contribution of the various physical and chemical processes, i.e., weathering, cation exchange, and water–aquifer matrix interaction in aquifers of BRB. In the present study area, groundwater chemistry is mainly controlled by local as well as regional geological pattern. For example, solute might be introduced from the weathering of Himalayan and Siwaliks rocks in groundwater of NW-region; however, groundwater chemistry of N-region is mainly controlled by weathering of Himalayan (the Higher Himalayas, the Lesser Himalaya, and the Siwaliks), Eastern Syntaxes, and Trans-Himalayan rocks. In the case of S-aquifers, the provenance of the solutes within the groundwater is primarily considered to be the diverse mafics and ultramafic of the Naga thrust belt. These are strong evidences that geology (i.e., change in lithofacies, tectonic setup) controls the hydrogeochemistry and the disposition of the redox-sensitive solutes, like As. More related information regarding groundwater of South Asia is available in Mukherjee et al. (2018).

18.2 Study Area

This work was carried out in Brahmaputra alluvial floodplain, and Assam consists of three different tectono-morphic provenances, classified according to location and geology/tectonic of the study area. The study area is constrained by two distinct orogenic belts, i.e., the Eastern Himalayas and Naga thrust belt

(Indo-Burmese Range) (Fig. 18.1). The present study consists of the northwestern (NW), the northern (N) zones (situated along the Eastern Himalayas) along the north bank of Brahmaputra River, and southern (S) zone (adjoining Indo-Burma Range) located at southern side of Brahmaputra river bank in Assam, India. In the study area, the Brahmaputra main river channel receives many tributaries from the different directions along its course. These small and large tributaries eroded/carry sediments from various litho-formation and deposit as potential aquifer sediments in the Brahmaputra alluvial basin. The Brahmaputra River originates at an elevation of around 5200 m of Kailash Mountain (Tibet), where it is called as Tsangpo. The Tsangpo receives many tributaries. These tributaries are draining or eroding igneous rocks of Trans-Himalayan batholith and associated Paleozoic to Eocene sedimentary rock (Goodbred et al. 2014). Subsequently, the Tsangpo flows around the Eastern Syntaxis (Namcha Barwa peaks) and enters in Arunachal Pradesh (India) as Siang or Dihang, where it flows over the highly metamorphosed rock formation, consisting deformed meta-sedimentary, meta-igneous rocks and calc-alkaline plutons of the Trans-Himalaya Plutonic Belt (TPB). Afterward, the Siang River enters the Assam alluvial floodplain and is called as Brahmaputra River. Next, it flows as Jamuna River at the Indo-Bangladesh border near Dhubri. Some major northern tributaries, e.g., the Subansiri, the Jia Bhareli, the Manas, the Tipki, and the Puthimari, are draining Eastern Himalayan rocks (in NW- and N-regions) and merged into Brahmaputra main river channel. Eastern Himalayan rock formation composed medium to high-grade metamorphic rocks, i.e., gneisses, schist, quartzite, and phyllite and granitic rocks of Higher Himalayas (Dutta et al. 1983). Along the southern bank, the river channel receives many tributaries which flow through the western part of the Indo-Burman Ranges. This area comprises ultramafic, mafic rocks, pelagic, and volcanic-arc sediments associated with ophiolites from Naga thrust belt (Acharyya 2007). Therefore, the basin is characterized by sediments from various rock types and some of these aquifers sediments are crucial factor for As enrichment in groundwater of BRB.

18.3 Methods

Groundwater sampling has performed by following the procedure of Mukherjee and Fryar (2008), collected one hundred ninety-nine (199) groundwater samples from different locations, i.e., NW # 107, N # 40, and S # 52 of Brahmaputra River from public water supply wells. All groundwater samples are collected from shallow aquifers system, where depth varies from 4 to 62 m below ground level (bgl). The essential field parameters, e.g., pH, E_H, temperature (T °C), dissolved oxygen (DO), and specific conductance (EC), were measured by a multiparameter probe (Hanna 9282). The groundwater sampling started after stabilization of all field parameter and sample collected by the standard hydrogeochemical procedure (Woods 1981). After collection, all groundwater samples were filtered by 0.45 μm filters. Groundwater samples were preserved by 6 N HNO_3 (pH $\sim$ 2) for cations (major and trace metal). Unpreserved groundwater samples collected for HCO_3^- analysis and samples for other anions were preserved by $CHCl_3$ (Böttcher et al. 1990). Samples for ^{18}O and ^2H were collected in 8-mL HDPE bottles without headspace. The manual titration method with 0.1 N H_2SO_4 was used to obtain the HCO_3 concentration by the US Geological Survey alkalinity calculator (http://or.water.usgs.gov/alk). Ion chromatography (IC) was used to analyze all the major groundwater anion. The concentrations of major cation and trace metal were measured by inductively coupled plasma with optical emission spectrophotometer (ICP-OES, Thermo Fisher ICAP 6000) with accuracy better than 3%. Stable isotopes analysis was done by dual inlet isotope-ratio mass spectrometer (DI-IRMS) for δ^2H and continuous-flow isotope-ratio mass spectrometer (CF-IRMS) for $\delta^{18}O$. The Geochemist's Workbench (GWB 10.0.4) software with V8. R6+ database was used to calculate mineral saturation state in groundwater samples and to construct the stability diagrams for K_2O–Na_2O–CaO–Al_2O_3–SiO_2–H_2O systems.

18.4 Results and Discussion

18.4.1 Groundwater Chemistry

Stable isotope values of $\delta^{18}O$ vary from −2.6 to −7.66‰ VSMOW, and δ^2H varies from −12.7 to −49‰ VSMOW in groundwater of BRB. Supposing that shallow groundwater in all studied regions has been recharged under modern climatic conditions, i.e., present-day precipitation/rainfall (controls by southeastern (SE) monsoon), infiltration from surface water, and lateral groundwater inflow from rivers. The trends of isotopic compositions (δ^2H and $\delta^{18}O$) for N-, NW-, and S-groundwater samples ($\delta^2H = 7.1\ \delta^{18}O + 5$; $\delta^2H = 7.3\ \delta^{18}O + 4.3$; and $\delta^2H = 6.8\ \delta^{18}O + 2.7$, respectively) are subparallel to global meteoric water line (GMWL: $\delta^2H = 8\ \delta^{18}O + 10$) of Craig (1961). Thus, the groundwater composition of BRB is influenced by slight evaporation through recharging water.

The groundwater solutes composition and physical parameters (i.e., pH, E_H, and DO) in the aquifers of three different tectonomorphic regions (NW, N, and S), given in Table 18.1. Groundwater of study area is circum-neutral to slightly alkaline, having pH values from 6.5 to 8.5. The redox-sensitive parameter specifically E_H and dissolved oxygen (DO) gives low values (less than 1 mg/L, mean values 0.4–0.7 mg/L for all studied regions), indicating reducing condition in groundwater of BRB. The values of total dissolved solids (TDS) give a huge variation among different alluvial aquifers of BRB, and it varies from 2911 to 9737 µM in NW side and 1951–10,524 µM in N-region. However, the groundwater of S-region shows highest TDS value varying from 5258 to 22,451 µM. In brief, groundwater is dominated by Ca^{2+} and Mg^{2+} cation in NW- and N-regions, whereas Na^+ cation extensively present in S-groundwater. HCO_3^- is the most dominant anion in the groundwater sample of all studied regions but highest concentration occurs in S-aquifer (Fig. 18.2) and contributing ~90% to the anion budget in groundwater of

Table 18.1 Statistical summary of selected parameters, solutes, and stable isotope compositions of the groundwater for each of the regions in the study area

		Northwestern region (n = 107)			Northern region (n = 40)			Southern region (n = 52)		
Sample no		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Depth	m bgl	3.3	59.2	29.1	7.3	30.4	18.4	23	61	49.2
ORP		−185	−17.2	−142.2	−178	−83.8	−116.1	−173.1	−38.6	−94.20
E_H	mV	28.08	197.8	72.3	37.2	130.9	97.1	41.9	177.1	120.1
pH		6.08	7.8	6.9	7.0	8.7	7.9	6.8	8.3	7.4
SC	µS	58	385	184	44	340	212	234	825	437
DO		0.13	2.72	0.67	0.09	3.67	0.43	0.04	1.02	0.41
Na	µM	172	4478	688	138	680	350	450	6383	2354
K	µM	25	464	84	49	467	82	37	407	58
Ca	µM	118	1511	342	72	912	496	89	1369	645
Mg	µM	62	1278	312	25	612	240	34	1679	580
Cl	µM	48	881	128	30	540	123	42	767	81
HCO_3	µM	1028	4020	2114	728	4861	2672	1885	13,036	6855
SO_4	µM	1.4	214	41	7.2	162.4	30.9	5	161	18
NO_3	µM	4.4	500	38	bdl	118.6	24	6.2	150.5	20
TDS	µM	2911	9737	4904	1951	10,524	6465	5258	22,451	12,259
Si	µM	428	2071	1142	357	3392	1714	714	3214	1415
Sr	µM	309	10,227	1180	256	3187	1861	546	4831	2250
Fe	µM	11.6	732.4	268.7	3.7	947.3	480.8	0.4	999.5	140.2
Mn	µM	0.88	106.8	20.5	0.7	74.2	28.4	bdl	12.6	3.4
As	µM	bdl	1.79	0.28	bdl	2.45	0.68	bdl	5.53	1.77
Zn	µM	0.11	9.73	1.37	0.47	12.23	1.72	0.12	19.5	7.34
TOC	µM	390	2901	996	415	3170	1448	763.	2463	1541
$\delta^{18}O$	‰	−2.68	−7.66	−4.78	−4.05	−6.59	−5.42	−4.99	−6.81	−6.00
$\delta^{2}H$	‰	−12.7	−49.1	−29.9	−22.4	−41.83	−33.3	−30.9	−45.9	−39.6

Below detection level concentrations are marked as bdl. Below ground level is marked as bgl (modified from Verma et al. 2016)

BRB. However, the concentrations of Cl^- and SO_4^{2-} are generally low. Furthermore, groundwater of NW- and N-regions is highly enriched with Fe and Mn, compared to S-region.

Ternary diagram (Fig. 18.3) shows major cations, i.e., $Na^+ + K^+$, Ca^{2+}, and Mg^{2+} in their relative molar proportions. According to Fig. 18.3, most of NW groundwater samples plot between $Na^+ + K^+$ and Ca^{2+}; however, N groundwater samples mostly cluster near Ca^{2+} and few plot toward $Na^+ + K^+$. Most of the groundwater samples of S-region plot close to $Na^+ + K^+$ corner. Ternary plot of major anions (HCO_3^- and $SO_4^{2-} + Cl^-$) and dissolved silica (SiO_2) shows that groundwater samples of all different studied regions plot near HCO_3^-. Therefore, groundwater composition of S-region is dominated by Na–Ca–HCO_3

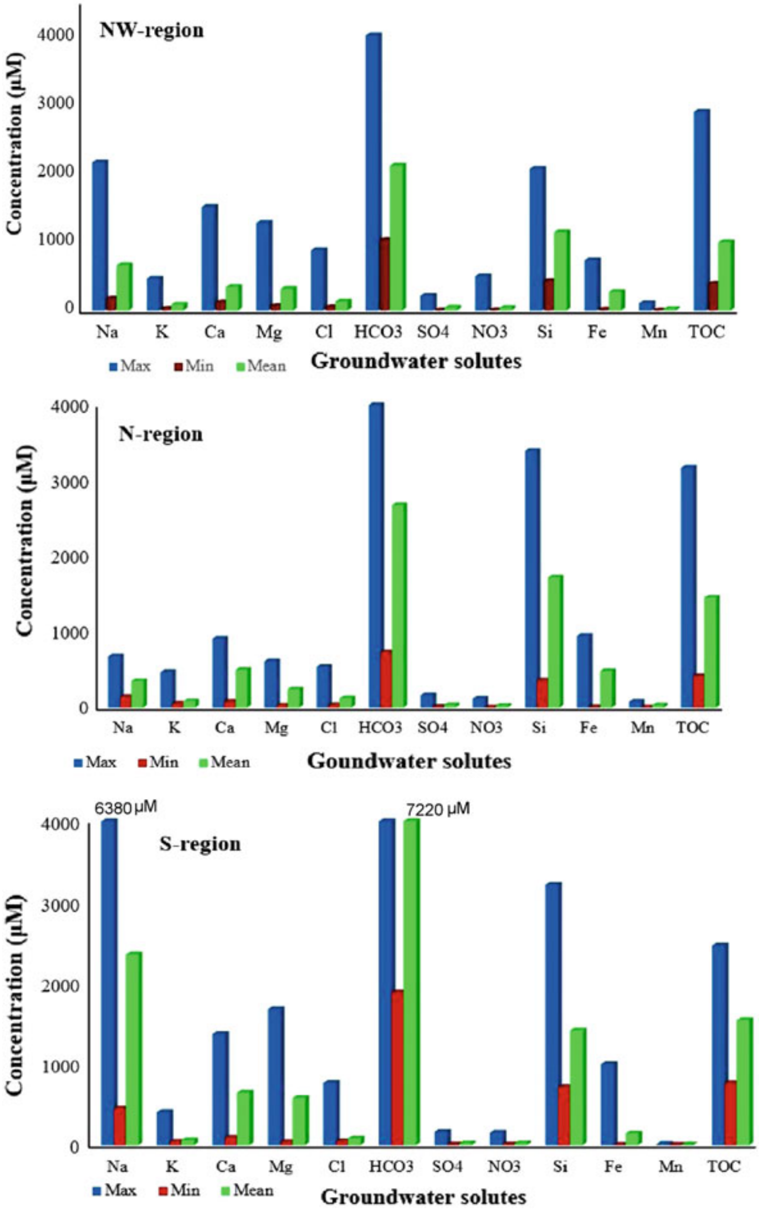


Fig. 18.2 Statistical summary of groundwater solutes in the aquifers of different regions in the study area

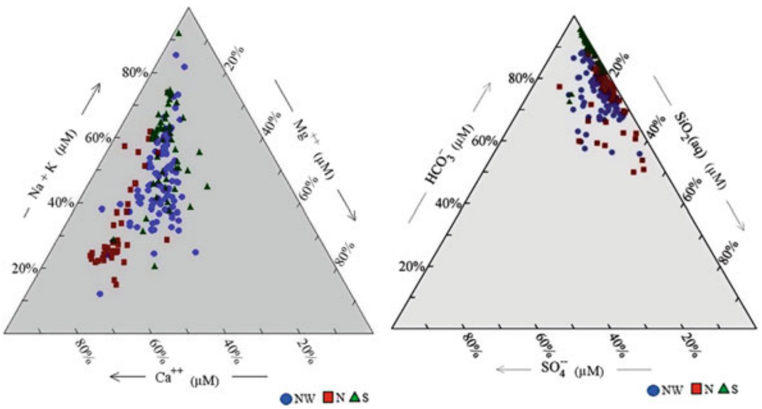


Fig. 18.3 Ternary plot shows relative molar proportions of Ca^{2+}, Mg^{2+}, Na^{+} + K^{+} and relative concentration of HCO_3^{-}, SO_4^{2-} + Cl^{-} and dissolved Si in all studied sites (blue for NW, red for N, and green for S-aquifers)

hydrogeochemical facies, whereas groundwater samples from NW- and N-regions vary between Ca–HCO_3 and Ca–Na–HCO_3.

Geochemical weathering of aquifer sediments is primary controlling factor to introduce major ions (K^{+}, Na^{+}, Ca^{2+}, Mg^{2+}, SO_4^{2-} and Cl^{-}) and trace metal (Fe, Mn, Cr, Cu, Zn, As, etc.) in groundwater by breakdown of aquifer mineral compositions (Nesbitt and Young 1989; Drever 1997). These weathering processes are evaluated by bivariate relationship of Na^{+} normalized molar ratio of Ca versus Mg and HCO_3. Groundwater samples of N-region show best correlation among molar ration of Ca/Na versus Mg/Na and HCO_3/Na ($r^2 = 0.80$, 0.91, respectively), compared to NW- and S-groundwater samples, i.e., Ca/Na versus Mg/Na and HCO3/Na ($r^2 = 0.66$, 0.41; for NW-region and $r^2 = 0.73$, 0.54; for S-region). Accordingly, silicate and carbonate minerals weathering are supposed to be the dominant mechanism in chemical evolution of groundwater in aquifers of BRB. The cation exchange reaction also plays an important role in groundwater chemical evolution. The effect of cation exchange reaction on the water chemistry was estimated by the bivariate relationship of corrected bivalent cations [by subtracting associated anion (HCO_3^{-} and SO_4^{2-})] concentrations versus corrected Na* (Na* = Na − Cl) (McLean and Jankowski 2000). This bivariate relationship suggested that cation exchange has no influence on groundwater evolution of NW- and N-regions; however, groundwater chemistry of S-region is slightly effected by cation exchange process.

Thermodynamic stability simulation is performed to evaluate geochemical weathering processes due to minerals–water interaction, among groundwater and mineral phases (aluminosilicates), and depends on the dissolution and precipitation of mineral phases (Tardy 1971; Drever 1997). The thermodynamic stability of minerals phase in groundwater is measured by saturation index (SI) calculation and gives undersaturated, equilibrium, and saturated minerals species (Table 18.2).

Table 18.2 Saturation index of selected phases in groundwater from the three study regions

Name of minerals	Formula	NW-region			N-region			S-region		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Anhydrite	$CaSO_4$	−4.96	−2.54	−3.69	−4.58	−2.96	−3.67	−339	−3.16	−10.5
Arsenolite	As_4O_6	−57.8	−21.9	−32.3	−58.6	−37.1	−50.7	−55.2	0.86	−32.5
As_2O_5	As_2O_5	−35.0	−27.5	−30.8	−37.5	−29.8	−33.6	−33.5	−1.72	−23.7
Birnessite	MnO_2	−22.1	−11.1	−18.8	−17.3	−10.7	−13.3	−11.1	−5.84	−7.91
Bixbyite	Mn_2O_3	−21.4	−6.7	−16.2	−15.4	−5.53	−9.09	−8.10	−3.42	−5.44
Calcite	$CaCO_3$	−2.55	0.02	−1.30	−1.62	0.53	−0.11	−2.12	1.54	0.02
CO_2(g)		−2.91	−0.83	−1.80	−3.47	−1.55	−2.77	−2.36	3.09	−0.83
Dolomite	$CaMg(CO_3)_2$	−5.05	0.06	−2.61	−3.41	0.78	−0.50	−4.62	7.40	1.12
Ferrihydrite	$Fe(OH)_3$	−3.11	4.22	0.16	0.81	4.97	3.77	−1.23	19.81	5.64
Goethite	FeOOH	1.27	8.61	4.55	5.20	9.37	8.16	3.12	23.82	9.69
Hematite	Fe_2O_3	7.55	22.23	14.10	15.42	23.74	21.32	3.52	21.45	14.93
Magnetite	Fe_3O_4	7.65	26.01	16.32	17.51	28.63	25.68	−0.83	25.15	15.85
Manganite	MnOOH	−10.7	−3.46	−8.17	−7.78	−2.83	−4.61	−8.98	−4.75	−6.73
Siderite	$FeCO_3$	−1.00	1.83	0.55	−0.88	2.41	1.72	−1.23	2.11	0.75
Pyrolusite	MnO_2	−19.9	−8.95	−16.1	−15.1	−8.47	−11.1	−16.4	−5.13	−11.7
Rhodochrosite	$MnCO_3$	−1.51	0.66	−0.57	−1.64	1.33	0.55	−1.85	0.27	−0.54
Quartz	SiO_2	0.10	0.86	0.52	0.02	1.09	0.74	0.32	1.18	0.66

Stability diagram (Fig. 18.4) suggested that groundwater samples of NW area mostly plot in kaolinite stability zone, indicating weathering of k-feldspar, plagioclase, and muscovite. However, N and S samples mostly plot in transition between kaolinite and smectite stability field, indicating solutes in groundwater might be resulting from chemical leaching of k-feldspar, plagioclase, biotite, and some ferromagnesium silicate minerals, i.e., pyroxene, amphibole, and olivine (Drever 1997; Sarin et al., 1989; and Singh et al., 2005).

18.4.2 Arsenic in Groundwater

The groundwater As range in different alluvial aquifers of BRB is shown in Fig. 18.5, and it is rising to 5.53 µM As or more than around 50 times the WHO drinking water guideline value ($\geq$0.13 µM or10 µg/L). Groundwater samples from two distinct tectonic setting, i.e., Eastern Himalayas (NW and N) and Naga thrust belt/Indo-Burmese Range (S), show striking variance in the groundwater arsenic concentrations. The N- and NW-regions are relatively low in dissolved arsenic concentrations than the S-regions, which might be caused by the differences in the geology, tectonic evolution, and the distance of the two regions from their provenances. Among the groundwater sampled, 68% contains dissolved As greater than 0.13 µM (10 µg/L being the WHO permissible limit) and ranges from below

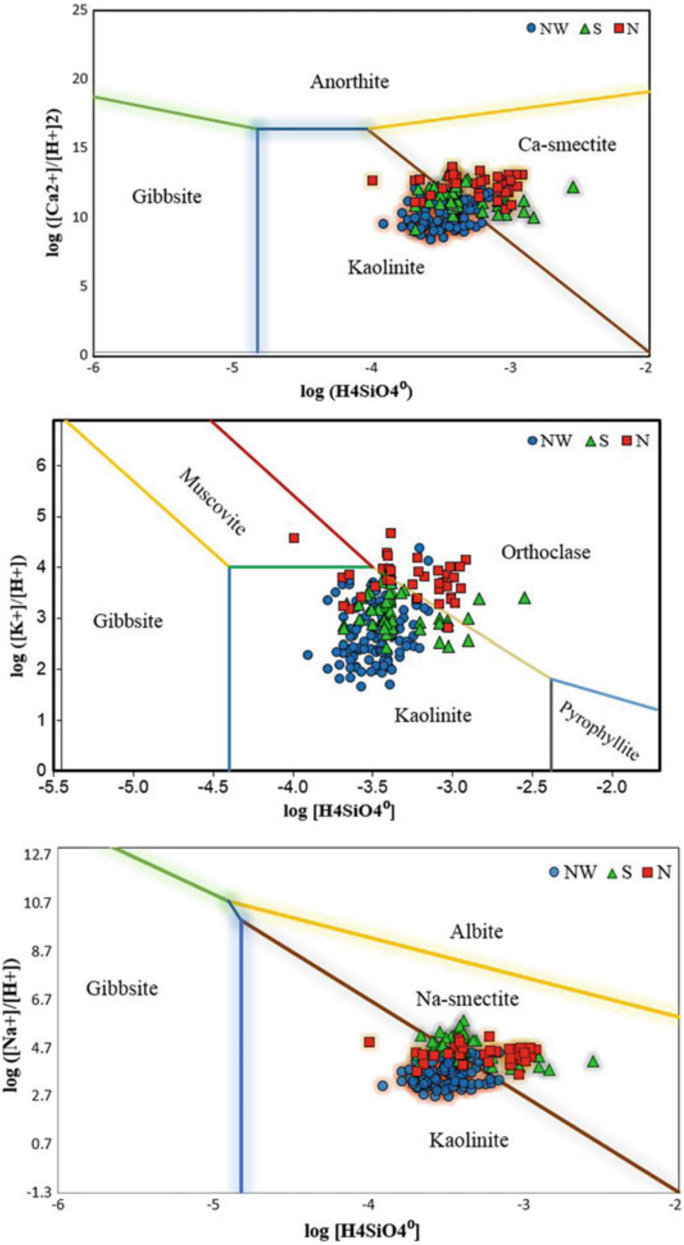


Fig. 18.4 Stability diagrams show minerals expected to be in thermodynamic equilibrium with the groundwater samples for standard temperature (25 °C) and pressure (1 atm.) where a denotes solute activity calculated by GWB (following Tardy 1971; Drever 1997; Mukherjee et al. 2009) (modified from Verma et al. 2016)

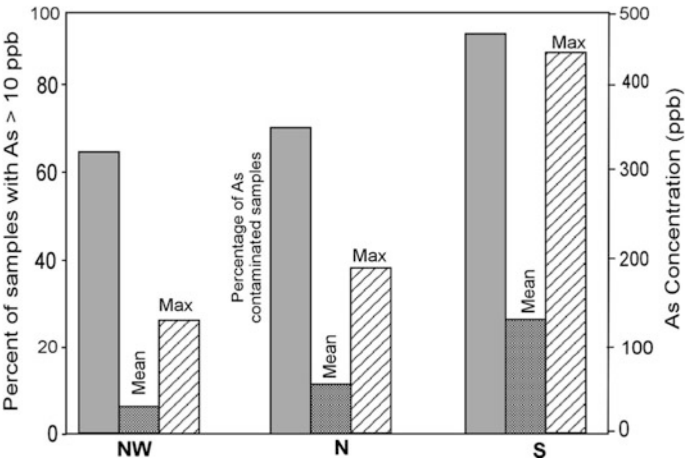


Fig. 18.5 Plot shows percentage of the samples having groundwater arsenic concentrations ≥ 10 μg/L, along with the maximum and mean concentration of As in the groundwater samples (modified from Verma et al. 2015)

detection limit (bdl) to 5.53 μM for all studied sites in BRB. In NW-regions (Darrang and Udalguri districts), the highest As concentration was 1.79 μM (mean 0.28 μM), while in N-region (Lakhimpur district), As concentrations were ranging from bdl to 2.45 μM (mean 0.68 μM), (Supplementary Table 18.1). However, As shows highest concentration in the groundwater of S-region, where aquifers are heavily affected by As (maximum 5.53 μM), and about 92% groundwater samples collected are contaminated with As. Because all the collected groundwater samples are constrained to shallow depths (<40 m bgl), hence variance of depth does not contribute to the differences in groundwater arsenic.

Redox-sensitive solutes (e.g., Fe and Mn) exhibit high concentration in BRB. The mean value of dissolved Fe concentration in NW-region was 268 μM, and in N part it was 480 μM; however, it shows relatively low concentration in S-region (mean: Fe 140 μM). The mean values for Mn were 20–28 μM in NW- and N-regions, respectively, much higher than S-region (Mn 3.37 μM). It can possibly be inferred that the As distribution, chemistry, fate, and transport in the present area of study should be similar to that of the Bengal Basin, further downstream owing to the proximity and similarity in the geologic and hydrologic systems in these areas.

Multivariate statistical relationship of As with different redox-sensitive solutes has been evaluated in study area by nonparametric Spearman's rho (ρ) correlations to understand the As fate and mobilization processes. This indicates that the fate of As in different regions of the BRB is controlled by different processes. Dissolved as shows negative to very weak positive correlation with E_H, which demonstrated a redox-dependent release of As in aquifers of all the studied regions in the BRB. Many studies have already proposed the hypothesis of As mobilization by reductive dissolution of Fe/Mn hydr(oxides) or other associated minerals in the presence of abundant organic carbon (Islam et al. 2004; Harvey et al. 2002; Bhattacharya et al. 1997; Dowling et al. 2002; Stüben et al. 2003, etc.). As correlates moderate to good correlation with redox-sensitive species, i.e., Fe [$\rho = 0.44$], Mn [$\rho = 0.20$] in NW-region. Similarly, Fe and Mn correlate moderately to strong with As (i.e., Mn [$\rho = 0.33$], Fe [$\rho = 0.63$] in N part of study area. Such type of correlations has been discussed by many studies (Bhattacharya et al. 1997; Nickson et al. 2000; Dowling et al. 2002; Stüben et al. 2003). The reductive dissolution of Fe/Mn oxyhydroxides is the most plausible mechanism for arsenic release into the groundwater of the NW and N part in BRB. On the other hand, in the groundwater of southern aquifers As does not give positive correlation with these redox-sensitive species, i.e., with Fe [$\rho = -30$], Mn [$\rho = -0.35$]. Such conditions have been observed by Swartz et al. (2004) and Mukherjee and Fryar (2008), which indicates the interconnection of the multiple processes that simultaneously operates, leading to the coexistence of these elements. The fact that these species do not show significant correlation or sometimes negative correlation indicates that multiple hydrogeochemical processes control the arsenic mobilization in the S region of BRB and the groundwater arsenic distribution scenario cannot be attributed to one single process causing it.

18.5 Synthesis

The present study interprets the groundwater solute chemistry, hydrogeochemical evolution, arsenic distribution, and fate in aquifers of three district tectono-morphic regions of Brahmaputra river basin (BRB). These regions are located in northwestern (NW), northern (N), and southern (S) site of Brahmaputra River along two distinct orogenic belts, i.e., Eastern Himalayas (NW and N) and Indo-Burma Range or Naga Hills (S) in Upper Assam, India. The present study and earlier work (Verma et al. 2015, 2016) are suggested that the hydrochemistry and groundwater evolution is mainly dependent on the tectono-morphic influence on sediment mineralogy and their interactions with groundwater along groundwater flow path in BRB. Based on previous studies, the aquifers have some similarity, to that of the downstream, extensively studied, Bengal Basin but the source and distribution of As in BRB are still not much well studied expect few publications. It has confirmed through different hydrogeological methods that the groundwaters of tectono-morphic aquifers are mainly influenced from a geological and geomorphic evolution of host rocks. Previous study (Verma et al. 2016) mentioned that NW- and N-aquifers sediments might be derived from weathering of granitic (felsic) Eastern Himalayan (Higher, Lesser, Siwaliks) rocks, and Trans-Himalayan Plutonic Belt (in N-region). S-aquifers, situated close to Naga ophiolite belt, contain extensively mafic and ultramafic rocks, calc-alkaline rocks, gabbroic complex (ophiolite), and arc-related volcanic rocks that might be primary sediment provenance in S-region. Therefore, it is quite clear that aquifer sediments in northern and southern sites of Brahmaputra River alluvial plain are derived from different orogenic provenances. The redox-sensitive parameter specifically E_H and dissolved oxygen (DO) gives low values, indicating reducing condition in groundwater of BRB. Stable isotopic composition (δ^2H and $\delta^{18}O$) in groundwater suggests that the groundwater composition of BRB is influenced by slight evaporation through recharging water. Groundwater composition of BRB is dominated by Na–Ca–HCO_3 and Ca–Na–HCO_3 hydrogeochemical facies.

In the present study, thermodynamic calculation and molar ratios suggested silicate and carbonate minerals weathering are supposed to be the dominant mechanism in chemical evolution of groundwater in aquifers of BRB. In NW-region, groundwater solutes are mostly derived from weathering felsic minerals, e.g., k-feldspar, plagioclase, and muscovite. However, groundwater of N and S-regions, indicating solutes in groundwater, might be resulting from chemical leaching of k-feldspar, plagioclase, biotite, and some ferromagnesium silicate minerals, i.e., pyroxene, amphibole, and olivine. Cation exchange has no influence on groundwater evolution of NW- and N-regions; however, groundwater chemistry of S-region is slightly effected by cation exchange process. More than 68% samples are enriched with dissolved As in groundwater of all different tectono-morphic sites in BRB, but highest As enrichment occurs in S-aquifers (As $\sim$ 5.53 μM) and almost 92% collected groundwater sample from S-site is contaminated with dissolved As. Spearman's rho (ρ) correlations of As with other parameters suggest that reductive dissolution of Fe/Mn oxyhydroxides is the most plausible mechanism for arsenic release into the groundwater of the NW and N part in BRB. However, As mobilization in groundwater of S-regions possibly controlled multiple hydrogeochemical processes and the groundwater As enrichment cannot be influenced by one single mechanism.

References

Acharyya SK (2007) Collisional emplacement history of the Naga-Andaman ophiolites and the position of the eastern Indian suture. J Asian Earth Sci 29(2):229–242

Ahmed KM, Bhattacharya P, Hasan MA, Akhter SH, Alam SM, Bhuyian MAH, Imam MB, Khan AA, Sracek O (2004) Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview. Appl Geochem 19:181–200

Bhattacharya P, Chatterjee D, Jacks G, (1997) Occurrence of arsenic-contaminated groundwater in alluvial aquifers from the Bengal Delta Plain, Eastern India: options for a safe drinking water supply. Water Resou Dev, 13:79–92

Bhattacharya P, Jacks G, Jana J, Sracek A, Gustafsson JP, Chatterjee D (2001) Geochemistry of the Holocene alluvial sediments of Bengal Delta Plain from West Bengal, India: implications on arsenic contamination in groundwater. Groundw Arsen Contamination Bengal Delta Plain Bangladesh 3084:21–40

Bhattacharya P, Welch AH, Stollenwerk KG, McLaughlin MJ, Bundschuh J, Panaullah G (2007) Arsenic in the environment: biology and chemistry. Sci Total Environ 379:109–120

Bhattacharya P, Mukherjee A, Mukherjee AB (2011) Arsenic contaminated groundwater of India. In: Nriagu J (ed) Encyclopedia of environmental health. Elsevier B.V, Netherlands, pp 150–164

Böttcher J, Strebel O, Voerkelius S, Schmidt HL (1990) Using isotope fractionation of nitrate–nitrogen and nitrate–oxygen for evaluation of microbial denitrification in sandy aquifer. J Hydrol 114:413–424

Charlet L, Polya DA (2006) Arsenic in shallow, reducing groundwater in Southern Asia: an environmental health disaster. Elements 2:91–96

Chetia M, Chatterjee S, Banerjee S, Nath J, Singh L, Srivastava B, Sarma P (2011) Groundwater arsenic contamination in Brahmaputra river basin: a water quality assessment in Golaghat (Assam), India. Environ Monit Assess 173:371–385

Craig H (1961) Isotopic variations in meteoric water. Sci 133:1702–1703

Dutta SK, Gill GKS, Srinivasan J (1983) Geology of the Subansiri and Kamala valleys. In: Proceedings of symposium on geology and mineral resources of North eastern Himalayas. G.S.I., Misc. Pub. no. 43, pp 9–14

Drever JI (1997) The geochemistry of natural waters, third edn. Prentice Hall, Upper Saddle River, New Jersey

Dowling CB, Poreda RJ, Basu AR, Peters SL, Aggarwal PK (2002) Geochemical study of arsenic release mechanisms in the Bengal Basin groundwater. Water Resour Res 38(9):1–18

Fendorf S, Michael AH, van Geen A (2010) Spatial and temporal variations of groundwater arsenic in South and Southeast Asia. Science 328(5982):1123–1127

Faure G (1998) Principles and applications of geochemistry, second edn. Prentice Hall, Upper Saddle River, New Jersey

Goodbred SL, Paolo PM, Ullah MS, Pate RD, Khan SR, Kuehl SA, Rahaman W (2014) Piecing together the Ganges-Brahmaputra-Meghna River delta: use of sediment provenance to reconstruct the history and interaction of multiple fluvial systems during Holocene delta evolution. Geol Soc Am Bull 126(11–12):1495–1510

Guillot S, Charlet L (2007) Bengal arsenic, an archive of paleohydrology and Himalayan erosion. Environ Sci Health Part A 42:1785–1794

Guillot S, Garçon M, Weinman B, Gajurel A, Tisserand D, France-Lanord C, Charlet L (2015) Origin of arsenic in Late Pleistocene to Holocene sediments in the Nawalparasi district (Terai, Nepal). Environ Earth Sci 74(3):2571–2593

Harvey CF, Swartz CH, Badruzzaman ABM, Keon-Blute N, Yu W, Ali MA, Jay J, Beckie R, Niedan V, Brabander D, Oates PM, Ashfaque KN, Islam S, Hemond HF, Ahmed MF (2002) Arsenic mobility and groundwater extraction in Bangladesh. Science 298:1602–1606

Islam FS, Gault AG, Boothman C, Polya DA, Charnock JM, Chatterjee D, Lloyd JR (2004) Role of metal-reducing bacteria in arsenic release from Bengal delta sediments. Nature 430 (6995):68–71

Mahanta C, Choudhury R, Basu S, Hemani R, Dutta A, Barua PP, Saikia L (2015) Preliminary assessment of arsenic distribution in Brahmaputra River Basin of India based on examination of 56,180 public groundwater wells. In: Safe and sustainable use of arsenic-contaminated aquifers in the gangetic plain. Springer International Publishing, pp 57–64

McLean W, Jankowski J (2000) Groundwater quality and sustainability in an alluvial aquifer, Australia. In: Sililo A (ed), XXX IAH Congress on Groundwater: Past Achievements and Future Challenges. A.A. Balkema, Rotterdam

Mukherjee A, Fryar AE (2008) Deeper groundwater chemistry and geochemical modeling of the arsenic affected western Bengal basin, West Bengal, India. Appl Geochem 23:863–892

Mukherjee A, Bhattacharya P, Shi F, Fryar AE, Mukherjee AB, Xie ZM, Sracek O, Jacks G, Bundschuh J (2009) Chemical evolution in the high arsenic groundwater of the Huhhot basin (Inner Mongolia, PR China) and its difference from the western Bengal basin (India). Appl Geochem 24:1835–1851

Mukherjee A, Scanlon B, Fryar A, Saha D, Ghoshe A, Chowdhuri S, Mishra R (2012) Solute chemistry and arsenic fate in aquifers between the Himalayan foothills and Indian craton (including central Gangetic plain): Influence of geology and geomorphology. Geochim Cosmochim Acta 90:283–302

Mukherjee A, Verma S, Gupta S, Henke KR, Bhattacharya P (2014) Influence of tectonics, sedimentation and aqueous flow cycles on the origin of global groundwater arsenic: paradigms from three continents. J Hydrol 518:284–299

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore, ISBN 978-981-10-3888-4

Nordstrom DK (2009) Natural arsenic enrichment: effects of diagenetic tectonichydrothermal cycle. Geol Soc Am Abstracts Progr 41(7):217

Nriagu JO, Bhattacharya P, Mukherjee AB, Bundschuh J, Zevenhoven R, Loeppert RH (2007) Arsenic in soil and groundwater: an overview. Trace Metals other Contam Environ 9:3–60

Nickson RT, McArthur JM, Ravenscroft P, Burgess WG, Ahmed KM (2000) Mechanism of arsenic release to groundwater, Bangladesh and West Bengal. Appl Geochem 15:403–413

Nesbitt HW, Young GM (1989) Formation and diagenesis of weathering profiles. J Geol 97:129–147

Ravenscroft P, Brammer H, Richards KS (2009) Arsenic pollution: a global synthesis. Wiley-Blackwell, Cichester, UK

Saunders JA, Lee MK, Uddin A, Mohammad S, Wilkin RT, Fayek M, Korte NE (2005) Natural arsenic contamination of Holocene alluvial aquifers by linked tectonic, weathering, and microbial processes. Geochem Geophys Geosyst 6(4)

Sarin MM, Krishnaswami S, Dilli K, Somayajulu BLK, Moore WS (1989) Major ion chemistry of the Ganga–Brahmaputra river system: weathering processes and fluxes to the Bay of Bengal. Geochim Cosmochim Acta 53:997–1009

Singh SK, Sarin MM, France-Lanord C (2005) Chemical erosion in the eastern Himalaya: major ion composition of the Brahmaputra and δ13C of dissolved inorganic carbon. Geochim Cosmochim Acta 69(14):3573–3588

Stüben D, Berner Z, Chandrasekharam D, Karmakar J (2003) Arsenic enrichment in groundwater of West Bengal, India: geochemical evidence for mobilization of As under reducing conditions. Appl Geochem 18(9):1417–1434

Smedley PL, Kinniburgh DG (2002) A review of the source, behaviour and distribution of arsenic in natural waters. Appl Geochem 17:517–568

Smedley PL (2005) Arsenic occurrence in groundwater in South and East Asia-scale, causes and mitigation. In: Towards a more effective operational response: arsenic contamination of groundwater in South and East Asian countries, vol II Technical Report, World Bank Report No. 31303

Swartz CH, Blute NK, Badruzzaman B, Ali A, Brabander D, Jay J, Besancon J, Islam S, Hemond HF, Harvey CF (2004) Mobility of arsenic in a Bangladesh aquifer: inferences from geochemical profiles, leaching data, and mineralogical characterization. Geochim Cosmochim Acta 68:4539–4557

Tardy Y (1971) Characterization of the principal weathering types by the geochemistry of waters from some European and African crystalline massifs. Chem Geol 7:253–271

Verma S, Mukherjee A, Choudhury R, Mahanta C (2015) Brahmaputra river basin groundwater: solute distribution, chemical evolution and arsenic occurrences in different geomorphic settings. J Hydrol Reg Stud 4:131–153

Verma S, Mukherjee A, Mahanta C, Choudhury R, Mitra K (2016) Influence of geology on groundwater-sediment interactions in varied arsenic enriched tectono-morphic aquifers of the Brahmaputra River Basin. J Hydrol 540:176–195

Wood WW (1981) Guidelines for Collection and Field Analysis of Ground-Water Samples for Selected Unstable Constituents. In: US Geological Survey, Techniques of Water Resources Investigation, Book 1 (Chapter D2)

Zheng Y (2006) The heterogeneity of arsenic in the crust: a linkage to occurrence in groundwater. Geol Soc Am Abstracts Progr 38(7):179

Chapter 19
Groundwater Quality of Meghna River Basin Aquifers

Abhijit Mukherjee, Prosun Bhattacharya and Kazi Matin Ahmed

Abstract The Meghna river basin in the eastern parts of Bangladesh is regarded as one of the most enriched groundwater systems of South Asia. The river, together with Ganges and Brahmaputra, forms the largest fluvio-deltaic system of the world. The fluvial depositional processes have resulted in the formation of the confined to semi-confined, multilayered aquifer system of the area, with groundwater composition ranging between Ca–HCO_3–Ca–Na–HCO_3 and Mg–Ca–Cl hydrochemical facies. The highly As-polluted groundwater chemistry is characterized by reducing postoxic environments and being dominated by metal-/metalloid-reducing

---

A. Mukherjee (✉)
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee
Applied Policy Advisory to Hydrogeosciences (APAH) Group, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

P. Bhattacharya
KTH-International Groundwater Arsenic Research Group, Department of Sustainable
Development, Environmental Science and Engineering, KTH Royal Institute of Technology,
Teknikringen 76, SE-100 44 Stockholm, Sweden
e-mail: prosun@kth.se; prosun.bhattacharya@usq.edu.au

P. Bhattacharya
School of Civil Engineering and Surveying & International Centre for Applied
Climate Science, Faculty of Health, Engineering and Sciences,
University of Southern Queensland, Toowoomba QLD 4350, Australia

K. M. Ahmed
Department of Geology, Faculty of Earth and Environmental Sciences,
University of Dhaka, Dhaka 1000, Bangladesh
e-mail: sohel_87@yahoo.com; kazimatin@yahoo.com; samin029@yahoo.com

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_19

processes in the presence of abundant organic matter in the abandoned channels of the Meghna floodplains. The various redox-sensitive solutes are found to be coexisting, suggesting partial redox equilibrium condition with overlapping redox zones. The reductively dissolved As, after being liberated from its source minerals, tends to remain in solution because of the complex interplay among the redox-sensitive hydrogeochemical processes.

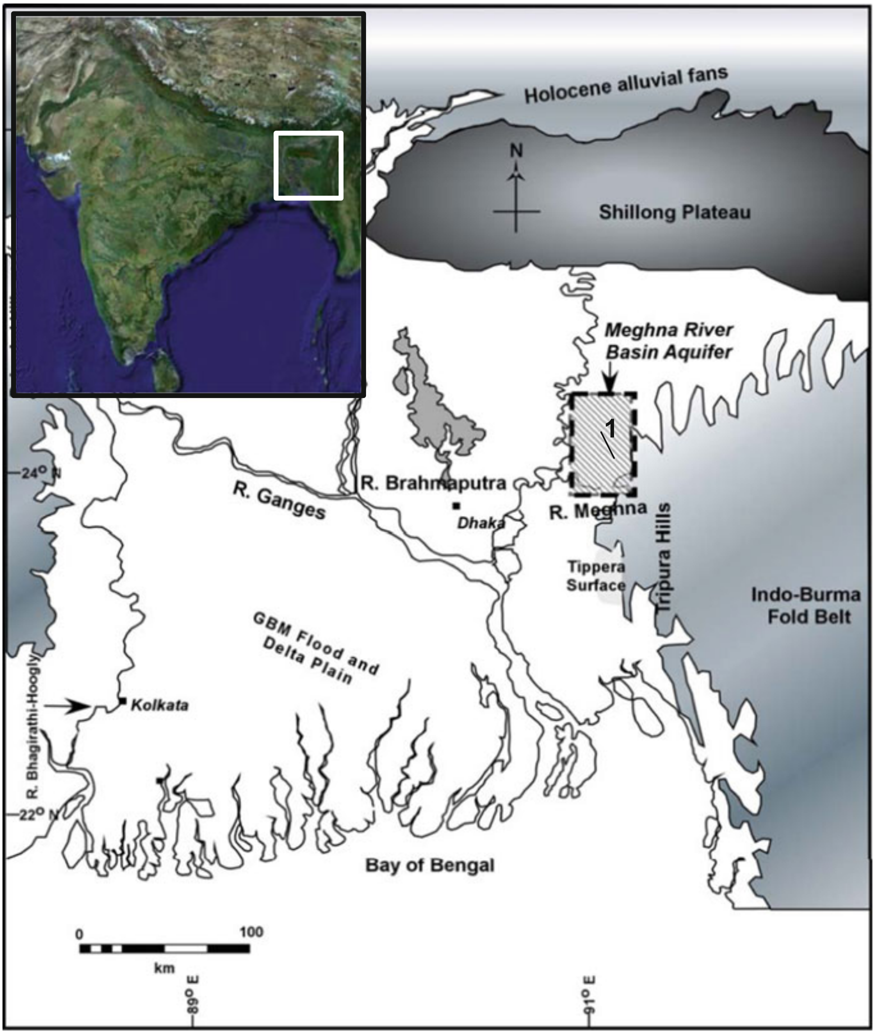


Fig. 19.1 Map of Ganges–Brahmaputra–Meghna (GBM) delta plain, showing the locations of the Meghna river basin aquifers. Line 1 represents the location of the hydrostratigraphic cross sections shown in Fig. 19.2

19.1 Introduction

The Meghna River, originating from the Tripura Hill of the northeastern part of Indian subcontinent, flows in the eastern parts of Bangladesh and is regarded as one of the most important rivers of South Asia. The river forms a substantial channel in the Kishoreganj district of Bangladesh, by the confluence of the River Surma and River Kushiyara, which stem out from the Barak River of India. After its confluence with the combined channel of the Ganges and Brahmaputra rivers (Chap. 1, Fig. 1.1), Meghna drains down to the Bay of Bengal, thereby forming the largest and most extensive fluvial delta system of the world, termed as the Ganges–Brahmaputra–Meghna (GBM) delta (Fig. 19.1). Although it has a short course in contrast to the other South Asian mega rivers, the Meghna possibly has the widest river channel, at some locations being up to 12 km wide. The extensive alluvial deposits from the river have developed some of the most groundwater-enriched aquifers of eastern Bangladesh (Fig. 19.1) (Ravenscroft 2003). More related information regarding groundwater of South Asia is available in Mukherjee (2018).

The study area in the Meghna river basin aquifer (MRBA) mostly encompasses the Brahmanbaria district of Bangladesh and covers the Brahmanbaria Sadar Thana and Ashuganj administrative areas. The area is a part of the geologically defined Chandina Formation, composed of the Chandina flood and delta plain (CFDP) deposits, and is surrounded by the Meghna flood plain in the west and Lalmai deltaic plain in the east. The CFDP is generally a very low relief land, being at a little higher elevation than the bordering floodplains. The CFDP is composed of alluvial facies, dominated by silt, silty loam, silty clay, which are characterized by typically fining-upward cycles. The Chandina Formation overlies the Pleistocene-aged Madhupur Clay and Pliocene-aged Dupi Tila Formation. It is succeeded on the top by the Meghna alluvium. The area is sensitive to neotectonic movements, resulting to rapid channel avulsions and frequent switching of the Meghna and Old Brahmaputra rivers. Thus, close proximity to the Tripura Hills in the east and Shillong Plateau in the north, the dynamic tectono-fluvial processes result in rapid sediment subsidence and high rate of deposition (Morgan and McIntire 1959). Consequently, a thick pile of Holocene-aged fine-grained sediments has got deposited in the basin, with the basement of the Madhupur Clay and Dupi Tila sediments (Alam et al. 2003; Mukherjee et al. 2009). The thickness of the alluvium decreases both east and westward from the study area. The Holocene/younger sediments are gray in color and enriched in natural organic matters (NOMs), while the older sediments are characterized by brown to red colored, NOM-deprived, oxidized sediments.

The channel switching of the Meghna River and Brahmaputra River forms confined-to-unconfined, multi-tiered aquifer system (Broms and Fogelström 2001; Bhattacharya et al. 2006; Mukherjee et al. 2008) (Fig. 19.2a). The groundwater level is shallow in the Holocene-aged, extensive sandy unconfined to low-yield aquifers and fluctuates annually with recharge–discharge seasons (MPO 1987; Allison et al. 2003). These aquifers are extensively exploited by innumerable

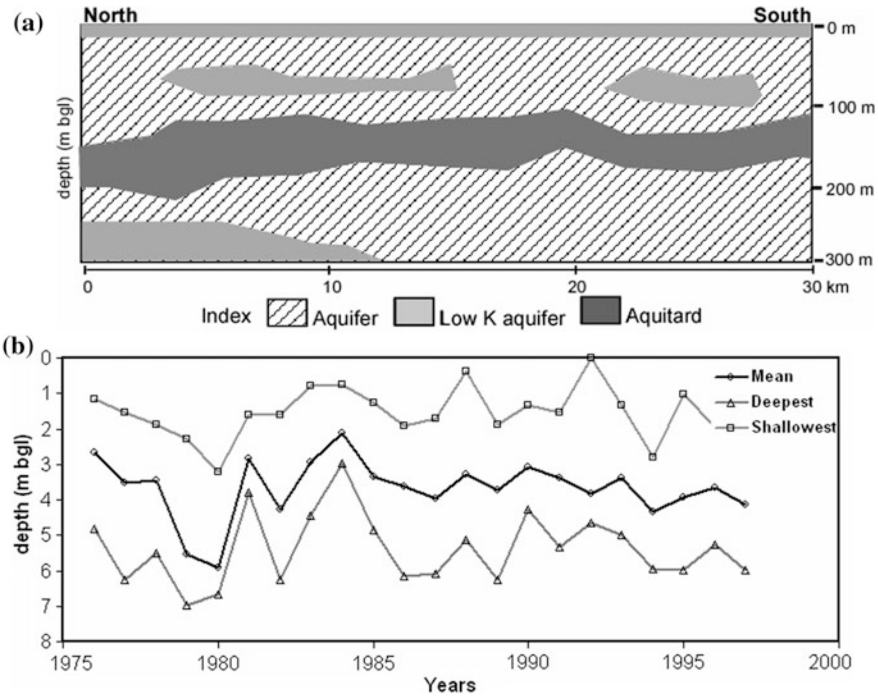


Fig. 19.2 **a** Hydrostratigraphic cross section of the aquifer types present along line 1 in Fig. 19.1; **b** the groundwater levels from 1976 to 1997 in surficial aquifers of the MRBA

hand-pumped, shallow tube wells. The maximum drop in groundwater level occurs in the month of April–May when the levels may reach up to 5–7 m below the ground (Fig. 19.2b). During the monsoon season, wide-scale flood recurrently occurs in the area, due to high rates of precipitation and rejected recharge of groundwater. The amount of annual fluctuation of groundwater level depth varies from 2 to 5 m in the area. The multiple-layered aquifer system of area also results to segregation of the water quality (Figs. 19.2a and 19.3). The deeper Dupi Tila sands also form prolific aquifers and are being exploited in the nearby Lalmai Hills and Madhupur Tract. The aquifer exists under confined conditions at a depth of more than 180 m. The recent-aged aquifers are typically enriched with groundwater arsenic (As) and iron (Fe), which are significantly low in Dupi Tila aquifers, available at greater depths, in and around the study area (BGS/DPHE/MML 2001). The upper parts of the Dupi Tila are characterized by low arsenic and iron. It is likely that the deeper aquifer receives recharge through the exposed Dupi Tila sediments in the Tripura Hills.

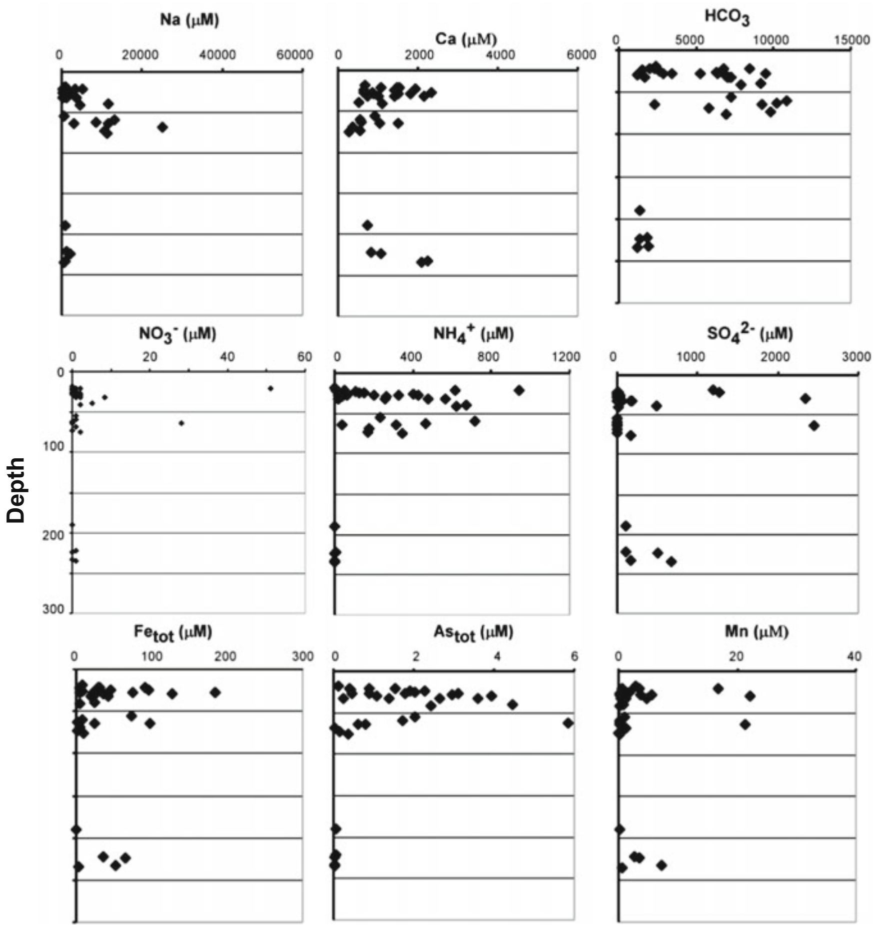


Fig. 19.3 Plot of concentrations (in μM) of selected groundwater solutes in the various aquifers of MRBA, along depth. bgl: below ground level

19.2 Groundwater Chemistry

19.2.1 Major Solutes and Hydrochemical Facies

The pH of the groundwater is found to be circumneutral, ranging between 6.2 and 7.6, with a mean of 6.9. The pH was not found to have any systematic variation with depth (Broms and Fogelström 2001; Bhattacharya et al. 2006). Groundwater temperatures were typically in the range of 26.1–27.6 °C (Table 19.1). Distinct variations in water chemistry were observed with the depth of the wells (Broms and Fogelström 2001; Bhattacharya et al. 2006). The groundwater is characterized by at least six hydrochemical facies (Fig. 19.4), with none predominating. Although most

Table 19.1 Statistical summary of the groundwater chemistry of the Meghna river basin aquifer in Bangladesh

Parameters	Unit	Maximum	Minimum	Mean	Median	Std. Dev.
Depth	m bgl	234.7	18.3	63.7	32.0	67.3
pH		7.6	6.4	6.9	6.9	0.3
Eh	mV	299.0	184.0	206.3	184.0	37.4
As	µg/L	439.0	1.8	111.1	81.7	108.6
As(III)	µg/L	302.0	bdl	54.0	19.0	67.6
Ca	mg/L	93.3	11.5	46.5	42.9	22.5
Fe	mg/L	10.3	0.0	2.1	1.3	2.3
K	mg/L	130.0	0.8	10.6	6.6	21.4
Mg	mg/L	73.3	4.3	27.1	20.3	17.5
Mn	µg/L	1218.0	3.3	170.5	42.2	308.1
Na	mg/L	574.0	4.6	88.2	30.0	123.5
NH_4	mg/L	16.1	bdl	4.3	3.0	4.3
Si	mg/L	20.2	0.2	2.9	1.1	4.2
Sr	µg/L	299.6	12.0	95.8	68.5	69.5
Zn	µg/L	105.8	2.9	25.1	18.1	23.4
Cl	mg/L	519.0	4.0	81.6	34.9	116.1
NO_3–N	mg/L	4.9	bdl	0.3	0.1	0.9
SO_4	mg/L	34.4	bdl	4.0	0.3	8.6
HCO_3	mg/L	663.0	74.0	322.3	384.0	191.8
PO_4	mg/L	16.3	0.1	3.5	2.7	3.9
TOC	mg/L	21.8	0.2	4.5	2.7	4.8

bgl below ground level, *bdl* below detection level

of the groundwater is of Ca–HCO_3 facies, several waters are of Ca–Mg–HCO_3, Ca–Na–HCO_3, and Mg–Ca–Cl types (Broms and Fogelström 2001; Bhattacharya et al. 2006). Among these, most of the water to a depth of 50 m bgl is of Ca–HCO_3 type, whereas the groundwater existing at an intermediate depth of 50–150 m below ground level (bgl) is generally of Mg–Cl or Mg–Ca–Cl types (Broms and Fogelström 2001; Bhattacharya et al. 2006; Mukherjee et al. 2008). The deeper samples (>150 m) mostly have Na + Ca and HCO_3 as the major ions (Fig. 19.3). Considerable variability is observed in concentrations of HCO_3^- (74–562 mg/l), Cl^- (5.3–76.8 mg/l), SO_4^{2-} (bdl–32.9 mg/l), and PO_4^{3-} (0.1–16.3 mg/l) and consistently low NO_3^- (bdl–0.8 mg/l), varying with depth (Table 19.1). The deeper groundwater in the older, pre-Holocene-aged aquifers is considered to be aged, with limited hydrogeochemical evolution (Mukherjee et al. 2008). EC values vary between 128 and 985 µS/cm. Groundwater collected from the intermediate depth aquifers is very distinct from the shallower and deeper aquifers, being mostly of Na–Cl–HCO_3 and Na–HCO_3–Cl types, and with EC values ranging between of 554 and 2080 µS/cm. In the deep aquifers (>150 m), groundwater samples were Ca–Na–Mg–Cl–HCO_3 or Ca–Cl–HCO_3 types with low concentrations of HCO_3^-

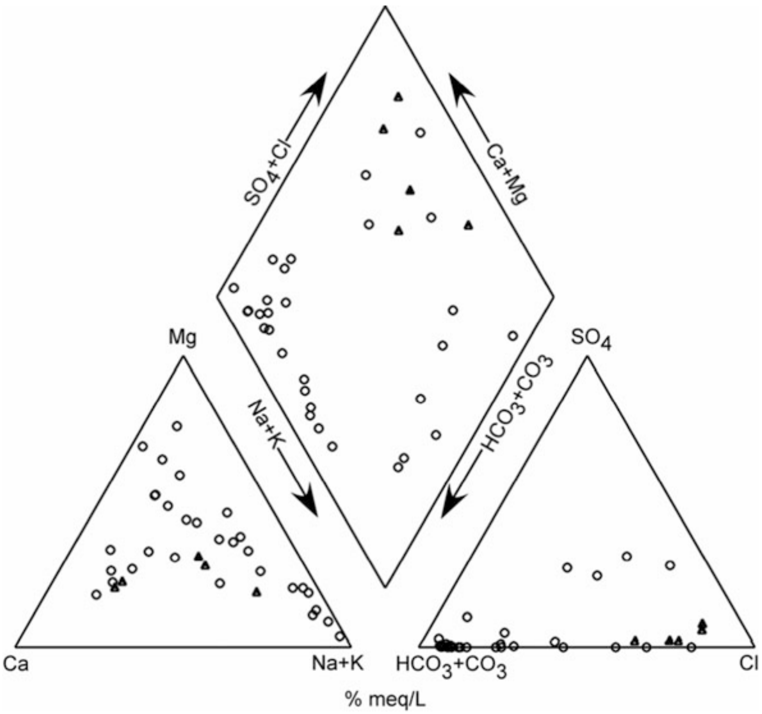


Fig. 19.4 Piper plot of the hydrogeochemical facies as identified in MRBA

(74–116 mg/l), NO_3^- (bdl–0.1 mg/l), and PO_4^{3-} (0.2–0.7 mg/l) and elevated levels of Cl^- (69.6–174 mg/l) and SO_4^{2-} (1.4–9.4 mg/l) (Table 19.1).

19.2.2 Minor Solutes, Redox Environment, and Groundwater Contaminants

Field-measured Eh values of the collected groundwater samples indicate moderately-to-strongly reduced conditions (−0.189 to <−0.304 V). Calculated values of redox potential (p_e) of the groundwater samples from MRBA fall around the Fe(II)–Fe(III) transition redox equilibrium zone (Parkhurst et al. 1996). However, all samples fall in the anoxic (postoxic) environment (Berner 1981), with mean Eh values between the range of Fe(III) reduction and As(V) reduction (Fig. 19.5). Therefore, metal [Fe(III)] reduction appears to be the dominant redox process (Mukherjee et al. 2008). The redox-sensitive solutes (NO_3^-, NH_4^+, SO_4^{2-}, Fe_{tot}, As_{tot}, and Mn) were found to have the maximum variability and concentrations in a shallow depth range of 30–50 m bgl. All these solutes show pronounced decrease in concentrations with depth, which is indicative of the controlling redox

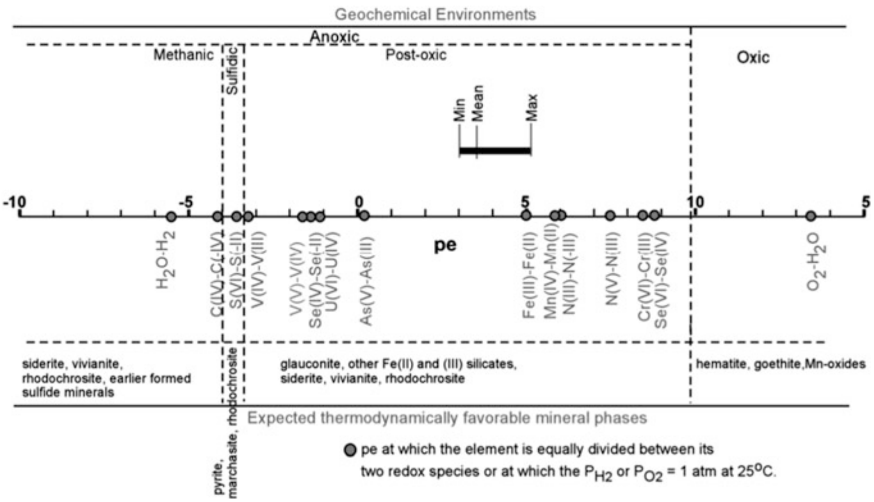


Fig. 19.5 Plot of the range of groundwater redox conditions encountered in the aquifers of MRBA, plotted against the equilibrium *pe* of the various redox couples. The plot is modified after Mukherjee et al. (2008)

processes. While the total arsenic (As_{tot}) concentrations in the shallow wells ranged between 10 and 335 μg/l, total Fe (Fe_{tot}) and Mn range between 285–10,301 μg/l and 9.6–1218 μg/l, respectively, demonstrating very high variability. In the intermediate wells, As_{tot}, $Fe_{tot,}$ and Mn concentrations were also variable, reaching up to maximum levels of 439, 5494, and 1177 μg/l in different wells. However, in MRBA, Fe, Mn, and SO_4^{2-} concentrations rebound for some samples >200 m depth, which indicates a revival of the metal-reducing condition at those depths or waters from different sources. However, in the deeper groundwater (>150 m), As_{tot} concentrations are low (below 10 μg/l), although the concentrations of Fe_{tot} and Mn range up to 3605 and 397 μg/l, respectively. CH_4 was not detected in the MBRA, but prior reports are available for CH_4 existence from groundwater of adjoining localities (e.g., Ahmed et al. 1998, 2004). In few areas with the MRBA, HS^- was also detected within a shallow depth of 60 m bgl indicating that at least sulfate-reducing condition exists in the aquifers. The As(III)/As_{tot} ratio in the MRBA is ~0.5, which seems to be consistent with the observed Eh values (Broms and Fogelström 2001; Bhattacharya et al. 2006; Mukherjee et al. 2008).

19.3 Hydrogeochemical Relationships and Processes

The presence of As-enriched groundwater in MRBA is a matter of severe public health concern for the largely groundwater-dependent inhabitants. The present study indicated that arsenic-rich groundwater is prevalent in the aquifers at depths of 18–41 m along a paleochannel parallel to the present Meghna channel. This belt possibly represents an abandoned paleomeander segment of the Meghna River and its tributaries.

In general, As_{tot} shows a strong negative correlation with Fe_{tot} ($r^2 = -0.73$) in the shallow groundwater, while the relatively few wells at the intermediate depths indicate moderate positive correlation ($r^2 = 0.51$). Moreover, strong negative correlations were observed between As_{tot} and Mn ($r^2 = 0.72$). The negative correlations between Fe_{tot}-As_{tot}, Fe_{tot}-HCO_3^-, and Fe_{tot}-PO_4^{3-} in the shallow-reducing aquifers indicate that Fe is non-conservative in this groundwater, with possibility of precipitation of Fe phases like siderite ($FeCO_3$) and perhaps also precipitation of vivianite ($Fe_3(PO_4)_2.8H_2O$). Both of these minerals can act as a sink for Fe(II) in reduced groundwater with high concentration of anions like HCO_3^- and PO_4^{3-} (Broms and Fogelström 2001; Bhattacharya et al. 2002; Anawar et al. 2003; Mukherjee et al. 2008).

Large accumulations of NOM are pervasive in the abandoned meander segments which can act as electron acceptors and trigger the series of redox reactions in the aquifers. Thus, in order to understand the trace metal cycling in this reduced groundwater of MRBA, it becomes imperative to delineate the redox reactions and terminal electron-accepting process (TEAP) that are taking place through multiple, coexisting biogeochemical processes. The common TEAPs for NOM oxidation are oxygen O_2, NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-}, and CO_2. Elevated PO_4^{3-} levels in groundwater can be caused by degradation of organic matter (Bhattacharya et al. 1997, 2002). The presence of NH_4^+ in appreciable quantities and its correlation with PO_4^{3-} is a clear indicator of degradation of organic matter. A strong positive correlation was found among DOC and As(III) ($r^2 = 0.82$; $p < 0.05$), HCO_3^- ($r^2 = 0.58$; $p < 0.001$), and NH_4^+ ($r^2 = 0.60$; $p < 0.001$) for the groundwater samples of the MRBA wells at various depths. Correlation between As_{tot} and PO_4^{3-} is moderate to weak, both in the shallow wells ($r^2 = 0.36$; $p < 0.001$) and in the wells at intermediate depths ($r^2 = 0.51$). HCO_3^- concentrations indicate significant positive correlation with As_{tot} ($r^2 = 0.56$), As(III) ($r^2 = 0.52$), and PO_4^{3-} ($r^2 = 0.50$), as well as Mn ($r^2 = 0.65$). A strong negative correlation was also observed between HCO_3^- and Fe_{tot} ($r^2 = 0.63$). Oxidation of organic matter results in elevated HCO_3^- levels (Parkes et al. 1990; Park et al. 2006).

Detection of HS^- in some of the groundwater, along with very low dissolved SO_4^{2-} concentrations, suggests ongoing sulfate reduction in the shallow-to-intermediate depth groundwater (Broms and Fogelström 2001). Also, since SO_4^{2-} concentrations do not indicate any specific relationship with As_{tot}, it may be suggested that two may not be genetically linked; i.e., pyrite oxidation may not be contributing to dissolved As, as has been suggested from some ares of the Bengal basin. There is a consistent lack of correlation between the SO_4^{2-} concentrations with Fe_{tot} and As_{tot}, thereby ruling out the possibility of sulfide oxidation as a major source of arsenic in groundwater of MRBA. On the contrary, a weak trend of negative correlation is observed between SO_4^{2-} and HCO_3^- concentrations in this groundwater (Broms and Fogelström 2001; Bhattacharya et al. 2006).

Dominance of As(III) in shallow MRBA groundwater indicates As(V) to As(III) reduction from the outer surface complexations of solid-phase Fe-oxyhydroxides by the As-tolerant microbial species through cellular detoxification process (Bhattacharya et al. 2002; Zheng et al. 2004, 2005), thereby sequentially leaching Fe(II) and As(III) in groundwater. Biogeochemical transformation of NOMs also leads to the generation of dissolved CH_4 in the areas with elevated arsenic levels in groundwater in SE Bangladesh (Ahmed et al. 1998).

So, it is evident that the organic matter degradation may not be the only mechanism in the study areas, which influence the hydrochemical processes. In a hydrochemical equilibrium condition, the redox processes would be expected to aggregate along specific zones, increasing by depth with enhanced redox potential and with minimal coincidence. However, in most of the study area, the presence of highest concentrations of various redox-sensitive solutes within ~50 m bgl suggests those reactions such as dissimilatory nitrate reduction and metal/metalloid reduction (which leads to their reductive dissolution and mobilization) occurring at similar shallow depths. The coexistence of the redox-sensitive dissolved solutes with increasing depths, e.g., As, Fe, Mn, HS^{-}, and CH_4, indicates the existence of overlapping redox zones (Mukherjee et al. 2008). Even formation of pyrites within the metal-reducing zones has been suspected, alluding to the presence of the partial redox equilibrium dominating the redox-sensitive solute chemistry (Mukherjee et al. 2008) (Fig. 19.5).

References

Ahmed KM, Hoque M, Hasan MK, Ravenscroft P, Chowdhury LR (1998) Occurrence and origin of water well CH_4 gas in Bangladesh. J Geolo Soc India 51:697–708

Ahmed KM et al (2004) Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview. Appl Geochem 19(2):181–200

Alam M, Alam MM, Curray JR, Chowdhury MLR, Gani MR (2003) An overview of the sedimentary geology of the Bengal Basin in relation to the regional tectonic framework and basin-fill history. Sediment Geology 155(3–4):179–208

Allison MA, Khan SR, Goodbred SL, Kuehl SA (2003) Stratigraphic evolution of the late Holocene Ganges–Brahmaputra lower delta plain. Sediment Geol 155(3–4):317–342. ISSN 0037-0738, https://doi.org/10.1016/S0037-0738(02)00185-9

Anawar HM et al (2003) Geochemical occurrence of arsenic in groundwater of Bangladesh: sources and mobilization processes. J Geochem Explor 77(2–3):109–131

Berner RA (1981) A new geochemical classification of sedimentary environments. J Sediment Petrol 51:359–365

BGS/DPHE/MML (2001) Arsenic contamination of groundwater in Bangladesh. Technical report WC/00/19, British Geological Survey, Keyworth

Bhattacharya P, Chatterjee D, Jacks G (1997) Occurrence of arsenic-contaminated groundwater in alluvial aquifers from the Bengal delta plain, Eastern India: options for a safe drinking water supply. Water Resource Dev 13:79–92

Bhattacharya P, Jacks G, Ahmed KM, Khan AA, Routh J (2002) Arsenic in groundwater of the Bengal delta plain aquifers in Bangladesh. Bull Environ Contam Toxicol 69:538–545

Bhattacharya P, Ahmed KM, Hasan MA, Broms S, Fogelstrom J, Jacks G, Sracek O, Bromssen MV, Routh J (2006) Mobility of As in groundwater in part of the Brahmanbaria district, NE Bangladesh. In: Naidu R, Smith E, Owens G, Bhattacharya P, Nadebaum P (eds) Managing arsenic in the environment: from soil to human health. CSIRO Publishing, Melbourne, Australia, pp 95–115

Broms S, Fogelstrom J (2001) Field investigations of arsenic-rich groundwater in the Bengal Delta Plain, Bangladesh: an interbasinal comparison of mechanisms for arsenic translocation and test of low-cost remediation technology. M.Sc. thesis, Series 2001:18, Dept of Land and Water Engineering, KTH, Stockholm, Sweden

Morgan JP, McIntire WG (1959) Quaternary geology of Bengal basin, East Pakistan and India. Geol Soc Am Bull 70:319–342

MPO (1987) Groundwater resources of Bangladesh. Technical report 5, Master Plan Organization (MPO), Dhaka, Harza Engineering, USA, Sir M MacDonald & Partners, UK, Meta Consultants, USA and EPC Ltd., Dhaka

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore, ISBN 978-981-10-3888-4

Mukherjee A, von Brömssen M, Scanlon BR, Bhattacharya P, Fryar AE, Hasan MA, Ahmed KM, Jacks G, Chatterjee D, Sracek O (2008) Hydrogeochemical comparison and effects of overlapping redox zones on groundwater arsenic near the western (Bhagirathi sub-basin, India) and eastern (Meghna sub-basin, Bangladesh) of the Bengal basin. J Contam Hydrol 99(1–4):31–48

Mukherjee A, Fryar AE, Thomas WA (2009) Geologic, geomorphic and hydrologic framework and evolution of the Bengal basin, India. J Asian Earth Sci 34(3):227–244

Park J, Sanford RA, Bethke CM (2006) Geochemical and microbiological zonation of the Middendorf aquifer, South Carolina. Chem Geol 230:88–104

Parkes RJ, Cragg BA, Fry JC, Herbert RA, Wimpenny JWT (1990) Bacterial biomass and activity in deep sediment layers from the Peru margin. Trans R Soc Lond A331:139–153

Parkhurst DL, Christenson S, Breit GN (1996) Ground-water quality assessment of the Central Oklahoma aquifer, Oklahoma—geochemical and geohydrologic investigations. U.S. Geological Survey Water Supply paper 2357-C, 101 pp

Ravenscroft P (2003) Overview of the hydrogeology of Bangladesh. In: Rahman AA, Ravenscroft P (eds) Groundwater Resources Development in Bangladesh, University Press, Dhaka , pp 43–86

Zheng Y et al (2004) Redox control of arsenic mobilization in Bangladesh groundwater. Appl Geochem 19(2):201–214

Zheng Y et al (2005) Geochemical and hydrogeological contrasts between shallow and deeper aquifers in two villages of Araihazar, Bangladesh: implications for deeper aquifers as drinking water sources. Geochim Cosmochim Acta 69(22):5203–5218

Chapter 20
The Groundwater Flow, Chemistry and Pollutant Distribution in the Bengal Basin, Bangladesh and India

Madhumita Chakraborty, Abhijit Mukherjee and Kazi Matin Ahmed

Abstract The Bengal basin, situated along the Indo-Bangladesh border, forms the world's largest fluvio-deltaic basin and holds one of the most productive aquifer systems of the world, serving for about 2% of the world population living in the basin. On a basinal scale, the hydrostratigraphy represents a single continuous aquifer, which is broken into poorly connected multi-layered system by numerous discontinuous aquitards towards the south. Regionally, groundwater flows from north to south along hierarchical flow paths, which at places are interrupted by local flow systems due to extensive groundwater abstractions. The groundwater of the basin is dominantly Ca–HCO_3^- type, showing signatures of meteoric recharge altered by various biogeochemical processes controlled by the aquifer redox states. In spite of the abundance of freshwater in the BAS, it exhibits the presence of various ions above the permissible limits, resulting in groundwater contamination. The most toxic and widespread contaminant in the basin groundwater is arsenic, derived from the aquifer sediments. Although arsenic release is a geogenic process, anthropogenic activities such as heavy groundwater abstractions, use of fertilisers and contamination from sewage may contribute to its release.

M. Chakraborty · A. Mukherjee
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: madhumitageol@gmail.com

A. Mukherjee (✉)
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

A. Mukherjee
Applied Policy Advisory To Hydrogeosciences Group, IIT Kharagpur,
Kharagpur 721302, West Bengal, India

K. M. Ahmed
Department of Geology, University of Dhaka, Curzon Hall Campus,
1000 Dhaka, Bangladesh

© Springer Nature Singapore Pte Ltd. 2018
A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_20

Keywords Bengal basin · Groundwater flow · Groundwater chemistry
Arsenic pollution

20.1 Introduction

The Bengal basin is situated along the Indo-Bangladesh border and encompasses major parts of Bangladesh and some parts of eastern and north-eastern India (including states such as West Bengal, Tripura and Assam) (Chap. 1, Figs. 1.1, 1.3 and 1.5). The Bengal basin is known to be the largest fluvio-deltaic system of the world (with an areal extent of about 200,000 km^2) (Coleman 1981; Alam et al. 2003) and is bounded by the world's largest orogen, the Himalayas to the north and the world's largest submarine fan, the Bengal fan to the south. The Bengal basin is drained by the Ganges, Brahmaputra and Meghna river systems and is thus synonymously known as the Ganges–Brahmaputra–Meghna (GBM) basin. The GBM system drains down the rapidly eroding sediments from about two-thirds of the actively rising Himalayas and brings down the single highest sediment flux in the world (of $\sim$1060 million tonne/year) to the basin, before depositing the entire load of sediments to the Bay of Bengal, forming the Bengal Fan (Milliman et al. 1995; Dowling et al. 2002; Mukherjee et al. 2009b). More related information regarding groundwater of South Asia is available in Mukherjee (2018).

20.1.1 *Basin Boundaries*

The north-eastern margin of the basin is circumscribed by the Garo, Khasi and Jaintia hills (progressively from west towards east), collectively known as the Shillong Plateau (Mukherjee et al. 2009b). The north and west of the basin is bordered by the Indian Shield and Rajmahal Hills. The eastern margin of the basin is delineated by the Tripura Hills and the Indo-Burmese Range towards the north, and the Chittagong Hills towards the south (Alam et al. 2003; Mukherjee et al. 2009b). To the south, the basin opens up into the Bay of Bengal (Fig 20.1).

20.1.2 *Physiographic Units*

Physiographically, the basin can be divided into the 'Pleistocene Uplands,' which are thought to be floodplain deposits of palaeo-GBM river system and the relatively flat, low-lying 'Holocene Deposits' (Morgan and McIntire 1959). Among the major Pleistocene units of the basin, the Barind Tract and the Madhupur Terrace are located at the north-western and north-central part of the basin, respectively (Fig. 20.1). Two other units are situated along the western part of the Tripura Hills and the eastern side of the Rajmahal Hills, in addition to several other smaller

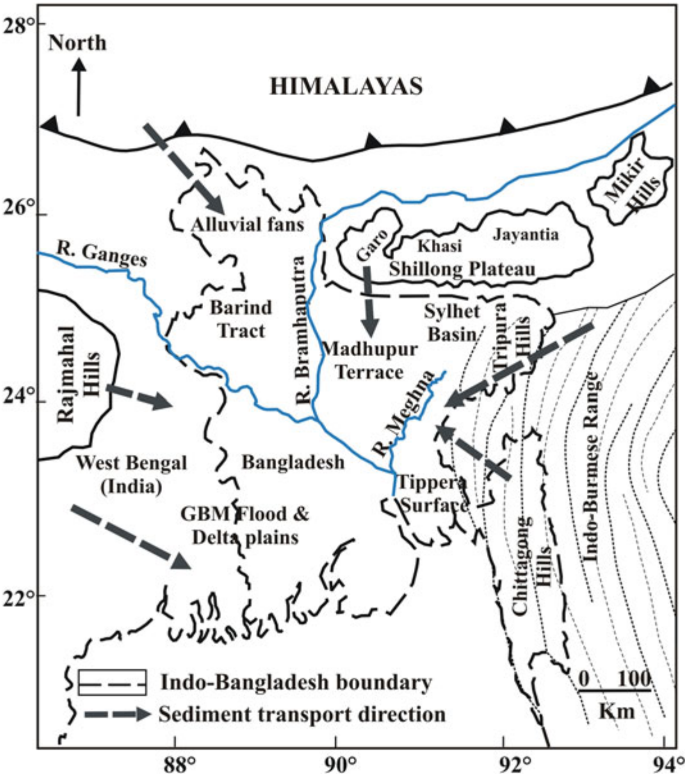


Fig. 20.1 Physiographic map of the Bengal basin and the basin boundaries (arrows indicate the sediment provenances of the basin) (modified from Mukherjee et al. 2009b)

outliers (Mukherjee et al. 2009b). The Holocene lowlands can geomorphologically be subdivided into the piedmont alluvial fans along the Himalayan foothills; the Tippera surface, characterised by its unique artificial rectangular drainage pattern constructed for agricultural purpose; the north-eastern Sylhet Basin; and the extensive GBM flood and delta plains to the south covering more than 80% ($\sim 10^5$ km^2) of the Bengal basin (Morgan and McIntire 1959; Umitsu 1987). These plains are made up of Holocene alluvium containing overbank deposits of silt and clay, incised by channel-fill sands, and show numerous channels, palaeochannels, meander scrolls and ox-bow lakes (Goodbred and Kuehl 2000; Allison et al. 2003) formed as a result of river channel switching and migration.

20.1.3 The Sediment Characteristics

Sedimentation in the basin was initiated in the late Cretaceous and was accelerated in middle Miocene. Since then, the active control of tectonics, fluvio-deltaic processes and glacio-eustatic changes (as a result of Pleistocene glaciation), accompanied by the huge sediment flux of the GBM river system, has resulted in the formation of up to 22-km-thick stratified, laterally discontinuous, highly heterogeneous sediment complex, derived from the Himalayas, the Indo-Burmese range and the Indian Shield (Ahmed et al. 2004; Mukherjee et al. 2009b) (Fig. 20.1). The sediment thickness increases towards the active delta front, to the south-east of the basin (Mukherjee et al. 2009b).

The sediment fabric of the basin is composed of intricate intercalations of gravel, sand, silt and clay, with relative abundance of moderate to well-sorted finer clastics (Datta and Subramanian 1997; Mukherjee et al. 2009b). Mineralogically, the basin sediments show heavy dominance of detrital mineral grains of quartz, and feldspar, along with some clay minerals (e.g. illite, kaolinite and smectite, in addition to some chlorite and traces of montmorillonite) and few heavy minerals (e.g. amphibole, pyrope garnet, epidote and some pyrite) (Datta and Subramanian 1997; Sarin et al. 1989).

In spite of gross similarities, the Pleistocene sediments exhibit markedly different characteristics than the Holocene deposits and are compact, mottled, reddish brown to tan in colour, with abundant calcareous and ferruginous nodules and low organic matter (OM) content signifying notable oxidation (Morgan and McIntire 1959). On the other hand, the Holocene sediments are dark, OM rich, reduced in nature, moist and loosely compacted (Morgan and McIntire 1959), signifying rapid burial under anoxic conditions. However, such generalisations may be loose because the differential evolution in the various isolated sub-basins has resulted in diverse sediment chemistry (Goodbred et al. 2003; Mukherjee et al. 2009b).

20.2 The Bengal Aquifer System

The alluvial sediments of the basin form one the most productive and rich aquifer systems of the world, the Bengal aquifer system (BAS) sustaining more than 2% of the world's population. The unconsolidated alluvium in the top few hundred metres of the sediment stack forms the most prolific aquifers within the basin. A basin-wide marine clay layer (Mio-Pliocene Upper Marine Shale) underlies the BAS forming a hydraulic basement to the aquifer system (Burgess et al. 2010). The complex depositional and diagenetic history has resulted in the development of multi-scale spatial variability within the hierarchical sedimentary units of the aquifers. To the western part of the basin, the hydrostratigraphic architecture has resulted in the development of a single unconfined to semi-confined continuous aquifer system, overlying a thick basal clay aquitard, which breaks up into multiple laterally connected, deeper aquifers units towards the south, locally disjoined by the intervening discontinuous clay aquitards, forming a confined, multi-aquifer system (Mukherjee et al. 2007a) (Fig. 20.2). The basal clay aquitard encompasses several deep isolated aquifer lenses within it. To the eastern part, the basin has broadly developed a two-aquifer system, where a thick discontinuous clay layer separates the shallow aquifer unit from the deeper aquifer, broadly at a depth of about 200 m

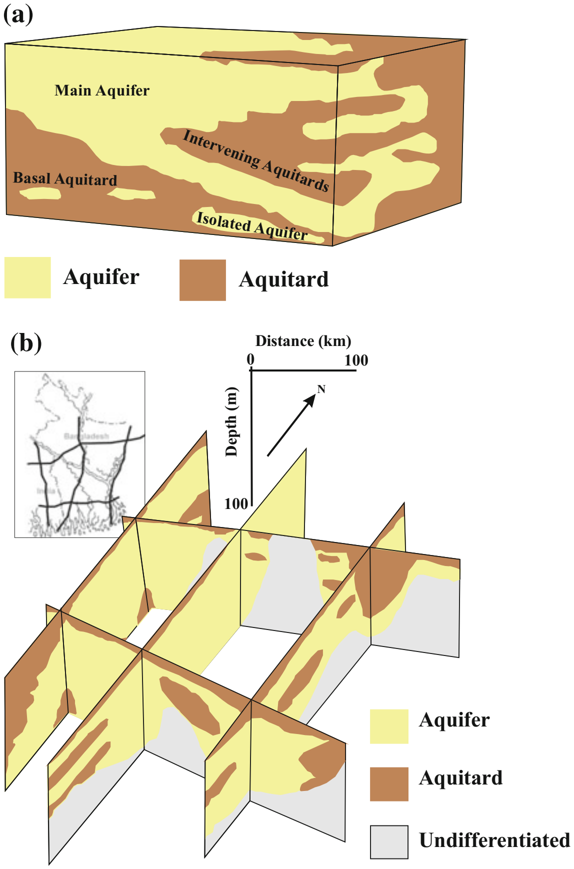


Fig. 20.2 Conceptual model of the hydrostratigraphy of the **a** western part of the BAS as developed by Mukherjee et al. 2007a (not to scale) (modified from Mukherjee et al. 2007a). **b** Eastern part of the BAS as developed by Goodbred et al. 2003, and Mukherjee 2006 (modified from Mukherjee et al. 2009b)

(Ahmed et al. 2004). Towards the southern parts of the Bengal basin, the lithology is dominated by a substantially higher fraction of intervening clay and silt layers forming an ‘interleaved’ pattern, while towards the northern and north-western parts of the basin, such low-permeability layers are sparse (Hoque et al. 2017) (Fig 20.2).

20.3 Groundwater Flow

On a basinal scale, the BAS is defined as a single continuous aquifer system, which is broken into several small and poorly connected, confined to semi-confined aquifer units on a local scale (Mukherjee et al. 2007a; Michael and Voss 2009a). Although the BAS is known to lack any regional confining layer, there are numerous local and discontinuous aquitards present across the basin. These low-permeability silt and clay layers are most commonly found in the southern part of the basin, while the northern areas are dominated by thick sequences of sands

(Hoque et al. 2017). The distribution of these low-permeability layers generates a higher hydraulic conductivity along the horizontal path than in the vertical direction and thus imparts a strong anisotropy in the hydraulic properties of the aquifer system (Michael and Voss 2009a). Michael and Voss (2009a) estimated the typical vertical anisotropy value to be 10^4. Thus, the distribution of the aquitard layers and the generated anisotropy are thought to be the primary control on the natural groundwater flow system (Michael and Voss 2009b), in the absence of the present extensive pumping scenario of the basin.

Micheal and Voss (2009b) suggested that in spite of the low basinal slope and the resulting low hydraulic gradient within the basin, the anisotropy generates large-scale (tens to hundreds of kilometres) deep basinal flow. The distribution of the low-permeability silt and clay aquitards dominant within the southern parts of the basin generates a regional multi-level hierarchical flow system, controlled by the hydraulic anisotropy generated by the layered architecture of the aquitards (Hoque et al. 2017). In the absence of extensive groundwater abstraction, the area experiences a regional north–south flow across the basin, with seasonal variations (Mukherjee et al. 2007a). The travel times for shallow groundwater (~ 100 m) flows are less than a hundred year, while deep regional (>150 m) flows may take thousands of years (Hoque and Burgess 2012).

The groundwater levels of the BAS show seasonal variance and are annually replenished by meteoric recharge (mostly, in the monsoons) and inflow from surface water system. After monsoonal flooding every year the groundwater levels return to an aquifer filled condition in many parts of the basin (excluding areas of extensive pumping) resulting in no-flow scenario (Mukherjee et al. 2007a). The groundwater in the basin is in close interaction with the surface water system, and under natural flow conditions during the pre-irrigation months, groundwater discharges to the river (Harvey et al. 2002).

During the 1970s, millions of tube wells were installed within the basin abstracting huge volumes of groundwater, largely for agricultural purposes (counting upto 25 to 75 wells per sq.Km of agricultural land in some parts of the basin), as well as for domestic and industrial use, from both shallow and deep levels (Shamsudduha et al. 2009). Under the low hydraulic gradients prevailing in the basin, the extensive groundwater exploitation practices substantially alter the natural groundwater flow paths and the water budget of the exploited aquifer systems (Michael and Voss 2009b). The large-scale groundwater abstractions across the basin have led to the formation of large cones of depression (up to 20 km in diameter), inducing the development of local flow systems controlled by the artificially enhanced vertical hydraulic gradients around the heavy abstraction points, accompanied by an increased rate of inflowing water towards the cones of depression (Mukherjee et al. 2007a, 2011). Severe water stresses accompanied by rapid decline in hydraulic heads are evidenced in urban centres within the basin, like Kolkata and Dhaka (>1 m/yr) along with many other areas (0.1–0.5 m/yr) (Shamsudduha et al. 2009) subjected to deep groundwater abstraction for dry-season rice cultivation (Mukherjee et al. 2007a; Hoque et al. 2014). Mukherjee et al. (2011) projected the present-day vertical hydraulic gradient to be <0.36 m/m and estimated the vertical flux to be stretching between ~9 x 10^6 m^3/d of inflow from the surface and *2 x 10^6 m^3/d of outflow from 200 m below ground level (bgl), under the present deep pumping scenario in the western part of the basin. The authors further showed that pumping strongly escalates the flow velocity (a particle which took >250 a to travel from >50 m bgl to a depth of 150 m under no-pumping scenario is simulated to reach the same depth in ~35 a, under the present pumping rates) and the groundwater flow paths are controlled by the disposition of the heavy pump stations. Harvey et al. (2006) argued that under pumping conditions, flows may reach a depth of 20–30 m in just 20–30 years. Deep pumping in the basin induces vertical inflow of the shallower groundwater to the deeper aquifers resulting in the mixing of the shallow and the deep groundwater, evidently altering the groundwater chemistry (Mukherjee et al. 2007a). The coastal belt shows a rise in the groundwater level (0.5–2.5 cm/yr), as a consequence of the rising sea level inducing increased seawater intrusion (Shamsudduha et al. 2009). Thus, the present groundwater pumping scenario has led to the increase in total recharge from land (taking into account the irrigational return flow), and a steady decline in groundwater levels resulting in enhanced inflow from the rivers (even sometimes backflow from naturally gaining rivers) and deeper seawater intrusion, accompanied by a decrease in the annual submarine groundwater discharge (Mukherjee et al. 2007a).

20.4 Groundwater Chemistry

The groundwater from most parts of the basin shows signatures of meteoric recharge, accompanied by some evaporation loss (Mukherjee 2006; Mukherjee et al. 2007b). However, the groundwater chemistry of the basin is widely varied and is controlled by processes such as carbonate dissolution, cation exchange, silicate weathering and aquifer redox states (Mukherjee et al. 2008a). The sediments eroded from the Ca-poor alkaline silicates of the Himalayas are mostly rich in Na and K, derived from incongruent dissolution of the minerals such as feldspar, mica and pyroxene (Galy and France-Lanord 1999; Mukherjee et al. 2009b). However, substantial amount of Ca and Mg is derived from carbonate dissolution and silicate weathering processes (Mukherjee et al. 2009b). The multi-level hierarchical flow system of the basin generates a highly heterogeneous groundwater chemistry with varying concentrations of different ions along the spatial stretch and depth axis (Hoque et al. 2017).

The groundwater is dominantly rich in Ca–HCO_3^-, with substantial amounts of Fe and Mn. The HCO_3^- is mostly derived from mineral weathering and OM oxidation (Mukherjee et al. 2008a). Broadly, the groundwater contains traces of NO_3^-, increasing CH_4 along depths, decreasing SO_4^2, Mn, Fe and As with depth, and no detectable H_2S or NO_2^- (Mukherjee et al. 2008a). Multiple concurrent processes contribute to the groundwater redox states in the aquifers, and such processes are depth dependent and hydrostratigraphically controlled (Mukherjee et al. 2008a). The groundwater of the basin exhibits simultaneous presence of many redox-sensitive solutes indicating partial redox equilibrium with overlapping redox zones (Mukherjee et al. 2008b). However, Fe(II)/Fe(III) serves as the most dominant redox couple in the groundwater resulting in a post-oxic environment (Mukherjee et al. 2008a). The anoxic nature of the groundwater corresponds well with the abundant presence of CH_4 and S^{2-}, with negligible dissolved O_2 (Ahmed et al. 1998; McArthur et al. 2001; Mukherjee et al. 2009b). Additionally, the low SO_4^{2-} concentrations in the basin waters accompanied by abundance of Fe and Mn also indicate strong reducing conditions persisting within the basin aquifers (Mukherjee et al. 2009b). The microbially mediated reduction of FeOOH coupled with oxidation of OM is the most dominant redox process within the basin sediments (Bhattacharya et al. 1997; Nickson et al. 2000). Local-scale re-oxidation involving the complex cycling of Fe-S-C phases occurs at places within the basin (Mukherjee et al. 2008a).

The chemical signatures of groundwater within the main aquifer system, the confined multilayer system and the isolated aquifers are strikingly distinctive. Towards the north-west, the continuous single aquifer is dominated by $Ca–HCO_3^-$ type waters, while towards the south, the layered aquifer system exhibits varied chemical signatures, broadly dominated by $Ca–Na–HCO_3^-–Cl^-$ species (Mukherjee et al. 2008a) (Fig. 20.3). The isolated aquifers have high concentration of total dissolved solid (TDS) dominated by Na–Cl and $Na–Cl–HCO_3$ species, which may represent the relict of the trapped connate water from proto-Bengal basin, evolved through cation exchange with the aquifer matrix or fresher recharge (Mukherjee et al. 2008a).

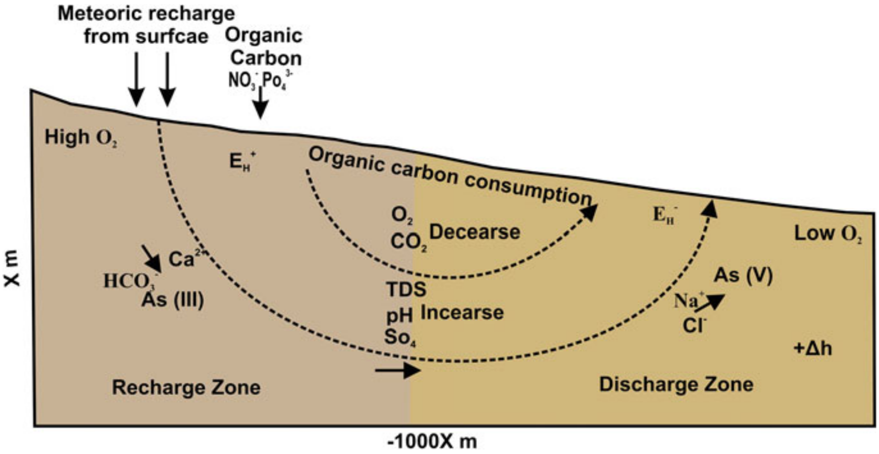


Fig. 20.3 Schematic diagram showing a typical hydrogeochemical evolution of groundwater along a regional flow path (modified after Mukherjee et al. 2014)

20.5 Groundwater Pollution

Groundwater serves as the major source of freshwater within the basin, sustaining more than 95% of the drinking water needs and ~70% of the irrigation water demands for the inhabitants of the basin (Hasan et al. 2007). However, despite the benefits, this has led to prolonged exposure of millions of inhabitants of the basin to the toxins present within the groundwater, resulting in various short-term to long-term health hazards.

In the West Bengal part of the basin, high levels of iron (>1 mg/L) in the groundwater are widespread, covering the districts of Bardhhaman, Howrah, Hooghly, Murshidabad, Nadia, N-24Parganas and S-24Parganas (CGWB 2010). During a basin wide survey of groundwater quality in Bangladesh, 23% of tube wells were found to contain iron concentrations greater than 5 mg/L (median 1.1 mg/L; max 61 mg/L), commonly in the Brahmaputra Valley in northern Bangladesh, whereas 35% of wells were measured with more than 0.5 mg/L (WHO permissible limit) of manganese (median 0.3 mg/L; max 10 mg/L) (BGS/DPHE 2001). 5.3% of tube wells (acc to BGS/DPHE 2001) were measured with boron concentrations exceeding 0.5 mg/L (WHO permissible limit), and these were mostly associated with high saline zones in the southern coast and in a north-eastern area in Bangladesh. High levels of fluoride contaminations (>0.15 mg/L) are found in the districts of Malda, Bardhaman and Nadia of West Bengal (CGWB 2010). A substantial amount of phosphorous (median 0.3 mg/L) is also found in the groundwater in many areas (BGS/DPHE 2001). High levels of nitrate (> 45 mg/L) are found in Bardhaman district of West Bengal (CGWB 2010) and sporadically in parts of Bangladesh, and are mostly being attributed to pollution from latrines (BGS/DPHE 2001). Local occurrences of excess chloride (> 1000 mg/L) are found in the southern West Bengal (CGWB 2010). Few samples from the southern coast of Bangladesh report high barium concentrations (BGS/DPHE 2001). Heavy metal contaminations, such as lead, cadmium, chromium and molybdenum, are also present in few places (BGS/DPHE 2001; CGWB 2010). BGS/DPHE (2001) reports severe uranium contamination (max: 47 μg/L; median concentration 0.42 μg/L) in parts of Bangladesh, particularly in dug wells under oxidising environments. The presence of saline groundwater pockets in the inland or along the coastal areas of the basin is also a major issue concerning the potability of the basin groundwater. However, the most widespread and toxic pollutant found in the groundwater of the basin is arsenic.

20.5.1 Arsenic Pollution in Groundwater

The magnitude of arsenic problem in the Bengal basin has been known to cause the ‘largest poisoning of a population in history’ (Smith et al. 2000) (Fig 20.4). Millions of people in West Bengal are exposed to arsenic levels above 10 μg/L

(WHO guideline value and recently upgraded Indian national standard for arsenic in drinking water). In Bangladesh, about 35 million people are at risk from arsenic levels above the Bangladesh national drinking water standard of 50 µg/L, while 77 million people are exposed to arsenic levels above 10 µg/L (BGS/DPHE 2001; Edmunds et al. 2015). Excess arsenic intake in human body, mainly through drinking water and rice (Chatterjee et al. 2010), leads to numerous health problems, even causing cancers (Chakraborty et al. 2015).

Despite the widespread arsenic contamination in the shallower aquifers, arsenic contamination seems to be relatively attenuated in the deep aquifers (Fig. 20.4). Arsenic in the groundwater of BAS is liberated from the basin sediments which are derived from multiple provenances (Hossain, 2006), mostly including the Himalayas and its foreland basin, the Indo-Burmese range, the Shillong Plateau and the Indian Shield (Mukherjee et al. 2009b), suggesting a non-point geogenic origin (Mukherjee et al. 2014). The typical arsenic concentrations in basin sediments range from 1 to 20 mg/Kg (Hossain 2006; Mukherjee et al. 2011), but varies between different lithologies: Arsenic concentrations in sands are typically lower than in silt, clay, peat and other OM rich layers (Harvey et al. 2006). In the Bengal basin sediments, solid-phase arsenic is principally bound to iron (oxy)(hydro)oxides (Harvey et al. 2006) and detrital pyrites (Mandal et al. 1998), along with silicates (Breit et al. 2001) and carbonates (Pal and Mukherjee 2009). Irrigational pumping is reported to result in the sequestration of up to 1360 tonnes of arsenic per year to ferric (hydro)oxides, in the paddy fields of Bangladesh (Edmunds et al. 2015).

Listed here are the most plausible and accepted hypotheses explaining the mobilisation phenomena of arsenic in the groundwater of the BAS (Fig 20.5). However, none of these alone explains the arsenic mobilisation scenario completely on a basinal scale, which often involves simultaneous operation of multiple processes as a function of the biogeochemical environment within the aquifers (Mukherjee et al. 2011).

- **Reductive dissolution of iron oxides/hydroxides:** The reducing environment within the shallow aquifers of the BAS promotes the dissimilatory metal reduction of ferric (hydr)oxides (coupled with degradation of in situ/surficial OM), resulting in the dissolution of ferrous ions into the groundwater, accompanied by simultaneous liberation of the sorbed arsenic (Bhattacharya et al. 1997; Nickson et al. 2000).
- **Pyrite oxidation:** Extensive irrigational pumping leads to water table decline and infiltration of oxygen-rich surface waters leading to aeration of the sediments accompanied by oxidation of pyrites and arsenopyrites resulting in liberation of the sorbed arsenic into the groundwater (Mallick and Rajgopal 1995; Das et al. 1996; Mandal et al. 1998). However, several workers have questioned the validity of this hypothesis on basinal scale (Ravenscroft et al. 2001; Ahmed et al. 2004).
- **Competitive ion exchange:** Various dissolved ionic species in the groundwater compete among each other and with the existing adsorbed species (including arsenic) for sorption sites, resulting in ionic exchange and mobilisation of

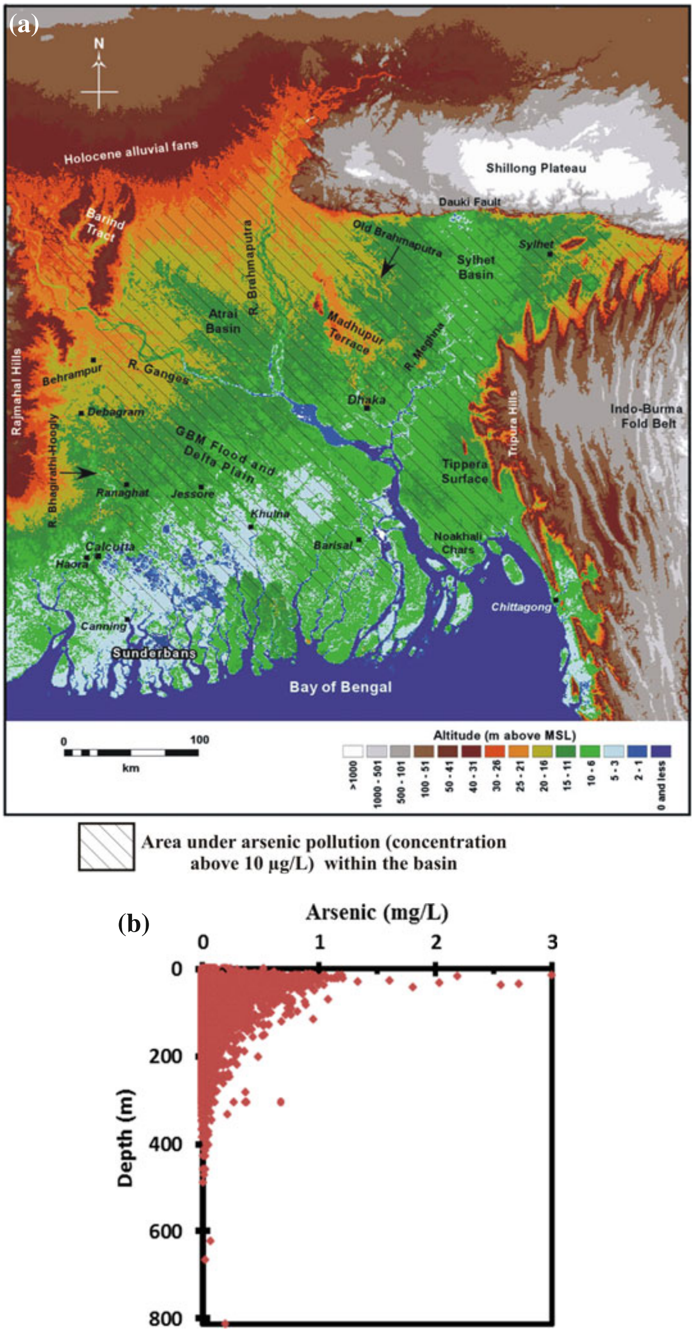


Fig. 20.4 **a** Spatial extent of arsenic contamination within the basin (modified from Chakraborty et al. 2015). **b** Depth distribution of arsenic in the basin (*data source* BGS/DPHE (2001); West Bengal Public Health Engineering Department (PHED), India)

weakly complexed species (like As (III)) into the groundwater. Phosphates are the strongest competitor for the sorption sites, followed by a weaker influence of silicates, carbonates/bicarbonates (Stollenwork et al. 2007) and the chlorine (from wastewater and pit latrines) (McArthur et al. 2012). However, its effect is mostly local and is negligible on a basinal scale.

- **Oxidation–reduction hypothesis:** A suitable explanation of sustained arsenic concentrations in the groundwater in spite of the prolonged flushing history lies in the oxic–anoxic cycling in the near-surface freshly deposited sediments caused by seasonal fluctuations of the water table (as a result of the monsoons and irrigational pumping) (Polizzotto et al. 2006). The oxic cycles trigger oxidation of pyrites, accompanied by transfer of the arsenic load to ferric (hydro) oxides, which in turn liberate the arsenic to groundwater in the subsequent reducing cycle (in the absence of enough pyrites to re-sequester the arsenic, due to dissolution and transport of sulphur in the preceding oxic cycle along with competition from various ions for the remaining adsorption sites), which is then carried to the aquifer depths by the groundwater flow (Polizzotto et al. 2006) (Fig. 20.5).

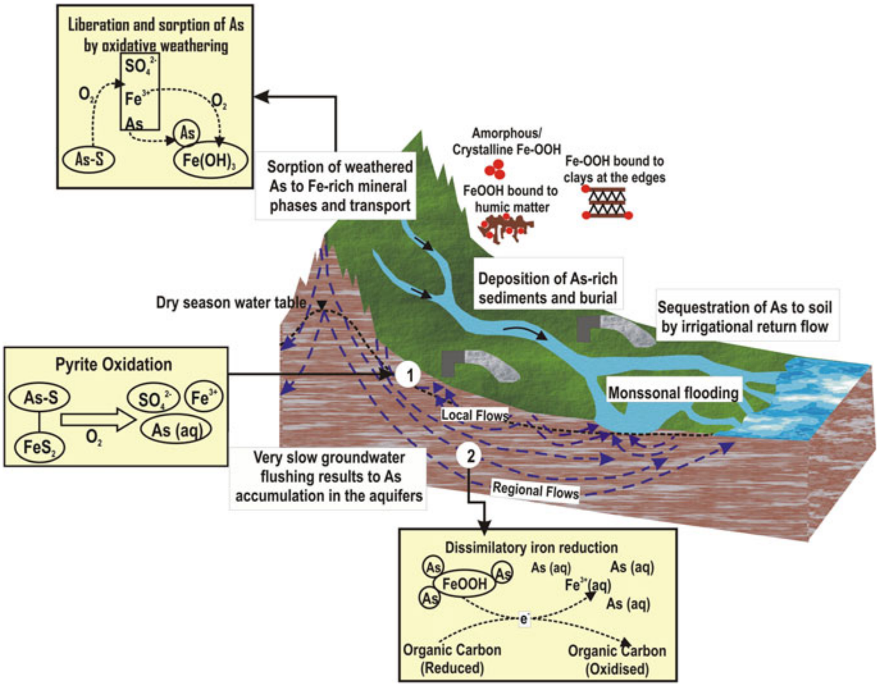


Fig. 20.5 Schematic diagram showing sources and mobilisation processes of arsenic within the basin sediments by (1) pyrite oxidation process in the near-surface sediments of highly irrigated areas, (2) reductive dissolution of iron oxides/hydroxides in the reducing aquifers of the basin, (modified from BGS/DPHE 2001; Fendrof et al. 2010; Hoque 2010)

The distribution of arsenic concentrations within the basin may seem to be extremely heterogeneous and even patchy (BGS/DPHE 2001), due to the integrated effect of the geomorphology, geology, hydrostratigraphy, depth, lithology, biogeochemical environment and anthropogenic influences. For example, the arsenic enrichment in the Holocene aquifers, in contrast to the low-arsenic Pleistocene aquifers, can be attributed to its sedimentological characteristics, i.e. finer grain sizes, abundant OM content, large iron (oxy)(hydro)oxide and adsorbed arsenic loading, discontinuous surficial clay caps (resulting to reducing environment within aquifers) and short flushing history, as compared to the Pleistocene units. Hydrostratigraphically, the presence of discontinuous confining layers within the aquifers inhibits the mixing of the shallower (arsenic-rich) and the deeper groundwater and thus attenuates the deeper groundwater arsenic contamination, which is common in areas underlain by thick palaeochannel sand (Burgess et al. 2010; Mukherjee et al. 2011). Anthropogenic factors (e.g. groundwater abstractions, land use patterns, fertilizers and sewage) may also contribute to arsenic contaminations. Extensive pumping causes lowering of the water table and enhanced inflow of oxygen-rich surface waters (Das et al. 1996) and surficial OM (Harvey et al. 2002) which perturbs the redox state of the aquifers and may mobilise arsenic (Mukherjee et al. 2007b). In West Bengal, Mukherjee et al. (2009a) reported widespread arsenic contamination in deeper aquifers and attributed it to basin evolution and land use patterns. The BAS constitutes a very rich repository of freshwater, and thus, persistent effects must be made to protect and nurture it for our future generations.

References

Ahmed KM, Hoque M, Hasan MK, Ravenscroft P, Chowdhury LR (1998) Occurrence and origin of water well CH_4 gas in Bangladesh. J Geol Soc India 51:697–708

Ahmed KM, Bhattacharya P, Hasan MA, Akhter SH, Alam SMM, Bhuyian MAH et al (2004) Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview. Appl Geochem 19:181–200

Alam M, Alam MM, Curray JR, Chowdhury MLR, Gani MR (2003) An overview of the sedimentary geology of the Bengal basin in relation to the regional tectonic framework and basinfill history. Sediment Geol 155:179–208

Allison MA, Khan SR, Goodbred SL, Kuehl SA (2003) Stratigraphic evolution of the late Holocene Ganges-Brahmaputra lower delta plain. Sediment Geol 155:317–342

BGS/DPHE (British Geological Survey/Department of Public Health Engineering [Bangladesh]) (2001) Arsenic contamination of groundwater in Bangladesh. In: Kinniburgh DG, Smedley PL (eds) Report WC/00/19, British Geological Survey Technical, Keyworth

Bhattacharya P, Chatterjee D, Jacks G (1997) Occurrence of arsenic contaminated groundwater in alluvial aquifers from delta plains, eastern India: options for safe drinking water supply. Int J Water Resour Dev 13:79–92

Breit GN, Foster AL, Sanzalone RF, Yount JC, Whitney JW, Welch AH et al (2001) Arsenic cycling in eastern Bangladesh: the role of phyllosilicates. Geol Soc Am Abst Prog 32(7):A192

Burgess WG, Hoque MA, Michael HA, Voss CI, Breit GN, Ahmed KM (2010) Vulnerability of deep groundwater in the Bengal Aquifer System to contamination by arsenic. Nat Geosci 3(2): 83–87

CGWB (Central Ground Water Board [India]) (2010) Ground water quality in shallow aquifers of India. Central Ground Water Board, Ministry of Water Resources, Government of India, Faridabad

Chakraborty M, Mukherjee A, Ahmed KM (2015) A Review of Groundwater Arsenic in the Bengal Basin, Bangladesh and India: from source to sink. Curr Pollution Rep 1:220–247. https://doi.org/10.1007/s40726-015-0022-0

Chatterjee D, Halder D, Majumder S, Biswas A, Nath B, Bhattacharya P et al (2010) Assessment of arsenic exposure from groundwater and rice in Bengal delta region, West Bengal, India. Water Res 44:5803–5812

Coleman JM (1981) Deltas: processes of deposition and models of exploration, 2nd edn. Burgess, Minneapolis

Das D, Samanta G, Mandal BK, Chowdhury TR, Chanda CR, Chowdhury PP et al (1996) Arsenic in groundwater in six districts of West Bengal, India. Environ Geochem Health 18(1):5–15

Datta DK, Subramanian V (1997) Textures and mineralogy of sediments from the Ganges–Brahmaputra–Meghna river system in the Bengal basin, Bangladesh and their environmental implications. Environ Geol 30(3):181–188

Dowling CB, Poreda RJ, Basu AR, Peters SL, Aggarwal PK (2002) Geochemical study of arsenic release mechanisms in the Bengal basin groundwater. Water Resour Res 38:1173–1190

Edmunds WM, Ahmed KM, Whitehead PG (2015) A review of arsenic and its impact in groundwater of the Ganges-Bramhaputra-Meghna delta, Bangladesh. Environ Sci Proc Impact. https://doi.org/10.1039/c4em00673a

Fendrof S, Micheal HA, van Geen A (2010) Spatial and temporal variations of groundwater arsenic in South and Southeast Asia. Science 328:1123–1127

Galy A, France-Lanord C (1999) Weathering processes in the Ganges-Brahmaputra basin and the riverine alkalinity budget. Chem Geol 159:31–60

Goodbred SL, Kuehl SA (2000) The significance of large sediment supply, active tectonism, and eustasy of margin sequence development: late quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta. Sed Geol 133:227–248

Goodbred SL, Kuehl SA, Steckler MS, Sarkar MH (2003) Controls on facies distribution and stratigraphic preservation in the Ganges-Brahmaputra delta sequence. Sed Geol 155:301–316

Harvey CF, Swartz CH, Badruzzman ABM, Keon-Blute N, YuW Ali MA et al (2002) Arsenic mobility and groundwater extraction in Bangladesh. Science 298(5598):1602–1606

Harvey CF, Ashfaque KN, Yu W et al (2006) Groundwater dynamics and arsenic contamination in Bangladesh. Chem Geol 228(1–3):112–136

Hasan MA, Ahmed KM, Sracek O, Bhattacharya P, von Brömssen M, Broms S, Fogelstrom J, Mazumder ML, Jacks G (2007) Arsenic in shallow groundwater of Bangladesh: investigations from three different physiographic settings. Hydrogeol J 15(8):1507–1522

Hoque MA (2010) Models for managing the deep aquifer in Bangladesh, Unpublished Ph.D. Thesis, University College London, London, 265 pp

Hoque MA, Burgess WG (2012) C dating of deep groundwater in the Bengal Aquifer System, Bangladesh: implications for aquifer anisotropy, recharge sources and sustainability. J Hydrol 44–445:209–220

Hoque MA, McArthur JM, Sikdar PK (2014) Sources of low arsenic groundwater in the Bengal Basin: investigating the influence of the last glacial maximum palaeosol using a 115-km traverse across Bangladesh. Hydrogeol J 22:1535

Hoque MA, Burgess WG, Ahmed KM (2017) Integration of aquifer geology, groundwater flow and arsenic distribution in deltaic aquifers—a unifying concept. Hydrol Process. https://doi.org/10.1002/hyp.11181

Hossain MF (2006) Arsenic contamination in Bangladesh—an overview. Agric Ecosyst Environ 113:1–16

Mallick S, Rajgopal NR (1995) Groundwater development in the arsenic affected alluvial belt ofWest Bengal—some questions. Curr Sci 70(11):956–958

Mandal BK, Chowdhury TR, Samanta G et al (1998) Impact of safewater for drinking and cooking on five arsenic-affected families for 2 years inWest Bengal, India. Sci Total Environ 218(2–3): 185–201

McArthur JM, Ravenscroft P, Safiullah S, Thirlwall MF (2001) Arsenic in groundwater: testing pollution mechanisms for sedimentary aquifers in Bangladesh. Water Resour Res 37(1): 109–117

McArthur JM, Sikdar PK, Hoque MA, Ghosal U (2012) Waste-water impacts on groundwater: Cl/Br ratios and implications for arsenic pollution of groundwater in the Bengal Basin and Red River Basin, Vietnam. Sci Total Environ 437:390–402

Michael HA, Voss CI (2009a) Estimation of regional-scale groundwater flow properties in the Bengal Basin of India and Bangladesh. Hydrogeol J 17(6):1329–1346

Michael HA, Voss CI (2009b) Controls on groundwater flow in the Bengal Basin of India and Bangladesh: regional modeling analysis. Hydrogeol J 17(7):1561–1577

Milliman JD, Rutkowski C, Meybeck M (1995) River discharge to sea: a global river index (GLORI). Texel, NIOZ, 125p

Morgan JP, McIntire WG (1959) Quaternary geology of Bengal Basin, East Pakistan and India. Geol Soc Am Bull 70:319–342

Mukherjee A (2006) Deeper groundwater flow and chemistry in the arsenic affected western Bengal basin, West Bengal, India. Ph.D. thesis, University of Kentucky, Lexington, USA, 248 pp

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore, ISBN 978-981-10-3888-4

Mukherjee A, Fryar AE (2008a) Deeper groundwater chemistry and geochemical modeling of the arsenic affected western Bengal basin, West Bengal, India. Appl Geochem 23(4):863–894

Mukherjee A, Fryar AE, Howell P (2007a) Regional hydrostratigraphy and groundwater flow modeling of the arsenic contaminated aquifers of the western Bengal basin, West Bengal, India. Hydrogeol J 15:1397–1418

Mukherjee A, Fryar AE, O'Shea BM (2009a) Major occurrences of elevated arsenic in groundwater and other natural waters. In: Henke KR (ed) Arsenic–environmental chemistry, health threats and waste treatment. Chichester, Wiley, pp 303–350

Mukherjee A, Fryar AE, Thomas WA (2009b) Geologic, geomorphic and hydrologic framework and evolution of the Bengal basin, India and Bangladesh. J Asian Earth Sci 34:227–244

Mukherjee A, Fryar AE, Rowe HD (2007b) Regional-scale stable isotopic signatures of recharge and deep groundwater in the arsenic affected areas of West Bengal, India. Journal of Hydrol 334(1):151–161

Mukherjee A, von Brömssen M, Scanlon BR, Bhattacharya P, Fryar AE, Hasan MA et al (2008b) Hydrogeochemical comparison and effects of overlapping redox zones on groundwater arsenic near the western (Bhagirathi sub-basin, India) and eastern (Meghna sub-basin, Bangladesh) of the Bengal basin. J Contam Hydrol 99:31–48

Mukherjee A, Fryar AE, Scanlon BR, Bhattacharya P, Bhattacharya A (2011) Elevated arsenic in deeper groundwater of the western Bengal basin, India: extent and controls from regional to local scale. Appl Geochem 26(4):600–613

Mukherjee A, Verma S, Gupta S, Henke KR, Bhattacharya P (2014) Influence of tectonics, sedimentation and aqueous flow cycles on the origin of global groundwater arsenic: paradigms from three continents. J Hydrol 518:284–299

Nickson RT, McArthur JM, Ravenscroft P et al (2000) Mechanism of arsenic release to groundwater, Bangladesh and West Bengal. Appl Geochem 15(4):403–413

Pal T, Mukherjee PK (2009) Study of subsurface geology in locating arsenic-free groundwater in Bengal delta, West Bengal, India. Environ Geol 56:1211–1225

Polizzotto ML, Harvey CF, Li G, Badruzzman B, Ali A, Newville M et al (2006) Solid-phases and desorption processes of arsenic within Bangladesh sediments. Chem Geol 228:97–111

Ravenscroft P, McArthur JM, Hoque B (2001) Geochemical and palaeohydrological controls on pollution of groundwater by arsenic. In: Chappell WR, Abernathy CO, Calderon RL (eds) Arsenic exposure and health effects IV. Elsevier Science Ltd., Oxford, pp 53–77

Sarin MM, Krisnaswami S, Dilli K, Somayajulu BLK, Moore WS (1989) Major ion chemistry of the Ganges-Brahmaputra river system: weathering processes and fluxes to the Bay of Bengal. Geochim Cosmochim Acta 54:1387–1396

Shamsudduha M, Chandler RE, Taylor RG, Ahmed KM (2009) Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. Hydrol Earth Syst Sci 13:2373–2385

Smith AH, Lingas EO, Rahman M (2000) Contamination of drinking water by arsenic in Bangladesh: a public health emergency. Bull World Health Organ 78(9):1093–1103

Stollenwerk KG, Breit NG, Welch AH, Yount JC, Whitney JW, Foster AL et al (2007) Arsenic attenuation by oxidized aquifer sediments in Bangladesh. Sci Total Environ 379:133–150

Umitsu M (1987) Late Quaternary sedimentary environment and landform evolution in the Bengal Lowland. Geograph Rev Jap Series B 60:164–178

Chapter 21
Hydrochemistry and Turnover of the Kerala Tertiary Aquifers, India

G. Jacks and D. S. C. Thambi

Abstract Coastal aquifers are subject to considerable stress globally. As coastal regions are densely populated areas, the water requirements are large which includes a demand for water within agriculture. Tertiary sections of the coastal sediments in southern Kerala have been investigated since the 1980s, and results are presented here. Four sections have been identified in the Tertiary sequence in southern Kerala, the Warkali, the Quilon, the Vaikom and the Alleppey beds. The Warkali and Vaikom beds are productive aquifers. The Warkali beds are extensively used for water extraction, and the groundwater level has sunk below sea level while there are boreholes into the Vaikom beds that are still artesian having a pressure head of up to 6 m above the present sea level. This indicates that the offshore cover of fine sediments is tight and little discharge occurs onto the seabed. The investigation has shown that the groundwater was recharged 22–34 Ka BP. when the sea level was 80–90 m below the present sea level. The recharge may have been interrupted by a drier period. Some of the samples show elevated chloride levels, but isotopic investigations ($\delta^{18}O$) show that this is not due to seawater intrusion but rather due to diffusion from pore water in intercalated clay layers. In spite of considerable pumping from the aquifers, there has been no remarkable change in chloride levels over the past 35 years. This is probably due to the freshwater/saline interface which is offshore, a common phenomenon caused by the low sea level during the last glacial maximum. Some of the samples show a reduced water with elevated iron concentrations. Unlike in the Bengal Delta, there is no connection with elevated arsenic concentration. The arsenic concentration has been found to be below 10 μg/l.

G. Jacks (✉)
Division of Land and Water Resources Engineering KTH,
SE-100 44, Stockholm, Sweden
e-mail: gunnjack@kth.se

D. S. C. Thambi
Central Ground Water Board, Thiruvanathapuram, Kerala, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_21

21.1 Introduction

Coastal plains and deltas are heavily populated globally, and the water requirement is high. About 25% of the population of India lives in coastal areas demanding water supply. In addition, irrigation accounts for 85% of all water use (Mukherjee et al. 2015). Saltwater intrusion is common along the peninsular coast of India (Dhiman and Thambi 2012; CGWB 2014; Priju et al. 2014; Anil Kumar et al. 2015; Chandrasekhar et al. 2014; Ballykraya and Ravi 1998; Thilagavathi et al. 2012), as well as in other parts of South Asia (Shammas and Jacks 2007; Askri et al. 2016; Suhartono et al. 2015). Along the Kerala coastal strip water demand is high as the population density is in the order of 1000–1500 persons per km^2. Groundwater has so far been the main source of water supply. The Holocene sediments contain limited amount of groundwater. At certain places, storms and tidal effects, etc., have caused an elevated salinity (Priju et al. 2014; Anil Kumar et al. 2015). In the phreatic aquifers overlying the Tertiary beds, salinity is seen periodically due to tidal effects and storms (Shaji et al. 2009). However, this does not seem to occur in the underlying Tertiary beds. CGWB has found that artificial recharge of the Tertiary beds is difficult due to limited connection with the overlying strata. Investigations by Central Ground Water Board of India have shown the Tertiary beds present on the southern Kerala coast contains extensive and high yielding aquifers (Thambi 2012). Four beds are identified: the Warkali, the Quilon, the Vaikom and more recently the Alleppey beds, overlying the Precambrian bedrock along the southern Kerala coast. The sediment characteristics are presented in Table 21.1.

A cross section of the geology along the southern Kerala coast is given in Fig. 21.1. More related information regarding groundwater of South Asia are available in Mukherjee (2018).

Table 21.1 Geological section of the southern Kerala coast (Thambi 2012)

Age		Formation	Lithology
Quaternary	Recent	Alluvium	Sand and clay
	Sub-recent	Laterite	Laterite capping
Tertiary	Lower	Warkali	Sandstones and clay, thin bands of
	Miocene		Lignite
	Lower	Quilon	Limestone and clays
	Miocene		
	Oligocene	Vaikom	Sandstones with pebbles and gravel
	Eocene		beds, clay, thin bands of lignite
	Eocene	Alleppey	Carbonaceous clay and sands
Precambrian	Archaean		Khondalites and charnockites

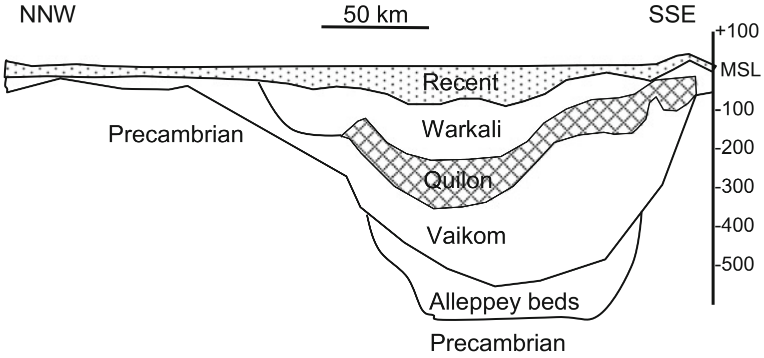


Fig. 21.1 Geologic crosssection for the coastal area in southern Kerala

21.2 Methods

At collection of samples pH, EC and temperature was analysed in the field. In general, samples were filtered through 0.45 μm filters. The data on which this report is based were collected over a period of approximately 30 years, and the methods for analysis have changed over time. For the major cations, AAS has been used while various methods were used for the anions. More recently ion chromatography has been used. Fluoride and nitrate were analysed by ion-selective electrodes. Isotope analysis $\delta^{18}O$ and ^{14}C were analysed at the Department of Geology at Lund University in Sweden. ^{14}C and ^{13}C were analysed on samples precipitated with $BaCl_2$ and $Ba(OH)_2$. The radiocarbon ages were corrected with respect to the ^{13}C values (Pearson and Hanshaw 1970).

Some sediment samples have been studied by X-ray diffraction at the Department of Material and Environmental Sciences at Stockholm University, Sweden.

21.3 Results

This study concerns the southern part of the Kerala coast from Thiruvananthapuram up to just south of Kochi. Along the coast from south, the water types vary from Ca–HCO_3 type via Na–HCO_3 to a brackish mixed type in the north (Fig. 21.2). This is an indication of freshwater flushing of a formerly saline aquifer (Mercado 1985), which can be observed in a diagram where Na/Cl ratios are plotted versus chloride in the groundwater. Due to ion exchange, calcium in the freshwater is exchanged for sodium on the aquifer material. When low salinities are reached, the results are increasing Na/Cl ratios (Fig. 21.3) (Mercado 1985). A similar distribution of water types is observed in Tertiary aquifers in Tanjavur and Karaikal on the

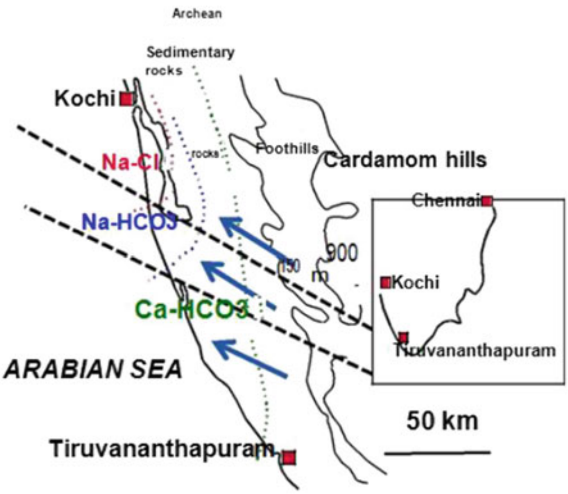
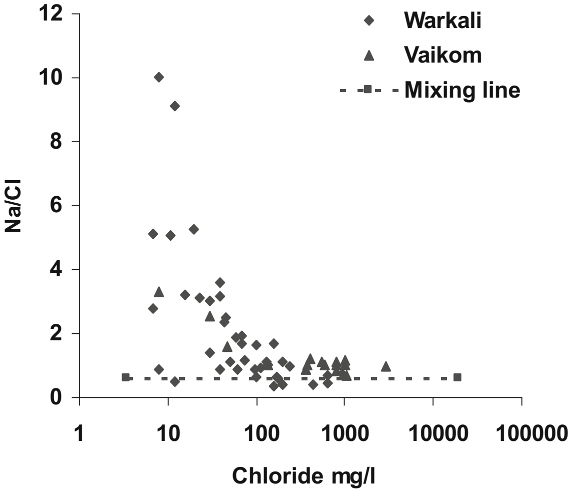


Fig. 21.2 Water-type distribution and proposed flow direction for the recharge along the Kerala coast

Fig. 21.3 Na/Cl ratio versus chloride content indicating predominantly freshwater flushing of a formerly saline aquifer



SE coast of India (Sukhija et al. 1996). The distribution of the water types indicates that faults in SE-NW direction are guiding groundwater flow (Fig. 21.2). These faults are sealed according to Soman (2002). The groundwater from nine wells has been dated by ^{14}C, and the ages vary between 22 and 34 Ka BP. Thus the recharge, as per these data, occurred just before last glacial maximum (LGM) when the sea level was 80–90 m below the present seawater level (Wikipedia 2016) (Fig. 21.4). These ages compare well with those found in Tertiary aquifers on the south-eastern

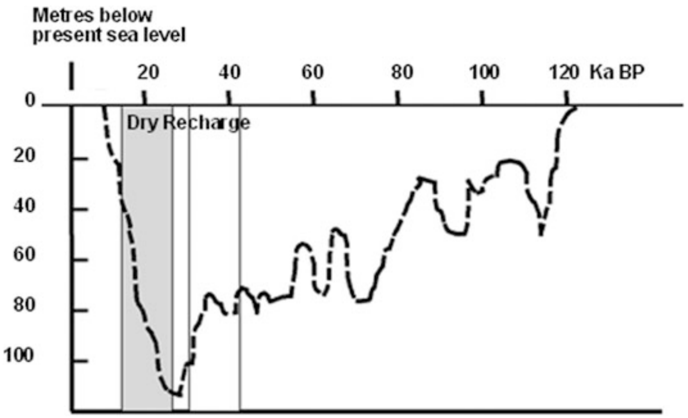
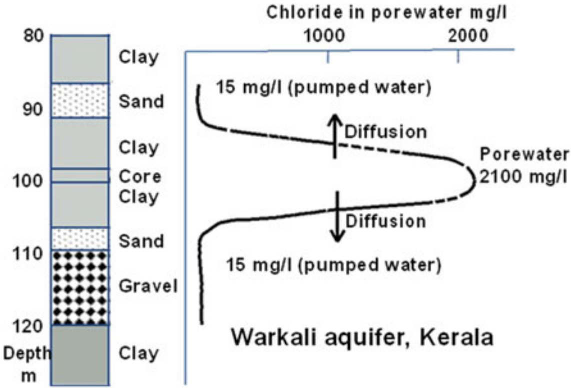


Fig. 21.4 Recharge period as per ^{14}C-dating of the groundwater in relation to seawater level over the last 120 Ka BP

Fig. 21.5 Chloride diffusion from an intercalated clay layer in a section of the Warkali aquifer



coast of Tamil Nadu in India (Sukhija et al. 1996). Possibly the recharge was interrupted by a drier period that started just at LGM (Last Glacial Maximum) (Overpeck et al. 1996; Kale et al. 2004; Chodankar et al. 2005; Prabhu et al. 2004). The chloride concentrations are slightly higher in the Vaikom section of the Tertiary and the delineating of the water types less distinct. The higher chloride levels are most probably not caused by mixing in of seawater but due to diffusion from intercalated clay layers. Chloride in the centre of a clay layer was analysed and was discovered to be 2000 mg/l while the surrounding aquifers had only 15 mg/l (Fig. 21.5). The opinion that diffusion from intercalated clay layers is the mechanism behind elevated chloride level at depth in the Tertiary beds is supported by Fig. 21.6 where $\delta^{18}O$ is plotted versus chloride. The $\delta^{18}O$ increase in dug wells due to evaporation but on the borewells, there is no change with increasing chloride and no trend towards the seawater ratio of $\delta^{18}O$. A similar origin of elevated chloride

Fig. 21.6 δ^{18}O versus chloride concentration in dug wells and Tertiary wells indicating chloride increase in Tertiary wells is not due to seawater intrusion but rather diffusion from clay layers

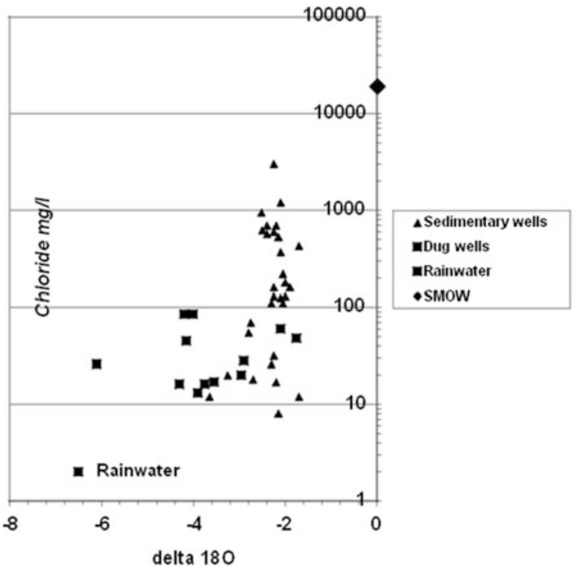


Table 21.2 Electric conductivity in µS/cm in wells in Alleppey district

Location	Aquifer	1985–1987	1993	2000
Karumadi	Vaikom		3100	3628
Thottapalli	Warkali		780	492
Kandiyor	Warkali		120	194
Kandiyor	Vaikom	670		283
Muttam	Warkali	710		635
Muttam	Vaikom	560		405
Thakazi	Warkali	490		455
Purakad	Warkali	418		406
Chudukad	Warkali	460		419
Mararikulam	Warkali	362		1415
Thanneermukkam	Warkali	1450		106
Pazhavangadi	Warkali	728		898

concentration has been found in a coastal aquifer in Albania (Kumanova et al. 2014). Despite heavy pumping, notably from the Warkali beds there is no tendency for increase in salinity or chloride (Table 21.2). This is in spite of the fact that some wells have a hydraulic head below that of the seawater level. No trend towards increased salinity was found in wells in the Tertiary beds as per Shaji et al. (2008). An extensive evaluation of the groundwater quality carried out in the Alappuzha district, centrally in the transect seen in Fig. 21.1 shows good quality water with few samples of elevated salinity (Sarath Prasanth et al. 2012). Similarly, Vinayachandran (2014) found no trend in electric conductivity over the past two decades.

Table 21.3 Selection of groundwater analyses from the Kerala Tertiary Aquifers. W stands for samples from the Warkali aquifer and V for samples from the Vaikom aquifer

Site	pH	EC	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	F^-	NO_3^-	PO_4^{2-}	SiO_2
Kumarakodi W	7.05	350	30	13	24	7.8	226	0	7.1	1.1	0	0	12
Chudukad W	8.20	419	21	5	14	2.0	55	0	31	0.21	12	–	–
Purakad W	8.10	649	27	18	61	5.0	103	1	134	0.51	0	–	–
Thanneermukkam V	7.90	1090	28	15	150	5.9	126	97	222	0.09	0	–	–
Mararikulam W	7.25	1415	33	15	233	22	253	0	350	2.62	15	–	–
Vettikad V	6.78	400	72	8.5	8.0	6.3	281	0	3.5	0.45	0	0.06	16
Arunootimangalam V	7.05	450	80	6.3	15	6.3	317	0	7.1	0.41	0	0.09	13
Muttam V	7.20	570	54	13	60	7.5	348	0	25	0.68	0.1	0.08	13
Nangiakulangava V	7.37	460	66	7.3	13	2.8	165	0	67	0.39	0	0.07	32
Karthikapally V	6.93	510	46	9.7	54	10	293	0	28	0.77	0	0.07	15

Table 21.4 Aragonite to calcite, qualitative recrystallization in the sediments

Strata	Site	Sample	Aragonite	Calcite
Present	Sea shore	Shells	XXX	
Recent	Mancumbu	Shells	XXX	X
Warkali	Khartikapally	Shells	XXX	
Warkali	Kandiyor	Shells	XX	XX
Quilon	Mancumbu	Shells	X	XX
Quilon	Khartikapally	Clay		X
Vaikom	Mancumbu	Shells	X	XXX
Vaikom	Mancumbu	Clay		XX

XXX major phase, *XX* abundant, *X* trace amounts

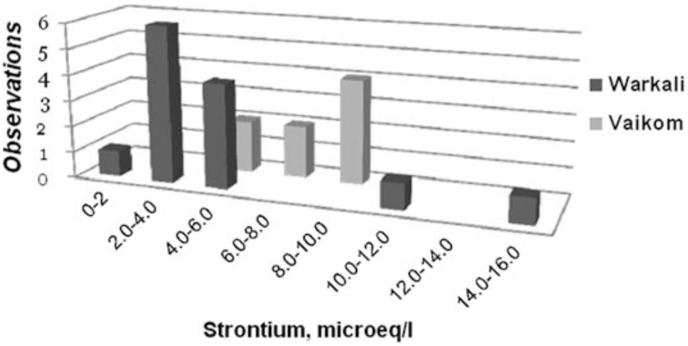


Fig. 21.7 Strontium in Warkali and Vaikom aquifers showing a tendency of higher strontium versus depth

A possible explanation for the stability in salinity is the large volumes involved and also, especially for the extensively pumped Warkali aquifer, that the freshwater–saltwater interface lies offshore which is a global phenomenon (Ericson et al. 2006; Post et al. 2013) and a relict from the last glaciation with its sea level at about 120 m below the present level (Wikipedia 2016). A selection of analyses from the Warkali and Vaikom aquifers is shown in Table 21.3.

The sediment samples show a slow conversion of aragonite to calcite with depth (Table 21.4).

A secondary effect of recrystallization is increasing strontium in the water (Fig. 21.7).

The presence of lignite bands (Table 21.1) is likely to be responsible for the reducing water with elevated iron concentrations seen in some wells. In such sections, the dissolved iron seems to be controlled by siderite which has been observed in X-ray studies (Fig. 21.8). As vivianite has also been seen in reducing sections, it is possible to conduce the mineral appears to control the solubility of phosphorus. The presence of groundwater with up to 1–2 mg/l of iron warranted the

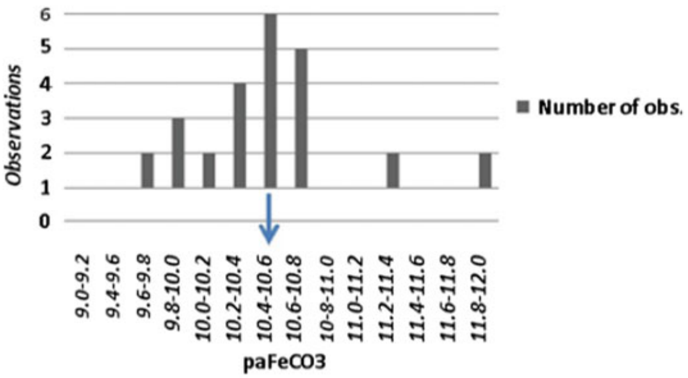


Fig. 21.8 Plot of paFeCO_3 in relation to solubility of siderite indicating the siderite governs the solubility of ferrous iron in reducing groundwater. paFeCO_3 stands for logaritm of acitivity of FeCO_3. The arrow indicates the solubility of siderite

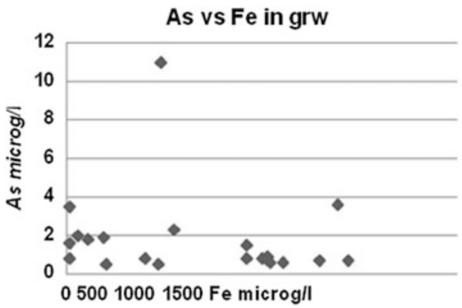


Fig. 21.9 Arsenic versus iron in reducing groundwater

analysis of arsenic after the finding of elevated arsenic in such groundwater in the Bengal Delta (Bhattacharya et al. 1997). However, only low levels of arsenic were found in the Tertiary aquifers and no relation to the soluble ferrous iron (Fig. 21.9).

The iodide content of the groundwater in dug wells in the recent sediment is a few µg/l while in the Tertiary beds it is in the order of tenths of µg/l up to 180 µg/l. This is similar to what was found in Karaikal and Tanjavur on the SE coast of India and in one part slightly higher (Sukhija et al. 1996). This is probably due to release of iodide from organisms incorporated in the sediments. Iodine is strongly concentrated by several marine algae (Shaw 1962). The Tertiary groundwater is an important contribution to the daily requirement of iodine in humans which is in the order of 100–150 µg/l (Fuge and Johnson 2015).

Another effect of aquifer–water interaction is the elevated content of fluoride in the Na–HCO_3 type of groundwater not seldom exceeding the permissible limit (Jacks et al. 2005; Raj and Shaji 2016).

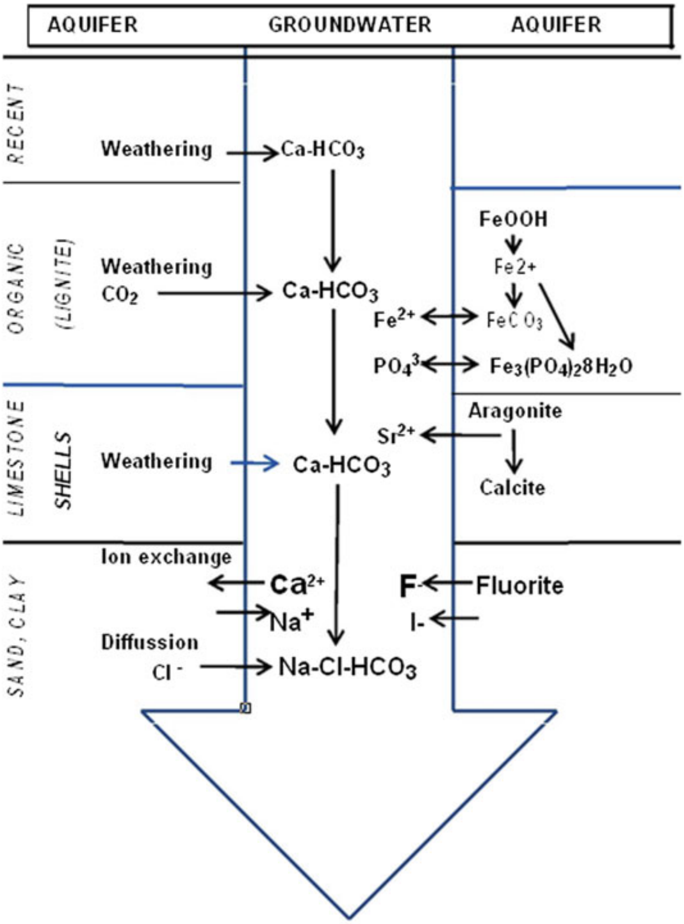


Fig. 21.10 Conceptual model for the hydrochemistry in the Tertiary beds. To the left processes involving major components, to the right those concerning minor constituents. The layering of the aquifer materials is fictive, in reality the components occur mixed

21.4 Conclusions

The Tertiary aquifers in the southern part of the Kerala coast are an important water source. In spite of heavy pumping, especially from the Warkali beds causing groundwater heads below sea level, there is no sign of increasing salinity and seawater intrusion. An elevated chloride content, mostly in the Vaikom beds, is likely to be due to diffusion of salinity from intercalated clay layers. Dating of the groundwater has shown ages of 22–34 Ka BP, thus just before LGM with a sea level that was 80–90 m below the present sea level. The reason that the recharge seems to have ended before the LGM with a still lower sea level might have been a drier SW monsoon. The groundwater composition in the Tertiary beds along the southern Kerala coast changes from Ca-HCO_3 groundwater in the south via a Na–HCO_3 groundwater further north to a mixed brackish water near Kochi. This indicates a freshwater flushing of a formerly saline aquifer. The presence of artesian wells, especially in the Vaikom beds, shows that there is a good cover of less permeable sediment on the top of the Tertiary beds offshore contrary to what has been found in a Bengal Delta site (Debnath and Mukherjee 2016) The movement of the groundwater may have been guided by sealed faults in the SE-NW direction. The water quality changes have secondary effects on the fluoride content. In the Na–$HCO_{3,}$ water fluoride mobilization is favoured (Fuge and Johnson 2015; Jacks et al. 2005). A generally higher strontium concentration in the Vaikom beds is likely to be due to the recrystallization of aragonite to calcite observed in the sediment pack. A conceptual model for the main processes in the Tertiary bed is seen in Fig. 21.10. Although the freshwater storage in the Tertiary aquifers is probably large, the switching over to treated surface water in larger towns is likely to be a good precaution for the future.

Acknowledgements The authors are grateful for the good cooperation with many colleagues during their work at the regional CGWB office in Thiruvananthapuram in Kerala.

References

Anil Kumar KS, Priju CP, Narasimha Prasad NB (2015) Study of saline water intrusion into the shallow coastal aquifers of Periyar river basin, Kerala using hydrochemical and electrical resistivity methods. Aquat Procedia 4:32–40

Askri B, Ahmed AT, Al-Shanfari RA, Bouglila R, Khamis Al-Farisi KB (2016) Isotopic and geochemical identification of groundwater salinization processes in Salalah coastal plain, Oman. Chem Erde 76:243–255

Ballykraya PN, Ravi R (1998) Natural fresh-water ridge as barrier against sea-water intrusion in Chennai city. J Geol Soc India 52(3):279–286

Bhattacharya P, Chatterjee D, Jacks G (1997) Occurrence of arsenic contaminated groundwater in the alluvial aquifers from Delta Plains, Eastern India: options for safe drinking water supply. Int J Water Res Dev 3(1):79–92

CGWB (2014) Report on the status of ground water quality in coastal aquifers of India. 121 pp. http://indiaenvironmentalportal.in

Chandrasekhar N, Selvakumar S, Srinivas Y, John Wilson JS, Simon Peter T, Magesh NS (2014) Hydrogeochemical assessment of groundwater quality along the coastal aquifers in southern Tamil Nadu, India. Environ Earth Sci 71:4739–4750

Chodankar AR, Banakar VK, Oba T (2005) Past 100 Ky surface salinity-gradient response in the Eastern Arabian Sea to the summer monsoon variation recorded by $\delta^{18}O$ of G. sacculifer. Global Planet Change 47:135–142

Debnath P, Mukherjee A (2016) Quantification of tidally-influenced seasonal groundwater discharge in the Bay of Bengal by seepage meter studies. J Hydrol 537:106–116

Dhiman SC, Thambi DS (2012) Ground water management in coastal areas. http://indiaenvironmentalportal.in, 6 pp

Ericson JP, Vörösmarty CJ, Dingman SL, Ward LG, Meybeck M (2006) Effective sea-level rise and deltas: causes of change and human dimension implications. Global Planet Change 50: 63–82

Fuge R, Johnson CC (2015) Iodine and human health, the role of environmental geochemistry and diet, a review. Appl Geochem 63:282–302

Jacks G, Bhattacharya P, Chaudhary V, Singh KP (2005) Controls on the genesis of some high-fluoride groundwaters in India. Appl Geochem 20:221–228

Kale VS, Gupta A, Singhvi AK (2004) Late Pleistocene–Holocene Paleohydrology of Monsoonal Asia. J Geol Soc India 64:403–417

Kumanova Xh, Marku S, Fröjdö S, Jacks G (2014) Recharge and sustainability of a coastal aquifer in northern Albania. Hydrogeol J 22:883–892

Mercado A (1985) The use of hydrogeological patterns in carbonate sand and sandstone aquifers to identify intrusion and flushing of saline water. Ground Water 23(5):635–645

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Mukherjee A, Saha D, Harvey CF, Taylor RC, Ahmed KM, Bhanja S (2015) Groundwater systems of the Indian Sub-Continent. J Hydrol Reg Stud 4:1–14

Overpeck JDM, Anderson S, Trumbore S, Prell W (1996) The southwest Indian Monsson over the last 18 000 years. Clim Dyn 12:213–225

Pearson FJ, Hanshaw BB (1970) Sources of dissolved carbonate species in groundwater and their effects on carbon-14 dating. Isotope Hydrol 271–285 (IAEA, Vienna)

Post VEA, Groen J, Kooi H, Person M, Ge S, Edmunds M (2013) Offshore fresh groundwater reserves as a global phenomenon. Nature 504:71–78

Prabhu CN, Shankar R, Anupama K, Taieb M, Bonnefille R, Vidal L, Prasad S (2004) A 200-ka pollen and oxygen isotopic record from two sediment cores from the eastern Arabian Sea. Palaeogeogr Palaeoclimatol Palaeoecol 214:309–321

Priju CP, Karthick P, Kumar A, Abdul Hameed E, Madhavan K, Narasimha Prasad NB (2014) Electrical resistivity sounding and hydrochemical investigation for delineating saline water intrusion in shallow aquifers of Ernakulam–Alappuzha coast. In: Proceedings pf the IWRM 2014. Allied Publishers, New Delhi, pp 1164–1172

Raj D, Shaji E (2016) Fluoride contamination in groundwater resources of Alleppey. Geosci Front. http://dx.doi.otg/10.1016/j.gsf.2016.01.002

Sarath Prasanth SV, Magesh NS, Jiteshlal KV, Chandrasekhar N, Gangadhar K (2012) Evaluation of groundwater quality and its suitability for drinking and agricultural use in the coastal stretch of Alappuzha District, Kerala, India. Appl Water Sci 2:165–175

Shaji E, Nayagam SP, Kunhambu V, Thambi DS (2008) Change in the groundwater scenario in Kerala over the last two decades. Golden Jubilee Memoir of the Geological Society of India 69:67–85

Shaji E, Vinaychandran N, Thambi DS (2009) Hydrogeochemical characteristics of groundwater in coastal phreatic aquifers of Alleppey district, Kerala. J Geol Soc India 74:585–590

Shammas M, Jacks G (2007) Seawater intrusion in the Salalah plain aquifer, Oman. Environ Geol 53:575–587

Shaw TL (1962) Halogenes in algae. In: Lein RA (ed) Physiology and biochemistry of Algae. Academic Press

Soman K (2002) Geology of Kerala. Geol. Soc. of India, 335 pp

Suhartono E, Purwanto P, Suripin S (2015) Seawater intrusion modeling on groundwater confined aquifer in Semarang. Proccdia Environ Sci 23:110–115

Sukhija BS, Varma VN, Nagabhushanam P, Reddy DV (1996) Differentiation of palaeomarine and modern seawater intruded salinities in coastal groundwaters of Karaikal and Tanjavur, India based on inorganic chemistry, organic biomarker fingerprints and radioactive dating. J Hydrol 174:173–201

Thambi DS (2012) Hydrochemistry of the Tertiary aquifers of Kerala, India. Indian Soc Appl Geochem Mem 2012:89–104

Thilagavathi R, Chidambaram S, Prasanna MV, Thivya C, Singaraja C (2012) A study on groundwater geochemistry and water quality in layered aquifers system of Pondicherry region, southeast India. Appl Water Sci 2:253–269

Vinayachandran N (2014) Hydrogeology and hydrochemistry of the aquifer systems of Kuttanad area, Kerala. Cochin University of Science and Technology, thesis, 227 pp. http://shodhganga.infiblinet.ac.in/handle/0603/54257

Wikipedia (2016) Past sea level. https://en.wikipedia.org/wiki/past_sea-level

Chapter 22
Arsenic in Groundwater: Distribution and Geochemistry in Nadia District, West Bengal, India

Debashis Chatterjee, Madhurina Mazumder, Sandipan Barman, Jishnu Adhikari, Amit Kundu, Aishwarya Mukherjee, Ayan Das, Pinaki Ghosh, Ujjal Mandal and Debankur Chatterjee

Abstract Groundwater in Bengal Delta Plain (BDP; West Bengal and Bangladesh) is contaminated with geogenic arsenic (As). Shallow aquifers (<50 m) are largely affected with high arsenic which frequently exceed WHO guideline value (10 μg L^{-1}). This large-scale "natural" arsenic groundwater contamination has generally been associated with strong to moderately reducing aquifer conditions of BDP like the As-affected areas of Nadia, West Bengal. The groundwater flow of the Holocene aquifers, is slow and sluggish with poor aquifer flushing. The deltaic sediments (from early-mid-Pleistocene–Holocene–Recent) are the major hosts for As. The geomorphologic features of Nadia are also important for As distribution. They are grouped into two major landforms, UDP (Upper Delta Plain) in the upper part of Nadia district and LDP (Lower Delta Plain) in lower part of the Nadia district. Both the landforms are adorned with several surface features. The arsenic content of the aquifer material is not regularly high (3–18 mg kg^{-1}); however, the

---

D. Chatterjee (✉) · M. Mazumder · S. Barman · A. Kundu · A. Das · P. Ghosh · U. Mandal
Department of Chemistry, University of Kalyani, Nadia 741235, West Bengal, India
e-mail: dbchat2001@rediffmail.com

J. Adhikari
Department of Geological Sciences and Environmental Studies, State University of New York at Binghamton, 4400 Vestal Parkway East, Binghamton, NY 13902, USA

A. Mukherjee
Department of Basic Science (Chemistry) and Humanities, Hooghly Engineering and Technology College, Pipulpati, Hooghly, West Bengal, India

D. Chatterjee
T.A. Pai Management Institute, 80, Badagabettu Manipal Udupi, Manipal 576104, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_22

groundwater arsenic content is often exceptionally high (up to 1186 μg L^{-1}). The most notable features of the groundwater are spatial heterogeneity and predominantly reducing conditions at near-neutral pH values (6.5–7.5) with high concentration of redox-sensitive species (notably Fe, Mn and As). Arsenic is released to groundwater mainly by desorption from Fe-oxyhydroxide/iron-bearing minerals (mostly coating on sand/mica) under local reducing conditions. The spatial as well as the depth dependent heterogeneity can be explained by the pattern of accumulation followed by random distribution of arsenic rich Fe-oxyhydroxide/Fe-bearing minerals in the aquifer sediments along with groundwater flow pattern. The issue of arsenic in the deeper aquifers is most challenging in regard to both the geological and public health point of view. All the affected Southeast Asian countries are now working hard to meet up with the WHO guideline value (>10 μg L^{-1}) for community water supply. In this context, deeper aquifer is the most reliable source of safer water as remediation technologies are in many cases incapable of yielding arsenic-safe water.

22.1 Introduction

Freshwater is essential for human survival. Supply of clean water also is an important contribution towards the economic development of the local population notably in rural areas. With increasing population especially in the developing countries, there is an increasing demand for water, starting from drinking water to that of the agriculture and industries. Rapid industrialization and growth in demand for water in agriculture has resulted in a significant percentage of water being diverted towards these purposes (Table 22.1). Groundwater has developed into an important source of freshwater and has contributed significantly towards both development of the life and health of the human population and the economy (Table 22.2).

The Nadia district lies in the central east part of BDP, on the eastern flank of the Bhagirathi river (latitude 22° 53′ 80″–24° 11′ 78″N latitude and 88° 09′ 58″–88° 48′ 30″E longitude) in West Bengal, India (Chap. 1, Fig. 1.1). It has its border with Bangladesh and encompasses an area of 3928.27 km^2 (1516 m^2) with a population size of 5,168,488 and density (1300 km^2/3400 $mile^2$) (Census Report 2011). The district has four subdivisions (Krishnagar Sadar, Ranaghat, Tehatta and Kalyani) with 17 blocks. Nadia is one of the most intensively cultivated districts in India with numerous rivers (regional and their distributaries/tributaries) and abandoned river courses with many depressions, meander scars, oxbow lakes. The average annual temperature of Nadia district varies from 40 to 10 °C with a mean annual rainfall of 55.15 in. (Kundu 2009).

Table 22.1 Few Asian countries freshwater resources (annual renewable quantity) and withdrawal pattern (%, sector wise)

Country	Annual internal renewable water resources		Annual withdrawals			Sectoral withdrawals (%)		
	Total (km^3)	Per capita (m^3)	Total (km^3)	% of water resources	Per capita (m^3)	Domestic	Industry	Agriculture
China	2800	2231	460.00	16	461	6	7	87
Vietnam	376	4827	29.00	8	410	13	9	78
India	1850	1896	380.00	21	612	3	4	93
Laos	270	50,392	0.99	0	259	8	10	82
Japan	547	4344	91.00	17	735	17	33	50
Thailand	110	1845	32.00	29	602	4	6	90
Nepal	170	7338	3.00	2	154	4	1	95
Bangladesh	1357	10,940	22.00	2	217	3	1	96
Cambodia	88	8195	0.52	1	66	5	1	94

Data source World Resources, OUP, New York (https://books.google.co.in/books)

Table 22.2 Main Asian countries groundwater recharge as well as withdrawal scenario

Country	Average annual groundwater recharge		Annual groundwater withdrawals					
	Total (km^3)	Per capita (m^3)	Total (km^3)	% of annual recharge	Per capita (m^3)	Domestic use (%)	Industry use (%)	Agriculture use (%)
China	870	693	75	9	70	–	46	54
Vietnam	84	1078	–	–	–	–	–	–
India	350	359	150	43	222	3	1	96
Laos	350	359	150	43	222	3	1	96
Japan	185	1469	13	7	104	29	41	30
Thailand	43	721	1	2	15	60	26	14
Nepal	–	–	–	–	–	–	–	–
Bangladesh	34	274	3	10	40	13	1	86
Cambodia	30	2790	–	–	–	–	–	–

Data source World Resources, OUP, New York (https://books.google.co.in/books)

In Nadia as in the rest of West Bengal, surface water was the most important source of water for supplying the increasing demand of water among the population. However, unregulated discharge of waste (both municipal and industrial) into the traditionally used surface water (in this case nearby rivers and streams) has made the source unsafe for drinking purposes. As a result, increasing trends of waterborne gastrointestinal diseases led the general population to lose faith in the surface water sources (Bantram and Lewis 2005). Groundwater was used to replace surface water to avoid bacterial diseases. Millions of hand-operated tube wells (both shallow and deep) were indiscriminately installed in the soft alluvium of BDP notably in Nadia by local initiative as well as by the government (Bhattacharya et al. 1997).

In West Bengal particularly Nadia, water supplied from sedimentary aquifers was considered to be safer in terms of low levels of microbial contamination during the initial part of the tube well installation program in the 1970s (PHED 1993). The groundwater structures are easy to operate and remain under the user's control. This has transformed groundwater into a "unique natural hidden freshwater resource" and as the more preferred source of water in rural areas where pipe water distribution system usually does not exist. In Nadia, demand of clean drinking water has resulted in increased dependence on groundwater. Simultaneously, the need for irrigation water compounded the demand for aquifer exploitation (mostly shallow, <50 m) and reached its peak during the height of the "Green Revolution" (Mclellan 2002).

In the last few decades (1970–2010), tube wells (mostly shallow, <50 m) have been drilled throughout the young alluvium of the Bengal Delta Plain (BDP) significantly in Nadia (both in UDP and LDP). This was done without considering about the possible hydrogeological repercussions. The demand for water (domestic, industrial, agricultural and hydropower) are increasing day by day. This large scale of groundwater development (uncoordinated and uncontrolled) ultimately has resulted in serious problems in As contamination.

In the late 1970s to early 1980s, when people started using groundwater for drinking, cooking and domestic purposes, a major health hazard was noticed in several parts of BDP especially in Nadia (Bhattacharya et al. 1997). A large part of the population was affected with "arsenicosis" (WHO 2004; IPCS 2001; Bhattacharyya et al. 2003b). In the next decade (mid-nineties), arsenicosis became the major public health issue in this part of the world (Bhattacharyya et al. 2003a). Mass poisoning due to As from groundwater has been addressed extensively in the international arena. Thousands of shallow-contaminated wells (As_T up to 1186 $\mu g\ L^{-1}$; Fe_T 10 mg L^{-1}) were identified in Nadia (Bhattacharyya et al. 2003a, b).

In the new millennium, consumption of groundwater As has emerged as a serious public health issue. A number of local as well as foreign agencies have been involved in efforts to eradicate the menace of arsenicosis from Nadia (RGNDWM 2001).

Drinking water is the major ingestion route of As into the human body. However, both soil and edible crops have now come to the forefront due to their ability to introduce As in the food chain (Nath et al. 2007). In Nadia, an agricultural development programme (the "Green Revolution") was launched in the early 1970s with local government encouragement to solve the problems of malnourishment in this area (Bhattacharya et al. 1997). The practice of irrigation with groundwater needs further studies to determine the enrichment of As in the food chain through irrigation water. The problem is further compounded in regions such as Nadia, which mostly depend on agriculture where intensive irrigation has been noticed (Bhattacharyya et al. 2003a).

Several attempts have been made to explain the origin and cause of mobilization of high As in groundwater and its extraordinary spatial distribution. A spatio-heterogeneity of As has also been identified in Nadia (Chatterjee et al. 2003, 2004, 2005. Many studies have been conducted to explain the mobilization of As in the groundwater. These primarily deal with the variable release of As in the groundwater (Bhattacharya et al. 1997). Sorbed As on secondary phases (principally Fe-/Mn-oxides/hydroxides) slowly breakdown and help in the release of As under local anoxic conditions (Bhattacharyya et al. 2003b; Islam et al. 2004). Several issues still remain unexplained in the context of control of As release specially related to the nature of host sedimentary environment. We also need a clear understanding of the various (bio-) geochemical processes that often regulate the dissolved iAs (including the ratio of As(V)/(III) varying up to 70% in reducing groundwater of UDP and LDP) in shallow aquifer of Nadia. This is important because such enhanced understanding will help in crafting policies (local/regional/national/international) to mitigate the As menace both in local and regional scales.

22.2 Regional Geology

Nadia lies in the central part of BDP within the Bengal Basin (BB). The BB is an asymmetric pericratonic basin, whose formation was initiated in the cretaceous. BB is bound by the Himalayas and the Shillong massif in the north, the Indo-Burman ranges (Assam-Arakan-Geosynclinal) in the east and the Indian shield in the west (Barman 1992).

The basin evolved with the break-up of the Gondwanaland during the Early Cretaceous (126 Ma). The collision of the Indian and Eurasian plates began in the

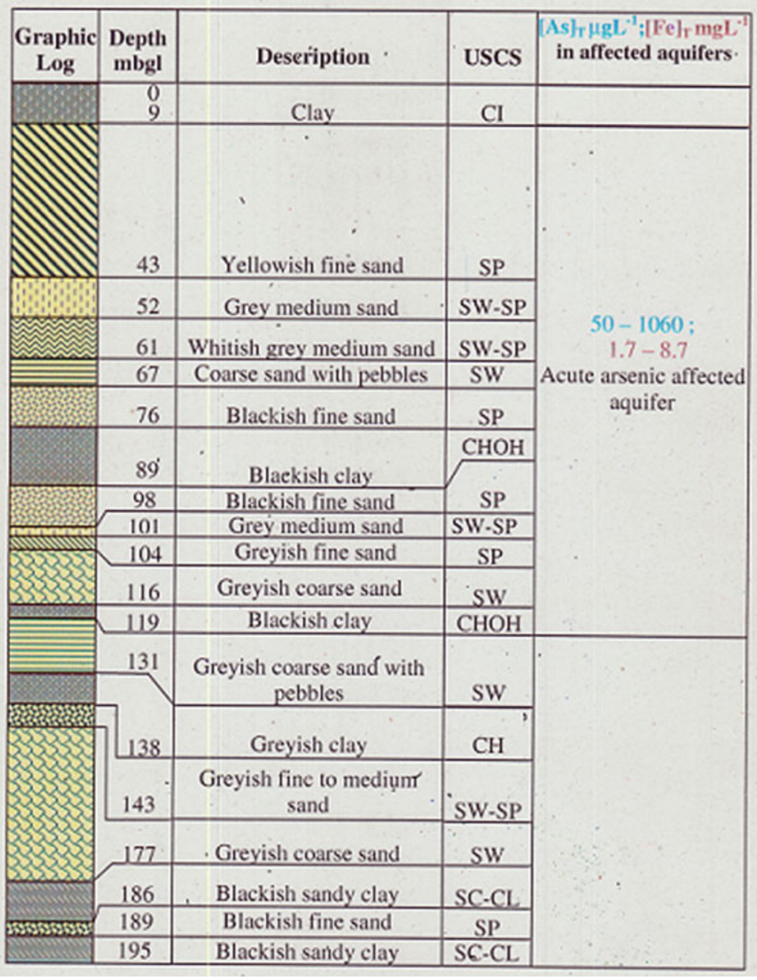
Early Eocene (40–41 Ma) and the associated uplift of the Himalayas resulted due to change in pattern and volume of sedimentation.

During the Miocene, the Himalayas experienced a major uplift and the Indo-Burman ranges more intensely folded, with consequent subsidence in the BB. The Surma Companion Hill groups were laid down in a riverine system and tide-dominated delta similar to the present Bengal Delta (Johnson and Alam 1991).

The BB acquired its present form in the Pliocene. Uplift of the Himalayas and Indo-Burman ranges continued as well as the coast moved backward to the south-west. During this time, the Shillong massif emerged and displaced tens of kilometres southwards (Johnson and Alam 1991). The course of the major rivers also has largely shifted.

Three broad stages identified in the formation of BDP are as follows: (1) the proto-Ganges–Brahmaputra delta formation immediately after the break-up of the Gondwanaland ($\sim$26 Ma), (2) transitional delta ($\sim$49.5–10.5 Ma) development after the collision of Indian and Eurasian plates and associated uplift of Himalaya, alluvial–estuarine modern delta with southward delta progression ($\sim$10.5 Ma—recent) and a successive sequence of sands, sandy silt, silt and mud. The prove-nance of modern delta has been primarily from the shield area (Chota Nagpur Plateau) (Nandy 2001). The BDP is also significantly fed by the Himalayan Rivers (3) flowing down through the Garo-Rajmahal Gap to the Bay of Bengal.

The As-bearing groundwater is largely hosted by the sediments deposited by the meandering river channels during the early-mid-Pleistocene and Holocene deposits (Chatterjee et al. 2005). The lithology of the central part of BDP (Nadia) indicates that the sedimentary successions include sand (channel facies) and silt as well as clay (overbank facies) and generally show a typical fining upward sequence (Bhattacharyya et al. 1997). The sediments generally overlie the older deposits, which comprise a sequence of poorly oxidized to unoxidized successive layers laid on the dissected as well as partially eroded older platform (Chatterjee et al. 2005). The underlying early-mid-Pleistocene sediments have been oxidized due to long exposure (Alam 1989; Goodbred and Kuehl 2000). The succeeding Holocene deposits are of iron-rich clastic minerals and finer sediments (sand, silt with abundant mica and heavy minerals). These sediments are generally unoxidized and grey in colour (Charlet et al. 2007; Goodbred and Kuehl 2000). Fine-grained overbank facies are rich in organic matter (Chatterjee et al. 2003). A typical lithology from arsenic-affected area (Chakdaha block) of Nadia district is presented to overview the simplified lithological facies (Fig. 22.1).



Graphic Log	Depth mbgl	Description	USCS	$[As]_T$ μgL^{-1};$[Fe]_T$ mgL^{-1} in affected aquifers
	0 9	Clay	CI	
	43	Yellowish fine sand	SP	50 – 1060 ; 1.7 – 8.7 Acute arsenic affected aquifer
	52	Grey medium sand	SW-SP	
	61	Whitish grey medium sand	SW-SP	
	67	Coarse sand with pebbles	SW	
	76	Blackish fine sand	SP	
	89	Blackish clay	CHOH	
	98	Blackish fine sand	SP	
	101	Grey medium sand	SW-SP	
	104	Greyish fine sand	SP	
	116	Greyish coarse sand	SW	
	119	Blackish clay	CHOH	
	131	Greyish coarse sand with pebbles	SW	
	138	Greyish clay	CH	
	143	Greyish fine to medium sand	SW-SP	
	177	Greyish coarse sand	SW	
	186	Blackish sandy clay	SC-CL	
	189	Blackish fine sand	SP	
	195	Blackish sandy clay	SC-CL	

Fig. 22.1 A typical lithology from arsenic-affected area (Chakdaha block) of Nadia district

22.3 Physiography and Geomorphology

The Ganga–Brahmaputra river system (including their tributaries and distributaries) fundamentally contributed towards the building of the BDP considered the world's largest modern delta. The dynamic delta building processes (heavy riverine sedimentation load, strong oceanic current, tectonic subsidence, major seismic events, sea level changes and marine incursions) have significantly influenced the quaternary geology of the BDP. The delta is continuously fed by regional rivers (Chaterjee et al. 2005). These rivers form an intricate network of channels (braided mains → meander belts → tidal creeks → fluvio-estuarine landform) during their flow path as they approach towards the sea (Chatterjee et al. 2005; Mukherjee et al. 2001).

The major physiographic territory and geology/geomorphic domains of BDP have been presented (Table 22.3) to focus on the progressive delta building processes. This has created aquifers of enormous economic potential. These aquifers were later found to be contaminated with arsenic (Bhattacharya et al. 1997). The arsenic-contaminated area of BDP (West Bengal part) is encompassed by the interfluves of Bhagirathi–Padma in the north and the Bay of Bengal in the south (Chatterjee et al. 2005). The Ganga has shifted eastwards from its original course and branched into two distributaries (Bhagirathi–Hooghly and Padma–Meghna). This has resulted in these rivers flooding the lowland areas of their alluvial plains every year during monsoon (CGWB 1999). The causes for the shifting of Ganga and other regional rivers have been poorly understood. Several probable causes such as elevation of the head of the main river in response to neotectonism and eustatic sea level changes have been proposed (Bhattacharya et al. 1997; CGWB 1999).

Table 22.3 Geology–geomorphic form and physiographic territory of BDP and allocation of arseniferrous belt

Physiographic territory (domain)	Geographic setting	Geology of the domain (macro form)
Extreme north and western up hills	Darjeeling Himalaya and Buxa Hills	Hard rocks (outcrop)
Mountainous and sub-Mountain Terrain	Darjeeling and foot of The Himalaya	Tertiary rocks (soft massive sandstones)
Barind	North-western parts of Malda and south Dinajpur	Upland terrace (Pleistocene—older lateritic alluvium)
Lateritic upland	Birbhum, Bankura, Purulia and parts of Midnapur	Archaean gneisses, schists and granites
[a]Upper Gangetic delta	Malda (only alluvium part), Murshidabad, Nadia, Bardhaman and North-24 Paraganas	Upper Delta Plain of meander belt (Holocene deposits)
Valley margin fan and marginal plain (recent alluvium deposits)	Bardhaman, Hooghly and parts of Midnapur	Holocene deposits
[a]Lower Gangetic delta	Kolkata, Howrah, parts of North-24 Paraganas and South-24 Paraganas	Lower Delta Plain including delta front (Holocene deposits)

[a] Arseniferrous belt

The geomorphologic features of modern BDP can be grouped into two major landforms [upper (older) delta plain (UDP) and lower (young) delta plain (LDP)]. The UDP is located in the northern part of the BDP. The UDP is adorned with a series of meander scars of varied wavelength and amplitude, abandoned channels and oxbow lakes. In UDP, abandoned meander scrolls as well as channels are the common features of the Nadia floodplain with a gradual southward slope. Levees, back swamps, inter-distributary inland swamps are the other general landform features of the UDP. The UDP arsenic occurrence in groundwater is often associated with meander belts as well as abandoned channels (Nath et al. 2005).

In Nadia, the LDP has a large Holocene sedimentation profile (~ 6–9 km) as there was slow and differential sinking of the delta platform (Chatterjee et al. 2005). The area is composed of several tidal creeks, tidal mud, fluvio-estuarine landform, conspicuous and distributary levees along with inter-distributary marsh complexes. The material make-up of the LDP consists of silt, sand and gravel (fining upwards sequence) with extensive clay capping of wide variable thickness (15–76 m) mostly in the eastern/south-eastern margin of Nadia (Bhattacharya et al. 1997; Smedley and Kinniburgh 2002). The geomorphologic features are formed in an interactive fluvial–estuarine–marine environment under the influence of sea level changes during geologically recent period (Pleistocene–Holocene) (Chatterjee et al. 2005).

The lithic framework of Nadia (both UDP and LDP) indicates that the Holocene delta is made up of largely fine-grained mica grains (channel fill/even finer floodplain deposits) that are characteristic of shifting meander belts and river courses (Chatterjee et al. 2005). The meso- and micro-landforms are the products of the inland fluvial (upper part) and/or estuarine–marine (lower part) influence (Chatterjee et al. 2005).

In UDP, the arsenoferrous belt lies mostly within the meander belts of the Nadia and often associated with various geomorphic units. The levels of arsenic contaminations are also different in UDP and varying within the Holocene aquifer (both vertical and lateral units). The south-east fluvial floodplains (Bhagirathi–Hooghly and Ichamati Basin) are mostly arsenic-contaminated, whereas Gangetic fan (north-east) and adjacent areas are relatively free from arsenic contamination (Chatterjee et al. 2005; Jana 2004).

The arsenical “hot spots” of LDP are often concentrated mostly in the inland fluvial–estuarine lower unit, with the estuarine–marine depositional regime (marine delta unit) generally free of arsenic (Chatterjee et al. 2004). Arsenic and iron enriched groundwater are commonly restricted to the young alluvial plain of LDP where the present landscapes have evolved from channel shifting (Chatterjee et al. 2005; Jana 2004). Finally, high As and Fe groundwater appears to have association with the paleo-channels and their meander belts. The sediments of the meander belts are mostly enriched with arsenic (Nath et al. 2005; Jana 2004).

22.4 Hydrogeological Features

Nadia is characterized by highly productive Holocene aquifers. The three-dimensional configuration of the Holocene aquifers is complex. These aquifers are mostly inferred to be younger ($\sim$11,000–13,000 years BP) in the absence of reliable and extensive dating (CGWB 1999; Nath et al. 2008a). Hydraulic conductivity values span in few orders of magnitude that provide highly transmissive multilayer sedimentary aquifers. Silt and clay predominate in the upper few meters with varying specific yield values (2–5%) (CGWB 1999).

The limited data from pumping in the Nadia aquifer indicate a leaky response, suggesting that relatively more water (even rich with As) is flowing in from distant source (PHED 1993). Regionally and locally, the Nadia aquifer is best described as unconfined in nature with high potential (Nath 2006; CGWB 1999). In Nadia, more recent alluvial sediments and groundwater are often associated with elevated level of arsenic (>50 $\mu g\ L^{-1}$). This young deltaic sediment has been extensively exploited for their high yield and shallow accessibility. The upper-most part of the aquifer ($\sim$4–12 m) has a capping unit (silt and/or clay), resulting in a semi-confining condition where the piezometric surface is usually within 3–6 m of the ground level (RGNDWM 2001; IFCPAR 2004).

Aquifer recharge occurs mostly during monsoon (June/July–October) and major discharge is due to pumping (long-term groundwater abstraction). A significant backflow ($\sim$60–80%) from irrigation wells have also been noticed (RGNDWM 2001). The trans-boundary north-west flowing rivers also receive considerable base flow during the dry season. Numerous natural ponds, bils (man-made ponds) and abandoned channels are thought to be possible zones of discharge (leakage) during the monsoon and recharge during the summer. The water table (piezometric surface) gets lower during summer by a few metres ($\sim$2–5/7 m) due to pumping for Boro cultivation (summer paddy) (Jana 2004; Bhattacharyya et al. 2003a; Chakraborty 2006).

Such practice of high delta Boro cultivation may intensify the anoxic nature of the aquifer and may lead to As release in the groundwater (Charlet et al. 2007). On a local scale, however, enhanced groundwater flow will occur near major regional rivers due to seasonal inundation that creates an imbalance in the hydrological regime (Mukherjee et al. 2008). In monsoon, the floodwater level in the river is recedes more quickly than the groundwater level and a circulation occurs between aquifer groundwater and channel flow. The regional water level fluctuation (water level changes between dry and rainy season) as well as localized flow cause aquifer (significantly upper levels) flushing and may increase the As in groundwater (Nath et al. 2007). Understanding the hydraulic equilibrium of the Holocene aquifers is important to explain the changes in the shallow aquifer redox chemistry.

22.5 Distribution of Arsenic in Groundwater

22.5.1 *Local Distribution (Nadia District)*

Several studies have been carried out in the UDP-LDP (Nadia district) to understand the distribution of Arsenic in groundwater (spatial variability and depth distribution). Shallow aquifers (>50 m) are mostly exploited for drinking water supply in rural areas of Nadia (RGNDWM 2001; IFCPAR 2004; Chakraborty 2006; Nath 2006). The top part (10–45 m) of this aquifer has generally been considered for water quality survey (65–80%). The As in groundwater in north and north-east of the district are generally significantly above 10ppb with a patchy

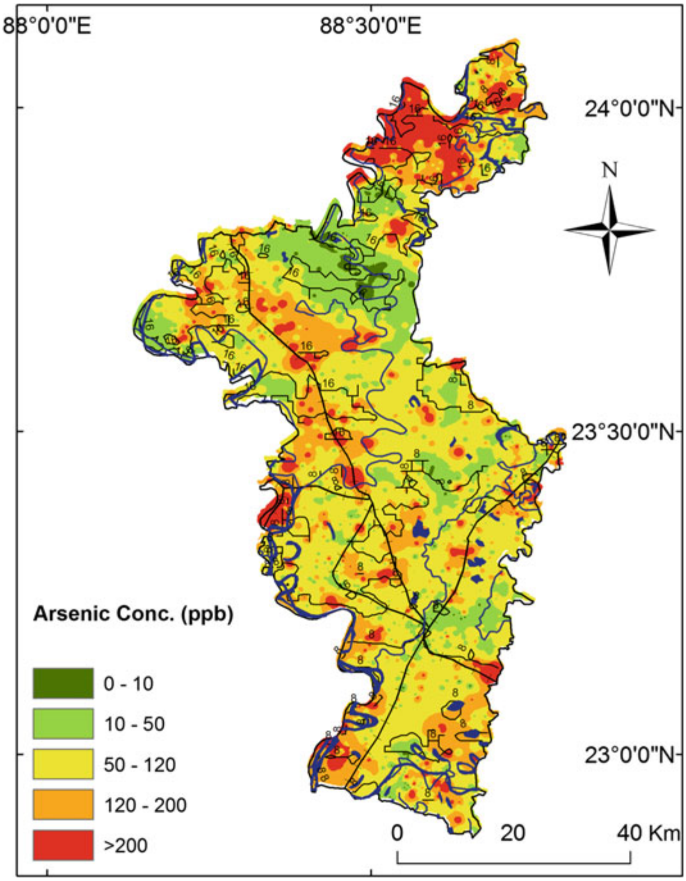


Fig. 22.2 Arsenic distribution map of Nadia district

distribution (0–1186 ppb) elsewhere (IFCPAR 2004) (Fig. 22.2). The groundwater As variability can have several features (very high/high >200 μg L^{-1}; moderate 200 μg L^{-1} < As_T > 80 μg L^{-1}; low <50 μg L^{-1} even safe <10 μg L^{-1}). The patchy distribution means high arsenic concentration zones (Arsenic "hot spots" marked in red in Fig. 22.2) occur in close vicinity with low As zones (marked in green). The zonal shapes (varying between elongated to circular) may be due to sediment morphology and local hydrogeological conditions. It is important to note that the geographical spread of the high/low As zones in BDP/Nadia does not follow a uniform pattern. The study of the zonal shape, distribution pattern and characteristics can be further modified with the availability of new groundwater quality data.

A depth dependent variation of As in groundwater has also been noticed in Nadia/BDP. This should be taken into consideration to explain spatial heterogeneity of As both within and between affected areas and along with abstraction depth. Availability of wells of different depths is important to create a better picture of the spatial heterogeneity.

A distinction in the As concentration between shallow (<50 m) and deep aquifer (>100 m) has been noticed in Nadia district. Exploitation of deeper aquifer (~70–80% of the drinking water supply) provides the most viable option for safe drinking water supply (Nath et al. 2007). Presently, community water supply is also catered by deep pumping wells (8′ dia. and electrically operated), and the quality of water depends on screen depth (filter slots) and lithological control. Recent, studies reveal that a few deeper wells are unsafe (Nath et al. 2007, 2008a; RGNDWM 2001; IFCPAR 2004). Exploitation of deeper aquifer should be critically reviewed before recommending long-term use.

22.6 Groundwater Quality and Chemistry

A survey of the groundwater quality from aquifers in Nadia district indicates that As concentration often exceeds WHO guideline values (>10 μg L^{-1}). The As concentrations in groundwater vary over wide range of magnitude. Variation of As concentrations show little regional trend and also display a significant short-range spatial variability.

The chemical composition of the groundwater from Nadia district varies both regionally and between aquifers. The characteristic chemical features of high Arsenic groundwater are high alkalinity (>250 mg L^{-1}), Fe (>0.15 mg L^{-1}), Ca^{2+} (>80 mg L^{-1}), Mg^{2+} (>20 mg L^{-1}), silicate (7.15–29.0 mg L^{-1}), Cl^- (6–123 mg L^{-1}) and PO_4^{3-} (1.1–7.79 mg L^{-1}), and low NO_3^- (<1 mg L^{-1}), SO_4^{2-} (1–13 mg L^{-1}) and F^- (<1 mg L^{-1}) concentrations. The groundwater has the low E_h (generally less than 100 mV), low to very low D.O. (<1 mg L^{-1}, often absent), moderate conductivity and nearly neutral pH (6.5–7.5). The physico-chemical composition of the groundwater shows large variation, and contains high concentrations of redox-sensitive species (As, Fe, Mn) and relatively low concentrations of D.O., nitrate, sulphate and chloride. The most dominant anion is bicarbonate (250–700 mg L^{-1}), and the cation is Ca^{2+} (80–150 mg L^{-1}). The water is generally Ca–HCO_3 type and fresh (conductivity 580–1100 µs/cm) (Bhattacharyya et al. 2003b; Chatterjee et al. 2003; Nath et al. 2007).

There is an almost positive correlation (even logarithmic) in between As_T, PO_4–P and bicarbonate, whereas the correlation with Fe is not significant (Bhattacharyya et al. 2003b; Chatterjee et al. 2003, 2005). The correlation between dissolved elements and As is usually not perfect, and positive correlation is mostly applicable locally (Bhattacharyya et al. 2003b). Few researchers have found a positive correlation between As and Fe; however, such relationship does not hold good for the entire BDP, particularly several parts of Nadia district (Smedley and Kinniburgh 2002; BGS and DPHE 2001). The commonly observed negative correlations (As vs. NO_3^-, As vs. SO_4^{2-}, As vs. D.O. and As vs. E_h) are also useful to understand arsenic mobilization in Nadia. Such association suggests that As mobilization is under anoxic condition, where high As groundwater is often associated with high Fe.

In Nadia, the As spatial and depth distribution pattern is atypical where there is a spatial variability of groundwater As. This heterogeneity of As distribution is a manifestation of the host environment and lithogeochemical character of the affected aquifers. The As distribution (bell shaped) of the depth profile can also be explained by vertical distribution of redox elements. The concentration of dissolved redox elements is largely the function of local redox driver (distribution and concentration of organic matter). Their breakdown (microbial processes) may control the vertical distribution of redox elements. A few local conditions (geomorphological features, land use pattern, pumping and local recharge) are also important to maintain the concentration of dissolved redox elements in the groundwater.

High As(III)/As_T ratio is another important feature of the anoxic groundwater. The maximum observed As(III) concentration is 820 ug L^{-1} for As_T concentration of 1186 ug L^{-1} (Nath et al. 2007). As a result, identifiable health outcomes among human beings (health effect of As) have been frequently encountered (patients) in several As “hot spots” (e.g. Ghetugachi Kaliachack, Domkal, Jampukur) (Bhattacharyya et al. 2003a; BGS and DPHE 2001). In deep and intermediate aquifer, there is relatively low As(III) concentration (Nath et al. 2007; RGNDWM 2001). This results in an interruption in the redox equilibrium of the aquifer. This influence varies in various depths of the BDP/Nadia (Gault et al. 2005). This dis-equilibrium suggest that As(V) will lag behind As(III) in groundwater due to the higher charge of the arsenate species.

The physical nature of aquifer is important to understand the As mobility in groundwater. The natural hydraulic regime (with a gradual southward slope) of Nadia has a major role on As mobility, significantly on a long-term basis. Lack of natural groundwater flux and micro-topographic influences aids in controlling As mobility. As (V) is less likely to be in the dissolved phase thereby increasing concentration of As(III) in the system. Finally, it is likely that high As groundwater may not persist in Nadia if groundwater flow was more dynamic.

22.7 Sediment Geochemistry

In Nadia, the deltaic sediment is typically young alluvium. The sediment has abundant quartz (50–70%), mica (10–20%), feldspar (5–25%) along with minor amounts of heavy minerals (pyroxenes, magnetite, Fe_2O_3) and chlorite as well as kaolinite (Biswas et al. 2014a; Chakraborty et al. 2006; IFCPAR 2004; Bhattacharyya et al. 2003b). Nonmagnetic/and feebly magnetic minerals are reported to be As-free, whereas Fe-bearing clastic minerals (biotite, chlorite, illite, Fe-coated grain) are mostly As traps (Pal and Mukherjee 2009; Bhattacharyya et al. 2003b; Neidhardt et al. 2014). The surface clay layer (often sandy) extends over the entire district, and thickness varies considerably (2–14 m). For example, in north-eastern part (Karimpur and Tehatta blocks), the clay horizon (6–10 m) occurs at the top with fine-to-medium sand/silty sand zone underneath (Jana 2004). In the north-western part (Nakashipara and Kaliganj, UDP), the clay horizon occurs at different successive levels starting from the top (0–7, 36–50, 60–64, 70–110, 125–155 m) with a gradual downward trend of finer sand (often truncated). There are large tracts of low lands which were once a part (older bed) of the regional river (Bhagirathi–Ganga) (RGNDWM Report 2001) In the western part (Nabadwip, Krishnaganj, Hanskhali and Ranaghat, UDP/partly LDP), the top clay layer is relatively thin (up to 4 m) with clay horizons (including clay lens) also occurring at the various intermediate depth ranges (20–22, 36–38, 40–44 and 60–68 m). Fine-to-course sand mixed with silt has been found at all depths in between the semi-continuous clay layers (DFG-BMZ Report 2013). In the upper portion of the surface clay layer, the occasional presence of natural organic matter (even agricultural residues) has been noticed and the sediments are mostly brown in colour. In the southern part (Chakdaha and Haringhata, LDP), the surface sandy clay layer is relatively thicker (up to 14 m) with varying thickness which is thinner along the east margin (Biswas et al. 2014a). In the upper portion, the presence of plant debris is common. The sediment is usually light brown in colour. The oxides/hydroxides of Fe and Mn mottles (mostly brown to black) are also noticed in the water table fluctuation zones (2–10 m) (Biswas et al. 2014a).

In Nadia, a positive correlation has been noticed in the sedimentary distribution of As (As_T-3 to 18 mg kg^{-1}), Fe (Fe_T-0.7 to 9.7%) and organic carbon (C_{org}-0.01 to 1.4%) (Bhattacharyya et al. 2003b). In BDP the sediment concentration of As varies between ~3–18 mg kg^{-1}, and the average (2.2 mg kg^{-1}) is not very high when compared with world average values (Earth crust—1.8 mg kg^{-1}; rocks—0.5–2.5 mg kg^{-1}; coal-average—10 mg kg^{-1}) (NAS 1997; Clarke and Sloss 1992). The As content of the regional river bed samples of the BDP (Ganges—2.03 mg kg^{-1}, Brahmaputra—2.79 mg kg^{-1} and Meghna—3.49 mg kg^{-1}) has also been reported to be lower than sediment Arsenic content (Chatterjee et al. 2005; Datta and Subramanian 1998). The major rivers (Bhagirathi, Jalangi, Churni, Ichamati and Bhairab) running through the As "hot spots" (Karimpur, Tehatta, Kaliganj, Shantipur, Chakdaha and Haringhata) usually contain low Arsenic (1–3 μg L^{-1}/below detection limit) (RGNDWM 2001). Such low As content of sediments in the affected areas is unusual for locations where there is high As mobilization in groundwater.

The hydrostratigraphic framework of shallow (<50 m) aquifers (lithological campaign) has been studied. It has been found that the sedimentary Holocene aquifers of BDP (Nadia district) are mostly divided into three subsets of aquifers which are regionally distributed (3-D) and interconnected (Biswas et al. 2014b). The upper aquifer is unconfined which is extended continuously up to the level of surface clay (often sandy) layer and aerially distributed with greater thickness in north-west, east and southern margins. The aquifer is complex and runs parallel to the regional and local rivers (Biswas Doctoral Thesis 2013). Lithological campaign (drilling operation) reveals that another aquifer is present in the central floodplain (mostly floodwater movement area) within the overbank deposits with limited vertical extension (discontinuous and local in nature). This aquifer is laterally connected with the upper sandy clay and sand layers. Nevertheless, field observation reveals that the silt content is high. Both the aquifers show similar nature of groundwater composition as well as sediment colour (often grey/reducing sand). In the palaeo-interfluvial zone (mostly north–south-central part, north-west-southern part and southern-central part), another aquifer has been observed which is often found underneath the grey sand aquifers and vertically extends up to 70 m where drilling ended (Biswas et al. 2014a, b). The palaeo-interfluvial aquifer is mostly composed of brown sand (typically Fe-oxide coating on sand grain/oxidized sand) (Biswas et al. 2014b). The contrast in both colour and grain size in between grey sand and brown sand aquifer is particularly important because the former is often contaminated with As unlike the latter (Biswas et al. 2014a, b).

22.7.1 Minerological Study

Mineralogical study (XRD; Fig. 22.3) has been conducted to identify principal minerals from sediment of arsenic-affected area (BH-6, 20–22 m, Ghetugachi, Chakdaha block). The study reveals that As-bearing mineral peaks (pyrite—2.71 Å,

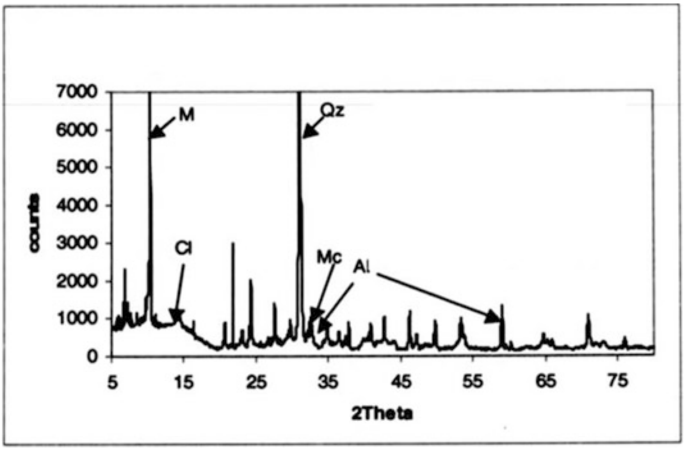


Fig. 22.3 Mineralogical study (XRD) to identify principal minerals from sediment of arsenic-affected area (BH-6, 20–22 m, Ghetugachi, Chakdaha block). Qz quartz, M muscovite, Cl clinochlore chlorite, Mc microcline, Al albite

arsenopyrite—2.66 Å) are absent. Major minerals are quartz, mica and sodic feldspar. However, it seems that these minerals are not diagenetically available in the sediments (Chakraborty 2006). Authigenic framboidal pyrite is occasionally found as small precipitating agent in silty-/clayey-rich part of sediments, indicating prevailing reducing conditions of the aquifer. In-situ authigenic pyrite formation in the aquifers is a sink rather than a source (Nath et al. 2008a, b).

High As (>200 μg L^{-1}) aquifer sediments are generally composed of silty sands (mostly grey), whereas low As (<50 μg L^{-1}) aquifer sediments contains mostly sand (medium to course) (Charlet et al. 2007). This suggests that high As sites are reducing in nature with more sediment–water interaction and high residence time. Absence of peat has also been reported in Nadia district during drilling campaigns (Nath et al. 2010). It is interesting to note that the peat was previously advocated to be responsible for the As release in groundwater (McArthur et al. 2001, 2004). High Fe contents of the sediment are usually associated with high As in groundwater. The amount of Fe-rich bulk solid in sediment act as a major controlling factor to release As in groundwater. Nature, mineralogy and solid phase chemistry of these sediments contribute towards maintenance and the regulation of the redox condition and adsorption/desorption processes. Lithological examination under microscope reveals that Fe-oxides/hydroxides along with reworked/weathered secondary Fe minerals are common constituents along with free HFO. This could be the possible reason behind the relationship between high As and Fe in groundwater (Nath et al. 2008a, b). Decoupling of Fe and As is also observed suggesting that the relationship is more local than regional (Nath et al. 2008a; Horneman et al. 2004).

The carbon (C_{org}, av.) content of the Nadia sandy sediment is usually low (up to 0.2%); however, the fine-grained sediments (over bank deposits) contain higher amount (up to 0.4%). The carbon and sulphur contents of Nadia sediments are similar (up to 0.2–0.4%) and often remained unchanged in between low and high As sites (Bhattacharyya et al. 2003b; Nath et al. 2008b). In Nadia, the carbon from sedimentary origin is inadequate to act as principal electron donor for reduction of Fe-bearing minerals (even microbiologically) and surface derived fresh organic matter may play an important role (Rowland et al. 2006).

22.8 High As in Shallow Aquifer: Geochemistry and Mobilization

The groundwater elemental concentrations (As-up to 1.1 mg L^{-}, Fe-up to 8.4 mg L^{-}, Mn-up to 2.4 mg L^{-}) is the primary concern in terms of both public health and mitigation options. The As map (Fig. 22.2) of Nadia shows that there is a clear zonal difference in the degree of contamination (spatial and vertical). These differences are due to interplay of several geochemical processes (Figs. 22.4 and 22.5) that often control such distribution pattern. Moreover, an adequate understanding of the As release mechanism is the need of the day because it will help in mitigating the As menace. Several human activities (rapid change in local land use pattern, large-scale groundwater development for crop production, degraded ponds, sanitation installation) may also contribute towards the release of As at least locally (Nath et al. 2008a; Biswas et al. 2011; Neumann et al. 2010). These local inputs play a key role to regulate the redox process (Fig. 22.5) increasing the complex interaction between different redox parameters (Polizzotto et al. 2008). This can

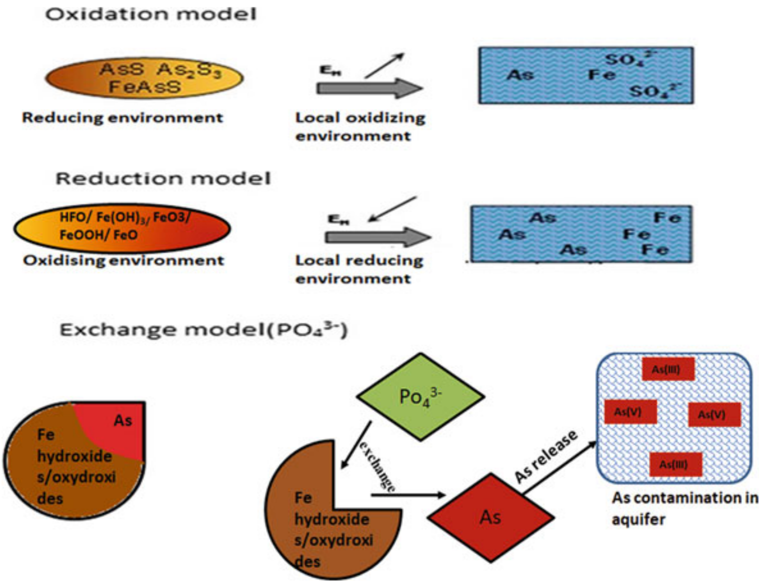


Fig. 22.4 Geochemistry and mobilization of arsenic in shallow aquifer

also help the Terminal Electron Accepting Processes (TEAPs) thereby releasing more As in groundwater (Neumann et al. 2010). The role of fresh organic matter is crucial because under local anaerobic condition, the breakdown of organic matter is faster and release more energy (supply and flow of electron) (Mailloux et al. 2013). In Nadia, the As contamination is profound in shallow aquifers and more precisely in the water table fluctuation zone (up to 8 m). Arsenic cycling (adsorption–desorption) occurs in oxic-anoxic zone (regulating redox environment) where As is released (transport) laterally and then pushed downwards by fresh recharge (Harvey et al. 2002; Polizzotto et al. 2008). Fresh biotite (weather and reworked) plays a key role because the faster rate of weathering of biotite bound Fe(II) (Fig. 22.6) (IFCPAR 2004). There is also evidence for the microbial cycling of As in shallow aquifers of BDP (including Nadia). In this process, metal-reducing bacteria help to mobilize As from sediment to groundwater (Islam et al. 2004). This geomicrobiological process is complex and depends on local environmental conditions. Several factors are important to govern the process such as redox state of the sediment, decomposition/mineralization of organic matter, presence of electron donor/acceptor and bacterial population (Oremland and Stolz 2005). Microbial mobilization of As is also controlled by reduction of Fe(III) in oxic/oxic-anoxic interphases and the re-oxidation of Fe(II) with the fixation of As(V) (Lovely 1993).

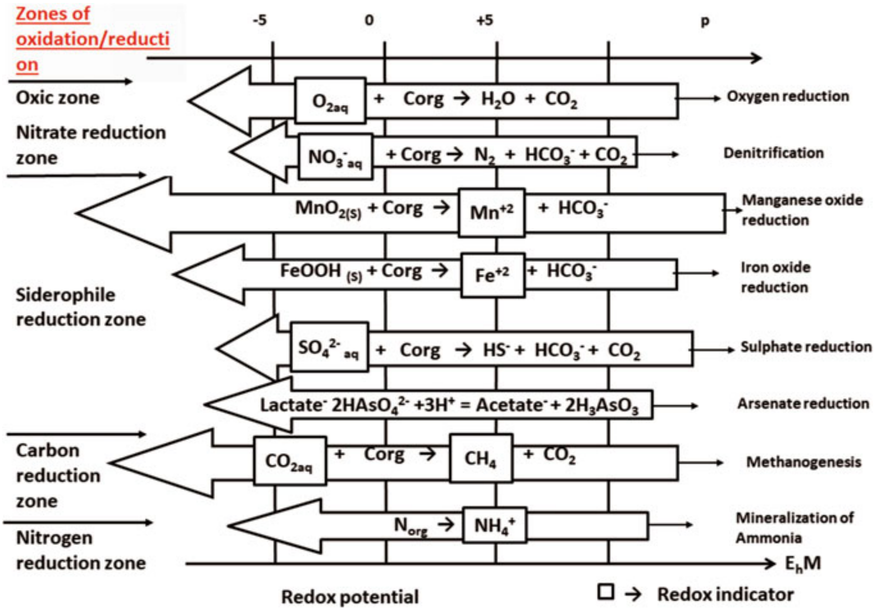


Fig. 22.5 Redox processes and release mechanism with the help of degradation of organic matter in a sequential pattern (redox staircase)

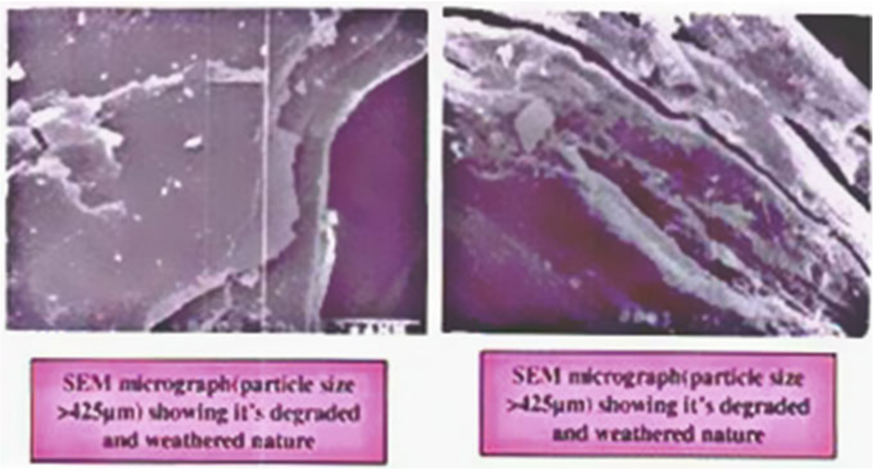


Fig. 22.6 SEM study of fresh biotite collected from arsenic-affected area (Debagram, Nadia district)

The Fe-As redox system requires a source of degradable organic carbon (electron donor) resulting in the decoupling/coupling of Fe and As (Islam et al. 2004; Gault et al. 2005; Ghosh et al. 2014; Bhattacharyya et al. 2003b; Chatterjee et al. 2005, Nath et al. 2008a; Oremland and Stolz 2003). The decoupling may be due to Fe(II) phase transformation following Fe(III) reduction, where inorganic As sorption process is involved followed by As reduction [As(V) to As(III)]. The microbial decoupling process may likely increase As(III) and bicarbonate concentration in the groundwater. Supply of fresh organic matter, microbial population diversity, presence of oxidants (NO_3^-, Mn^{2+}, SO_4^-), water table fluctuation and sediment–water interaction plays an important role in the microbial As mobilization in groundwater. The nature, surface chemistry and bioavailability of the secondary reduced iron phases are important factors in the microbial Fe cycling (Oremland and Stolz 2003, 2005).

The major sources of As are the meta sediments of lesser Himalayan Belt and the Chota Nagpur Peninsular Plateau (Acharya et al. 1999; BGS and DPHE 2001). Leaching of As occurs from the sources and are deposited in BDP via the aqua transit route and buried in anoxic waterlogged environments (Chatterjee et al. 2005; BGS and DPHE 2001). However, the spatial heterogeneity of As distribution and their variability in Nadia is perplexing. The large area of occurrence of natural As and their depth distribution in Holocene alluvium sediments advocates for a multi-source provenance of the As rather than a single source.

The scale of the problem in Southeast Asia further emphasizes the disavowal of such single source which cannot lead to such a large and varied distribution pattern of As in BDP. The standard Indian literature on the Geology (Wadia 1975) indicates source rocks and minerals in the sediments of lesser Himalayan Belts. The most common As-bearing minerals with a large As content (e.g. arsenopyrites) are absent in those areas. The Himalayan source of As may not be the single major source of high As in groundwater of this part of the globe.

The sedimentary source of As (primary as well as secondary) in the young Holocene aquifers of the Southeast Asia, significantly in BDP, may also be associated with the noninland sources. The foothills of the Himalayas is important to built up the Holocene depositional morphology in BDP. Moreover, the marine incursions during sea level changes might have also played a crucial role for As sourcing and enrichment in BDP/Nadia (Chatterjee et al. 2005).

The fluvio-estuarine geomorphology of BDP and delta building process played a significant role in controlling the As distribution in BDP, particularly in Nadia. The fluvio-depositional environment changed quite frequently (basinal influence). This resulted in the deposition of the suspended load of river (mostly colloidal particles of iron oxides/hydroxides and/or iron-bearing minerals) depending on physiography of the basin and topography of the area. The reduction of the flow velocity (slow/sluggish riverine condition) led to deposition of the fine sands and the coarse silt on the levee slope and/or crevasses splay front. Redox conditions prevailing in the BDP shallow aquifer in different geological timescales could have actively aided in the metal deposition in sedimentary environment. Nadia is usually recognized with several marshy land and swampy areas where As hot spots are common.

In BDP, studies have observed that the high As groundwater is present in the shallow (<50 m) aquifers (Bhattachryya et al. 2003b; Chatterjee et al. 2003, 2005). The sediments of this aquifer are relatively young, and groundwater flushing is poor in comparison to the rest of the stratigraphic column. As/Fe ratio also decreases with depth in the shallow aquifer along with a different pattern of As/Fe molar ratio in the deeper aquifers (>150 m) where dissolved As shows sharp reduction (RGNDWM 2001; DFG-BMZ 2013). Several studies have also revealed that a few deeper wells also yield relatively high As (Nath et al. 2007; Bhattachryya et al. 2003b; Biswas 2013). This suggests that the release mechanism of As is quite different in the shallow aquifer than that of the deeper aquifers.

The groundwater chemistry reveals that As is unequivocally present in anoxic groundwater with high bicarbonates and redox species (Fe/Mn). Several hydro-biogeochemical processes are going on in the shallow aquifer of BDP and support in the release of As in groundwater under homogeneous aquifer condition with heterogeneous distribution pattern notably for redox elements like As, Fe, Mn (Fig. 22.7). The incredible spatial heterogeneity of As in groundwater makes it difficult to isolate a specific set of geochemical process. However, a combined complex suite of microbially mediated biogeochemical and hydrochemical reactions and processes occur simultaneously in a very narrow band of water at the redox boundary/zonation thereby releasing high As in groundwater.

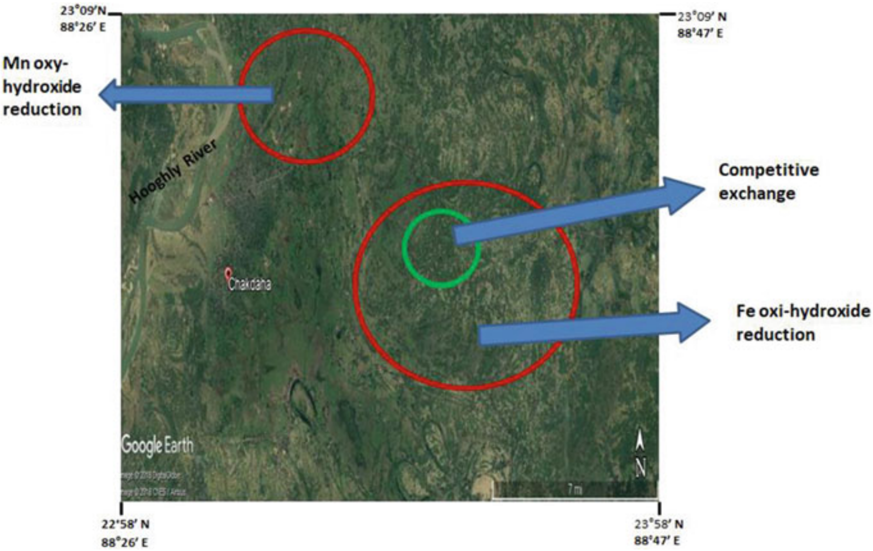


Fig. 22.7 Multimechanism pathways of As release in Chakdaha block of Nadia district based on Mazumder, thesis, 2013. Picture sourced from Google Earth

The As mobilization mechanism in the deeper aquifer may be different from the shallow aquifer. The dissolution of carbonate/mixed carbonate is a major factor for As release in the deeper aquifer of BDP. The groundwater in deeper aquifer occasionally in several parts of Nadia district reveals relatively high concentration of arsenic and manganese with respect to WHO guideline value (<10 ppb) where iron content is relatively low. The presence of redox elements along with high alkalinity in the deeper aquifers indicates that carbonates act as host environment for As release. The As in deeper aquifer also highlights the enrichment of As in terminal Pleistocene–Holocene platform that was previously thought to be free of As (Chatterjee et al. 2005; RGNDWM 2001; IFCPAR 2004; Nath et al. 2007).

Finally, the major challenge is to explain the role of host sedimentary environment (mostly Holocene) and their interaction with groundwater (sediment-water interaction) which is possible influencing the release of As in groundwater.

22.9 Conclusion

Supply of safe water to areas with high groundwater arsenic contamination is a major challenge to protect human health. Arsenic was first discovered in the aquifers of West Bengal, India in early 80s and later it was detected in Bihar, Assam, Nagaland, Tripura, Madhya Pradesh, Mizoram, UP and notably in Bangladesh. The source of Arsenic (secondary) in groundwater is geogenic in origin. The important host sedimentary environment is the As-rich fine-grained Fe-oxyhydroxides in the aquifer sediments. The groundwater in Nadia is often reducing in nature with high Fe(II), bicarbonate and As. Reductive dissolution of iron oxide/hydroxides is interpreted as the principal cause of As release in the environment under local reducing conditions. However, several other mechanisms (competitive exchange, infiltration, biogeochemical) have also put forward to explain the elevated levels of As in shallow aquifer of Nadia district. Recently, a few deeper wells have also been found to be contaminated with As where the dissolution of carbonate/mixed carbonate is the key factor for As release. The contamination in the deeper wells is a serious issue from public health point of view because deeper aquifers are mostly exploited for safe/low As drinking water supply. In this context, safe drinking water supply and risk mitigation measures pose a great challenge in BDP notably in Nadia district, where As removal technologies depend on technological feasibility and cost factor. The Southeast Asian countries are now working hard to meet up with WHO guideline value ($>10\ \mu g\ L^{-1}$) for their National Standard, and it is important that the remediation technologies should yield As-safe water for community supply in anticipation of the future scenario. Until then, deeper aquifer in the BDP is the most reliable source for safe drinking water supply.

References

Acharyya SK, Chakraborty P, Lahiri S, Raymahashay BC, Guha S, Bhowmik A (1999) As poisoning in the Ganges delta. Nature 401:545–545

Alam M (1989) Geology and depositional history of cenozoic sediments of the Bengal Basin. Palaeogeogr Palaeoclimatol Palaeoecol 69:125–139

Bantram J, Lewis K (2005) Focussing on improved water and sanitation for health. Lancet 365:810–812

Barman AR (1992) Geological history and hydrocarbon exploration in Bengal Basin. Indian J Geol 64:235–258

BGS & DPHE (2001) Arsenic contamination of groundwater in Bangladesh. In: Kinniburgh DG, Smedley PL (eds) British geological survey WC/00/19, Keyworth

Bhattacharya P, Chatterjee D, Jacks G (1997) Occurrence of arsenic-contaminated groundwater in alluvial aquifers from delta plains, Eastern India: options for safe drinking water supply. J Water Resour Dev 13:79–92

Bhattacharyya R, Chatterjee D, Nath B, Jana J, Jacks G, Vahter M (2003a) High arsenic groundwater: mobilization, metabolism and mitigation—an overview in the Bengal Delta Plain. Mol Cell Biochem 253:347–355

Bhattacharyya R, Jana J, Nath B, Sahu SJ, Chatterjee D, Jacks G (2003b) Groundwater As mobilization in the Bengal Delta Plain, the use of ferralite as a possible remedial measure—a case study. Appl Geochem 18:1435–1451

Biswas A, Majumder S, Neidhardt H, Halder D, Bhowmick S, Mukherjee-Goswami A, Kundu A, Saha D, Berner Z, Chatterjee D (2011) Groundwater chemistry and redox processes: depth dependent arsenic release mechanism. Appl Geochem 26:516–525

Biswas A (2013) Arsenic geochemistry in the alluvial aquifers of West Bengal, India: implications for targeting safe aquifers for sustainable drinking water supply (Doctoral dissertation, KTH Royal Institute of Technology)

Biswas A, Bhattacharya P, Mukherjee A, Nath B, Alexanderson H, Kundu AK, Jacks G (2014a) Shallow hydrostratigraphy in an arsenic affected region of Bengal Basin: Implication for targeting safe aquifers for drinking water supply. Sci Total Environ 485:12–22

Biswas A, Neidhardt H, Kundu AK, Halder D, Chatterjee D, Berner Z, Bhattacharya P (2014b) Spatial, vertical and temporal variation of arsenic in shallow aquifers of the Bengal Basin: controlling geochemical processes. Chem Geol 387:157–169

Census report of India (2011) Report prepared by Registrar General and Census Commissioner of India, Government of India, New Delhi

CGWB (1999) High incidence of As in groundwater in West Bengal. Central Groundwater Board, India. Ministry of Water Resources, Government of India

Chakraborty S (2006) Groundwater contamination in Chakdaha and adsorption studies on Muscovite and Biotite Mica to understand their role in Arsenic Mobilization. Unpublished PhD thesis, University of Kalyani, India

Charlet L, Chakraborty S, Appelo CAJ, Roman-Ross G, Nath B, Ansari AA et al (2007) Chemodynamics of an As “hotspot” in a West Bengal aquifer: a field and reactive transport modeling study. Appl Geochem 22:1273–1292

Chatterjee D, Chakraborty S, Nath B, Jana J, Bhattacharya R, Basu Mallik S et al (2003) Mobilization of arsenic in sedimentary aquifer vis-à-vis subsurface iron reduction processes. J Phys IV 107:293–296

Chatterjee D, Chakraborty S, Nath B, Jana J, Mukherjee P, Sarkar M (2004) Geochemistry of arsenic in deltaic sediment. Geochem Cosmochim Acta 68:A514

Chatterjee D, Roy RK, Basu BB (2005) Riddle of arsenic in groundwater of Bengal Delta Plain—role of noninland source and redox traps. Environ Geol 49:188–206

Clarke LB, Sloss LL (1992) Trace elements. London: IEACR/49. IEA Coal Research

DFG-BMZ Report (2009–2013) Role of micro-biogeochemical processes in mobilization of As in the aquifer sediments of the Bengal Delta Plain: an experimental approach

Datta DK, Subramanian V (1998) Distribution and fractionation of heavy metals in the surface sediments of the Ganges-Brahmaputra-Meghna river system in the Bengal basin. Environ Geol 36(1–2):93–101

Gault AG, Islam FS, Polya DA, Charnock JM, Boothman C, Chatterjee D, Lloyd JR (2005) Microcosm depth profiles of arsenic release in a shallow aquifer, West Bengal. Mineral Mag 69 (5):855–863

Ghosh D, Bhadury P, Routh J (2014) Diversity of arsenite oxidizing bacterial communities in arsenic-rich deltaic aquifers in West Bengal, India. Front microbiol 5:602

Goodbred SL, Kuehl SA (2000) The significance of large sediment supply, active tectonism eustasy on marginal sequence development: late quaternary stratigraphy and evolution of the Ganges–Brahmaputra Delta. Sed Geol 133:227–248

Harvey CF, Swartz CH, Badruzzaman ABM, Keon-Blute N, Yu W, Ali M. A, ... Oates PM (2002) Arsenic mobility and groundwater extraction in Bangladesh. Sci 298(5598):1602–1606

Horneman A, van Geen A, Kent DV, Mathe PE, Ahmed KM et al (2004) Decoupling of As and Fe release to Bangladesh groundwater under reducing conditions. Part I: evidence from sediment profile. Geochim Cosmochim Acta 18:3459–3473

IFCPAR (Indo-French Centre for the Promotion of Advance Research) (2004) Report on “Geochemistry of Ganga Sediment and Groundwater: arsenic Mobilization”. University of Kalyani, Nadia, West Bengal, India and University of Grenoble, France

IPCS (2001) Arsenic and arsenic compounds, 2nd edn. English and Bengali version. WHO and WHO-WBVA, Geneva, Switzerland

Islam FS, Gault AG, Boothman C, Polya DA, Charnock JM, Chatterjee D, Lloyd JR (2004) Role of metal reducing bacteria in arsenic release in Bengal Delta Sediments. Nature 430:68–71

Jana J (2004) Jenesis of arseniferrous groundwater in the Bengal Delta Plain in West Bengal, Eastern India. Unpublished PhD thesis, University of Kalyani, India

Johnson SY, Alam AM (1991) Sedimentation and tectonics of the Syhlet trough. Geol Soc Am Bull 103:1513–1527

Kundu MC, Mondal B (2009) Agricultural activities influence nitrate and fluoride contamination in drinking groundwater of an intensively cultivated district in India. Water Air Soil Pollut 198 (1-4):243–252

Lovley DR (1993) Dissimilatory metal reduction. Annu Rev Microbiol 47:263–290

Mailloux BJ, Trembath-Reichert E, Cheung J, Watson M, van Geen et al (2013) Advection of surface-derived organic carbon fuels microbial reduction in Bangladesh ground water. Proc Natl Acad Sci U S A 110(14):5331–5335

Majunder S (2013) Pollution assessment of arsenic in groundwater: geochemistry and analytical aspects.

McArthur JM, Ravencroft P, Safiullah S, Thirlwall MF (2001) Arsenic in groundwater: testing pollution mechanism for sedimentary aquifers in Bangladesh. Water Resour Res 37:109–117

McArthur JM, Banerjee DM, Hudson-Edwards KA, Mishra R, Purohit R, Ravenscroft P et al (2004) Natural organic matter in sedimentary basins and its relation to As in anoxic ground water: the example of West Bengal and its worldwide implications. Appl Geochem 19:1255–1293

Mclellan F (2002) Arsenic contamination affects millions in Bangladesh. Lancet 359:1127–1129

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Mukherjee M, Sahu SJ, Jana J, De Dalal SS, Chatterjee D (2001) Scope of natural geochemical material in the removal of arsenic in drinking water. River Behav Contam 24:1–7

Mukherjee A, von Bromssen M, Scanlon BR, Bhattacharya P, Fryar AE, Hasan MA, Ahmed KM, Chatterjee D, Jacks G, Sracek O (2008) Hydrogeochemical comparison and effects of overlapping redox zones on groundwater arsenic near the western (Bhagirathi sub-basin, India) and Eatsren (Meghna sub-basin, Bangladesh) margins of the Bengal Basin. Contam Hydrol 99:31–48

Nandy DR (2001) Geodynamics of North Eastern India and the adjoining region. ACB Publication, Kolkata

NAS (1977) Medical and biological effects of environmental pollutants: arsenic. National Academic of Sciences, Washington DC

Nath B (2006) Aquifers bearing low and high arsenic groundwater—a comparative study on litho- and hydrochemistry in Chakdaha block, Nadia district, West Bengal. Unpublished PhD thesis, Jadavpur University, India

Nath B, Berner Z, Basu Mallik S, Chatterjee D, Charlet L, Stüeben D (2005) Characterization of aquifers conducting groundwaters with low and high arsenic concentrations: a comparative case study from West Bengal, India. Miner Mag 69:841–853

Nath B, Sahu SJ, Jana J, Mukherjee-Goswami A, Roy S, Sarkar MJ, Chatterjee D (2007) Hydrochemistry of arsenic-enriched aquifer from rural West Bengal, India: a study of the arsenic exposure and mitigation option. Water Air Soil Pollut 190:95–113

Nath B, Stuben D, Basu Mallik S, Chatterjee D, Charlet L (2008a) Mobility of arsenic in West Bengal aquifers conducting low and high groundwater arsenic. Part I: comparative hydrochemical and hydrogeological characteristics. Appl Geochem 23:977–995

Nath B, Stuben D, Basu Mallik S, Chatterjee D, Charlet L (2008b) Mobility of arsenic in West Bengal aquifers conducting low and high groundwater arsenic. Part II: comparative hydrochemical and hydrogeological characteristics. Appl Geochem 23:996–1011

Nath B, Basu Mallik S, Stüben D, Chatterjee D, Charlet L (2010) Electrical resistivity investigation of the arsenic affected alluvial aquifers in West Bengal, India: usefulness in identifying the areas of low and high groundwater arsenic. Environ Earth Sci 60:873–884

National Research Council (NRC) (2001) Arsenic in drinking water. National Academy of Sciences, Washington DC

Neidhardt H, Berner ZA, Freikowski D, Biswas A, Majumder S, Winter J, Gallert C, Chatterjee D, Norra S (2014) Organic carbon induced mobilization of iron and manganese in a West Bengal aquifer and the muted response of groundwater arsenic concentrations. Chem Geol 367:51–62

Neumann RB, Ashfaque KN, Badruzzaman ABM, Ali MA, Shoemaker JK, Harvey CF (2010) Anthropogenic influence on groundwater arsenic concentration in Bangladesh. Nat Geosci 3:46–52

Oremland RS, Stolz JF (2003) The ecology of arsenic. Science 300(5621):939–944

Oremland RS, Stolz JF (2005) Arsenic, microbes and contaminated aquifers. Trends Microbiol 13 (2):45–49

Pal T, Mukherjee PK (2009) Study of subsurface geology in locating arsenic-free groundwater in Bengal delta, West Bengal, India. Environ geol 56(6):1211–1225

PHED (1993) National drinking water mission project on Arsenic pollution on groundwater in West Bengal. Final report, Steering Committee on As investigation. Government of West Bengal, India

Polizzotto ML, Kocar BD, Benner SG, Sampson M, Fendorf S (2008) Near-surface wetland sediments as a source of arsenic release to ground water in Asia. Nature 454:505–509

RGNDWM (Ministry of Rural Water and Development) (2001) Phase-II report. Univ. Kalyani, Nadia, West Bengal, India

Rowland HAL, Polya DA, Lloyd JR, Pancost RD (2006) Characterization of organic matter in a shallow, reducing, arsenic-rich aquifer, West Bengal. Org Geochem 37:1101–1114

Smedley PL, Kinniburgh DG (2002) A review of the source, behavior and distribution of arsenic in natural waters. Appl Geochem 17:517–568

Wadia DN (1975) Geology of India. Tata McGraw-Hill, New Delhi

World Health Organization (2004) Guidelines for drinking-water quality: recommendations, vol 1. World Health Organization

Chapter 23
Groundwater Arsenic in Nepal: Occurrence and Temporal Variation

T. H. Brikowski, L. S. Smith and A. Neku

Abstract In Nepal, over two million people are exposed to excessive natural arsenic (10–1500 ppb) in groundwater. The majority of these people live in the agricultural Terai region, on the edge of Ganges floodplain at the base of the Himalayan foothills. The remainder are exposed via deep wells in the Kathmandu Valley in a primarily urban setting. Tube wells down to 50 m in the Terai commonly exhibit cyclical, temporally correlated variation in dissolved arsenic, iron, and other species. In Nawalparasi, the most arsenic-affected district, these wells tap thin (2 m) gray sand aquifers embedded in a thick (>50 m) sequence of organic clays. Monsoon recharge refreshes these aquifers, temporarily minimizing dissolved arsenic concentrations. Post-monsoon, average groundwater compositions exhibit increasing water–rock interaction with time (increasing TDS and cation exchange, forming increasingly Na-HCO^- waters) and increasing dissolved arsenic and iron. Collectively these observations strongly support a model of reductive mobilization of arsenic from adjacent clays into aquifers in the Terai, tempered by repeated flushing during periods of heavy precipitation. In Kathmandu Valley, moderately elevated arsenic (up to 150 ppb) may be leached from overlying silts and clays, but concentrations remain constant throughout the year. In the Terai, effective mitigation is challenging, depending primarily on well-switching (marking contaminated wells) and installation of household point-of-use filters. Mitigation in the urban setting will emphasize blending with clean surface water from mountain reservoirs.

Keyword Arsenic · Nepal · South Asia · Hydrology

T. H. Brikowski (✉)
Geosciences Department, The University of Texas at Dallas,
800 W. Campbell Rd., Richardson, TX 75080-3021, USA
e-mail: brikowski@utdallas.edu

L. S. Smith
Filters for Families, Denver, CO, USA

A. Neku
Association of Professional Geoscientists of Ontario, Toronto, Canada

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_23

23.1 Introduction

Groundwater arsenic poses a scattered but significant hazard in Nepal. This natural contamination was detected in the mid-1990s as concern spread following identification of severe contamination in West Bengal and Bangladesh in the 1980s (Mukherjee et al. 2006; Muehe and Kappler 2014). The earliest published reports of arsenicosis in Nepal appeared around 2000 (e.g., Tandukar et al. 2001), and initial testing indicated a sparse but clustered distribution of tube wells yielding arsenic well above the 50 ppb Nepalese standard (Neku and Tandukar 2003; Shrestha et al. 2004a). Two population groups are exposed to groundwater arsenic hazard in Nepal: (1) about 1 million people residing in the low-lying agricultural lands of the Terai near the border with India and (2) around 1 million people residing in the Kathmandu Valley (estimated from 2011 census). Fortunately the problem is concentrated in a few districts, and only 1.8% of over 1 million tube wells tested in the Terai by 2008 exceed the 50 ppb Nepal arsenic standard, while a net 5.3% exceeded the WHO guideline of 10 ppb (Malla et al. 2007; NASC/UNICEF 2007; NASC 2012). Mitigation via centralized arsenic removal plants has been relatively ineffectual, while point-of-use household filtration has been much more successful (NASC 2012). In some areas, piped gravity flow systems transmitting mountain recharge directly to some villages in the Terai was quite effective.

While hazard from arsenic is important, by far the greatest drinking water hazard in Nepal is pathogens, since only 35% of the population has access to basic sanitation (WHO Country Brief). Household filtration units are greatly beneficial in this situation by simultaneously and cost-effectively mitigating both pathogens and arsenic (Hussam et al. 2007).

In all cases in Nepal, the proximal source of groundwater arsenic seems to be the Late Tertiary to Quaternary silt and clay deposits (Dowling et al. 2002; Gurung et al. 2005), likely derived from arsenic-bearing Himalayan shales (Lower Siwalik, Smith et al. 2004; Guillot et al. 2015). Aqueous mobilization of the arsenic requires specific hydrochemical conditions, and it is the distribution of those conditions that leads to the strongly clustered nature of the groundwater arsenic hazard in Nepal. These conditions undergo prominent seasonal changes in the Terai (Suenaga et al. 2004; Brikowski et al. 2014), making it difficult to fully characterize the arsenic hazard in Nepal.

23.2 Setting

Groundwater arsenic occurrences in Nepal are spatially restricted or clustered, often in proximity to current or paleo-wetlands and organic overbank silts and clays. Such distribution is characteristic of Asian Arsenic Crisis regions lying outside the Ganges delta. A crucial task in arsenic hazard assessment in such settings is determining the spatial and temporal controls on arsenic distribution. In most of South Asia, the most practical criterion is the color of the aquifer material, where orange oxidized aquifers typically yield below-limit arsenic (McArthur et al. 2004). Such sands are common in deep aquifers in both Bangladesh and Nepal (DHPE 1999; van Geen et al. 2003, 2006; Nath et al. 2005), and close to surface streams in Nepal (Brikowski et al. 2014). Especially in Nepal, drilling and pumping costs preclude extensive switching to deeper wells. Marking of shallow contaminated wells has been successful in reducing exposure to arsenic in drinking water in the Terai.

Downstream along the Ganges floodplain, widespread arsenic-affected areas occur in the upper delta plain where extensive peat deposits are present (Bangladesh, West Bengal, McArthur et al. 2004). At a finer scale within that zone paleo-channels filled with overbank fines tend to exhibit increased shallow groundwater arsenic (Hoque et al. 2012). In the middle Ganges, e.g., Bihar, Northern India, groundwater arsenic is predominantly found in near-channel areas (Chakraborti et al. 2003; Kumar et al. 2010). In headwater portions of the Ganges floodplain (the Terai), elevated arsenic occurrences are strongly clustered between major antecedent rivers that penetrate the Great (crystalline) Himalaya (Fig. 23.1). Elevated groundwater arsenic in the Terai is found almost exclusively on the undisturbed peat-rich floodplain and Churia Hills alluvial fan in the foreland basin south of the Main Frontal Thrust (MFT, compare points north and south of the MFT, Fig. 23.2). Surficial aquifers here form from material eroded from the thrust wedge north of the MFT, the leading edge of which is composed of earlier floodplain and later debris fan sediments. These are the Siwalik Formation (Nakayama and Ulak 1999; Suresh et al. 2004), forming the Churia Hills in Nawalparasi, which rise up to a kilometer above the Terai. Strongly elevated groundwater arsenic is concentrated in materials sourced from the fine-grained Lower Siwalik Formation (Smith et al. 2004), comprised of Late Miocene meandering stream deposits formed during the initial uplift of the Himalaya (Yin et al. 2010; Upreti 1999; Huyghe et al. 2005).

23.3 Tube well Development

During the water decade, 1980–1990 and afterward, the United Nations and local government agencies encouraged developing countries in Asia to install millions of shallow and deep tube wells as an alternative to surface water that could provide pathogen-free drinking water. Groundwater pumping also increased greatly as a part of the Green Revolution in West Bengal (India) and Bangladesh in order to achieve food-grain sufficiency (Acharyya et al. 2000; Harvey et al. 2006). The tube wells were installed without testing for abiotic contaminants, and starting in the late 1980s, many of those tube wells were found to have arsenic concentrations greater than the WHO guideline of 10 ppb. In Nepal, over one million mostly private tube wells in the Terai have now been tested in successive blanket testing programs (see next section). In a few municipalities, deep wells were drilled to provide central water supply. These were limited to the Kathmandu Valley and some of the larger population centers of the Terai.

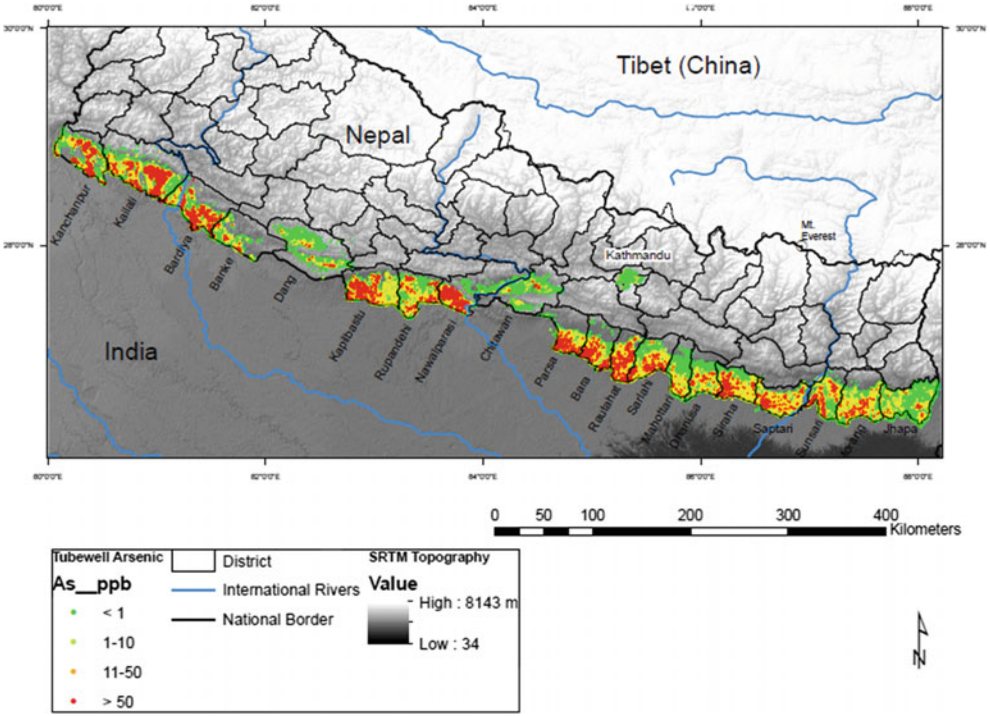


Fig. 23.1 Distribution of arsenic measured in tube wells, Terai, Nepal. Arsenic data from NASC (2012). Topography shaded to emphasize relief in MFT foreland

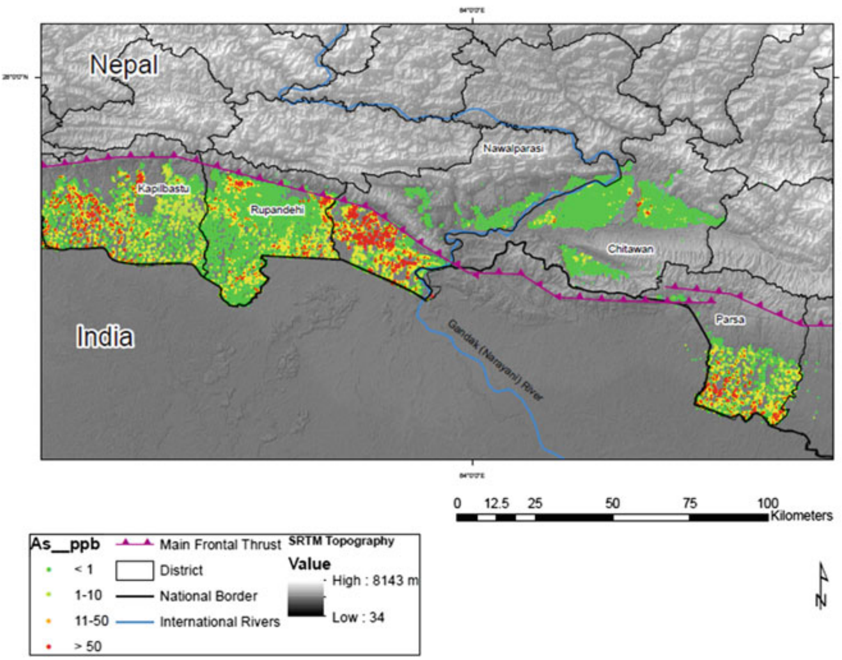


Fig. 23.2 Distribution of tube well arsenic in Nawalparasi and vicinity, Nepal. Note very few above-limit values are found north of the Main Frontal Thrust (arsenic data from NASC 2012)

23.4 Blanket Arsenic Testing

The provenance and grain-sized constraints on the distribution of elevated groundwater arsenic in the Terai cause occurrences to be strongly clustered (Fig. 23.1). The district most affected by this is Nawalparasi (Fig. 23.3), about 150 km WSW of Kathmandu. Initial blanket testing of some 18,000 tube wells (about 16% of existing Terai wells at the time; Environmental and Public Health Organization “ENPHO” of Nepal, Shrestha et al. 2004a) revealed this pattern in the early 2000s. A 2007 survey primarily funded by UNICEF increased the total number of tested wells in the Terai to about 640,000, confirming the clustered pattern of groundwater arsenic in great detail (Malla et al. 2007; NASC/UNICEF 2007). By 2008, the total number of sampled wells exceeded 1 million (NASC 2012). Of these, 5.3% were found to exceed 10 ppb arsenic (WHO guideline), and 1.7% exceeded 50 ppb (Nepal standard). Well, usage was also recorded for these sites, and out of 15.9 million individuals using groundwater in the Terai, about 10% are exposed to arsenic concentrations above the WHO guideline (979,000 exposed to 10–50 ppb arsenic, 328,000 to >50 ppb).

Initially, 12% of wells tested in that most affected district of Nawalparasi were found to exceed the Nepalese arsenic standard of 50 ppb (31,676 wells), and a total of 29% exceed 10 ppb WHO guideline. Within the most strongly affected districts,

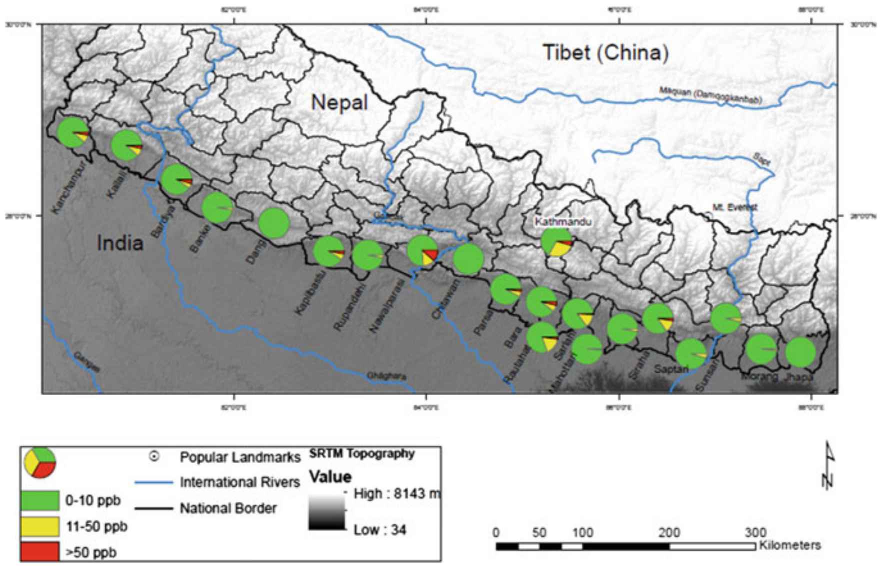


Fig. 23.3 Arsenic pie chart classification for Terai districts of Nepal (NASC 2012) and Kathmandu Valley (after Shrestha et al. 2013; Gurung et al. 2007; Chapagain et al. 2009). The most arsenic-affected districts (red and yellow) are Nawalparasi and Kathmandu

some local areas (Village Development Council or VDC's) were severely impacted; e.g., in Ramgram municipality, 44% of wells sampled exceeded 50 ppb arsenic, and informal surveys in that area indicate 30% of the population exhibit symptoms of arsenicosis (Smith 2004). Arsenic impacts are more widespread in West Bengal and Bangladesh (delta regions of the Ganges), where 77–93% of wells in some districts exhibit above-limit arsenic, and 15–25% of the population exhibit severe arsenicosis (skin lesions, Chowdhury et al. 2000).

Concern over Terai groundwater arsenic inspired studies of potential groundwater arsenic contamination in Kathmandu Valley. Groundwater pumping has grown steadily since the mid-1980s and now comprises half of the water supply in the valley. Early studies identified mild arsenic contamination of these supply wells (Khatiwada et al. 2002; JICA/ENPHO 2005). Later studies clarified that moderately elevated arsenic is restricted to the deeper alluvial aquifer (about one-third of deep samples exceed 10 ppb, maximum about 145 ppb; Figs. 23.1 and 23.3 and Shrestha et al. 2013; Gurung et al. 2007; Chapagain et al. 2009). In addition, the shallow aquifer exhibited alarming levels of pathogens and nutrients (Warner et al. 2008).

23.5 Hydrogeology

Hydrologic activities by the Nepalese government necessarily focus on surface water resources and flood hazard, primarily managed by the Department of Hydrology and Meteorology, Ministry of Population and Environment. Subsurface hydrogeology is primarily evaluated by the Department for Water Supply and Sewerage (DWSS). Prior to 2000, this was handled by the Groundwater Resources Development Board, Ministry of Irrigation.

23.6 Terai

The Terai, lying at the base of the Himalayan foothills, is subject to relatively rapid clastic sedimentation where antecedent rivers emerge from the mountains and relatively slow peat swamp deposition between those clastic fans. Shallow usable aquifers tend to be isolated sand channels within thick organic clays.

As in much of South Asia, arsenic exposure in the Terai is primarily via groundwater extracted by shallow tube well, most of which are ≤ 30 m deep (e.g., 98% of UNICEF-sampled wells in Nawalparasi). The surficial aquifers of the Terai are uniquely thin gray sands (channel deposits, typically ≤ 2 m) hosted by quite thick organic clays (overbank deposits, $\gg$50 m, Neku 2011; Williams et al. 2004); in Bangladesh clays are typically ≤ 10 m thick (McArthur et al. 2001; Dhar et al. 2008). The continuity of these near-surface aquifers in Nawalparasi is quite variable. Near the base of the Churia Hills at Sunawal, short-duration tracer tests found some aquifers continuous up to a kilometer north–south (perpendicular to the range front), and maximum local groundwater velocities were meters to tens of meters per day (pers. commun., L. S. Smith 2005). Other nearby aquifers exhibited one to two orders of magnitude lower velocity. All of these aquifers appear to be braided to meandering stream channel deposits and therefore tend to be narrow in the direction parallel to the range front. Areas downstream from the thickest exposures of Lower Siwalik Formation in Nawalparasi exhibit the highest concentrations of arsenic (Fig. 23.4).

Total thickness of clay deposits has a strong impact on groundwater arsenic concentrations in the Terai, in addition to the provenance effects described above. The thrust margin and Himalayan foreland basin allow rapid accumulation of sediment in Nepal's Terai. Consequently, extensive wetlands are formed, dominated by overbank fine sediments to form the thick organic clays. These paleo-wetlands are interspersed between the coarser megafans deposited by the antecedent rivers (Gupta 1997). The resulting inverse grading yields a wedge of fine sediments thinning southwestward away from the MFT, giving way to much coarser sediments (Fig. 23.4) at the Nepal–India border. Elevated arsenic is correlated with the thickness of these clays, with values up to 800 ppb where clay thickness and percentage of clay in the penetrated section are large (Figs. 23.4 and 23.7). Where surficial clay thickness is less than 10 m near the southern border with India, arsenic drops below 50 ppb (Shrestha et al. 2004b). A sampling bias appears closest to the Churia Hills where the clay wedge thickness is well over 50 m, yet groundwater arsenic concentrations in shallow tube wells are typically ≤ 50 ppb. In this area, wells are typically shallow (mean depth 18 m) because no deep aquifers are found; as a result, wells in this area generally don't penetrate to depths (>20 m) where arsenic typically peaks in this region.

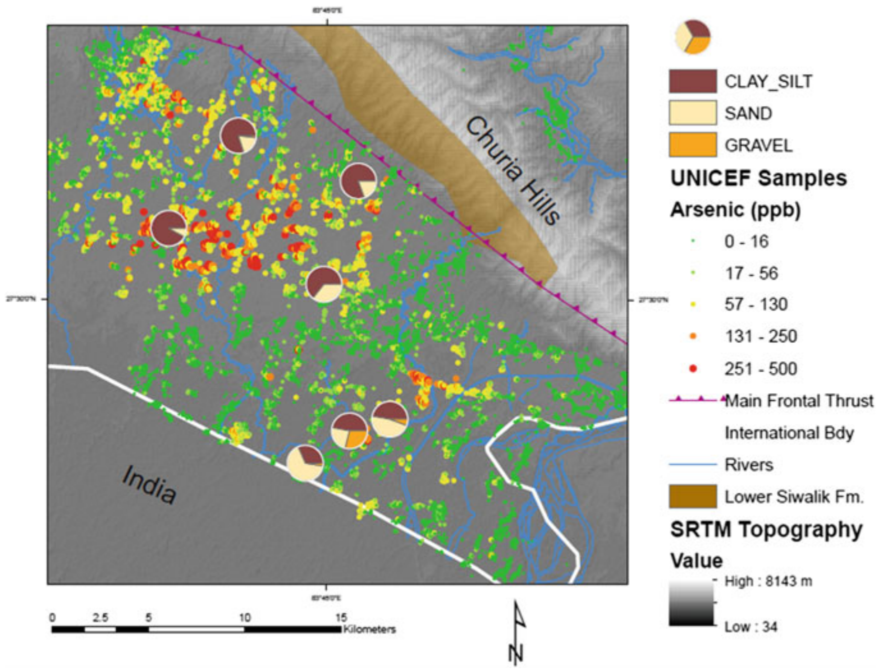


Fig. 23.4 Comparison of ENPHO-derived tube well lithostratigraphy (Shrestha et al. 2004b) and As concentrations NASC (2012). Fraction of clay (dark brown) in penetrated thickness decreases southward away from Churia Hills. Detailed well logs available in Brikowski et al. (2014)

An important but poorly known recharge zone occurs at the base of the foothills in many areas (the boulder or "Bhabhar" zone, Rao and Pathak 1996), composed of debris-flow boulders in a fine matrix. Depth to water in the Bhabhar zone is highly variable seasonally (from 3 to 30 m, Baker 2004), and stream discharge often decreases substantially in this zone as streams emerge from the Churia Hills. This recharge likely supplies the deeper aquifers (10 m thick sand-gravel at around 100 m depth) used for municipal supply in a few locations in the Terai (e.g., Parasi municipal well).

Subsurface stratigraphy in this area is not well known, but scattered studies have been carried out. These include early USAID-funded studies (summarized in Rao and Pathak 1996), mostly unpublished logs of cuttings from 2% of the ENPHO/ Nepal Red Cross Society-sampled wells (NRCS, Shrestha et al. 2004b), detailed lithostratigraphy of four boreholes by the USGS, including one corehole (Williams et al. 2004), and a detailed effort using clustered piezometers (Brikowski et al. 2014; Neku et al. 2004; Neku 2011). Sediment analyses and lithologs for four 20–30 m deep wells in Nawalparasi described by Gurung et al. (2005), indicate 70–90% silt-clay in the section with little variation in sediment chemistry, and highly elevated dissolved arsenic concentrations in the fine-grained and organic-rich horizons. In the Terai, a few wells penetrate to 100 m (e.g., 6 out of

31,676 UNICEF-sampled wells in Nawalparasi), generally serving as central water supply in larger municipalities such as Parasi. Williams et al. (2004) note that the Parasi water supply well penetrates to 90 m depth, about 70% of which is clay, producing water with <5 ppb arsenic from 5 m thick sand-gravel aquifers at the bottom of the well.

23.7 Kathmandu Valley

The Kathmandu Valley is a classic alpine alluvial basin, floored by the Paleozoic and pre-Cambrian Kathmandu Complex (Shrestha et al. 1996). Above these are coarse alluvial fan deposits of Plio-Pleistocene age that form the deep aquifer in the valley (Lukundol/Bagmati Formation, Pandey and Kazama 2011). Above this is the Kalimati clay, forming a thick, organic-rich aquitard ("clay", Fig. 23.5). The clay is overlain by extensive alluvial fan and lacustrine deposits (Sakai et al. 2016) forming the shallow aquifer. Warner et al. (2008) note that low iron content and salinity of the shallow aquifer waters make it preferable for many users, despite their high bacteria and nutrient levels. Extraction from both aquifers appears to exceed recharge (average drawdowns of 8 m between 2000 and 2005, Gautam and Prajapati 2014). Gurung et al. (2007) investigated the trace element chemistry of these units, concluding arsenic content was much higher in the clay aquitard and is the likely source of dissolved arsenic in the deep aquifer. Low oxidation–reduction

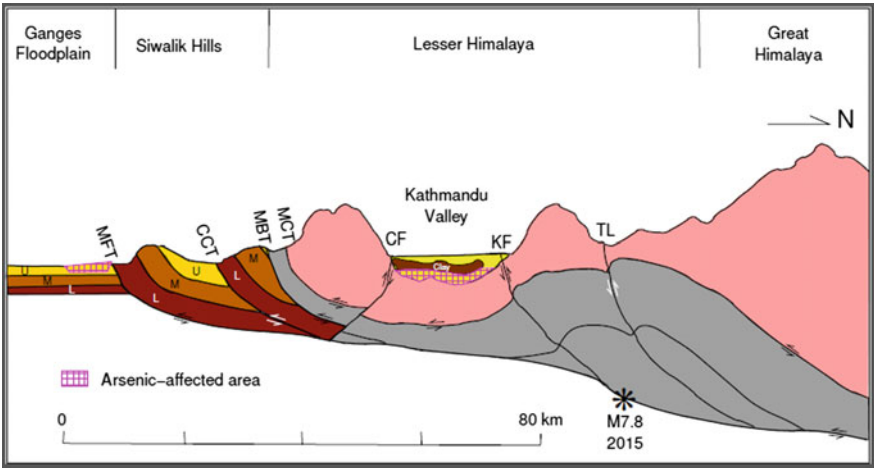


Fig. 23.5 Schematic N-S cross section through the Himalaya and including Kathmandu Valley. Magenta hatching indicates areas of high groundwater arsenic, found only in deep Kathmandu Valley alluvium (beneath thick clays) and on the Ganges floodplain in shallow subsurface deposits derived from exposures of Lower Siwalik. "L-M-U" are Lower, Middle, and Upper Siwalik Formation, respectively. The projected focus of 2015 earthquake shown by asterisk. Adapted from Sakai et al. (2016) and Upreti (1999)

potential and high iron content in the deep aquifer waters suggest that arsenic mobilization is via a reductive dissolution/desorption processes (Shrestha et al. 2013), similar to those responsible for mobilization in the Terai sediments.

23.8 Major Chemical Features

Groundwater arsenic in Nepal exhibits many of the features common in the Asian Arsenic Crisis area. These include a peak in arsenic concentrations at about 20 m depth (dashed line, Fig. 23.6), and decoupled spatial relationship with a shallower

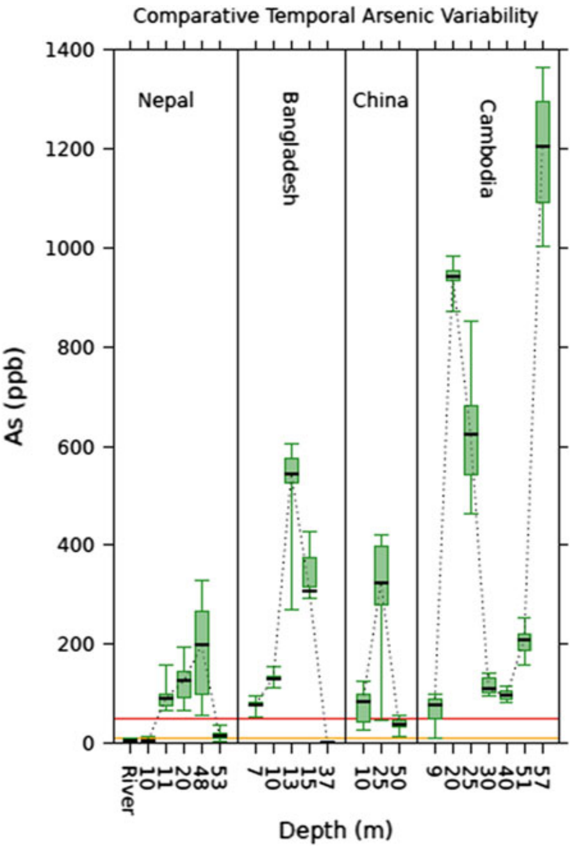


Fig. 23.6 Comparison of groundwater arsenic depth and temporal variability, Nepal and other areas. Box and whiskers show temporal variation of arsenic observed in each area. The dotted line shows approximate depth distribution of (median) arsenic, generally peaking at 20 m depth. Red line indicates Nepal arsenic limit (50 ppb), yellow indicates WHO guideline (10 ppb). In Bangladesh, an oxygenated (orange) sand aquifer is present below 30 m depth, yielding minimal arsenic. In Cambodia, arsenic is believed to be flushed from shallow clays into deeper sandy aquifers. Data sources are Nepal (Brikowski et al. 2014), Bangladesh (Dhar et al. 2008), China (Duan et al. 2015), and Cambodia (Polizzotto et al. 2008)

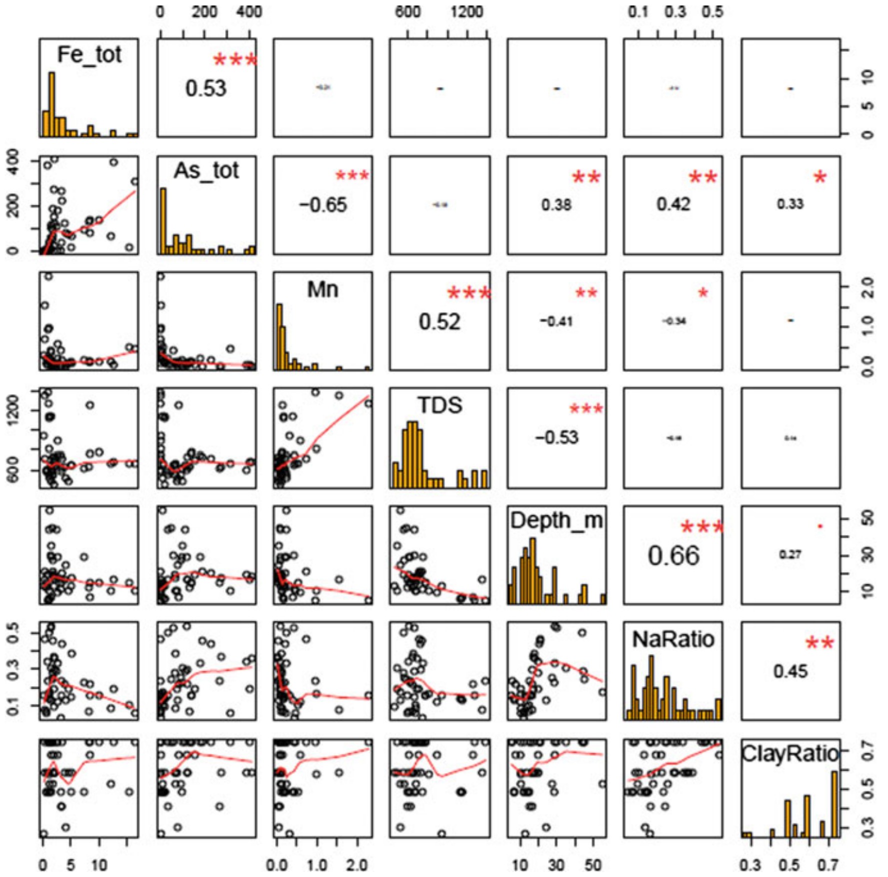


Fig. 23.7 Spearman correlation matrix, major species of interest for arsenic mobilization, Nawalparasi wells, Nepal Terai. Upper triangle: Confidence levels shown in upper right corner: triple asterisk 99.9%, double asterisk 99.0% (critical $\rho = 0.45$), single asterisk 95.0%, and filled circle 90.0%. Spearman *R* given in center of the cell, 49 total samples. Diagonal shows histogram of parameter distribution. Lower triangle shows scatter plot of corresponding two variables. "As.tot" is total arsenic; "NaRatio" is Na+K cation ternary coordinate; and "ClayRatio" is estimated fraction (abundance) of clay in the borehole, based on average for that VDC. These two-tailed values computed using *R* statistics package (R Core Team 2013)

peak in dissolved iron composition. In the Terai, redox-sensitive species including iron, arsenic, and to some degree sulfate correlate well in time and space (Fig. 23.7).

23.9 Temporal Variability

The thin, locally recharged, near-surface aquifers tapped by most of the tube wells in the Terai encourage cyclical variability in dissolved species including arsenic. The strongly monsoonal climate in Nepal's Terai yields very wet conditions in the usual June–September rainy season, followed by an extended dry season, ending in a two month period (April–May) of almost no rain. The most direct effect is typically a 2 m variation in head in the wells over the course of the year (Brikowski et al. 2014). Fifty meter deep aquifers show one-tenth that magnitude of head variability. In general, the 20 m deep aquifers show a decreasing trend in total dissolved solids (TDS) after head in the aquifers reaches a maximum, with total variation in TDS ranging up to 300 ppm. These variations are consistent with a simple monsoonal flushing model, whereby relatively oxygenated and low-salinity freshwater recharge enters the aquifers, minimizing arsenic concentrations. After the recharge events, pore waters slowly equilibrate with the surrounding aquifer, become more reducing, and exhibit time and depth-increasing indications of cation exchange with clays. Simultaneously, redox-sensitive dissolved species such as iron and arsenic steadily increase in concentration as water levels fall in the shallow aquifers after monsoon ends (Brikowski et al. 2014; Yadav et al. 2015). The implication is that the fresh monsoon recharge re-stabilizes iron oxy-hydroxides that adsorb arsenic into the aquifer matrix. Return to strongly reducing conditions by the end of the dry season begins to dissolve the iron oxy-hydroxides again, mobilizing iron and arsenic into the groundwater. Effects of this cyclicity can be observed at the surface by prominent iron staining of well pads toward the end of the dry season in most areas of the Terai (Neku 2011). Similar coupling between cyclical water level fluctuation and arsenic has been observed in many other areas (Fig. 23.6), typically resulting in negative correlation between arsenic concentrations and water levels; however, studies in Cambodia (Polizzotto et al. 2008) and China (Duan et al. 2015) find the opposite trend, concluding that rainy season recharge flushes arsenic from shallow clays (released by microbial reduction), increasing arsenic concentrations in underlying aquifers. It should be noted that studies that filter samples at the wellhead tend to find much greater temporal variation of arsenic. Johnston et al. (2015) working in the Terai observed higher concentrations of As in borehole sediments immediately above the water table minimum, suggesting seasonal downward transport and temporary trapping of arsenic at those depths. In all these cases, the hydrologic setting of the shallow aquifers is a key determinant of arsenic mobility, as well as their spatial relationship to the organic clays that appear to supply the dissolved arsenic.

In the Kathmandu Valley, only minimal seasonal variation has been reported in wells with arsenic above 10 ppb (Shrestha et al. 2013; Chapagain et al. 2010). These wells are deep and would be highly unlikely to be rapidly influenced by surficial conditions.

23.10 Chemical Influence of Clays

In the Terai, strong correlations between chemical parameters and clay abundance highlight the major role played by the intrafan organic clays in arsenic mobilization. The clay's effect on redox conditions is the primary mechanism for this control. For instance, lack of correlation between dissolved metals and TDS in a study of single-visit well samples (Brikowski et al. 2005) supports the concept that something other than simple rock reaction controls As concentrations (Fig. 23.7). The very strong correlation (99.9% certain) between Na+K total cations suggests a flow-path-length dependent mechanism, and very strong correlation between Na+K and clay abundance indicates this mechanism depends on net exposure to clay minerals. The very strong correlation between As and Fe is consistent with redox-controlled mobilization (Schaefer et al. 2017). Strong correlation (95–99% certain) between arsenic concentration, clay abundance, and well depth implies strong control by aquifer lithology and strong influence by clay abundance on redox state.

23.11 Summary

The population of Nepal is exposed to two diverse groundwater arsenic hazards: scattered clusters of shallow tube wells with up to 1500 ppb arsenic in the Terai (Ganges floodplain) and a few deep wells in the Kathmandu Valley with up to 150 ppb arsenic. To further complicate evaluation of the hazard, the relatively isolated shallow aquifers of the Terai can exhibit profound temporal variability in arsenic content. The clusters of high-arsenic wells in the Terai correlate primarily with fine-grained source material (reworked Lower Siwalik) deposited in thick sequences of organic clay and located between alluvial megafans emerging from the Himalaya. The second arsenic hazard in Nepal is the deep wells of the Kathmandu Valley, which have become increasingly important as a relatively clean source of water for that rapidly growing city. Mitigation of these hazards has encountered variable success, as different approaches are attempted subject to the societal and environmental complications endemic to the region. In the Terai, a moderately successful program of well-switching (marking contaminated wells) is underway. This approach may be insufficient given the temporal variability of arsenic observed in typical tube wells. Instead, installation of household filters seems to have been the most successful approach in the Terai. Deep wells and major arsenic removal projects in the Terai are not economically feasible at this time. In Kathmandu Valley, arsenic removal is possible, but may be more simply managed by year-round blending with uncontaminated well water and surface water from mountain reservoirs. The latter will be the primary option when the "mega-water diversion" project from Melamchi Khola is completed by the end of this decade.

Acknowledgements The original research summarized in this review was supported by NSF Grant INT-0331798 (Brikowski) and Fulbright Senior Scientist (Smith) and Fulbright Visiting Scientist (Shrestha) grants. Field support provided by Filters for Families INGO, Kathmandu, Nepal. Travel supported by Geological Society of America Student Research Grant (Neku), drilling supported by WaterAid Nepal, chemical analysis supported by UNICEF/DWSS. Tracer tests supported by UNDP SGP Grant (Smith). UTD Geosciences Contribution #1308.

References

Acharyya K, Lahiri S, Raymahashay BC, Bhowmik A (2000) Cases and solutions: arsenic toxicity of groundwater in parts of the Bengal basin in India and Bangladesh: the role of quaternary stratigraphy and Holocene sea-level fluctuation. Environ Geol 39:1127–1137. URL: http://link.springer-ny.com/link/service/journals/00254/bibs/0039010/00391127.htm

Baker T (2004) Deep tube well study Nepal 2003–2004. Technical report. Water Aid Nepal, Kathmandu, Nepal

Brikowski TH, Leybourne MI, Shrestha SD, Bhattacharya P, Neku A, Smith L (2005) Geochemical indicators of groundwater arsenic mobilization mechanisms in the Ganges floodplain of Nepal, vol 38, No 8. Geological Society of America Abstracts with Programs

Brikowski TH, Neku A, Shrestha SD, Smith LS (2014) Hydrologic control and temporal variability of groundwater arsenic in the Ganges floodplain of Nepal. J Hydrol 518. https://doi.org/10.1016/j.jhydrol.2013.09.021 (Special Issue: Arsenic in hydrological processes: Speciation, bioavailability and management)

Chakraborti D, Mukherjee SC, Pati S, Sengupta MK, Rahman MM, Chowdbury UK, Lodh D, Chanda CR, Chakraborti AK, Basu GK (2003) Arsenic ground-water contamination in Middle Ganga Plain, Bihar, India: a future danger? Environ Health Perspect 111:1194–1201. URL: http://ehpnet1.niehs.nih.gov/docs/2003/5966/abstract.html

Chapagain SK, Shrestha S, Nakamura T, Pandey VP, Kazama F (2009) Arsenic occurrence in groundwater of Kathmandu Valley, Nepal. Desalin Water Treat 4:248–254 (2nd International conference on wastewater treatment in small communities (SmallWat07), Seville, Spain, 11–15 Nov 2007)

Chapagain SK, Pandey VP, Shrestha S, Nakamura T, Kazama F (2010) Assessment of deep groundwater quality in Kathmandu Valley using multivariate statistical techniques. Water Air Soil Pollut 210:277–288. https://doi.org/10.1007/s11270-009-0249-8

Chowdhury U, Biswas B, Chowdhury T, Samanta G, Mandal B, Basu G, Chanda C, Lodh D, Saha K, Mukherjee S, Roy S, Kabir S, Quamruzzaman Q, Chakraborti D (2000) Groundwater arsenic contamination in Bangladesh and West Bengal, India. Environ Health Perspect 108:393–397. https://doi.org/10.2307/3454378

Dhar R, Zheng Y, Stute M, van Geen A, Cheng Z, Shanewaz M, Shamsudduha M, Hoque M, Rahman M, Ahmed K (2008) Temporal variability of groundwater chemistry in shallow and deep aquifers of Araihazar, Bangladesh. J Contam Hydrol 99:97–111. https://doi.org/10.1016/j.jconhyd.2008.03.007

DHPE (1999) Groundwater studies for arsenic contamination in Bangladesh. Main (project) report, Bangladesh Department of Public Health Engineering, British Geological Survey, London, England. URL: http://www.bgs.ac.uk/arsenic/Bangladesh/

Dowling CB, Poreda RJ, Basu AR, Peters SL (2002) Geochemical study of arsenic release mechanisms in the Bengal Basin groundwater. Water Resour Res 38:18. https://doi.org/10.1029/2001wr000968

Duan Y, Gan Y, Wang Y, Deng Y, Guo X, Dong C (2015) Temporal variation of groundwater level and arsenic concentration at Jianghan Plain, central China. J Geochem Explor 149:106–119. https://doi.org/10.1016/j.gexplo.2014.12.001

Gautam D, Prajapati RN (2014) Drawdown and dynamics of groundwater table in Kathmandu Valley, Nepal. Open Hydrol J 8:17–26. URL: http://benthamopen.com/contents/pdf/TOHYDJ/TOHYDJ-8-17.pdf

Guillot S, Garçon M, Weinman B, Gajurel A, Tisserand D, France-Lanord C, Geen Av, Chakraborty S, Huyghe P, Upreti BN, Charlet L (2015) Origin of arsenic in late Pleistocene to Holocene sediments in the Nawalparasi district (Terai, Nepal). Environ Earth Sci 74:2571–2593. https://doi.org/10.1007/s12665-015-4277-y

Gupta S (1997) Himalayan drainage patterns and the origin of fluvial megafans in the Ganges foreland basin. Geology 25:11–14. https://doi.org/10.1130/0091-7613(1997)025<0011:HDPATO>2.3.CO;2

Gurung JK, Ishiga H, Khadka MS (2005) Geological and geochemical examination of arsenic contamination in groundwater in the Holocene Terai Basin, Nepal. Environ Geol 49:98–113. https://doi.org/10.1007/s00254-005-0063-6

Gurung JK, Ishiga H, Khadka MS, Shrestha NR (2007) The geochemical study of fluvio-lacustrine aquifers in the Kathmandu Basin (Nepal) and the implications for the mobilization of arsenic. Environ Geol 52:503–517. https://doi.org/10.1007/s00254-006-0483-y

Harvey C, Ashfaque K, Yu W, Badruzzaman A, Ali M, Oates P, Michael H, Neumann R, Beckie R, Islam S, Ahmed M (2006) Groundwater dynamics and arsenic contamination in Bangladesh. Chem Geol 228:112–136. https://doi.org/10.1016/j.chemgeo.2005.11.025 (Annual conference of the Soil-Science-Society-of-America, Denver, CO, 03 Nov 2003)

Hoque M, McArthur J, Sikdar P (2012) The palaeosol model of arsenic pollution of groundwater tested along a 32 km traverse across West Bengal, India. Sci Total Environ 431:157–165. https://doi.org/10.1016/j.scitotenv.2012.05.038

Hussam A, Munir AKM, Alauddin M, Hossain ZA, Khan AH, Chusuei CC (2007) A simple and effective arsenic filter based on composite iron matrix: development and deployment studies for groundwater of Bangladesh. J Environ Sci Health Part A 42:1869–1878. https://doi.org/10.1080/10934520701567122

Huyghe P, Mugnier JL, Gajurel AP, Delcaillau B (2005) Tectonic and climatic control of the changes in the sedimentary record of the Karnali River section (Siwaliks of western Nepal). Island Arc 14:311–327. https://doi.org/10.1111/j.1440-1738.2005.00500.x

JICA/ENPHO (2005) Arsenic vulnerability in groundwater resources in Kathmandu Valley. Final report, Kathmandu

Johnston SG, Diwakar J, Burton ED (2015) Arsenic solid-phase speciation in an alluvial aquifer system adjacent to the Himalayan forehills, Nepal. Chem Geol 419:55–66. https://doi.org/10.1016/j.chemgeo.2015.10.035

Khatiwada NR, Takizawa S, Tran TVN, Inoue M (2002) Groundwater contamination assessment for sustainable water supply in Kathmandu Valley, Nepal. Water Sci Technol 46(147–154):34

Kumar M, Kumar P, Ramanathan AL, Bhattacharya P, Thunvik R, Singh UK, Tsujimura M, Sracek O (2010) Arsenic enrichment in groundwater in the middle Gangetic Plain of Ghazipur District in Uttar Pradesh, India. J Geochem Explor 105:83–94. https://doi.org/10.1016/j.gexplo.2010.04.008

Malla P, Joshi A, Taylor J (2007) The state of Arsenic in Nepal. Technical report. NASC (Nepal Arsenic Steering Committee)/UNICEF, Kathmandu, Nepal, 116 pp and CD-ROM

McArthur JM, Ravenscroft P, Safiulla S, Thirlwall MF (2001) Arsenic in ground-water; testing pollution mechanisms for sedimentary aquifers in Bangladesh. Water Resour Res 37:109–118. https://doi.org/10.1029/2000WR900270

McArthur J, Banerjee D, Hudson-Edwards K, Mishra R, Purohit R, Ravenscroft P, Cronin A, Howarth R, Chatterjee A, Talukder T, Lowry D, Houghton S, Chadha D (2004) Natural organic matter in sedimentary basins and its relation to arsenic in anoxic ground water: the example of West Bengal and its worldwide implications. Appl Geochem 19:1255–1293. https://doi.org/10.1016/j.apgeochem.2004.02.001

Muehe EM, Kappler A (2014) Arsenic mobility and toxicity in south and south-east Asia a review on biogeochemistry, health and socio-economic effects, remediation and risk predictions. Environ Chem 11:483–495. https://doi.org/10.1071/EN13230

Mukherjee A, Sengupta MK, Hossain MA, Ahamed S, Das B, Nayak B, Lodh D, Rahman MM, Chakraborti D (2006) Arsenic contamination in groundwater: a global perspective with emphasis on the Asian scenario. J Health Popul Nutr 24(142–163):154

Nakayama K, Ulak PD (1999) Evolution of fluvial style in the Siwalik Group in the foothills of the Nepal Himalaya. Sediment Geol 125:205–224. https://doi.org/10.1016/s0037-0738(99)00012-3

NASC (2012) The state of Arsenic in Nepal-2011. Technical report. Nepal National Arsenic Steering Committee/National Red Cross Society, Kathmandu, Nepal (Draft available 2012, scheduled for official release in 2017)

NASC/UNICEF (2007) Report on blanket tube well testing in Sunsari, Bara, Dhanusha, Rupandehi, Kailali & Kanchanpur Districts-2007. Technical report. Nepal Arsenic Study

Committe/UNICEF, Kathmandu. URL: http://un.org.np/sites/default/files/report/tid_68/2010-10-01-UNICEF-Arseinic-Water.pdf (Prepared by Genesis Consultancy, Ltd.)

Nath B, Berner Z, Mallik SB, Chatterjee D, Charlet L, Steuben D (2005) Characterization of aquifers conducting groundwaters with low and high arsenic concentrations: a comparative case study from West Bengal, India. Mineral Mag 69:841–854. https://doi.org/10.1180/0026461056950292

Neku A (2011) Hydrogeological investigation of arsenic contaminated groundwater in Nawalparasi, Nepal. PhD dissertation, Geosciences Dept., U. Texas-Dallas

Neku A, Tandukar N (2003) An overview of arsenic contamination in groundwater of Nepal and its removal at household level. J Physique IV 107:941–944

Neku A, Tandukar N, Yokota H (2004) Relationship of arsenic with other key geo-chemical parameters in groundwater of Nawalparashi/Nepal. In: Smith LS (ed) Proceedings of the NSF-fulbright workshop on groundwater arsenic in Nepal, WaterAid Nepal, Filters for Families, Kathmandu, Nepal

Pandey VP, Kazama F (2011) Hydrogeologic characteristics of groundwater aquifers in Kathmandu Valley, Nepal. Environ Earth Sci 62:1723–1732. https://doi.org/10.1007/s12665-010-0667-3

Polizzotto ML, Kocar BD, Benner SG, Sampson M, Fendorf S (2008) Near-surface wetland sediments as a source of arsenic release to ground water in Asia. Nature 454:505–508. https://doi.org/10.1038/nature07093

R Core Team (2013) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org/

Rao GK, Pathak D (1996) Hydrogeological conditions in the Terai plain of Nawalparasi District, Lumbini zone, Nepal, with special reference to groundwater recharge. J Appl Hydrol 9:69–75

Sakai H, Fujii R, Sugimoto M, Setoguchi R, Paudel MR (2016) Two times lowering of lake water at around 48 and 38 ka, caused by possible earthquakes, recorded in the Paleo-Kathmandu lake, central Nepal Himalaya. Earth Planets Space 68:1–10. https://doi.org/10.1186/s40623-016-0413-5

Schaefer MV, Guo X, Gan Y, Benner SG, Griffin AM, Gorski CA, Wang Y, Fendorf S (2017) Redox controls on arsenic enrichment and release from aquifer sediments in central Yangtze River Basin. Geochim Cosmochim Acta 204:104–119. https://doi.org/10.1016/j.gca.2017.01.035

Shrestha SD, Karmacharya R, Rao GK (1996) Estimation of groundwater resources in Kathmandu Valley, Nepal. J Groundwater Hydrol 38:29–40. https://doi.org/10.5917/jagh1987.38.29

Shrestha BR, Whitney JW, Shrestha KB (eds) (2004a) State of arsenic in Nepal - 2003. Environment and Public Health Organization-National Arsenic Steering Committee (Nepal), USGS, Kathmandu (Includes CD-ROM)

Shrestha SD, Brikowski TH, Smith LS, Shei TC (2004b) Grain size constraints on arsenic concentration in shallow wells of Nawalparasi, Nepal. In: Smith LS (ed) Fulbright-NSF workshop on groundwater arsenic in Nepal, U.S. Fulbright Fellowship Program, Kathmandu, Nepal

Shrestha SM, Rijal K, Pokhrel K (2013) Arsenic contamination in the deep and shallow groundwater of Kathmandu Valley, Nepal. Sci World 11. https://doi.org/10.3126/sw.v11i11.8548

Smith LSS (ed) (2004) Fulbright-NSF workshop on groundwater arsenic in Nepal, U.S. Fulbright Fellowship Program, Kathmandu, Nepal

Smith LSS, Shrestha SD, Brikowski TH, Shei TC (2004) Abundant arsenic sources are discovered in the Nepal Himalayas. Nepal J Geol 8

Suenaga K, Ganzawa N, Mato Y, Neku A, Tandukar N, Wakabayashi M (2004) Report on hydrogeological investigation at Kunuwar Village in Nepal. In: The 9th forum on arsenic contamination of groundwater in Asia. Asia Arsenic Network and Research Group for Applied Geology, Yokohama, Japan

Suresh N, Ghosh SK, Kumar R, Sangode SJ (2004) Clay-mineral distribution patterns in late Neogene fluvial sediments of the Subathu sub-basin, central sector of Himalayan foreland basin: implications for provenance and climate. Sediment Geol 163:265–278. https://doi.org/10.1016/j.sedgeo.2003.07.006

Tandukar N, Bhattacharya P, Mukherjee AB et al (2001) Preliminary assessment of arsenic contamination in groundwater in Nepal. In: Proceedings of the international conference on arsenic in the Asia-Pacific region: managing arsenic for our future. CSIRO-Land and Water, Adelaide, South Australia, pp 103–105

Upreti B (1999) An overview of the stratigraphy and tectonics of the Nepal Himalaya. J Asian Earth Sci 17:577–606. https://doi.org/10.1016/s1367-9120(99)00047-4

van Geen A, Zheng Y, Versteeg R, Stute M, Horneman A, Dhar R, Steckler M, Gelman A, Small C, Ahsan H, Graziano JH, Hussain I, Ahmed KM (2003) Spatial variability of arsenic in 6000 tube wells in a 25 km^2 area of Bangladesh. Water Resour Res 39:1140. https://doi.org/10.1029/2002WR001617

van Geen A, Zheng Y, Cheng Z, Aziz Z, Horneman A, Dhar R, Mailloux B, Stute M, Weinman B, Goodbred S, Seddique A, Hoque M, Ahmed K (2006) A transect of groundwater and sediment properties in Araihazar, Bangladesh: further evidence of decoupling between As and Fe mobilization. Chem Geol 228:85–96. https://doi.org/10.1016/j.chemgeo.2005.11.024

Warner NR, Levy J, Harpp K, Farruggia F (2008) Drinking water quality in Nepal's Kathmandu Valley: a survey and assessment of selected controlling site characteristics. Hydrogeol J 16:321–334. https://doi.org/10.1007/s10040-007-0238-1

Williams VS, Whitney JW, Breit JW, George N, Yount JC, Amatya SMC (2004) Preliminary observations on the geology and geochemistry of arsenic-bearing sediments in Nawalparasi District, Nepal. In: Kansakar DR (ed) Summary final report of arsenic testing and finalization of groundwater legislation project and proceeding of the seminar on arsenic study in groundwater of Terai, USGS/GWRDP/The World Bank. World Bank, World Bank, pp 73–83

Yadav IC, Devi NL, Singh S (2015) Spatial and temporal variation in arsenic in the groundwater of upstream of Ganges River Basin, Nepal. Environ Earth Sci 73:1265–1279. https://doi.org/10.1007/s12665-014-3480-6

Yin A, Dubey C, Kelty T, Webb A, Harrison T, Chou C, Clrier J (2010) Geologic correlation of the Himalayan orogen and Indian craton: Part 2. Structural geology, geochronology, and tectonic evolution of the Eastern Himalaya. Geol Soc Am Bull 122:360–395. https://doi.org/10.1130/b26461.1

Chapter 24
Arsenic Contamination of Groundwater in Indus River Basin of Pakistan

Arslan Ahmad and Prosun Bhattacharya

Abstract Arsenic (As) contamination of drinking water from groundwater sources is an issue of public health concern in many parts of the world, including South Asia. The presence of As in groundwater of Pakistan was reported around the city of Karachi as early as 1997. Widespread occurrences of As are reported in groundwater through a number of subsequent studies in the provinces of Punjab and Sindh, the two most populated provinces in the Indus River basin of Pakistan and thereby emerged as an issue of public health concern. These studies have revealed that concentrations of As are elevated by a factor of 10–250 as compared to the WHO drinking water guideline. Both natural and anthropogenic processes have been primarily indicated as cause for elevated As concentration in groundwater. An increasing number of studies also show evidence that irrigation with As contaminated groundwater is associated with elevated As concentrations in agricultural products. The future research should therefore focus on the detailed understanding of the complexities of the geological and hydrogeological setting of Pakistan and to outline the sources of As and the mechanisms of transport to the Indus basin aquifers.

A. Ahmad (✉)
KWR Water Cycle Research Institute, Groningenhaven 7, 3433 PE Nieuwegein,
The Netherlands
e-mail: Arslan.Ahmad@kwrwater.nl

A. Ahmad · P. Bhattacharya
KTH-International Groundwater Arsenic Research Group, Department of Sustainable
Development, Environmental Science and Engineering, KTH Royal Institute
of Technology, Teknikringen 76, 100 44 Stockholm, Sweden
e-mail: prosun.bhattacharya@usq.edu.au; prosun@kth.se

P. Bhattacharya
Faculty of Health, Engineering and Sciences, School of Civil Engineering
and Surveying & International Centre for Applied Climate Science,
University of Southern Queensland, Toowoomba QLD 4350, Australia

A. Ahmad
Department of Environmental Technology (ETE), Wageningen Univeristy
and Research (WUR), Weilanden 9, 6708WG Wageningen, The Netherlands

© Springer Nature Singapore Pte Ltd. 2018
A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_24

Keywords Arsenic · Indus River basin · Groundwater · Aqueous environment Drinking water Pakistan

24.1 Introduction

Arsenic (As), a known carcinogen, occurs as a natural element in the Earth's crust. It is the 20th most abundant element in the upper crust with concentrations ranging between 1 and 2 mg/kg (Pontius et al. 1994). Emissions of As in the environment may be caused through both natural and anthropogenic processes (Borba et al. 2003; Gunduz et al. 2010; MacDonald et al. 2016; Marszałek and Wąsik 2000; Woo and Choi 2001). In aqueous environments, As can exist both in inorganic and organic forms, though in natural waters the former generally predominates (Pontius et al. 1994; Smedley and Kinniburgh 2002). Redox potential (E_h) and pH strongly control As speciation in aqueous environments (Mohan and Pittman 2007; Pontius et al. 1994; Smedley and Kinniburgh 2002; Wang and Mulligan 2006). Depending upon the redox condition, inorganic As can exist in two oxidation states: arsenite [As(III)] and arsenate [As(V)]. Arsenite [As(III)] mainly occurs under reducing conditions, e.g., in alluvial aquifers with abundant organic matter, whereas As(V) occurs mainly in well-oxidized systems. Since redox kinetics of As is generally slow in the presence of oxygen alone, both forms may also exist together.

Geogenic As contamination of drinking water from groundwater sources is an issue of public health concern in many parts of the world, including a major part of South Asia (Nriagu et al. 2007). The presence of As in groundwater of Pakistan (Chap. 1, Fig. 1.1) has been recognized as an issue of immediate public health concern. Many studies have reported correlation of elevated As concentration in drinking water (or food) to the observed negative effects on human health in Pakistan (Abbas et al. 2012; Afridi et al. 2011a, b, c; Baig et al. 2011b, c; Fatmi et al. 2009, 2013; Kazi et al. 2009, 2011; Nafees et al. 2011; Wadhwa et al. 2011a, b). The issue is not highlighted extensively in international scientific literature compared to the neighboring countries, e.g., Bangladesh and India. Thus, in this chapter, we aim to present a brief overview of the current status of As contamination in groundwater in different parts of the Indus River basin of Pakistan. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

24.2 The Indus River Basin of Pakistan

Pakistan forms the western part of the Asian subcontinent with a land area of 0.7961 million km^2. It is located between the latitudes of 24° to 37°N and latitudes of 61° to 76°E. The country extends for 1700 km in the NE–SW direction while the E–W breadth is about 1000 km with a diverse mosaic of landforms formed by diverse geological setting comprising orogenic belt, sedimentary basins, magmatic and metamorphic rocks, and associated mineralization (Kazmi and Jan 1997). Nearly 60% of the land area in the northern and western part of Pakistan is characterized by geologically complex mountain areas and incised highland topography while the remaining part is characterized by the alluvial plains of the Indus River system comprising its tributaries (Chap. 1, Fig. 1.3).

The Indus River basin (Chap. 1, Figs. 1.3 and 1.4) has a total area of 1.12 million km^2, distributed between Pakistan (47%), India (39%), China (8%), and Afghanistan (6%). Indus River originates from Tibet in China, runs the full stretch of the Khyber Pakhtunkhwa (KPK), Punjab, and Sindh provinces in Pakistan, and finally empties into the Arabian Sea (Ashraf et al. 1991). River Indus and its tributary rivers (Sutlej, Ravi, Chenab, and Jhelum) are the main sources of freshwater in Pakistan (Bhatti et al. 2017; Raza et al. 2016). The flow of the Indus decreases in winter and floods the banks during the monsoon season (FAO 2012).

The Indus basin irrigation system in Pakistan is the backbone of the country's economy. It includes 3 major multipurpose storage reservoirs, 19 barrages, 12 link canals, 45 major irrigation canal commands (covering over 18 million hectares), and more than 120,000 watercourses delivering water to farms and other productive uses. These canals operate concomitantly with a vast practice of groundwater extraction from private tube wells (Yu et al. 2013).

Indus basin is an extensive unconfined groundwater aquifer system, covering a gross command area of approx. 16 million ha (FAO 2012; Qureshi 2011). During the last decades, there has been a shift from surface water resources to groundwater resources within the Indus basin, mainly attributed to increase in population, availability of inexpensive drilling techniques, and adaptive behavior due to climate change.

24.3 Extent of Arsenic Contamination of Groundwater in Indus River Basin

The first case of groundwater As contamination in Pakistan was reported by Rahman et al. (1997). They analyzed groundwater samples from Karachi, the biggest city of Pakistan and a megacity in Asia, and reported As concentration of 80 μg/L. The authors attributed the contamination of the groundwater source to uncontrolled industrial discharge and open dumping of waste. The issue of As in groundwater gained more attention in 1999, while the Pakistan Council of Scientific and Industrial Research (PCSIR) and the Pakistan Council of Research in Water Resources (PCRWR) conducted a survey to determine the prevalence of As in groundwater (Azizullah et al. 2011; Haque 2005; Haque and Nasir 2015). The survey was preliminary and limited to only six districts in Punjab (Jhelum, Chakwal, Attock, Rawalpindi, Sargodha, and Gujarat). The survey reported that 14% of the 308 collected samples were contaminated with As concentration of >10 μg/L, the WHO guideline for As in drinking water (Haque 2005). Subsequently, a national survey was initiated in 2001 with a joint effort of UNICEF, LG&RD, PCRWR, and PCSIR. This time groundwater from 35 districts was analyzed, both in field and laboratory. It was found that the field kits underestimated

Table 24.1 Arsenic contamination in groundwater of the four provinces in Pakistan according to the National Survey of 2001 (Haque 2005)

	No. of samples		% of samples with As higher than WHO guideline	
Province	Field	Lab.	Field	Lab.
Baluchistan	619	71	1.3	1.4
KPK	1560	156	0.3	22.0
Punjab	4315	428	12.2	36.0
Sindh	2218	193	11.0	26.0
Total	8712	848	9.0	28.0

As concentration. Nevertheless, it was revealed that As contamination was prevalent in the two most populated provinces of Indus River basin in Pakistan, namely Punjab and Sindh (Haque 2005, Haque and Nasir 2015). The results by province are presented in Table 24.1.

Later on, more surveys were conducted by PCRWR, as part of the National Water Quality Monitoring Program (NWQMP) in various parts of the country (Azizullah et al. 2011; Farooqi 2015). It was confirmed that As in groundwater was widespread in major districts of Punjab (e.g., Multan, Sheikhupura, Lahore, Kasur, Gujranwala and Bahawalpur, Rawalpindi, Sargodha, and Sialkot) and Sindh (e.g., Hyderabad, Karachi, Sukkur) (Azizullah et al. 2011; Farooqi 2015). It was estimated that in Punjab over 20% of the population was exposed to As concentrations higher than the WHO guideline. In Sindh, even worse situation was reported, with 36% of population exposed to As concentrations higher than the WHO guideline (Ahmad et al. 2004). More cases of groundwater As contamination in Punjab and Sindh are discussed in the next sections.

24.3.1 Punjab

Nickson et al. (2005) were the first ones to study As contamination of groundwater in Punjab with the aim of elucidating the mobilization mechanism. Their study was based in Muzaffargarh District of Punjab which lies on the Thal Doab, between the Indus River and the Chenab River. It was proposed that the elevated As concentrations in the samples collected from the urban wells in Muzaffargarh were due to the reduction of iron oxides, triggered by the presence of high natural organic matter (NOM).

Arsenic contamination of groundwater in eastern Punjab has been reported (Farooqi et al. 2007a, b). In Kalalanwala and Kot Asadullah villages of Kasur District, 91% of the groundwater samples were contaminated with As, reaching up to 1900–2400 μg/L. The concentration of As was significantly higher at shallow depths, with predominance of As(V) as the aqueous species (Farooqi et al. 2007a, b). Masuda et al. (2010) studied the geochemical characteristics of aquifer sediments in the same study area, however, could not identify the main mechanism of As mobilization and proposed that the As contamination was either due to the anthropogenic sources, e.g., industrial waste, or from leaching of naturally occurring detrital chlorite (Masuda et al. 2010).

Several studies have focused on As contamination of groundwater sources in and around Lahore city. More than 7 million people live in Lahore and use groundwater for drinking and other household purposes. Taskeen et al. (2009) reported As concentrations higher than WHO guideline in the groundwater samples collected in old Kahna, a small town near Lahore. The As concentration in samples collected from Ravi River in Lahore was reported to be 2400 µg/L (Farooqi et al. 2009). The untreated industrial and sewage wastes arising from industries and metropolitan activities make their passage to the Ravi River. The water from Ravi River is used for irrigation where it could be the cause of soil contamination (Farooqi 2015). Akhter et al. (2010) reported groundwater As concentrations ranging between 24.6 and 71.6 µg/L in Lahore. Another study conducted by Akhtar et al. (2014) reported high As in the groundwater samples collected from adjacent areas of two dumping sites (Mehmood Booti landfill and Saggian landfill) in the vicinity of Lahore. Muhammad and Zhonghua (2014) also investigated the influence of a landfill site on groundwater quality near Lahore. Sixteen sampling points in the vicinity of the landfill for groundwater sampling were used. It was found that As concentrations were much higher than the WHO guideline in all the samples.

A recent study by Sultana et al. (2014) investigated the temporal variation in As concentration and the influence of abstraction depth in three selected villages in the proximity of Lahore (Manga Mandi, Shamki Bhattian, and Kalalanwala). Thirty groundwater samples were collected, 20 from shallow hand pumps installed at 24–36 m, 9 samples from 40 to 80 m, and 1 sample from a deep tube well 80–200 m in depth. Arsenic concentration in the water samples varied considerably ranging from 1 to 525 µg/L. 84% samples showed As levels higher than the WHO guideline. Elevated As concentrations were noticed compared to 2007 (Farooqi et al. 2007a). The highest concentrations of As were found to be present in the shallow aquifers. Therefore, the authors proposed that the increase in As concentration was due to increased fertilizer use between the two sampling campaigns. Abbas et al. (2015) studied the quality of drinking water from the source wells and distribution system in Lahore. A total of 50 groundwater samples were collected from various urban settlements in Lahore (Shahdara, Mughalpura, Gulberg, Misri Shah, Shad Bagh, Ichhra, Basti Saden Shah, University of Engineering and Technology, Queens Road, Ali park, Gunj bakhsh town, Quaid-e-Azam Estate (Township), and Bank Square (Old Anarkali)). All the samples showed As concentrations higher than the WHO guideline and concentrations ranged between 13.4 and 82.8 µg/L.

In a recent study, Abbas et al. (2016) investigated the spatial variability of groundwater chemistry in seven towns within Lahore city focusing on the distribution of As (and fluoride). Based on the investigations on 472 well water samples, the study indicated significant variations in the distribution of As, total dissolved solids (TDS), alkalinity (HCO_3) and NO_3 in groundwater. In general, As concentrations were found to be considerably high in the northeastern part of the city which was attributed to the heterogeneity of the aquifers as well as major industrial activities. Major ion chemistry of the groundwater samples indicated considerable variations with predominance of Ca–Mg–HCO_3–SO_4 water type together with a range of other Mg–Ca–HCO_3–SO_4, Ca–Mg–HCO_3–SO_4–Cl, Ca–HCO_3–SO_4, and Ca–Mg–SO_4–HCO_3 water types which indicate that both carbonate weathering and probable silicate weathering control the major ion chemistry of the groundwater. Results of hierarchical cluster analysis revealed that the distribution and mobilization of As in groundwater were predominantly controlled by pH. Thus, the groundwater chemistry is primarily controlled by mineral dissolution and precipitation reaction during the water–solid phase interactions in the aquifers and the elevated concentration of As controlled by pH under the oxic conditions in the aquifers.

Malana and Khosa (2011) studied randomly collected groundwater samples in Dera Ghazi Khan District of Punjab. 22% of the 32 collected samples contained high As concentrations. The mechanism of As mobilization could not be elucidated; however, based on the data, it was proposed that the mobilization might be due to the reduction of iron oxides in the presence of natural organic matter (NOM).

Shakoor et al. (2015) studied the groundwater samples from three previously unexplored rural areas in Punjab (Chichawatni, Vehari, Rahim Yar Khan). Total 62 samples were collected. It was found that 53% of the groundwater samples had higher As concentration than the WHO guideline, ranging between 1.5 and 201 μg/L. Moreover, As(V) was the dominant specie of As, though As(III) was also present. Rafique et al. (2014) aimed to assess the quality of drinking water in Jampur Tehsil located in Rajanpur District in South Punjab. Based on the analysis of the samples collected from different sources, e.g., as hand pump, injector pump, tube well, and water supply line, it was reported that majority of the population was exposed to elevated levels of As.

24.3.2 Sindh

In Sindh, Manchar Lake and groundwater in the vicinity have been under focus of many studies. Manchar is the largest freshwater lake in Pakistan, situated in Dadu District. Its water is used for agriculture, fishing, drinking, and general household use (Farooqi 2015). Arain et al. (2008) studied As in Manchar Lake in summer and winter seasons and reported As concentrations that were 6–8 times higher than the WHO guideline for As in drinking water. In summer, As concentrations ranged from 60.4 to 88.9 μg/L, and in winter, they ranged from 64.9 to 101.8 μg/L. Another study by Arain et al. (2009) showed that water in Manchar Lake contained As concentrations in the range of 35–157 μg/L. Moreover, the groundwater samples collected from the adjacent areas of the lake showed As concentrations that were significantly higher than the WHO guideline, in the range of 23.3–96.3 μg/L. Arain et al. (2009) also revealed that the vegetables and selected crops accumulated higher As compared to food commodities collected from unaffected areas. Kazi et al. (2009) evaluated the impact of As toxicity on health of local population around Manchar Lake by studying the biological samples (scalp hair and blood). Strong correlations were observed between As concentrations in drinking water versus hair and blood samples of exposed skin disease (Kazi et al. 2009). Arain et al. (2007) analyzed the groundwater samples from different depths in districts Matiari and Khairpur Mirs. Approximately 40% of the samples indicated As concentration of ≥ 50 µg/L and 15% of the samples indicated As concentration of >250 µg/L.

Khan et al. (2008) reported that As concentrations in the groundwater samples collected in Hyderabad city were in the range of 25–1286 µg/L. A study at Jamshoro District of Sindh reported As concentrations ranging between 13 and 106 µg/L in groundwater (Baig et al. 2009). The authors concluded that the elevated As in the groundwater was due to widespread waterlogging from Indus River irrigation system that caused high saturation of salts and led to enrichment of As in shallow groundwater (Baig et al. 2009). Baig et al. (2011a) studied the uptake of As by grain crops grown on agricultural soils in three sub districts of Khairpur (Faiz Ganj, Thari Mirwah and Gambat), irrigated by tube well water and canal water. The tube well water contained much higher average As concentration (15.4 ± 2.31 µg/L at Faiz Ganj, 31 ± 8.21 µg/L at Thari Mirwah and 98.5 ± 68.7 µg/L at Gambat) than the canal water. Baig et al. (2011a) reported that a significantly high accumulation of As was taken place in grains grown on tube well water compared to those grown on canal water. The authors proposed anthropogenic activities (agricultural, industrial, domestic) for the increased concentration of As in tube well water.

The As contamination of drinking water in Thar Desert has been under focus of many studies. Tharparkar District is an extreme arid area, freshwater is scarce, and (deep) groundwater is saline. Rashid et al. (2012) carried out a study in which they collected 99 water samples from 33 different locations in Tharparkar District. Groundwater samples of two villages, namely Murid Khan Umarani and Khan Khanjar Reham, were found contaminated with As concentrations of higher than the WHO guideline. Brahman et al. (2013a) studied the groundwater contamination by As and its species in Diplo and Chachro subdistricts in Tharparkar. All groundwater samples were collected directly from the wells that were >12 m deep. The concentrations of As were 10–250 times higher than the WHO guideline. In Chachro, As concentrations up to 1390–2480 µg/L were reported, and in Diplo, 112–840 µg/L As concentrations were reported. Although As(V) was reported to be the dominant specie in water, As(III) was also present in significant concentration. The authors proposed that pyrite oxidation and evaporative concentration of As in shallow aquifer were the mechanisms involved in As mobilization. Brahman et al. (2014) reported As concentrations in the range of 360–683 µg/L in the samples collected from surface water ponds in Nagarparkar, a subdistrict in Tharparkar. In another study, Brahman et al. (2013b) investigated As and (F^-) contamination of groundwater in Mithi and Nagarparkar subdistricts of Tharparkar. Groundwater samples were collected from 14 different villages (Bhalwa, Danodandhal, Veraval, Nagarparkar, Islamkot, Moryotar, Sakrio, Pabuar, Mithi, Jeeando Daras, Budhe Jo

Tar, Mthrao, Lunyo, and Haday Jo Tar). Arsenic concentrations ranging from 100 to 3830 μg/L were reported, and As(V) was found to be the dominant specie of As. Arsenic showed positive correlation with all studied physicochemical parameters except NO_3^-, CO_3^{2-} and pH.

24.4 Conclusion and Future Outlook

In groundwater across Punjab and Sindh provinces, that constitute an extensive part of Indus River basin, As concentrations significantly higher than the WHO guideline have been reported in a number of research studies as well as national surveys. Both natural and anthropogenic processes have been primarily indicated as cause for elevated As concentration in groundwater. An increasing number of studies also show evidence that irrigation with As contaminated groundwater is associated with elevated As concentration in agricultural products.

The future research should therefore focus on the detailed understanding of the complexities of the geological setting of Pakistan to outline the sources of As from different geotectonic domains and the metallogenic provinces and their transport to the Indus basin across the provinces of Punjab and Sindh. Moreover, detailed hydrogeological studies are also imminent to unravel the mechanistic understanding of the mechanisms of As mobilization in groundwater in different parts of the Indus basin.

References

Abbas S, Qureshi EMA, Ahmad F, Vehra S, Khan AU (2012) An assessment of relationship between arsenic in drinking water, health status and intellectual functioning of children in district Kasur. Pak J Nutr 11(2):150–153

Abbas Z, Su C, Tahira F, Mapoma HWT, Aziz SZ (2015) Quality and hydrochemistry of groundwater used for drinking in Lahore, Pakistan: analysis of source and distributed groundwater. Environ Earth Sci 74(5):4281–4294

Afridi HI, Kazi TG, Kazi N, Kandhro GA, Baig JA, Shah AQ, Wadhwa SK, Khan S, Kolachi NF, Shah F, Jamali MK, Arain MB, Sirajuddin A (2011a) Evaluation of essential trace and toxic elements in biological samples of normal and night blindness children of age groups 3–7 and 8–12 years. Biol Trace Elem Res 143(1):20–40

Afridi HI, Kazi TG, Kazi N, Kandhro GA, Shah AQ, Baig JA, Khan S, Kolachi NF, Wadhwa SK, Shah F (2011b) Evaluation of arsenic, cadmium, lead, nickel, and zinc in biological samples (scalp hair, blood, and urine) of tuberculosis and diarrhea male human immunodeficiency virus patients. Clin Lab 57(11–12):867–878

Afridi HI, Kazi TG, Shah F, Sheikh HUR, Kolachi NF (2011c) Evaluation of arsenic, cadmium, lead, and nickel in biologica samples (scalp hair, serum, blood, and urine) of Pakistani viral hepatitis (A-E) patients and controls. Clin Lab 57(11–12):847–857

Ahmad T, Kahlown MA, Tahir A Rashid H (2004) Arsenic an emerging issue: experiences from Pakistan, pp 449–466

Akhtar MM, Tang Z, Ammar SD, Muhammad TS (2014) A study to investigate and compare groundwater quality in adjacent areas of landfill sites in Lahore city. Nat Environ Pollut Technol 13(1):1–10

Akhter G, Ahmad Z, Iqbal J, Shaheen N, Shah MH (2010) Physicochemical characterization of groundwater in urban areas of Lahore, Pakistan, with special reference to arsenic. J Chem Soc Pak 32(3):306–312

Arain GM, Aslam M, Majidano SA, Khuhawar MY (2007) A preliminary study on the arsenic contamination of underground water of Matiari and Khairpur Districts, Sindh, Pakistan. J Chem Soc Pak 29(5):463–467

Arain MB, Kazi TG, Jamali MK, Jalbani N, Afridi HI, Shah A (2008) Total dissolved and bioavailable elements in water and sediment samples and their accumulation in Oreochromis mossambicus of polluted Manchar Lake. Chemosphere 70(10):1845–1856

Arain MB, Kazi TG, Baig JA, Jamali MK, Afridi HI, Shah AQ, Jalbani N, Sarfraz RA (2009) Determination of arsenic levels in lake water, sediment, and foodstuff from selected area of Sindh, Pakistan: estimation of daily dietary intake. Food Chem Toxicol 47(1):242–248

Ashraf M, Tariq J, Jaffar M (1991) Contents of trace metals in fish, sediment and water from three freshwater reservoirs on the Indus River, Pakistan. Fish Res 12(4):355–364

Azizullah A, Khattak MNK, Richter P, Häder DP (2011) Water pollution in Pakistan and its impact on public health—a review. Environ Int 37(2):479–497

Baig JA, Kazi TG, Arain MB, Afridi HI, Kandhro GA, Sarfraz RA, Jamal MK, Shah AQ (2009) Evaluation of arsenic and other physico-chemical parameters of surface and ground water of Jamshoro, Pakistan. J Hazard Mater 166(2–3):662–669

Baig JA, Kazi TG, Shah AQ, Afridi HI, Kandhro GA, Khan S, Kolachi NF, Wadhwa SK, Shah F, Arain MB, Jamali MK (2011a) Evaluation of arsenic levels in grain crops samples, irrigated by tube well and canal water. Food Chem Toxicol 49(1):265–270

Baig JA, Kazi TG, Shah AQ, Afridi HI, Khan S, Kolachi NF, Kandhro GA, Wadhwa SK, Shah F (2011b) Evaluation of toxic risk assessment of arsenic in male subjects through drinking water in southern Sindh Pakistan. Biol Trace Elem Res 143(2):772–786

Baig JA, Kazi TG, Shah AQ, Khan S, Kolachi NF, Afridi HI, Kandhro GA, Wadhwa SK, Baig AM, Shah F, Kanhar FH (2011c) Determination of arsenic scalp hair of Pakistani children and drinking water for environmental risk assessment. Hum Ecol Risk Assess 17(4):966–980

Bhatti MT, Anwar AA, Aslam M (2017) Groundwater monitoring and management: status and options in Pakistan. Comput Electron Agric 135:143–153

Borba RP, Figueiredo BR, Matschullat J (2003) Geochemical distribution of arsenic in waters, sediments and weathered gold mineralized rocks from Iron Quadrangle, Brazil. Environ Geol 44(1):39–52

Brahman KD, Kazi TG, Afridi HI, Naseem S, Arain SS, Ullah N (2013a) Evaluation of high levels of fluoride, arsenic species and other physicochemical parameters in underground water of two sub districts of Tharparkar, Pakistan: a multivariate study. Water Res 47(3):1005–1020

Brahman KD, Kazi TG, Afridi HI, Naseem S, Arain SS, Wadhwa SK, Shah F (2013b) Simultaneously evaluate the toxic levels of fluoride and arsenic species in underground water of Tharparkar and possible contaminant sources: a multivariate study. Ecotoxicol Environ Saf 89:95–107

Brahman KD, Kazi TG, Baig JA, Afridi HI, Khan A, Arain SS, Arain MB (2014) Fluoride and arsenic exposure through water and grain crops in Nagarparkar, Pakistan. Chemosphere 100:182–189

FAO (2012) Irrigation in Southern and Eastern Asia in figures: AQUASTAT Survey—2011. In: Frenken K (ed) Food and Agricultural Organization of the United Nations, Rome, p 487

Farooqi A (2015) Arsenic and fluoride contamination: a Pakistan perspective

Farooqi A, Masuda H, Firdous N (2007a) Toxic fluoride and arsenic contaminated groundwater in the Lahore and Kasur districts, Punjab, Pakistan and possible contaminant sources. Environ Pollut 145(3):839–849

Farooqi A, Masuda H, Kusakabe M, Naseem M, Firdous N (2007b) Distribution of highly arsenic and fluoride contaminated groundwater from east Punjab, Pakistan, and the controlling role of anthropogenic pollutants in the natural hydrological cycle. Geochem J 41(4):213–234

Farooqi A, Masuda H, Siddiqui R, Naseem M (2009) Sources of arsenic and fluoride in highly contaminated soils causing groundwater contamination in Punjab, Pakistan. Arch Environ Contam Toxicol 56(4):693–706

Fatmi Z, Azam I, Ahmed F, Kazi A, Gill AB, Kadir MM, Ahmed M, Ara N, Janjua NZ (2009) Health burden of skin lesions at low arsenic exposure through groundwater in Pakistan. Is river the source? Environ Res 109(5):575–581

Fatmi Z, Abbasi IN, Ahmed M, Kazi A, Kayama F (2013) Burden of skin lesions of arsenicosis at higher exposure through groundwater of taluka Gambat district Khairpur, Pakistan: a cross-sectional survey. Environ Geochem Health 35(3):341–346

Gunduz O, Simsek C, Hasozbek A (2010) Arsenic pollution in the groundwater of Simav Plain, Turkey: its impact on water quality and human health. Water Air Soil Pollut 205(1–4):43–62

Haque IU (2005) National action plan for arsenic mitigation, 2005–09 (Pakistan), Islamabad, Pakistan, p 65

Haque IU, Nasir M (2015) Monitoring and impact evaluation system for arsenic mitigation interventions—arsenic contamination areas of Pakistan. Int J Environ Monit Anal 3(3–1): 67–78

Kazi TG, Arain MB, Baig JA, Jamali MK, Afridi HI, Jalbani N, Sarfraz RA, Shah AQ, Niaz A (2009) The correlation of arsenic levels in drinking water with the biological samples of skin disorders. Sci Total Environ 407(3):1019–1026

Kazi TG, Baig JA, Shah AQ, Arain MB, Jamali MK, Kandhro GA, Afridi HI, Kolachi NF, Khan S, Wadhwa SK, Shah F (2011) Determination of arsenic in scalp hair of children and its correlation with drinking water in exposed areas of Sindh Pakistan. Biol Trace Elem Res 143 (1):153–162

Kazmi AH, Jan QM (1997) Geology and tectonics of Pakistan. Graphic Publishers, Karachi

Khan FA, Javed A, Iqbal J, Munshi AB, Siddiqui I (2008) Occurrence and severity of arsenic in urine, hair and nails through contaminated drinking water in Pakistan. Pak J Sci Ind Res 51 (4):220–224

MacDonald AM, Bonsor HC, Ahmed KM, Burgess WG, Basharat M, Calow RC, Dixit A, Foster SSD, Gopal K, Lapworth DJ, Lark RM, Moench M, Mukherjee A, Rao MS, Shamsudduha M, Smith L, Taylor RG, Tucker J, Van Steenbergen F, Yadav SK (2016) Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. Nat Geosci 9(10):762–766

Malana MA, Khosa MA (2011) Groundwater pollution with special focus on arsenic, Dera Ghazi Khan-Pakistan. J Saudi Chem Soc 15(1):39–47

Marszałek H, Wąsik M (2000) Influence of arsenic-bearing gold deposits on water quality in Zloty Stok mining area (SW Poland). Environ Geol 39(8):888–892

Masuda H, Mitamura M, Farooqi AM, Muhanmad N, Owada M, Okazaki K, Seddique AA (2010) Geologic structure and geochemical characteristics of sediments of fluoride and arsenic contaminated groundwater aquifer in Kalalanwala and its vicinity, Punjab, Pakistan. Geochem J 44(6):489–505

Mohan D, Pittman CU Jr (2007) Arsenic removal from water/wastewater using adsorbents—a critical review. J Hazard Mater 142:1–53

Muhammad AM, Zhonghua T (2014) Municipal solid waste and its relation with groundwater contamination in lahore, Pakistan. Res J Appl Sci Eng Technol 7(8):1551–1560

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Nafees AA, Kazi A, Fatmi Z, Irfan M, Ali A, Kayama F (2011) Lung function decrement with arsenic exposure to drinking groundwater along River Indus: a comparative cross-sectional study. Environ Geochem Health 33(2):203–216

Nickson RT, McArthur JM, Shrestha B, Kyaw-Myint TO, Lowry D (2005) Arsenic and other drinking water quality issues, Muzaffargarh District, Pakistan. Appl Geochem 20(1):55–68

Nriagu JO, Bhattacharya P, Mukherjee AB, Bundschuh J, Zevenhoven R, Loeppert RH (2007) Arsenic in soil and groundwater: an overview. Trace Met Contam Environ 9:3–60

Pontius FW, Brown KG, Chen C-J (1994) Health implications of arsenic in drinking water. Am Water Work Assoc 86(9):52–63

Qureshi AS (2011) Water management in the Indus basin in Pakistan: challenges and opportunities. Mt Res Dev 31(3):252–260

Rafique HM, Abbas I, Sohl MA, Shehzadi R, Ramay SM, Imran M, Al-Zaghayer Y, Mahmood A, Sohl MN (2014) Appraisal of drinking water quality of Tehsil Jampur, Pakistan. Desalin Water Treat 52(25–27):4641–4648

Rahman A, Lee HK, Khan MA (1997) Domestic water contamination in rapidly growing megacities of Asia: case of Karachi, Pakistan. Environ Monit Assess 44(1–3):339–360

Rashid U, Alvi SK, Perveen F, Khan FA, Bhutto S, Siddiqui I, Bano A, Usmani TH (2012) Metal contents in the ground waters of Tharparkar district, Sindh, Pakistan, with special focus on arsenic. Pak J Sci Ind Res 55(1):49–56

Raza M, Farooqi A, Niazi NK, Ahmad A (2016) Geochemical control on spatial variability of fluoride concentrations in groundwater from rural areas of Gujrat in Punjab, Pakistan. Environ Earth Sci 75(20):1364

Shakoor MB, Niazi NK, Bibi I, Rahman MM, Naidu R, Dong Z, Shahid M, Arshad M (2015) Unraveling health risk and speciation of arsenic from groundwater in rural areas of Punjab, Pakistan. Int J Environ Res Public Health 12(10):12371–12390

Smedley PL, Kinniburgh DG (2002) A review of the source, behaviour and distribution of arsenic in natural waters. Appl Geochem 17(5):517–568

Sultana J, Farooqi A, Ali U (2014) Arsenic concentration variability, health risk assessment, and source identification using multivariate analysis in selected villages of public water system, Lahore, Pakistan. Environ Monit Assess 186(2):1241–1251

Taskeen A, Naeem I, Siddique Z (2009) Public health risk of Arsenic contamination in food at old Kahna, Lahore, Pakistan. Asian J Chem 21(4):2845–2848

Wadhwa SK, Kazi TG, Chandio AA, Afridi HI, Kolachi NF, Khan S, Kandhro GA, Nasreen S, Shah AQ, Baig JA (2011a) Comparative study of liver cancer patients in arsenic exposed and non-exposed areas of Pakistan. Biol Trace Elem Res 144(1–3):86–96

Wadhwa SK, Kazi TG, Kolachi NF, Afridi HI, Khan S, Chandio AA, Shah AQ, Kandhro GA, Nasreen S (2011b) Case-control study of male cancer patients exposed to arseniccontaminated drinking water and tobacco smoke with relation to non-exposed cancer patients. Hum Exp Toxicol 30(12):2013–2022

Wang S, Mulligan CN (2006) Occurrence of arsenic contamination in Canada: sources, behavior and distribution. Sci Total Environ 366:701–721

Woo NC, Choi MC (2001) Arsenic and metal contamination of water resources from mining wastes in Korea. Environ Geol 40(3):305–311

Yu W, Yang Y-C, Savitsky A, Alford D, Brown C, Wescoat J, Debowicz D, Robinson S (2013) Indus Basin of Pakistan: impacts of climate risks on water and agriculture. Directions in development; countries and regions. World Bank, Washington, DC

Chapter 25
The Hydrogeological and Geochemical Characteristics of Groundwater of Sri Lanka

C. B. Dissanayake and Rohana Chandrajith

Abstract In Sri Lanka, water has played a key role in the development of the country and economic status and is deeply embedded in the culture and traditions of the people. The island is predominantly underlain by high-grade metamorphic rocks with scattered sedimentary sequences in which groundwater is considered as one of the most precious natural resources. It is also a more reliable water resource, less subject to temporal variation, and is widely used for domestic purposes, small-scale irrigation as well as for industries. Six distinct groundwater aquifers identified in the island are (a) shallow and deep karstic aquifers in the Miocene beds, (b) coastal sandy aquifers, (c) alluvial aquifers in lower reaches of river basins, (d) deeply confined aquifers in the metamorphic terrain, (e) shallow regolith aquifers of the metamorphic terrain and (f) lateritic aquifers in the south-western region. Groundwater is extracted from deep wells as well as shallow wells of which the shallow aquifers play an important role in providing domestic water supplies throughout the country. Rapid expansion of urban, rural and semi-urban settlements in recent years led to increasing stress on both the quantity and quality of water in aquifers. Both natural and anthropogenic contaminations of groundwater cause certain health problems among the population, although the relation between them is yet to be understood well. In view of the recent climate change scenario, contemporary issues on the sustainable use of groundwater in Sri Lanka need to be addressed urgently.

Keywords Hard rock terrain · Shallow regolith aquifers · Water hardness
Dental fluorosis · Dry zone

C. B. Dissanayake · R. Chandrajith (✉)
Department of Geology, Faculty of Science, University of Peradeniya,
Peradeniya, Sri Lanka
e-mail: rohanac@pdn.ac.lk

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_25

25.1 Introduction

Sri Lanka (Chap. 1, Fig. 1.1), a humid tropical island in the Indian Ocean, located at the southern tip of India, has some unique geological, geomorphological, climatic and geochemical characteristics. It lies between the latitudes 5° 55′N and 9° 55′N; and longitudes 79″ 42′E and 81° 52′E. The length of the island is 440 km from north to south and a maximum width of 226 km, with a total area of 65,621 km^2. The shoreline has a total length of about 1,600 km with a variety of coastal landforms. Even though the island is relatively small in size, its widely varying topography, geology and climate with major changes within a short distance impart some unique features. The topographic configuration of the island has a centrally located highland region that is surrounded by a lowland plain that has had a remarkable influence on the climate, hydrology and biodiversity. Geologically, a variety of rocks, mainly of the high-grade metamorphic types that are followed by Miocene limestone sequences, are observed.

The island of Sri Lanka is situated in the path of two monsoons, the south-west and the north-east monsoons. It is drained by 103 river basins in varying size, but groundwater plays an important role as a main potable water source for the community. Despite this, the island has vast areas of water deficiency where the greater part of the country experiences dry spells for several months of the year while surplus of water can be observed in the wet zone region. In both dry and wet regions of the country, groundwater is the main source of potable water. The average annual rainfall of Sri Lanka is 1,900 mm that provides 131,220 Gm^3 of water of which 78,000 Gm^3 seeps down to replenish groundwater while about 51,300 Gm^3 is available as stream flow for irrigation or other purposes (Gunatilaka 2008). However, different geological and climatic conditions in the country give rise to some special geochemical characteristics to the groundwater through prolonged water–rock interaction. These major changes in the hydrogeochemistry within the island have a major influence on the health of its 22 million population. Many people living mainly in the dryer regions use groundwater as their main drinking water source and are heavily influenced by the geochemistry of the groundwater, resulting in certain diseases such as dental and skeletal fluorosis (Chandrajith et al. 2012; Dissanayake 1991), as well as chronic kidney diseases (Chandrajith et al. 2011a; Nanayakkara et al. 2013) among others. The aim of this review is to explore the special features of groundwater in Sri Lanka pertaining to their occurrence with respect to the geology, geomorphology and climate. Special emphasis is given to the geochemical characteristics of the groundwater with their diversity and impact on the health of the population. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

25.1.1 Geomorphology, Geology and Climate of Sri Lanka

The surface configuration of Sri Lanka is well demarcated with a low, flat coastal terrain and centrally elevated mountain masses (Fig. 25.1). Although it is a small island, the country is very complex in its geomorphology, which is mainly controlled by geological structure and tectonics (Vitanage 1970, 1972). Based on the height and slope characteristics, the island can be divided into three well-demarcated physiographical regions named as coastal lowlands, uplands and

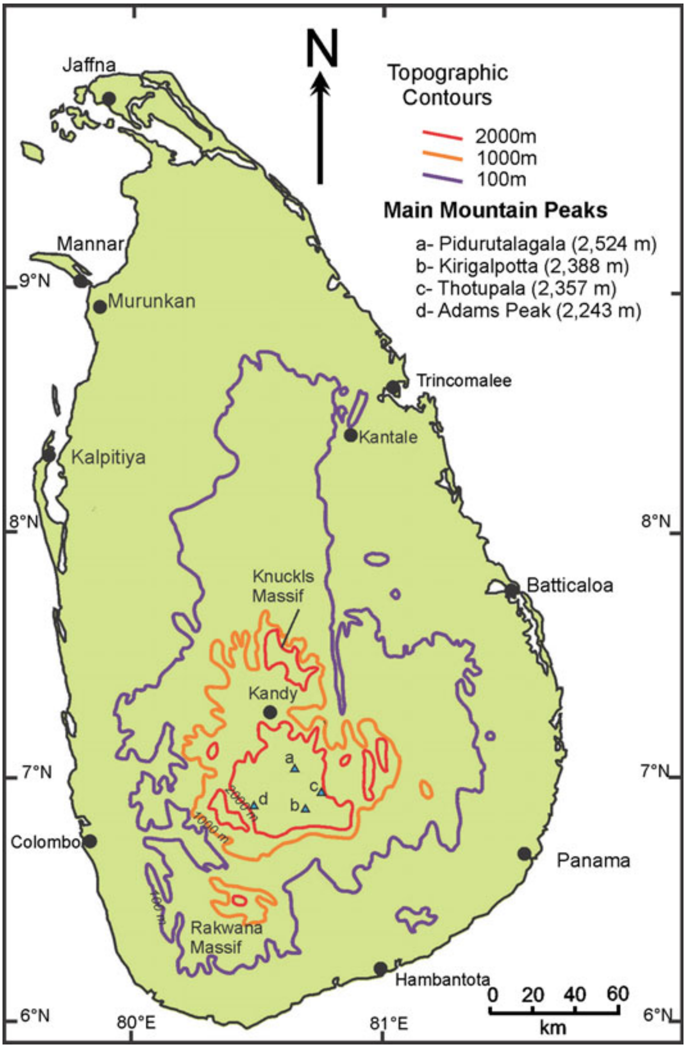


Fig. 25.1 Generalized geomorphology of Sri Lanka

highlands. These morphological features are sometime referred as first, second and third peneplains, respectively. These morphological regions show a series of irregular scarps or breaks-in-slope at elevations 30–270, 270–1,060 and 1,060–2,400 m, respectively (Vitanage 1972). Almost 90% of the land area of the country is drained by 103 distinct natural river basins of which the Mahaweli Ganga (335 km) is the longest in the country. The river originates at an altitude of over 2,250 m asl draining over 15% of the land mass of the island. Most of the rivers in Sri Lanka originate either from highlands or from uplands, displaying a radial pattern of drainage.

Geologically, Sri Lanka forms a part of the very old and stable continental mass consisting Precambrian metamorphic rocks and a small fragment of Gondwana supercontinent. Over 90% of the island is made up of amphibolite to granulite facies rocks, while the rest is mainly sedimentary rocks. The sequences of sedimentary rocks are found mainly in the north and north-western coastal belt and also in some isolated patches elsewhere in the island (Fig. 25.2). The Proterozoic crust of Sri Lanka is subdivided into three major lithological units on the basis of lithological, geochronological and geochemical characteristics (Cooray 1994) as Highland Complex (former Highland and south-west group), Vijayan Complex (former eastern Vijayan Complex) and Wanni Complex (former western Vijayan Complex). The folded belt of the Highland Complex is bounded by the Vijayan Complex in the east and the Wanni Complex in the west.

The Highland Complex is the largest unit and is considered as forming the integral part of the Precambrian rocks of Sri Lanka. Included in this unit are supracrustal rocks together with a variety of igneous intrusions predominantly of granitoid composition that now occur as banded gneisses. The rocks comprising the Highland Complex are mainly of granulite facies, the prominent rocks being varieties of granulites, charnockites, quartz feldspar garnet sillimanite graphite schist (khondalites), quartzites, marbles and calc silicate gneisses. Based on the field and petrological evidences, it has been inferred that over 50% of the rocks in the Highland Complex is of granitoid origin (Cooray 1994). The depositional age of supracrustal rocks of this unit ranges from 3.2 to 2.0 Ga (Kröner and Williams 1993; Milisenda et al. 1994) and the age of granitoids ranges from 1.85 to 1.90 Ga (Hölzl et al. 1994; Milisenda et al. 1994), while granulite grade metamorphism occurred at 610 Ma (Hölzl et al. 1994). The amphibolite gneissic terrain of the Vijayan Complex flanking the east of the Highland Complex consists of varieties of gneisses and granitoids ranging in composition from tonalite to leuco-granite and containing minor xenoliths of metaquartzites and calc silicate rocks. Among the other noteworthy features of this unit is the occurrence of NW trending suites of dolerite dikes believed to have originated in the late Jurassic–Cretaceous period (Takigami et al. 1999; Yoshida et al. 1989). The granitoids in the Vijayan Complex intruded around 1.0 Ga ago (Hölzl et al. 1994). The other main geological region of Sri Lanka, the Wanni Complex, consists predominantly of scattered relics of supracrustal rocks and meta-igneous rocks of granodioritic gneisses. These rocks form part of a variety of amphibolite to granulite facies rocks such as

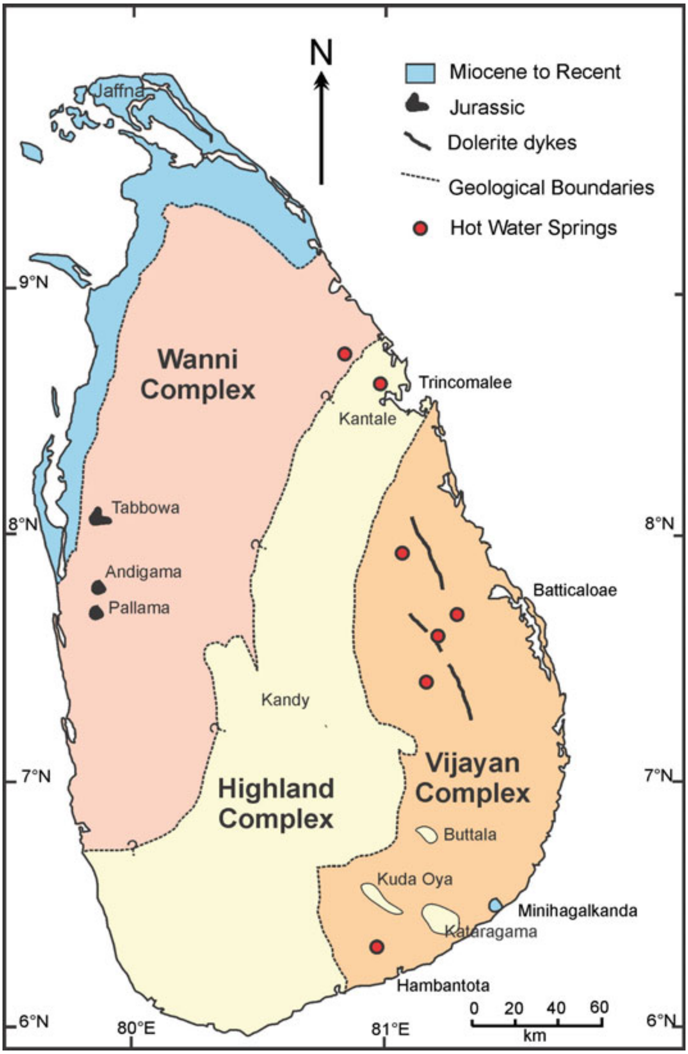


Fig. 25.2 Major geological subdivisions and generalized geological map of Sri Lanka (modified after Cooray 1994)

metasediments of pelitic to semi-pelitic composition. The Wanni Complex is ca 1,000–1,100 Ma old with Nd model ages (Milisenda et al. 1994).

The Miocene sedimentary rocks form a major sedimentary sequence that can be found along the north-western and northern coasts of the island. It occupies an area of about 5,000 km^2 running as a 20–25-km-wide belt. These rocks are fossiliferous with creamy coloured rocks dipping towards the west, overlying the crystalline rocks. Most of these limestone beds have been subjected to several periods of post-Miocene karstic weathering and large-scale block faulting. Gravity studies indicated that Miocene limestone rocks reach a maximum thickness of over 500 m (Hatherton et al. 1975). However, later gravity interpretations inferred that they occur as multiple sedimentary layers over the Precambrian basement (Tantirigoda and Geekiyanage 1988). The thickness of the limestone layers of the northern region is about 400 m, while some other upper Gondwana rocks are found at a depth of 3.55 km. From among other sedimentary formations in Sri Lanka, scattered outcrops of Jurassic beds are found in Tabbowa (Fig. 25.2) and Andigama–Pallama areas in the north-western part of the island. These basins are characterized as isolated Jurassic sedimentary pockets within the Precambrian basement. Major rock types at Tabbowa are arkose, feldspathic sandstone, siltstone and mudstone, while in Andigama–Pallama, the beds consist of brown shale, black carbonaceous shales with calcareous sandstones (Pathirana 1986). A small outcrop of lower Miocene shale and limestone beds also occur in the southern coastal belt of the island at Minihagalkande that is overlain by Quaternary deposits. The outcrop is semicircular cliff-like exposure consisting of a non-fossiliferous basal bed of ferruginous grit and sandstone that are 1–2-m-thick overlain by about 15 m of brownish and yellowish sandy and clayey beds (Cooray 1984). An isolated faulted sedimentary basin is also observed in the area of Kinniya near Trincomalee, north-east of Sri Lanka (Dias et al. 2012). However, detailed investigations are yet to be conducted in the region to find the extension of the basin.

Geologically, the island of Sri Lanka had been subjected to a series of deformations at various steps displaying a multitude of geological structures, fractures and lineaments (Vitanage 1985). These structural elements have a major impact on the hydrology and hydrogeology notably the availability of deep water in fractured rocks as primary porosity and permeability are not present in high-grade crystalline rocks which consist of nearly 90% of the land mass of Sri Lanka.

25.1.2 Climate of Sri Lanka

Sri Lanka has a tropical and monsoonal climate displaying marked seasonal rainfall patterns. These are dominated by two monsoon periods and two inter-monsoon periods. The two monsoons, namely south-west and north-east monsoons, display vastly different circulation features which in effect determine the seasonality of the climate of Sri Lanka. The island of Sri Lanka is characterized by three main climatic zones, namely dry zone, intermediate zone and the wet zone, each with its characteristic rainfall patterns (Fig. 25.3). The highest intensity of rainfall occurs in the western slopes of the central highlands that exceeds 4,000 mm per year, while the lowest is recorded in Mannar Island in the north-west with values about 750 mm per year (Bastiaanssen and Chandrapala 2003).

The temperature differences, however, are not marked, though the regions with highest elevations show a lower temperature throughout the year. Even though the land area of Sri Lanka is relatively small, the spatial variation of annual rainfall is

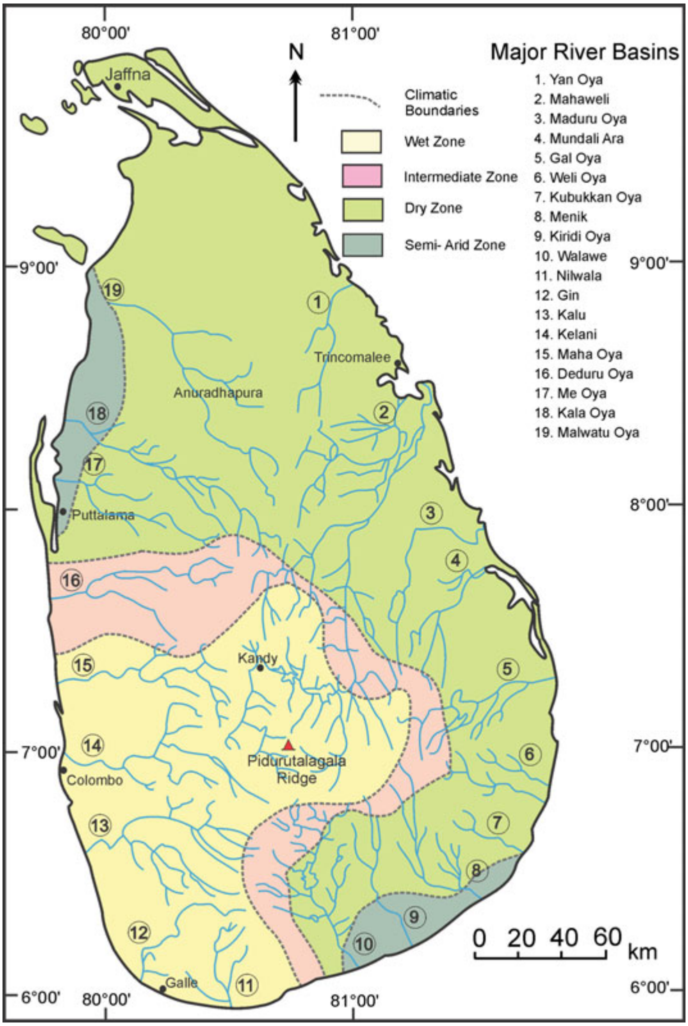


Fig. 25.3 Climatic binderies and river basins in Sri Lanka

remarkable, ranging from 850 mm in the driest parts to more than 5,500 mm in the wettest parts. The south-west monsoon occurs usually from May to September with strong winds and continuous rain particularly in the central, western and south-western sectors of the island. The rest of the island is mostly dry where the north-east monsoons bring rains from October to January. The dry zone receives on average an annual rainfall about 1,450 mm. However, the evapotranspiration is excessively high (Domrös 1979). Recent climate change investigations in Sri Lanka showed a definite climate change in the country where both temperature and rainfall had changed over the last 30 years (Wickramagamage 2015). Interestingly, the temperature warning pattern is quite similar to the global pattern. The combined effects of temperature and decreasing rainfall undoubtedly have consequences on Sri Lanka for its groundwater, water quality and quantity as well as community health.

25.2 Groundwater Resources in Sri Lanka

Based on studies carried out for over last three decades by various water sector organizations and individual researchers, six main types of groundwater aquifers have been identified (Panabokke 2007). These aquifer types are (a) shallow and deep karstic aquifers in the Miocene beds, (b) coastal sandy aquifers, (c) alluvial aquifers in lower reaches of river basins, (d) deep confined aquifers in the metamorphic terrain, (e) shallow regolith aquifers of the metamorphic terrain and (f) lateritic (Cabook) aquifers in the south-western region (Fig. 25.4).

25.2.1 Shallow and Deep Karstic Aquifers in the Miocene Beds

Only 9% of the land area of Sri Lanka consists of Miocene limestone sequences that are confined to the north and north-western part of the island (Fig. 25.2). The vertical thickness of the Miocene limestone beds exceeds 90 m in some cases and is underlain by thick sandstone sequences (Cooray 1984). On top of the limestone beds is a patchwork of unconsolidated marine and non-marine Quaternary deposits such as red earth, yellow-brown sands, dune and beach sands and lagoonal deposits. These limestone formations are characterized by both shallow confined karstic aquifers and deep confined aquifers.

From a hydrogeological point of view, shallow aquifers are developed on alluvial or lacustrine sedimentary formations. These rain-fed aquifers occur as lenses in unconsolidated sediments lying over limestone beds. They have been considered as highly productive, but extremely vulnerable to pollution (Chandrajith et al. 2016). In the last few decades, extensive development activities such as resettlements and commercial agricultural development have been initiated in the region and this lead to overexploitation of groundwater resources mainly from shallow aquifers. Saline water intrusion is also a common problem particularly along the coastal belt.

Deep confined aquifers in the limestone and sandstone formations extend to an average depth of 60 m. Tectonically, the NW-SE and NE-SW running joint systems in the limestone beds are important for recharging of the aquifers and provide the most important conduits for water infiltration. These aquifers occur as a series of several isolated hydrological basins (Davis and Herbert 1988; Basnayake 1988). Fault zones in limestone sequences form hydrogeological barriers segregating aquifers into a series of isolated blocks. There are seven isolated hydrogeological basins that were identified in this limestone belt, known as Madurankuli,

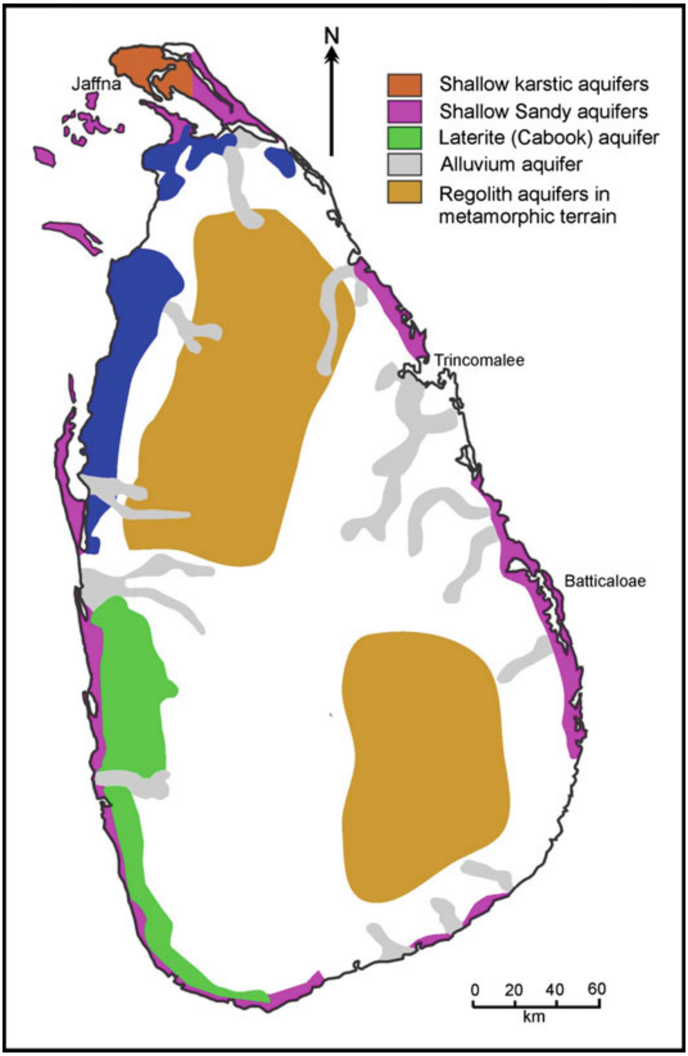


Fig. 25.4 Major aquifer types in Sri Lanka (modified after Panabokke 2007)

Vanathavillu, Silavathurai, Murunkan, Mulankavil, Paranthan–Kilinochchi and Mulathivu basins (Davis and Herbert 1988) (Fig. 25.5). These aquifer systems show a high degree of heterogeneity and anisotropy, which makes them behave differently from the metamorphic crystalline rock aquifers which are found elsewhere in the country (Chandrajith et al. 2016; Thilakerathne et al. 2015). Such karst aquifer features with interior cavern systems in the region have hardly been explored up to the present (Fig. 25.6).

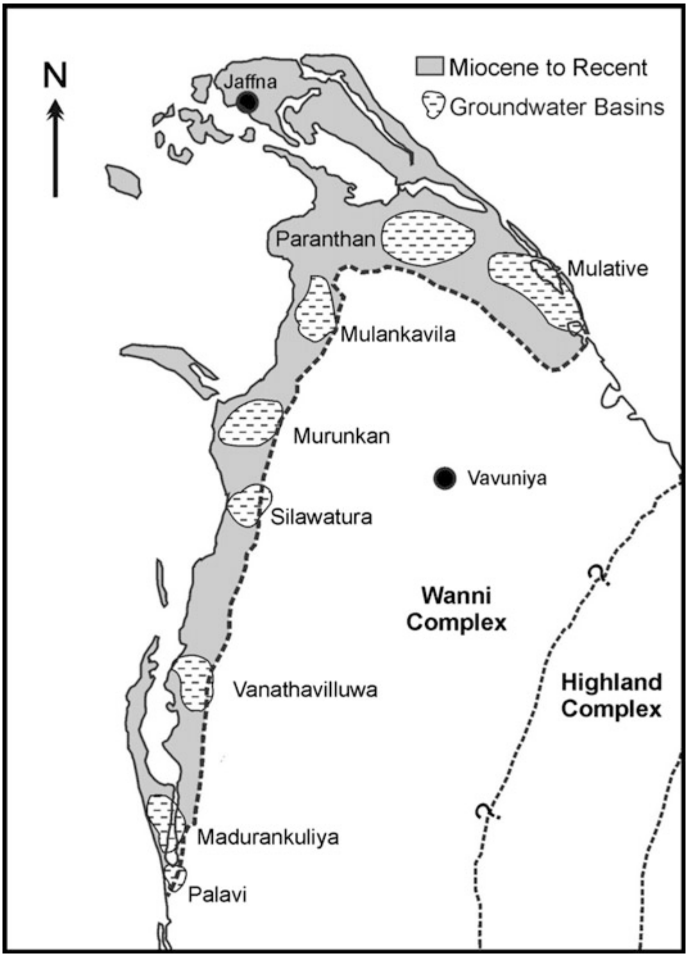


Fig. 25.5 Sedimentary groundwater basins in the northern Sri Lanka (modified after Davis and Herbert 1988)

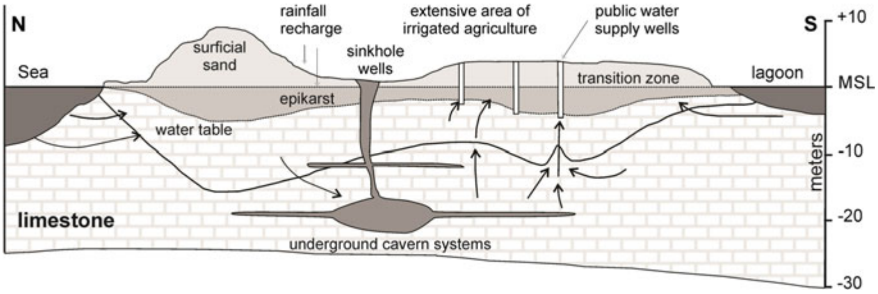


Fig. 25.6 Generalized hydrogeological cross section of Jaffna Peninsula (modified after Joshua et al. 2013). Arrows indicate pathways of recharge water

25.2.2 Coastal Sand Aquifers

Coastal sand aquifers in Sri Lanka are confined to spits and bars (e.g. Kalpitiya Peninsula and Mannar Island), raised coastal beaches (e.g. Nilaweli Kuchchaveli Pulmoddai and Kalkuda) and in sand dunes (e.g. Hambantota) or barrier beaches (Panabokke and Perera 2005). Total extents of these aquifers are estimated as 140,000 ha and are known to be highly productive. Groundwater in such aquifers is very shallow extending to a depth of 3 m and mostly occurs as lenses in sand layers or in dunes. Coastal beach aquifers in the island are confined to the narrow strips of raised beaches or low sand dunes and in some cases bounded to coastal lagoons (Fig. 25.7a). These aquifer systems are an important water resource in Sri Lanka that provides adequate supplies of water for agriculture and domestic uses since most of the coastal belts are highly populated (Kodituwakku and Pathirana 2003). However, water in such aquifers is characterized by high conductivity and is highly vulnerable to salt water intrusion (Chandrajith et al. 2014). Among the sandy aquifers systems in Sri Lanka, unconfined sandy aquifers are found in the Kalpitiya Peninsula in the north-western coast of Sri Lanka (Fig. 25.1). It is characterized by

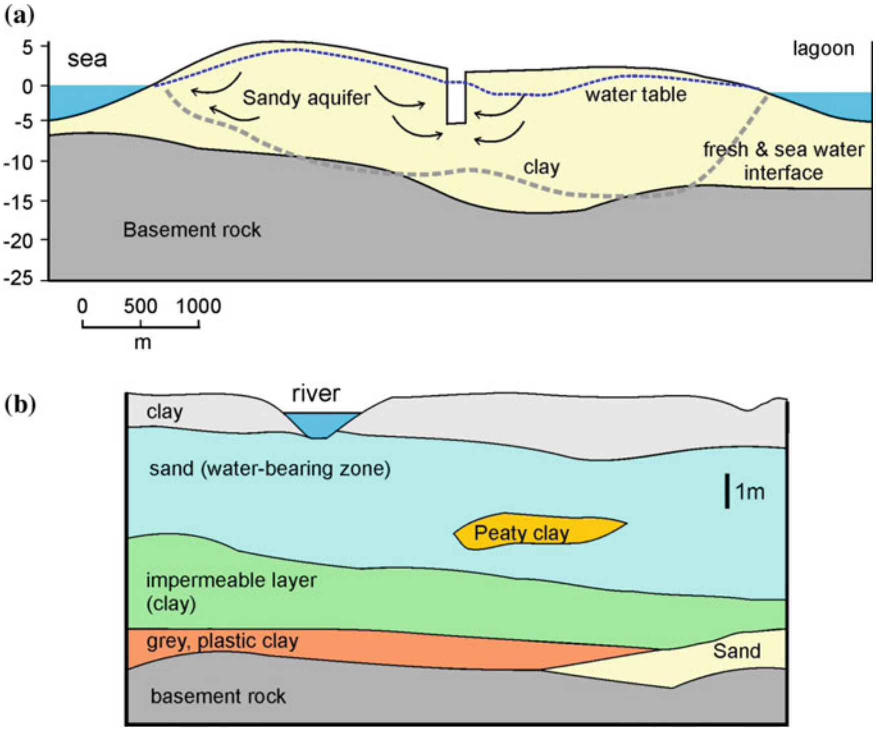


Fig. 25.7 Schematic cross sections of **a** sandy aquifer systems (modified after Panabokke and Perera 2005) and **b** alluvial aquifers (after Sirimanne 1957)

sandy aquifer media of marine origin during the Quaternary age. The area is flat with a slightly higher elevation in dunes, and the water table is relatively shallow (Jayasingha et al. 2011).

25.2.3 Alluvial Aquifers in Lower Reaches of River Basins

Alluvial aquifers mainly occur in floodplains of the lower reaches of river basins (Fig. 25.7b). Such aquifers are highly diversified and restricted to river valley deposits, buried river channels, small rivulets and stream beds with shallow alluvial deposits and inland valleys (Panabokke and Perera 2005). Many of these are associated with the major rivers of the country that cut across the coastal planes. A very large population of the country depends on these shallow aquifers for their domestic water use. Alluvial aquifers are a major source of water in the wet zone regions of Sri Lanka in which such aquifer is shallow and occurs as patches that are directly connected to surface waters in streams and rivers. Since such aquifers are recharged very quickly, people extract water without experiencing major drawdown hazards. Most of the major water supply schemes in urban areas in the wet zone are also based on alluvial aquifers associated with major rivers in the island.

25.2.4 Deep Confined Aquifers in the Metamorphic Terrain

As over 90% of Sri Lanka is made up of crystalline or hard rock terrains, a proper evaluation of the groundwater potential of the hard rock areas is absolutely essential. Although primary porosity and permeability are negligible in these rocks, structural discontinuities, such as foliations, faults, shear zones joints and associated deep-seated weathering, make these rocks good aquifers and often reach 70–100 m (Fig. 25.8). Axial regions of large-scale folds and lineaments are the most favourable sites for the occurrence of groundwater in the hard rock terrain. Quartzite, marble and fractured granites are by far the most productive aquifers, whereas charnockite, migmatite and gneisses devoid of fractures behave as aquicludes (Jayasena et al. 1986).

Socio-economic state and health conditions of the people particularly living in the dry zone of Sri Lanka are greatly influenced by the groundwater provided from deep confined aquifers. One of the ways of tapping deep groundwater in hard rock terrain is to drill deep holes or tube wells which penetrated mainly in the fractured aquifers. The tube well concept, which was first introduced to Sri Lanka around 1979, has now become a very popular means of supplying water to dry zone regions where surface water is scarce. Evaluation of the quality of groundwater and related hydrogeological conditions in fractured aquifers therefore is extremely important. The intensity of structural discontinuities in hard rocks depends on the type of rock, and the occurrence and movement of groundwater in the study area therefore are

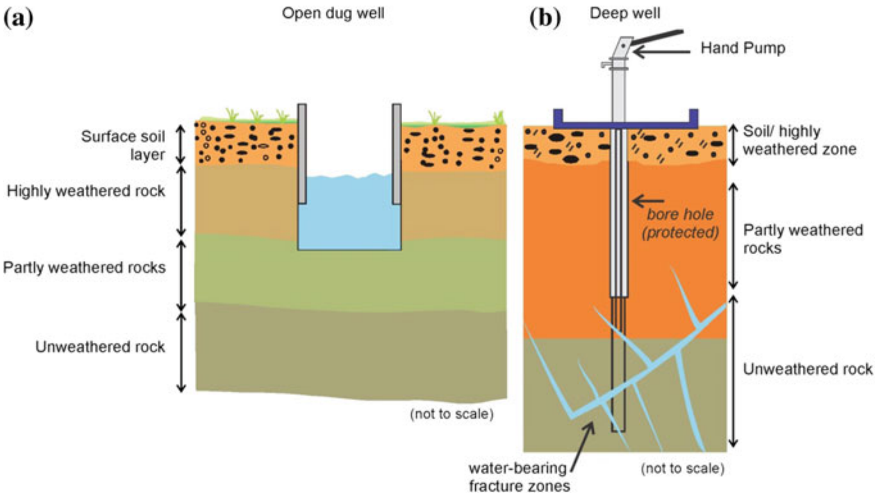


Fig. 25.8 Schematic cross section of shallow (**a**) and deep hard rock aquifers (**b**) in Sri Lanka

mainly controlled by the degree of weathering and the structure. The most striking difference between the shallow dug well and deep tube wells lies in their different physical and geochemical environments. Shallow wells are located mostly in the unconsolidated overburden, and the water table fluctuates seasonally; on the other hand, deep wells lie in the perennial water zones.

Another interesting observation in the hydrogeology of the Precambrian high-grade basement complex of Sri Lana is the occurrence of low enthalpy geothermal springs (Fig. 25.2) in which the measured surface temperatures ranged between 39 and 62 °C (Chandrajith et al. 2013). Although these hot springs of Sri Lanka have been known for centuries, the origin and the structure of these hydrothermal systems are still not well understood. The highest average reservoir temperature of 122 °C was noted in some hot springs based on silica geothermometry (Chandrajith et al. 2013). Geologically, hot springs are associated with metagranites, granitic gneisses and quartzite with some scattered bodies of dolerite dikes (Dissanayake and Jayasena 1988; Senaratne and Chandima 2011). An artesian type geothermal spring located in the Marangala region is associated with a dolerite dike of Cretaceous age (Senaratne and Chandima 2011). This spring drilled in 1983 to a depth of 21 m below ground level is in a SW-NE running lineament, and now springs water 3 m above the ground at a rate of 370 L/min. Hydrogeochemical and isotope investigations of thermal springs and nearby non-thermal groundwater reveal that both are hydrogeochemically and isotopically similar in composition. Stable isotope data suggested that both thermal water and non-geothermal water are recharged by the precipitation but geothermal water percolates deep downwards through faults and fractures and is heated by a steeper geothermal gradient (Chandrajith et al. 2013). Since Sri Lanka is not located close to an active tectonic boundary, volcanism is an unlikely source of heat as the youngest known igneous activity in Sri Lanka had occurred in Jurassic or late Cretaceous times. Geophysical investigation such as passive magnetotelluric soundings carried out on thermal springs indicated a reservoir system that extends around 2.5–3 km depth and revealed that dolerite dikes are not the source of heat although it could be acting as an impermeable barrier to form the reservoir (Nimalsiri et al. 2015).

25.2.5 Shallow Regolith Aquifers in Crystalline Rocks

These, though not interconnected due to the dense rocks lying under the regolith, are used for deep wells and shallow wells. Due to the high density of the metamorphic rocks, the aquifers will remain as isolated pockets fed from the infiltration rainwater through the cracks and fissures of the hard rocks. Weathering is often intensive with thicknesses of 2–10 m (Panabokke and Perera 2005). Particularly in the dryer part of the island, the soil profiles are relatively shallow compared to the wet zone where more intense rock weathering is common under wet humid conditions.

The dry zone reservoir cascade systems with thousands of reservoirs have a major impact on the recharge of these shallow regolith aquifers. Around 18,000 of these tanks are estimated to cluster into 3,500–4,000 cascade systems with the greatest concentrations in the north-west and north central dry zone districts (Mahatantila et al. 2008; Madduma-Bandara 1985). It has been recorded that 85% of the operational tanks are located within cascade systems, with 3.9 tanks on average in each cascade (Madduma-Bandara 1985). For over centuries, the dry zone population of Sri Lanka has depended on these water supplies from the tanks for domestic and irrigation needs. Structural discontinuities, such as faults, shear zones joints and lineaments, cause deep-seated weathering effects. Such structural discontinuities in hard rocks also create water-bearing zones. Therefore, the occurrence and movement of groundwater in these terrains are mainly controlled by the degree of weathering and the structure.

25.2.6 Lateritic (Cabook) Aquifers

Laterites, locally known as *Cabook*, are deeply weathered, rusty red colour saprolite that is rich in iron and aluminium nodules. Mineralogical analyses indicate that gibbsite is the most significant free aluminium mineral, whereas goethite and haematite are the main iron minerals in laterites (Dissanayake 1980). Intense weathering of underlying parent rocks under tropical humid conditions in the coastal plains of the western region of the country is characterized by lateritic soils. The region is a gently undulating plain with a high density of drainage paths. Laterites are important in the hydrogeology of the region that regulates the partitioning between heavy precipitations and surface run-off with higher recharge. Laterites are highly porous, and hence high water retention capacity contributes to high-potential groundwater supplies in the western region of the country. The monsoonal rain which feeds these aquifers is the main sources of the water. Overexploitation by the increasing population in these densely populated regions has caused major water deficiencies. High acidity is the main problem associated with groundwater in these lateritic aquifers.

25.3 Water Quality in the Groundwater of Sri Lanka

The marked climatic changes and the clear demarcation of the climatic zones with widely different rainfall patterns have had a major impact on the geochemistry of groundwater in Sri Lanka. Even though the underlying rocks do not change appreciably for each of the climatic zones, it is the rainfall and the rates of evaporation that has had the biggest impact on the changing concentrations of chemical species in the groundwater. These major changes of the quality of the water have resulted in impacts on agriculture and human health. This is all the more significant since a very large population, notably the farming community of the dry zone, depend heavily on the groundwater for all their domestic needs, notably drinking and cooking purposes. The percentage of those having pipe-borne water supply is only about 44% (about 9 million people), and about 3% (more than 0.6 million) have access to hand pump tube wells. However, 36% of the rural population has access to drinking water through protected dug wells, and about 15% of the population is unable to access a safe water source within 200 m of their residence (Fan 2015) emphasizing the fact that the water and health are significantly linked.

With the publication of the first Hydrogeochemical Atlas of Sri Lanka (Dissanayake and Weerasooriya 1985), preliminary information on the geochemical quality of the groundwater of the island was obtained. Even though 30 years have elapsed, the Atlas has not been updated and the need for the production of a modern Hydrogeochemical Atlas for Sri Lanka is greater than ever. One of the major contributions made through the Hydrogeochemical Atlas of Sri Lanka was the geochemical classification of groundwater. The groundwaters of Sri Lanka were classified into four main types as calcium type, magnesium type, sodium–potassium type and non-dominant cation type. Each of these water types were subdivided into the Cl^-, SO_4^2, HCO^-_3 and non-dominant anion (NDA) types. Calcium water type is found mainly areas in the northern, central as well as in some parts in north central, southern and eastern areas. The Cl^- types occur mainly in the north, while the HCO^-_3 type is found more in the central regions. The problem of salinity is also of significance in view of the heavy dependence on agriculture by the population, in these affected areas in the dry zone. The climatic changes and the accompanying low rainfall and higher temperatures have changed the geochemistry of the groundwater both spatially and temporally, the abandonment of wells used for decades by families due to heavy concentrations of same chemical species, notably Na, Ca and F serve as examples. The need to produce water quality maps for each region, and the need to update their maps has become a national priority. Salinity is markedly present in the more northerly areas, while dominant carbonate rocks are present in the central regions. Magnesium-type water is distributed is a small area in the country mainly in south-eastern region notably around Embilipitiya, while sodium–potassium-type water is abundant in large areas of the north, central, western and south-eastern dry zone of the country. The chloride subtype predominates due to the very high rates of evaporation, salinity and salt formation. Non-dominant cation-type waters predominate in the periphery of the central highlands and in some regions of the north central and southern regions. The $HCO^{-}{}_{3}$ and non-dominant anion subtypes are more prevalent in these regions.

Recently, groundwater quality covering all three climatic zones was analysed for 16 physico-chemical parameters and showed that there is a clear variation in water types between dry and wet climatic zones with mixed values in the intermediate zone (Rubasinghe et al. 2015). As indicated in their study, Ca–Mg-rich water of the chloride type predominates in the dry zone with Na–K water type being more abundant, bicarbonate being the common anionic species. In the dry zone, groundwater geochemistry is mainly controlled by water–rock interactions, weathering and evaporation processes while pollution is more common in the wet zone. Subsequent ion exchange processes contribute to the nature and chemical composition of the water in the dry and intermediate zones. Precipitation is a process dominant in the wet zone and which gives rise to contrasting groundwater chemistry. Salinity is more dominant in the dry zone as compared to the wet and intermediate zones (Rubasinghe et al. 2015).

One of the more interesting features in groundwater from different climatic regions in Sri Lanka is the drastic variation of water hardness (Fig. 25.9). As noted by Rubasinghe et al. (2015), the mean hardness of wet zone water was 79 mg/L while it was 236 mg/L in the dry zone where hardness up to 1,104 mg/L was also

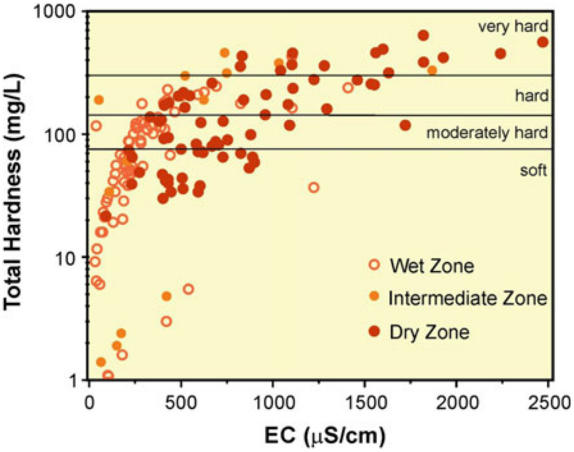


Fig. 25.9 Variation of hardness against the electrical conductivity of groundwater of Sri Lanka (after Rubasinghe et al. 2015)

recorded. About 30% of wells in the dry zone exceeded the permissible limit of 300 mg/L, and nearly 10% of the wells exceeded the allowable limit of 600 mg/L. Permanent hardness is also common in the dry zone regions as indicated with much higher sulphates levels (mean 29 mg/L) than other climatic regions. Even in the deep aquifers of the wet zone, higher hardness was recorded in wells located on crystalline limestone beds (Abeywickarama et al. 2015).

25.3.1 Water Quality in Karstic Aquifers in the Miocene Beds

The quality of water in karstic aquifers in Miocene beds and associated sand dunes was the subject of interest for years of which the Jaffna Peninsula was the main focus. The most striking feature of the karstic region is the absence of perennial rivers, and therefore, groundwater is the major source of water for both agriculture and domestic use. Rainfall is only seasonal and is the sole source of recharge of aquifers. Studies on karstic aquifers mostly considered geochemical conditions that are attributed to anthropogenic activities such as fertilizer applications in agriculture and septic tank leaching (Dissanayake and Weerasooriya 1987; Joshua et al. 2013). Nitrates in groundwater are more abundant and sometimes exceed the acceptable levels for drinking purposes. In recent years, the region was subject to substantial land-use changes. It has also been noted that the heavy extraction of freshwater by the wells had resulted in increasing influx of saline water causing deterioration of the quality of the groundwater. For instance in the Jaffna Peninsula, total agricultural water usage is 147,000 million litres per year from which 88,000 used in the dry season while 59,000 million litres per year used in the wet season (Punthakey and Gamage 2006).

Recently, karstic aquifers in the Jaffna Peninsula and Murunkan Basin have been studied in detail using hydrogeochemical and stable isotope data (Chandrajith et al. 2016; Thilakerathne et al. 2015). As indicated by these studies, both sea water intrusion and irrigation return flows contribute heavily to the compositions of karst aquifer water in these regions. A study on the major and trace element composition and environmental isotope ratios of oxygen and hydrogen ($\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$) in groundwater from the Jaffna region showed that the anion sequence is of the order of $HCO^{-}_{3} > Cl^{-} > SO_{4}^{-} > NO_{3}^{-}$ while the $Na^{+} + K^{+}$ contents in groundwater exceeded $Ca^{2+} + Mg^{2+}$ contents in most cases. Ionic relationships of major solutes indicated that open-system calcite dissolution is the most common rock–water interaction while sea water intrusions are evident in wells located close to the coast. In general, the groundwater in the region is contaminated by agricultural irrigation returns and associated evaporation (Chandrajith et al. 2016).

Another comprehensive study was carried out in the Murunkan Basin located in the north-west of Sri Lanka (Fig. 25.3) (Thilakerathne et al. 2015) in which the samples were taken from the limestone terrain as well as from metamorphic terrain and unconsolidated Quaternary terrains. They observed that there is a distinct geochemical difference between groundwater from the limestone terrain as against the metamorphic terrain. Bicarbonate–chloride-rich water is predominant in the limestone terrain, while saline water intrusions modified the composition in certain regions in the limestone belt. On the other hand, groundwater in the metamorphic terrain is modified by dissolving Ca–Mg-rich mineral phases and subsequent ion exchange processes (Thilakerathne et al. 2015). In decreasing order, bicarbonates, chloride and sulphate were the dominant anions in the groundwater from limestone aquifers while less bicarbonates and chloride contents were observed in metamorphic aquifers. In both Jaffna and Murunkan, the stable isotope composition of $\delta^{18}O$ and $\delta^{2}H$ of groundwater closely follows the meteoric composition but is modified by processes of evaporation. The significant enrichment of the isotope signature indicates a high vapour flux caused by evaporation under semi-arid conditions and due to slow infiltration. In the metamorphic terrain, however, evaporation is low at near the soil surface (Chandrajith et al. 2016).

25.3.2 Water Quality in Hard Rock Aquifers in the Dry Zone

Perhaps some of the most significant contributions in the field of hydrogeology during last three decades have come from studies on water quality in the metamorphic hard rock terrain giving more emphasis to the dry zone aquifers. After implementation of the deep well programme, more attention was required in the terms of water quality in these dry zone regions. Hardness, fluoride, chloride, Na, Ca, Mg and iron have received much attention due to their effect on human health. The chemical constituents of groundwater in hard rock terrain revealed relationships with the aquifer lithology (Jayasena et al. 2008). As shown in their study, groundwaters from mafic rocks have high dissolved solids, while quartzo-feldspathic metaclastic strata and granite yield water with low dissolved solids. The chloride content is higher in terrains underlain by pink feldspar granite and marble/calc gneiss. Obviously, higher concentrations of Ca and Mg ions are associated with crystalline limestones while groundwaters from charnockite-bearing areas tend to have non-dominant cations and more $CO_3{}^{2-} + HCO^{-}{}_3$ types (Jayasena et al. 2008; Abeywickarama et al. 2015). Most of the early studies indicate that the regolith characteristics, fracture intensity and climatic variations, play a significant role in the behaviour of the hydrochemistry in the hard rock terrain of Sri Lanka.

A unique feature of the geochemistry of the groundwater of Sri Lanka is the occurrence of a fluoride belt encompassing much of the hard rock terrain of the dry zone (Dissanayake and Weerasooriya 1985). Groundwater in the dry zone aquifers has high concentrations of fluoride that exceed the permissible levels (Fig. 25.10) (Chandrajith et al. 2012). High fluoride is notably found in deep wells posing a health hazard to the consumer. A well-known association between a chemical

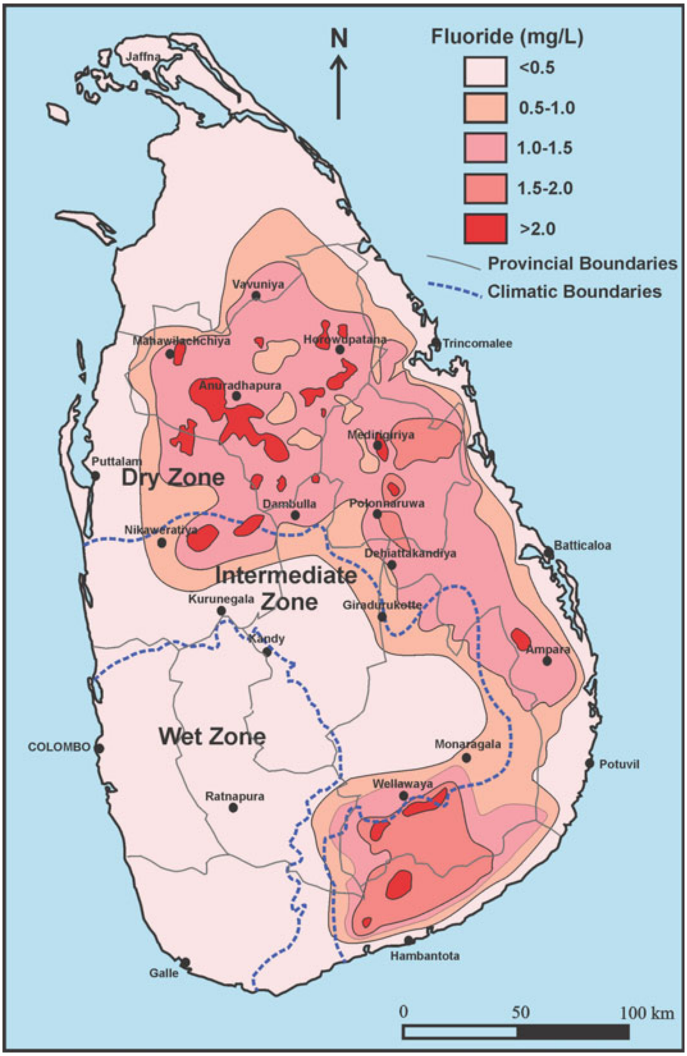


Fig. 25.10 Distribution of groundwater fluoride in Sri Lanka (after Chandrajith et al. 2012)

element in the drinking water and human health is that of fluoride with dental and skeletal diseases. Therefore, wide prevalence of dental and skeletal fluorosis can be observed in the dry zone of Sri Lanka associated with high fluoride groundwater. The hydrogeochemical map of fluoride clearly indicates that the climate and hydrological conditions play a major role in the geochemical distribution of fluoride in the groundwater. The very high fluoride levels in the groundwater are associated with fluoride-bearing minerals in the rocks, while water–rock interaction and high evaporation lead to subsequent concentration (Dissanayake 1991). Fluoride, on account of its chemical similarity to the hydroxyl ions, is easily taken up by the water when in association with fluoride-bearing minerals in rocks and soils. The marked difference in the fluoride levels in the wet zone and the dry zone is clearly significant and indicates that this is an effect of climate change although the dry zone of Sri Lanka is no different from the wet zone as far as the types of rocks and minerals are concerned. It was noted that in dry zone areas, over 25% groundwater wells had more than the recommended level of fluoride (0.6 mg/L) for tropical countries (Chandrajith et al. 2012).

In the last two decades, endemic occurrence of chronic kidney disease of unknown aetiology (CKDu) is observed in certain isolated patches in the dry zone of Sri Lanka and has now become an emerging health issue (Nanayakkara et al. 2013; Chandrajith et al. 2011b). The CKDu exclusively occurs in regions where groundwater is the main source of drinking water and is more common among the farming community. Histopathological investigations on the disease suggest that a focal renal tissue ischaemia might play a major role in the pathogenesis of CKDu which is more in favour of vascular injury than toxic nephropathy caused by heavy metals such as Pb, Cd and U (Nanayakkara et al. 2012). Due to its remarkable geographic distribution and histopathological evidence, the disease is believed to be an environmentally induced problem. The aetiology of CKDu is attributed to the high fluoride in these regions (Dissanayake 2005). however, other major ions in groundwater mainly Ca, Mg and Na contribute to the occurrence of the disease as contributory factors (Chandrajith et al. 2011a).

25.3.3 Water Quality in Coastal Sandy Aquifers

Groundwater quality in coastal sandy aquifers in Sri Lanka is greatly influenced by geological and anthropogenic activities. From among coastal sandy aquifers, aquifers in Kalpitiya and Panama regions received more attention (Jayasingha et al. 2011; Chandrajith et al. 2014). The majority of the land in the Kalpitiya area is used for agriculture in which coconut cultivations dominate while commercial cultivation of onion, chilly, gherkins, guava (*Psidium guajava* L.) is also widespread in the region. Such cultivations use excessive amounts of chemical fertilizers that lead to contamination of shallow groundwater. The dominant pollutant in groundwater in the Kalpitiya Peninsula is nitrate presumably due to intensive agricultural activities (Liyanage et al. 2011). The nitrate-N contents in this region vary from 0.60 to 212 mg/L in the dry seasons, while it is 0.20–149 mg/L in rainy seasons. In both dry and rainy periods, over 50% of wells in the region exceeded WHO drinking water guideline values for nitrate-N concentrations. The phosphate content in groundwater ranged from 0.20 to 5.70 mg/L in the dry season and 0.04–10.4 mg/L in the rainy period (Jayasingha et al. 2011).

The coastal aquifer system in Panama in the south-east coast is another important aquifer that has been investigated in detail (Chandrajith et al. 2014). One of the biggest threats of this aquifer is the salt water intrusion mainly from the nearby lagoon. Groundwater of this aquifers showed a ranking of major anions in the order Cl > HCO_3 > $SO^{2-}{}_4$ > N–NO_3, while cations showed a decreasing order of abundance with $Na^+ > Ca^{2+} > Mg^{2+} > K^+$. Dominant groundwater hydrogeochemical types were Na–Cl and mixed Ca–Mg–Cl. High nitrate-N in some locations indicated the influence of anthropogenic activities. The mixing of sea water with the fresh groundwater in the Panama sandy aquifer was investigated using non-reactive isotope geochemical traces.

The mixing calculations indicated that up to 11% of sea water and up to 18% of lagoon water could be intruded into the aquifer and intrusion is more intense towards the lagoon. Since the area is dominantly composed of unconsolidated sand with extremely high porosity and permeability, large-scale mixing can be expected. However, limited salt water mixing in the region indicated the occurrence of groundwater lenses in the region (Chandrajith et al. 2014).

25.4 Summary

Sri Lanka's unique geology and geomorphology have imparted some special characteristics in its hydrogeology and geochemistry. Much of the land in the island comprises of high-grade metamorphic rock with few sedimentary sequences. The island is also demarcated with marked climatological changes that have also resulted in well-defined climatic zones with their own hydrogeochemical characteristics. Even though the underlying geology does not show much variation among climatic zones, the hydrogeochemistry is markedly different in the dry zone as against the wet zone. The former is characterized by its high fluoride contents, water hardness and total dissolved solids. This special feature has a significant impact on the health of the population in the dry zone with dental and skeletal fluorosis and kidney diseases being prominent.

References

Abeywickarama B, Ralapanawa U, Chandrajith R (2015) Geoenvironmental factors related to high incidence of human urinary calculi (kidney stones) in Central Highlands of Sri Lanka. Environ Geochem Health 1–12

Basnayake BMSB (1988) Groundwater potentials in the sedimentary rock of Sri Lanka. In: L.J.D. Fernando Felicitation Volume. Geological Society of Sri Lanka, Peradeniya, pp 71–77

Bastiaanssen WGM, Chandrapala L (2003) Water balance variability across Sri Lanka for assessing agricultural and environmental water use. Agric Water Manag 58(2):171–192

Chandrajith R, Dissanayake CB, Ariyarathna T, Herath H, Padmasiri JP (2011a) Dose-dependent Na and Ca in fluoride-rich drinking water—another major cause of chronic renal failure in tropical arid regions. Sci Total Environ 409(4):671–675

Chandrajith R, Nanayakkara S, Itai K, Aturaliya TNC, Dissanayake CB, Abeysekera T, Harada K, Watanabe T, Koizumi A (2011b) Chronic kidney diseases of uncertain etiology (CKDue) in Sri Lanka: geographic distribution and environmental implications. Environ Geochem Health 33 (3):267–278

Chandrajith R, Padmasiri JP, Dissanayake CB, Prematilaka KM (2012) Spatial distribution of fluoride in groundwater of Sri Lanka. J Natl Sci Found Sri Lanka 40(4):303–309

Chandrajith R, Barth JAC, Subasinghe ND, Merten D, Dissanayake CB (2013) Geochemical and isotope characterization of geothermal spring waters in Sri Lanka: evidence for steeper than expected geothermal gradients. J Hydrol 476:360–369

Chandrajith R, Chaturangani D, Abeykoon S, Barth JAC, van Geldern R, Edirisinghe EANV, Dissanayake CB (2014) Quantification of groundwater–seawater interaction in a coastal sandy aquifer system: a study from Panama, Sri Lanka. Environ Earth Sci 72(3):867–877

Chandrajith R, Diyabalanage S, Premathilake KM, Hanke C, van Geldern R, Barth JAC (2016) Controls of evaporative irrigation return flows in comparison to seawater intrusion in coastal karstic aquifers in northern Sri Lanka: evidence from solutes and stable isotopes. Sci Total Environ 548:421–428

Cooray PG (1984) The geology of Sri Lanka. National Museums of Sri Lanka, Colombo (2nd revised edn.)

Cooray PG (1994) The Precambrian of Sri Lanka: a historical review. Precambr Res 66(1):3–18

Davis J, Herbert R (1988) Hydrogeology of the Miocene sedimentary belt of Sri Lanka. J Geol Soc Sri Lanka 1:45–63

Dias DP, Dissanayake CB, De Silva NR, Chandrajith R, Jayasinghe ULB, Nimalasiri TB (2012) Preliminary investigations on the hydrocarbon potential of a recently discovered black shale deposit in the north-east of Sri Lanka. Ceylon J Sci (Phys Sci) 16:31–36

Dissanayake CB (1980) Mineralogy and chemical composition of some laterites of Sri Lanka. Geoderma 23(2):147–155

Dissanayake CB (1991) The fluoride problem in the ground water of Sri Lanka—environmental management and health. Int J Environ Stud 38(2–3):137–155

Dissanayake CB, Jayasena HAH (1988) Origin of geothermal systems of Sri Lanka. Geothermics 17(4):657–669

Dissanayake CB, Weerasooriya SVR (1985) Hydrogeochemical atlas of Sri Lanka. Natural Resources, Energy & Science Authority of Sri Lanka, Colombo

Dissanayake C, Weerasooriya S (1987) Medical geochemistry of nitrates and human cancer in Sri Lanka. Int J Environ Stud 30(2–3):145–156

Dissanayake CB (2005) Water quality in the dry zone of Sri Lanka-some interesting health aspects. J Natn Sci Found Sri Lanka 33(3):161–178

Domrös M (1979) Monsoon and land use in Sri Lanka. GeoJournal 32:179–192

Fan M (2015) Sri Lanka's water supply and sanitation sector: achievements and a way forward, vol 35. Asian Development Bank, ADB South Asia working paper series

Gunatilaka A (2008) Water security and related issues in Sri Lanka: the need for integrated water resource management

Hatherton T, Pattiarachchi DB, Ranasinghe VVC (1975) Gravity map of Sri Lanka, 1: 1,000,000. Professional Paper 3. Geological Survey Department, Colombo, Sri Lanka

Hölzl S, Hofmann AW, Todt W, Köhler H (1994) U-Pb geochronology of the Sri Lankan basement. Precambr Res 66(1):123–149

Jayasena HAH, Singh BK, Dissanayake CB (1986) Groundwater occurrences in the hard rock terrains of Sri Lanka—a case study. Aqua AQUAA (4)

Jayasena HAH, Chandrajith R, Dissanayake CB (2008) Hydrogeochemistry of the groundwater flow system in a crystalline terrain: a study from the Kurunegala district, Sri Lanka. Environ Geol 55(4):723–730

Jayasingha P, Pitawala A, Dharmagunawardhane HA (2011) Vulnerability of coastal aquifers due to nutrient pollution from agriculture: Kalpitiya, Sri Lanka. Water Air Soil Pollut 219(1–4):563–577

Joshua WD, Thushyanthy M, Nanthagoban N (2013) Seasonal variation of water table and groundwater quality of the karst aquifer of the Jaffna Peninsula-Sri Lanka. J Natl Sci Found Sri Lanka 41(1):3–12

Kodituwakku KAW, Pathirana SRK (2003) North Eastern coastal sand aquifers in Trincomalee District, vol Technical Paper 18. Integrated Food Security Program, Colombo, Sri Lanka

Kröner A, Williams IS (1993) Age of metamorphism in the high-grade rocks of Sri Lanka. J Geol 101:513–521

Liyanage CE, Thabrew MI, Kuruppuarachchi DSP (2011) Nitrate pollution in ground water of Kalpitiya: an evaluation of the content of nitrates in the water and food items cultivated in the area. J Natl Sci Found Sri Lanka 28(2):101–112

Madduma-Bandara CM (1985) Catchment ecosystems and village tank cascades in the dry zone of Sri Lanka. Stratergies for river basin development. Reidel Publishing Company, Germany

Mahatantila K, Chandrajith R, Jayasena HAH, Ranawana KB (2008) Spatial and temporal changes of hydrogeochemistry in ancient tank cascade systems in Sri Lanka: evidence for a constructed wetland. Water Environ J 22(1):17–24

Milisenda CC, Liewa TC, Hofmanna AW, Köhler H (1994) Nd isotopic mapping of the Sri Lanka basement: update, and additional constraints from Sr isotopes. Precambr Res 66(1):95–110

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Nanayakkara S, Senevirathna ST, Karunaratne U, Chandrajith R, Harada KH, Hitomi T, Watanabe T, Abeysekera T, Aturaliya TNC, Koizumi A (2012) Evidence of tubular damage in the very early stage of chronic kidney disease of uncertain etiology in the North Central Province of Sri Lanka: a cross-sectional study. Environ Health Prev Med 17(2):109–117

Nanayakkara S, Senevirathna STMLD, Abeysekera T, Chandrajith R, Ratnatunga N, Gunarathne E, Yan J, Hitomi T, Muso E, Komiya T (2013) An integrative study of the genetic, social and environmental determinants of chronic kidney disease characterized by tubulointerstitial damages in the North Central Region of Sri Lanka. J Occup Health 56:28–38

Nimalsiri TB, Suriyaarachchi NB, Hobbs B, Manzella A, Fonseka M, Dharmagunawardena HA, Subasinghe ND (2015) Structure of a low-enthalpy geothermal system inferred from magnetotellurics—a case study from Sri Lanka. J Appl Geophys 117:104–110. https://doi.org/10.1016/j.jappgeo.2015.03.025

Panabokke CR (2007) Groundwater conditions in Sri Lanka: a Geomorphi perspective. National Science Foundation of Sri Lanka Colombo, Sri Lanka

Panabokke CR, Perera APGRL (2005) Groundwater resources of Sri Lanka. Water Resources Board, Sri Lanka, pp 3–13

Pathirana HDNC (1986) Sedimentary basins of Sri Lanka. In: Fernando LJD (ed) Felicitation Volume. Geological Society of Sri Lanka, Peradeniya, Sri Lanka, pp 71–77

Punthakey JF, Gamage PDN (2006) Coupled flow and salinity transport modelling and assessment of groundwater availability in the Jaffna Peninsula, Sri Lanka. In: Proceedings of 32nd WEDC International Conference

Rubasinghe R, Gunatilake SK, Chandrajith R (2015) Geochemical characteristics of groundwater in different climatic zones of Sri Lanka. Environ Earth Sci 74(4):3067–3076

Senaratne A, Chandima D (2011) Exploration of a potential geothermal resource at Wahawa Padiyatalwa area Sri Lanka. In: Proceedings, 36th Workshop on Geothermal Reservoir Engineering Stanford University, California

Sirimanne CHL (1957) Puttalam water supply from Mi Oya alluvium. Geological Survey of Ceylon, Colombo

Takigami Y, Yoshida M, Funaki M (1999) ^{40}Ar–^{39}Ar ages of dolerite dykes from Sri Lanka. Polar Geosci 12:176–182

Tantirigoda DA, Geekiyanage P (1988) An interpretation of gravity anomalies over the Jaffna peninsula in northern Sri Lanka. J Geol Soc Sri Lanka 1:30–34

Thilakerathne A, Schüth C, Chandrajith R (2015) The impact of hydrogeological settings on geochemical evolution of groundwater in karstified limestone aquifer basin in northwest Sri Lanka. Environ Earth Sci 73(12):8061–8073

Vitanage PW (1970) A study of the geomorphology and the morphotectonics of Ceylon In: UNESCO/ESCAFE 2nd International Seminar on geochemical prospects, methods and techniques, Bangkok, Thailand. ESCAFE

Vitanage PW (1972) Post-precambrian uplifts and regional neotectonic movements in Ceylon. In: Proceedings 24th IGC, pp 642–654

Vitanage PW (1985) The geology, structure and tectonics of Sri Lanka and South India. In: Cooray PG, Dissanayake CB (eds) Recent advances in the geology of Sri Lanka. Occasional Publication. CIFEG (International Center for Training and Exchange in the Geosciences), Paris, pp 5–15

Wickramagamage P (2015) Spatial and temporal variation of rainfall trends of Sri Lanka. Theor Appl Climatol 1–12

Yoshida M, Funaki M, Vitanage PW (1989) A Jurassic dolerite dyke from Sri Lanka and its palaeomagnetic analysis. J Geol Soc India 30:71–76

Part IV
Coastal Groundwater

Chapter 26
Monitoring the Coastal Groundwater of Bangladesh

Anwar Zahid, A. F. M. Afzal Hossain, M. Hazrat Ali, Kamrul Islam and Salah Uddin Abbassi

Abstract The low-lying topography and geographic position makes Bangladesh very vulnerable regarding the anticipated impacts of climate change that likely affects nearly all sectors of socio-economic life, where water sector is the most vulnerable and sensitive among them and country's coastal areas are at the greatest risk. The primary source of fresh water in the coastal belt is groundwater. But very few studies have been conducted to assess the influence of climate change on this resource. There is also high vulnerability to contamination with salinity due to mixing of pre-existing fresh and saline groundwater accelerated by irrigation pumping and vertical infiltration of salt water from periodic storm surge flooding. Changing climate and population stress might affect various components like recharge, discharge, storage, and water quality. The volume of water which is retained in the top soil is required for agriculture and has a role on the process of evaporation, recharge of groundwater, and innovation of runoff. Tidal saltwater wedge because of rising sea levels would cause to encroach further upstream in rivers, resulting salinity intrusion in aquifers. To know the evidence of changes in the events of hydrologic cycle including groundwater quality and storage is very important in order to adapt with the climate change impacts. The principal source of the irrigation water in Bangladesh is groundwater since decades and is one of the major factors making the nation almost self-dependent in crop production. Bangladesh being a very low-elevated country, where main part of the landform in the coast is up to 2–3 m above mean sea level, sea-level rise can cause increased intrusion of saline water both in surface water and in groundwater system. Inadequate safe water for irrigation and water supply will create more stress on fresh water. Therefore, it is important to map fresh water—saline water distribution

---

A. Zahid (✉)
Directorate of Ground Water Hydrology, Bangladesh Water Development Board, Dhaka, Bangladesh
e-mail: anwarzahidb@gmail.com

A. F. M. Afzal Hossain · M. Hazrat Ali · K. Islam
Institute of Water Modelling (IWM), Dhaka, Bangladesh

A. Zahid · S. U. Abbassi
Center for Water and Environment (CWE), Dhaka, Bangladesh

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_26

in coastal aquifers with other important physico-chemical parameters and predict future changes in this environment due to both climate change and anthropogenic stresses. Considering this, a monitoring network has been established by Bangladesh Water Development Board in 19 coastal districts with monitoring wells at variable aquifer depths down to 350 m. The objective of the project, under the support of Bangladesh Climate Change Trust, is to establish a long-term monitoring network to assess and monitor coastal water resources both on quantitative and on qualitative aspects. This paper focuses on to determine the potential of available fresh water resources and distribution of salinity in aquifers both spatially and vertically, mainly based on the monitoring data, for sustainable long-term use of very scarce fresh water in the region.

26.1 Introduction

The climate is an interactive cycle involving the atmosphere, oceans, and other water bodies includes groundwater, water as ice, and in land surface. Climate change is usually referred as the alteration that is slowly brought into weather situation and hydrological sequence in a time span from decades to millions of years. Though it occurs naturally, human activities can accelerate this. Over the past centuries, climate warming has been observed and influences various mechanisms of the hydrological cycle, such as increases in earth's normal atmospheric and ocean temperatures, extensive melting of ice, changing patterns of precipitation, increasing evaporation, rising of sea level, changes in soil moisture, and surface runoff. Studies mention that the global warming of temperature is mainly due to the elevated anthropogenic greenhouse gas concentrations since the middle of the twentieth century. Regular emissions of carbon dioxide, carbon monoxide, nitrous oxide, chlorofluoro carbon, methane, etc., cause global warming. Over the next century, the average surface temperature would increase by 1.5–4.5 °C. From 1906 to 2005, the increase in global surface temperature was 0.74 °C, and during the past 50 years, more rapid increase was observed (IPCC 2008). With respect to the base year 1990, the average rise in temperature would be 1.3 and 2.6 °C by the years 2030 and 2075, respectively, in Bangladesh (Ahmed and Alam 1999). Karmakar and Shrestha (2000) mentioned that using the 1961–1990 data, annual mean maximum temperature in Bangladesh by the years 2050 and 2100 would be increased by 0.40 and 0.73 °C, respectively, while mean annual temperature would increase by 0.22 and 0.41 °C, respectively. The increase in the average annual temperature was almost double than the previous years in the last decade. This warming could shift the zone of temperature, precipitation patterns, agricultural landforms, and rise in sea level. In Bangladesh, where low elevated coastal landforms are very vulnerable to sea water encroachment and submergence, both surface salinity and groundwater salinity may be accelerated with the raising sea level due to global warming. Based on the current trend of climate change, Bangladesh is likely to be in extreme vulnerable condition due to its geographic position and low-lying elevation. In the low-lying coastal areas, water resource is at utmost threat.

As a disaster-prone country, Bangladesh suffers from disasters like floods, storm surges, tropical cyclones, coastal and riverbank erosion, droughts and encroachment of saline water, almost regularly. The rural and agricultural developments have been recognized as the most priority sectors for poverty alleviation and to respond on the food demand of the country's growing population. More or less, every sector for socio-economic development can be affected by climate change. Among them the water and water-dependent agriculture are the most sensitive and vulnerable. Groundwater has provided about 97% of drinking water and 80% of dry season irrigation water in Bangladesh. For growing *Boro* paddy, irrigation water availability is compulsory. Worldwide, groundwater is the main source of fresh water but not many in-depth researches have been conducted to assess the impacts of climate change on this limited resource (IPCC 2001). Major components like recharge, discharge, reserve, and quality can be influenced by changes due to both climate and population pressures (UNESCO-IHP 2006).

In Bangladesh, the main source of irrigation water is groundwater since decades and also plays a vital role in making the country almost self-dependent in food grains. The rise in sea level can be the most significant consequence of global warming and climate change. The major portion of the coastal landform lies within 2–3 m above mean sea level. Sea-level rise can expand encroachment of brackish water or saline water both in surface and in groundwater systems, which will generate more pressure on the availability of fresh and safe water. Therefore, mapping of fresh water aquifers, groundwater—sea water interface in coastal aquifers and predicts future changes in this environment due to climate change and development stresses are important that can be achieved by generating adequate data and information establishing appropriate hydrogeological monitoring network.

Few hydrogeological studies were conducted to determine groundwater status in the coastal areas of Bangladesh. Bangladesh Water Development Board (BWDB) initiated study and investigation work on groundwater resources of the coastal belt in 1979, and the findings are presented in the Water Supply Paper entitled 'Ground Water in the Coastal Zone and Offshore Islands of Bangladesh' (BWDB 1979). Fresh water resources are always considered as valuable assets in the coastal zone where the surface water contains salinity most of the year. Analytical results of the investigation presented guidelines for the development and management of fresh groundwater resources in the coastal belt and recommended name of areas requiring further study. In 1982, UNDP prepared a report titled 'Ground Water Survey: the Hydrogeological Condition of Bangladesh' based on BWDB-UNDP study findings from all over the country (BWDB-UNDP 1982). The study indicated that the potential of deep aquifer is relatively unknown but there are indications that fresh water may be intruded. Development of the deep aquifer requires construction of deeper wells and consequently higher costs. More investigations were recommended to define the groundwater system in the area and to accurately determine the potential for development, mainly of deep groundwater. With the support of DANIDA, the Department of Public Health and Engineering (DPHE) carried out groundwater investigation in few areas of coastal districts (DPHE-DANIDA 2001). The findings reveal that potential aquifers in the coastal areas are mostly located at depths between 200 and 350 m, and heavy drilling equipment is required for the construction and testing of large diameter production wells to those depths. Special surface electrical resistivity survey equipment is recommended for identification of fresh water aquifers below the upper brackish water aquifers. Bangladesh Agriculture Development Corporation (BADC) undertook a groundwater salinity monitoring program during 2009–10 and 2010–11 in the southern region of Bangladesh (BADC 2011). The monitoring program covered May–June of 2011 and November–December of 2010. Salinity data were collected at every 3 m interval from 130 locations distributed over the Khulna, Dhaka, Barisal, and Chittagong divisions in the southern part of Bangladesh. The report made a comparison of the salinity status of the two periods on a district basis. The report recommended for intensive salinity data collection program, particularly using auto logger, in the coastal region to monitor the trend of salinity movement and to formulate mitigation and adaptation measures to cope with the impending climate change threat. Effect of salt water intrusion has long been documented as a limiting factor to perform the development of agriculture in the coastal belt. To reduce saline water inundation of agricultural lands by direct tidal flooding, the coastal embankment (polder) program has been undertaken. The study identified three salinity problem areas, namely (i) the Khulna region, (ii) the Comilla—Noakhali region or southern portion of the east region, and (iii) the Barisal district and the lower Meghna River. In the first two areas, the salinity problem is independent on the magnitude of discharge in the main rivers. For the third area, the salinity problem is directly related to the combined flow of the Ganges, Brahmaputra, and the Meghna and to development works outside Bangladesh which may reduce the dry season flow in any of the main rivers. In this study, mainly surface water salinity was monitored. Not much focus was given on groundwater.

The contamination of arsenic in shallow groundwater (10–50 m), high concentration of iron and brackish water occurs in the upper and at few places in deeper layers (down to about 300 m) forms a limitation to groundwater exploitation in the multi-layered aquifer system of the southern coastal belt (Zahid et al. 2008; DPHE-BGS 2001). Drinking water in the area is mostly discharged by the deep tubewells, and irrigation is restricted to surface water bodies. At very shallow depth (3–8 m), fresh water is also available from the recharge of seasonal precipitation, but during dry period, it turns to brackish. As the availability of fresh and safe water is an enormous crisis in the coastal areas, assessment and monitoring of probable impact of development stresses and climate change, i.e., the rise of sea level on fresh water source is required. In this context, Bangladesh Water Development Board has undertaken a project entitled ‘Establishment of Monitoring Network and Mathematical Model Study to Assess Salinity Intrusion in Groundwater in the Coastal Area of Bangladesh due to Climate Change’ under the finance of Bangladesh Climate Change Trust (BCCT), Ministry of Environment and Forest (BWDB 2013). The study area covers 19 coastal districts of Bangladesh which include Satkhira, Khulna, Bagerhat, Jessore, Narail, Shariatpur, Gopalganj, Barisal, Jhalokati, Bhola, Pirojpur, Barguna, Patuakhali, Chandpur, Lakshmipur, Noakhali, Feni, Chittagong, and Cox's Bazar and over 100 Upazilas under these 19 districts. The area lies on the Ganges and Meghna floodplains of lower delta in southern Bangladesh and extends inland till the Ganges delta and Meghna estuary region. Chittagong-Cox's Bazar coastal plain is also included within the project area.

The target of the study is to determine the hydrogeologic properties and water quality parameters in coastal groundwater to evaluate potential of its use emphasizing the following objectives requiring for agriculture, irrigation, and fresh water supply.

- Mapping and zoning of aquifer system down to the depth of 350 m analyzing lithologic logs of investigated boreholes.
- Assessment of groundwater chemistry and storage in coastal aquifers. Mapping spatial and depth distribution of important water parameters down to the depth of 350 m including arsenic, salinity, iron, manganese, etc.
- Determination and characterization of aquifer hydraulic properties by conducting slug tests and constant discharge aquifer pumping tests.

Policy makers, planners, stakeholders, users as well as population of these Upazilas (sub-districts) will get benefit from the continuous monitoring data and information for the planning of sustainable development of coastal water resources in water supply, agriculture, and other uses.

26.2 Establishment of Monitoring Network and Data Collection

A total of 42 groundwater monitoring well nests have been installed at 42 locations (Fig. 26.1) under 19 coastal districts considering lithology and hydrogeologic conditions for measuring water table, collection of water samples, and performing different chemical and aquifer hydraulic tests. Each well nest consists of 3–5 observation wells, i.e., piezometers down to the maximum depth of 350 m (Fig. 26.2). Number of installed line wells are 510 in 102 lines at different locations (5 wells in each line with the maximum depth of about 100 m) to evaluate surface water and shallow groundwater interaction. Lithologic logs have been prepared from collected sediment samples of all boreholes of nested and line wells. Based on these lithologs, sediment types, i.e., extension of aquifer units has been defined. Observers were engaged for measuring groundwater table of the installed wells. Survey has been conducted to measure RL (above mean sea level) of all completed observation wells under the project. All the installed observation points are geo-referenced.

For conducting aquifer pump tests in the deep fresh water aquifers in order to determine properties of aquifer sediment as well as to know the zone of influence to pumping, 18 production wells down to the maximum depth of 350 m have been installed and 19 constant discharge and 01 step-drawdown aquifer pump tests have

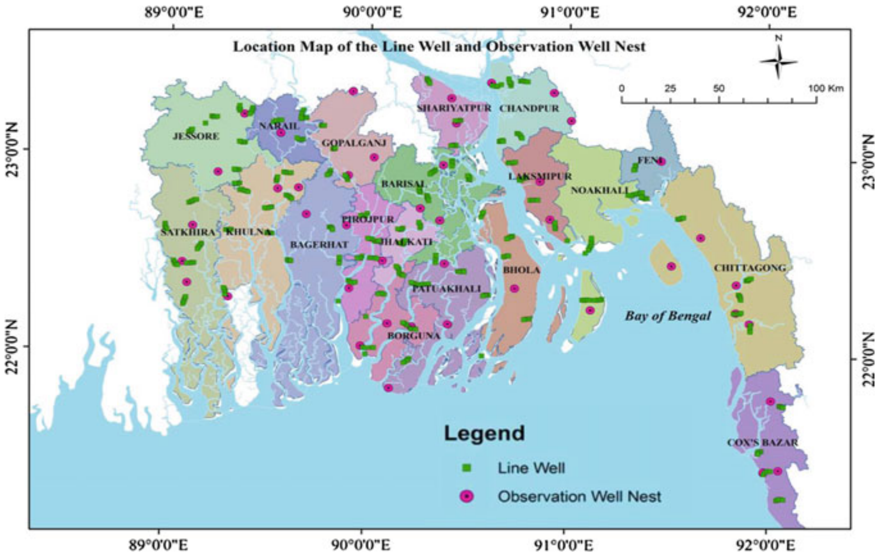


Fig. 26.1 Location map of the groundwater monitoring wells

been performed. Theis, Hautush, Hautush and Jacob, Theis (Recovery), Cooper and Jacob methods were used to analyze drawdown data for the confined to leaky confined aquifers. Electric conductivity (EC) of groundwater from pumping well was measured at two hours interval to monitor any change in salinity during pumping. About 124 numbers of slug tests have been conducted and data have been analyzed to estimate hydraulic conductivities as well as transmissivities of aquifer sediment at different depth levels. Havorslev and Bouwer and Rice methods were used, wherever applicable, to analyze slug tests data for semi-confined to confined aquifers.

Both dry and wet season groundwater samples (284 nos.) have been collected from the installed observation well nests for measuring important physico-chemical parameters (25 nos.) of water to assess the depth-wise quality of groundwater. Groundwater samples of dry and wet seasons (673 nos.) and nearby surface water samples (139 nos.) have been collected from many line wells, and for the rest of the line wells, water samples have been collected for once. Major physical parameters that have been measured are pH, Eh, EC, salinity, TDS and temperature, and main chemical parameters that have been measured are arsenic, calcium, magnesium, sodium, potassium, bi-carbonate, nitrate, phosphate, sulfate, chloride, iodine, bromine, silica, boron, fluoride, carbon dioxide, and manganese in the newly established BWDB laboratory using atomic absorption spectrophotometry (AAS), UV-VIS spectrophotometry, titration, and other standard methods. Analytical results were cross-checked by repeating the analysis of many samples in the laboratories of Bangladesh University of Engineering and Technology (BUET),

Fig. 26.2 Examples of installed nest of piezometers at Kolapara, Patuakhali (left), and Barisal Sadar (right)

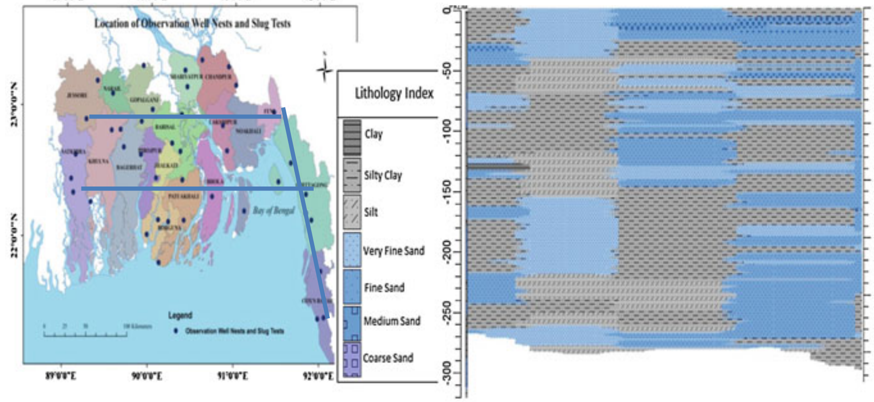
Department of Geology, University of Dhaka and Department of Public Health Engineering (DPHE).

26.3 Summarized Results and Findings

26.3.1 Extent and Characteristics of Aquifer Sediments

In the coastal belt of Bangladesh, hydrogeology as well as aquifer system is found very variable and complex. Within a short distance, alteration of aquifer-aquitard is highly variable. Appearance of clay or silty clay aquitards is not common in all locations. On a regional basis, aquifers down to the investigated depth of 350 m seem hydraulically connected, despite the effects of mechanical loading (Burgess et al. unpublished) (Fig. 26.3). However, in many places, 3–4 aquifer units are encountered and separated by aquitards and limited scale abstraction of groundwater from any aquifer depth might not affect the quality and groundwater table of the other aquifers. BWDB-UNDP (1982) described three aquifers on a regional basis. These aquifer units in the coastal belt are named as follows: shallow, i.e., the first aquifer that extends down to 50 to over 100 m depth, in many places overlain by an upper silt and clay unit of considerable thickness. The sediments of the aquifers consist of fine sand with clay lenses. The main or the second aquifer unit is generally underlain and overlain by aquitards that extend down to 250–350 m depth and composed of mainly fine to very fine sand, occasionally inter-bedded with lenses of clay. The second aquifer is either leaky/semi-confined or composed of stratified interconnected, sandy formations. The deep, i.e., the third aquifer is generally below the clay or silty clay aquitard which has been encountered to depths of 300–350 m. It consists of gray-colored fine sand, in places of alterations with silty clay or clay lenses. In many places, no significant clay or silty clay layer has been encountered at any depth down to 350 m.

C-C′: Lithologic Section from Feni to Cox’s Bazar



A-A′: Lithologic Section from Jessore to Feni

B-B′: Lithologic Section from Satkhira to Chittagong

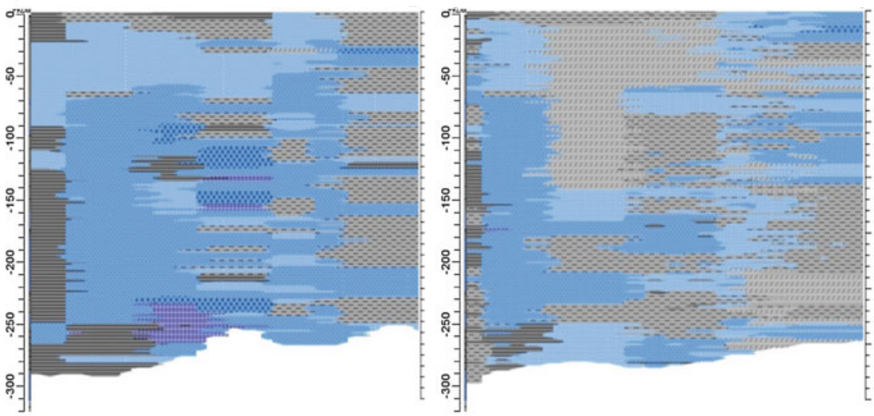


Fig. 26.3 Lithologic cross sections in the coastal areas of Bangladesh

The deep aquifer does not occur in some areas, e.g., south and southeast of Khulna town, Satkhira, Cox’s Bazar, and generally consists of a number of different stratigraphic layers. Two aquifers have been identified at Khulna town till the investigated depth of 325 m and generally discontinuous by 10–50 m thick clay and silty clay aquitards. The first aquifer is encountered at a depth of 35–100 m overlain by a 40 m thick aquitard. The second aquifer is encountered between depths of 150 and 270 m below surface. While, at Rupsha Upazila, Khulna, the aquifer continues till 280 m depth underlain by clay aquitard down to the investigated depth of 335 m. Based on the borehole lithologic log data, four aquifers have been identified in the investigated location at Feni Sadar down to the investigated depth of 280 m. In the Chittagong coastal zone, the Pliocene sediments exposed in the escarpment hills dip under the quaternary sediments of the coastal plain. The Pliocene sediments extend from 30 m near the foothills to 320 m on the offshore islands. Water in the shallow alluvial aquifers is of variable quality and contains pockets of intruded saline water from estuaries or coastal flooding. All over the coastal belt, the unpredictable occurrence of small fresh water pockets at shallow depth is reported. The protective clay layer is leaky or even absent in some places.

Hydraulic conductivity (HC) values estimated by conducting slug tests range between 1 and 25 m/day, 1 and 9 m/day, and 1 and 9 m/day for the shallow, the main, and the deep aquifers, respectively, that is typical for sandy alluvial aquifers. Transmissivity (T) was estimated, multiplied HC by aquifer thickness, between 100 and 2,300, 100 and 2,200, and 100 and 1,600 m^2/day for shallow, main, and deep aquifers, respectively. However, determination of the accurate thickness of aquifer was difficult in many cases as washed samples were collected from flowing water during drilling. Transmissivity values from long duration (up to 72 h), deep aquifer pump tests depict that Bagerhat, Chandpur, Jhalokathi, Khulna, Narail, Noakhali, Patuakhali deep aquifers have higher potential with T ranges between 769 and 3,224 m^2/day, while Barguna, Barishal, Cox's Bazar, Laksmipur deep aquifers show moderate potential with T values between 493 and 916 m^2/day and Chittagong, Feni, Jessore deep aquifers show low potential with T ranges between 144 and 370 m^2/day (Zahid et al. 2009, 2017). Storage coefficient values of deep aquifers were estimated between 0.0044 and 0.00016 that indicates that deep aquifers are leaky confined to confined in nature. For the controlled abstraction of groundwater for drinking use, deep production well can be installed having the discharge capacity of 0.20–0.40 cusec based on the extent of aquifer and properties of aquifer sediments. For abstraction of 12–14 h/day for such a discharge, limited numbers of wells can be installed maintaining appropriate well spacing, to avoid interference between two adjacent wells and to allow adequate recharge from surrounding aquifers. Aquifer pump tests results also illustrate that saline water from adjacent aquifers might not be encroached toward the pumping well during this discharge rate. However, the deep fresh groundwater may not be safe for a longer period of time, if no significant aquitard exists above or below the deep aquifer and where upper or lower aquifer units contain saline groundwater.

26.3.2 Trend of Groundwater Table Fluctuation

On a regional basis, the major components of groundwater flow are in vertical direction. These include the natural recharge from rainfall and flooding during the monsoon season, and the various discharges of water comprise mainly groundwater abstraction, during the dry season. Lateral groundwater movement is, on a regional scale, insignificant. The movement of groundwater and changing flow directions due to development of stresses have very significant role in the encroachment, intensity, and distribution pattern of groundwater salinity in the coastal area.

Analysis of long-term water table data of BWDB piezometers installed in upper aquifers shows that hydrographs are very variable in different parts of the country and variations can be significant on a local scale as well (WARPO 2000). On the other hand a degree of similarity is also found between different hydrographs, and this is quite closely related to the physiography and geological characteristics of the aquifer system. The impact of increasing groundwater development can often be clearly observed from hydrographs. Groundwater recedes more during the dry season and the rise is often delayed. When abstraction is intensive, groundwater table may decline permanently to a new equilibrium stage. However, seasonal water table fluctuation is more in the central and northern parts of the country where groundwater irrigation is extensive and this fluctuation is low or even nil near the coastline as groundwater irrigation in the southern coast is negligible due to salinity problem in upper aquifers. In March and April during the peak irrigation period, the trends of seasonal hydrograph are fairly smooth since many years and a sharp rise in the water table is noticed immediately when irrigation pumping is stopped in April and May. The water tables rise steadily until the levels are within about 1–2 m of the surface during the monsoon, which reveals that an active equilibrium occurred among the water table, deep rooted vegetation, and surface water (Ravenscroft 2003). Abstraction by shallow irrigation wells may also influence the fluctuations in the main aquifer water levels significantly. In the deeper part, these levels recover fast when irrigation pumping stops. This quick revival water levels in shallow aquifer reveals that there is a hydraulic connectivity between the shallow and the main aquifers, despite the mechanical loading effect (Burgess et al. Unpublished). Water levels may fall toward a new equilibrium condition, with intensive abstraction.

In observation well nests, installed in the coastal areas, the maximum groundwater level measured is very close for all three aquifers, except urban stressed areas like Chittagong and Khulna cities (Fig. 26.4). Groundwater pumping from the upper aquifer, during the dry irrigation period, influences the water levels in all aquifer units till the investigated depths of 350 m. But during the pumping test in the deep aquifer, detectable effect of water levels in piezometers screened in the shallow and the main aquifers was not observed. This indicates that the aquitards which divide aquifers are discontinuous regionally, but extended locally. Groundwater extraction from upper aquifers is generally balanced during monsoon period with the vertical percolation of rain and flood water and inflow from adjacent aquifers when pumping is ceased. However, in many areas under coastal districts, groundwater irrigation is not significant. Therefore, in the southern part, the seasonal fluctuation of water table is very negligible compared to that of northern part (Fig. 26.4).

Model simulation results (Zahid et al. 2015) describe that flowpaths and travel time of groundwater are generally influenced by hydrogeologic conditions. Continued abstraction for irrigation from the upper aquifer may reduce recharge from water percolation to the deeper aquifers. The water of the shallow, i.e., the first aquifer, normally has a higher head compared to the water head in the main, i.e., the second aquifer, due to pumping from the main aquifer. The shallow aquifer water may travel downward into the deeper units through aquitard breaks. The deep aquifer water level is higher than that of the main aquifer. Under the moderate abstraction of the deep groundwater, the shallow arsenic or chloride-rich groundwater is not likely to be moved into the deep aquifer. The mean travel time or age of

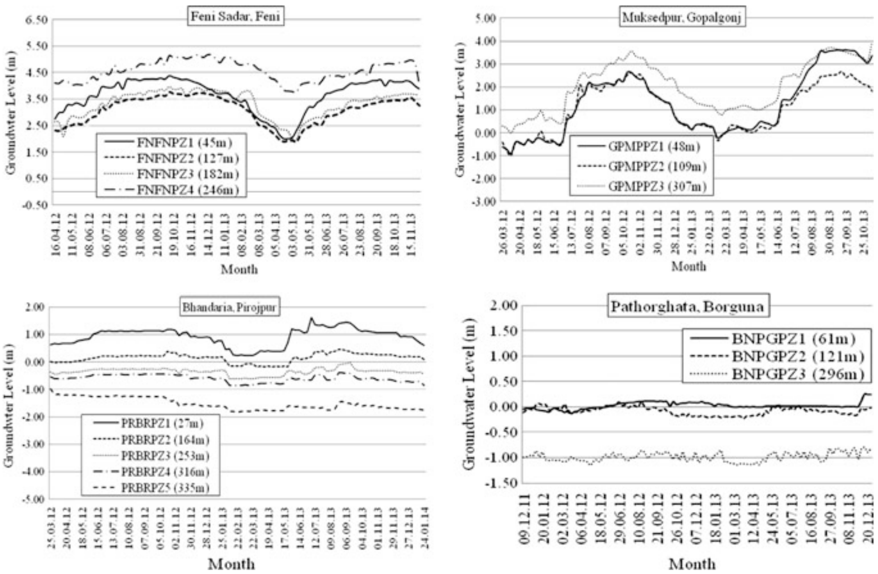


Fig. 26.4 Trend of groundwater level fluctuations in the northern (top) and southern (bottom) parts of the study area

groundwater for the upper and the lower parts of the first and the second and the upper part of the third aquifers at different hydrogeologic conditions are simulated from 37 to 234, 133 to 317, 832 to 2,485, 1,009 to 3,027, and 1,065 to 3,543 years, respectively, under current rate of water abstraction. Travel time of recharge water will be reduced in the first aquifer with growing irrigation pumping in future from lower part of the first aquifer. If extreme pumping continues from the 1st aquifer, average travel time will be increased for the second and the third aquifers.

26.3.3 Groundwater Quality

The groundwater in the coastal area is generally of the Na–Cl and the Na–Ca–Mg–HCO_3 types (Fig. 26.5). The trends of the Na–Cl type groundwater are $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > HCO_3^- > SO_4^{2-}$. The various causes of salinity in the coastal aquifers are noticed, including halite dissolution, sea water intrusion, presence of paleo-brackish water, etc. Among these, sea water encroachment is the most widespread source. However, vertical infiltration of saltwater due to storm surges or intrusion from brackish tidal rivers can occur more quickly than lateral subsurface migration of saltwater, particularly when inundation events are repetitive. The extreme groundwater abstraction in the coastal zone, even without climate change impact, is an important determinant of salinity intrusion.

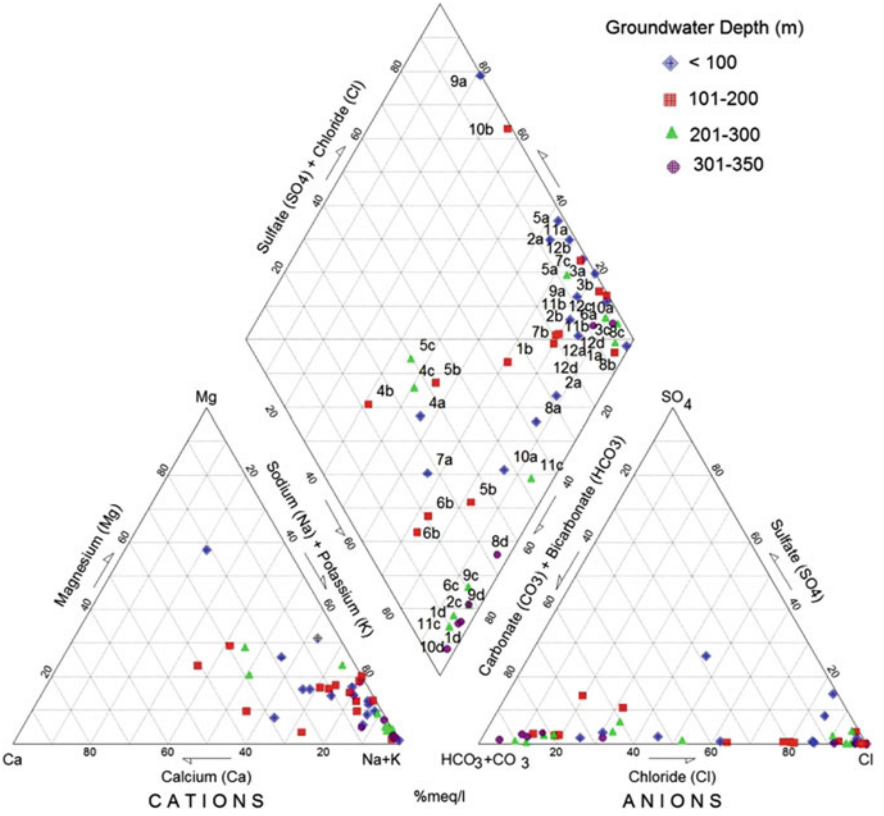


Fig. 26.5 Piper diagram showing depth-wise distribution of groundwater samples

Depth-wise distribution of maximum, minimum, and average concentration of different chemical parameters in coastal groundwater and their seasonal variability are presented in Table 26.1. In all natural water, Cl^- is present which indicates salinity level of that water. Chloride content is commonly less in groundwater but higher Cl^- may be present where the groundwater interacts with Cl^--rich surface water and sea water or any sanitation/sewerage system or industrial waste (Hem 1992). The concentration of Cl^- in groundwater of the tidal delta area ranges from 14.5 to 16,250 mg/l in wet season and 14 to 19,133 mg/l in dry season of the first aquifer. In the second aquifer, it ranges from 32.3 to 12,250 mg/l in wet season and 25 to 13,950 mg/l in dry season. The third aquifer shows the ranges of Cl^- concentration from 14 to 5,150 mg/l in monsoon and 15 to 14,517 mg/l in dry period.

A higher amount of Na^+ contains in groundwater, which is the richest member of the alkali-metal group. Primarily, the chemical decomposition of feldspar, feldspathoid, and some mica are the sources of Na^+ in groundwater. Agricultural by-product and industrial effluents are the other sources of Na^+ in groundwater contamination (Hem 1992). Typically, Na^+ concentrations of potable water are less

Table 26.1 Maximum, minimum, and average concentrations of different chemical parameters in coastal groundwater and their seasonal variability (in mg/l)

Element (mg/l)	First aquifer/shallow groundwater						Second aquifer/intermediate depth groundwater						Third aquifer/deep groundwater					
	Wet season			Dry season			Wet season			Dry season			Wet season			Dry season		
	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Ca	544	3.4	108.45	259	0.95	55	183.6	2.12	80.71	272.1	3.7	69.6	231.1	2.43	63.03	268.6	0.28	60.96
Mg	146.7	1.9	37.65	1,096.8	2.1	99.66	149	2.74	44.21	141.4	5.32	55.21	145	1.06	31.47	138.9	0.35	37.48
Na	3,000	4.2	647.8	8,848.4	11.6	1,323.89	2,610	3.2	585.41	1,999	5.8	713.5	2462.9	1.4	248.15	3087.2	4.08	746.72
K	142.03	0.25	37.53	246.75	0.2	26.28	26.35	0.75	9.91	59.5	0.35	13.5	29.5	1.1	8.63	48.54	0	9.36
Cl	16,250	14.5	3,376.69	19,133	14	3,987	12,250	32.3	3,406.93	13,950	25	4034	5150	14	903.8	14,517	15	1748
F	1.83	0.06	0.88	16.1	0.05	9.01	1.73	0.25	1.12	10.78	0.07	1.49	2.12	0.05	1.07	12.22	0	2.7
CO_3	54	0	12.93	13.5	0	1.64	18	0	5.5	3	0	1.41	36	0	3.87	18	0	2.85
NO_3	44.16	0.21	11.67	131.5	0.23	14.43	37.81	0.02	6.73	28.77	0.04	7.74	34.57	0.01	4.04	22.87	0.02	3.29
HCO_3	823.5	48.8	353.22	1,049.2	24.4	505.08	475.8	42.7	290.89	591.7	24.4	341.6	488	134.2	292.61	646.6	48.4	370.96
SO_4	32.12	3.89	10.5	208.1	1.84	12.1	699.9	3.16	97.89	629.9	2.74	94.91	130.5	0.14	24.07	688.0	0.14	44.89
PO_4	11.35	0.04	2.36	8.9	0.1	3.0	1.89	0.04	0.45	1.84	0.1	0.6	5.0	0.08	0.78	3.86	0.12	0.82
Br	4.4	0.06	1.28	6.58	0.03	0.33	7121	0.1	445.8	1.2	0.06	0.32	12.05	0.06	0.75	3.19	0	0.77
I	7.4	0.06	2.18	16.4	0.05	3.85	10.0	0.06	2.65	1.69	0.09	0.63	10.3	0.03	2.08	4.83	0.08	1.57
Fe	43.21	0.06	7.92	32.82	0.08	5.93	43.5	0.21	17.42	34.15	0.19	10.58	11.48	0.12	2.32	7.68	0.03	1.86
B	3	0	0.76	4.1	0	0.82	3	0	0.83	3.2	0.1	0.87	3.2	0	0.65	2.9	0	0.74
Mn	1.6	0	0.31	0.9	0	0.37	2.07	0	0.4	0.94	0.01	0.45	1.04	0	0.2	2.3	0.02	1.2
As	0.245	0	0.040	0.25	0	0.040	0.1	0	0.037	0.2	0	0.036	0.02	0	0.003	0.05	0	0.004
CO_2	2.52	0	0.61	2.32	0	0.46	1.74	0	0.68	2.9	0	0.58	1.55	0	0.63	1.16	0	0.46
SiO_2	63.46	22.46	37.14	53.8	4.3	30.75	53.2	7.6	29.2	52.8	6.9	29.69	76.6	3.2	25.35	108	18.8	53.2

than 20 mg/l, and excess of 200 mg/l gives rise to unacceptable taste. Excessively high concentration of sodium is observed in coastal areas where sea water intrusion is a common phenomenon. Sodium concentration of groundwater in the coastal aquifer ranges from 4.2 to 3,000 mg/l in wet season and 11.6 to 8,848.4 mg/l in dry season in the first aquifer. In the second aquifer, sodium concentration ranges from 3.2 to 2,610 mg/l in wet season and in dry season 5.8 to 1,999 mg/l. The third aquifer shows ranges of sodium from 1.42 to 2,462.9 mg/l in wet season and 4.08 to 3,087.2 mg/l in dry season. Maximum sodium concentration in groundwater is observed in the first aquifer and minimum value is observed in the second aquifer.

Bi-carbonate concentration ranges from 48.8 to 823.5 mg/l in monsoon and 24.4 to 1,049.2 mg/l in dry period of the first aquifer. In the second aquifer, it ranges from 42.7 to 475.8 mg/l in monsoon and 24.4 to 591.7 mg/l in dry season. The third aquifer shows the ranges of bi-carbonate concentration from 134.2 to 488 mg/l in monsoon and 48.4 to 646.6 mg/l in dry months. Maximum average concentration of 505.08 mg/l is observed in the dry season in first aquifer and minimum average concentration of 290.89 mg/l is observed in the monsoon in the second aquifer.

Iron is a common constituent of anoxic groundwater. In high Fe content, the changes from dissolved ferrous to semisolid ferric iron are the most problematic for drinking use, without filtration. During aeration, ferric oxide and hydroxides are precipitated from solution and are coated on surfaces (Appelo and Postma 1999). Groundwater iron concentration in the coastal area ranges from 0.06 to 43.21 mg/l in wet season and 0.08 to 32.82 mg/l in dry season in the first aquifer. In the second aquifer, it ranges from 0.21 to 43.5 mg/l in wet season and 0.19 to 34.15 mg/l in dry season. The third aquifer shows the ranges of iron concentration from 0.12 to 11.48 mg/l in wet season and 0.03 to 7.68 mg/l in dry season. Maximum average concentration of 17.42 mg/l is observed in the wet season of second aquifer and minimum average concentration of 1.86 mg/l is observed in the dry season in the third aquifer of the study area.

Manganese is an essential trace element, playing an important role as a co-factor for many enzyme systems. In the natural environment, manganese is found as Mn (ii) and Mn (iii) and Mn (iv) oxides. Manganese concentration in groundwater was detected between 0 (below detection limit) and 1.6 mg/l in wet season and 0–0.9 mg/l in dry season in the first aquifer. In the second aquifer, it ranges from 0.0 to 2.07 mg/l in wet season and 0.01 to 0.94 mg/l in dry season. The third aquifer shows the ranges of Mn concentration from 0 to 1.04 mg/l in wet season and 0.02 to 2.3 mg/l in dry season. Maximum average concentration of 1.2 mg/l is observed in the dry season in third aquifer and minimum average concentration of 0.2 mg/l is observed in the wet season in the third aquifer.

Arsenic concentration in groundwater of the active delta area ranges from 0 to 245 μg/l in wet season and 0 to 250 μg/l in dry season in the first aquifer. In the second aquifer, it ranges from 0 to 100 μg/l in wet season and 10 to 200 μg/l in dry season. The third aquifer shows the ranges of arsenic concentration from 0 to 20 μg/l in wet season and 0 to 50 μg/l in dry season. Maximum average concentration of 40 μg/l is observed in the wet and dry seasons in first aquifer and minimum average concentration of 3 μg/l is observed in the dry season in the third aquifer. The hydrogeological setup and subsurface geology determine the security of an aquifer. Where different aquifer units are separated by aquitards, movement of As is restricted. In Bangladesh, the source of As in groundwater is mostly geogenic and is released from the compounds in the course of natural processes (Bhattachryya et al. 1997; Nickson et al. 1998). High As groundwater may percolate downward through leaky aquitards or sandy pockets due to huge pumping for irrigation, which could eventually cause the contamination of As in deeper aquifers.

26.3.4 Saline Water Encroachment

The salinization rate depends on the pattern of lithologic, i.e., hydrostratigraphic conditions and properties of sediments that compose the aquifers. The current fresh and saline water border is the boundary of fresh water of the deep aquifer and is comparatively well detected. The spatial interface of fresh water and saline water can be seen that extends about 50–75 km inland in the western most part of the area but swings sharply to the south and lies approximately at the coast over most of the rest of the area. The presence of brackish water and saline water in the coastal aquifers of Bangladesh does not follow any regular trend. Aquifer units of different depth levels down to 350 m have been contaminated by salinity at many locations. It is interesting to compare this salinity boundary of the deep aquifer with the surface water equal salinity lines. In general, all these lines have a common shape, suggesting that the deep aquifer boundaries might be related to the deltaic arc limits. The coastal areas have already been suffering from salinity encroachment which is expected to be expanded due to climate change and sea-level rise. Much more work is needed to accurately define the fresh water—saline water interface and to monitor its seasonal and long-term movements. The confined nature of the deep aquifer in the coastal area and its relatively constant head prevent a large-scale seasonal intrusion of saline water.

Annual mean sea-level rise of 2 mm has occurred for the past century and during recent past, the rates are estimated about 2.8 ± 0.4 to 3.1 ± 0.7 mm (1993–1998). The normal rate for the twentieth century was 1.7 ± 0.5 mm/year, whereas, the rates were 1.8 ± 0.5 mm/yr during 1961 to 2003 and 3.1 ± 0.7 mm/year for 1993–2003. Sea-level rise is dependable with warming, and the modeling studies suggest that during the latter half of the twentieth century, the anthropogenic stresses contributed to rise in sea level (Woodworth and Blackman 2004). However, the anthropogenic contribution is difficult to quantify.

In the coastal zone, salinity of the composite and main aquifers is extremely variable and changes abruptly over short distances. In most areas, the water is too saline for drinking and irrigation use due to either connate salts or estuarine flooding. In some areas, flushing out the salt water has resulted in fresh water pocket, but the regional pattern of salinity distribution of the deep aquifer is uniform. The distribution from potable water to saline water is sharp and found within a short distance. The contour maps of groundwater chloride concentrations at different depth levels of coastal aquifers show that in the shallow (Fig. 26.6) aquifer,

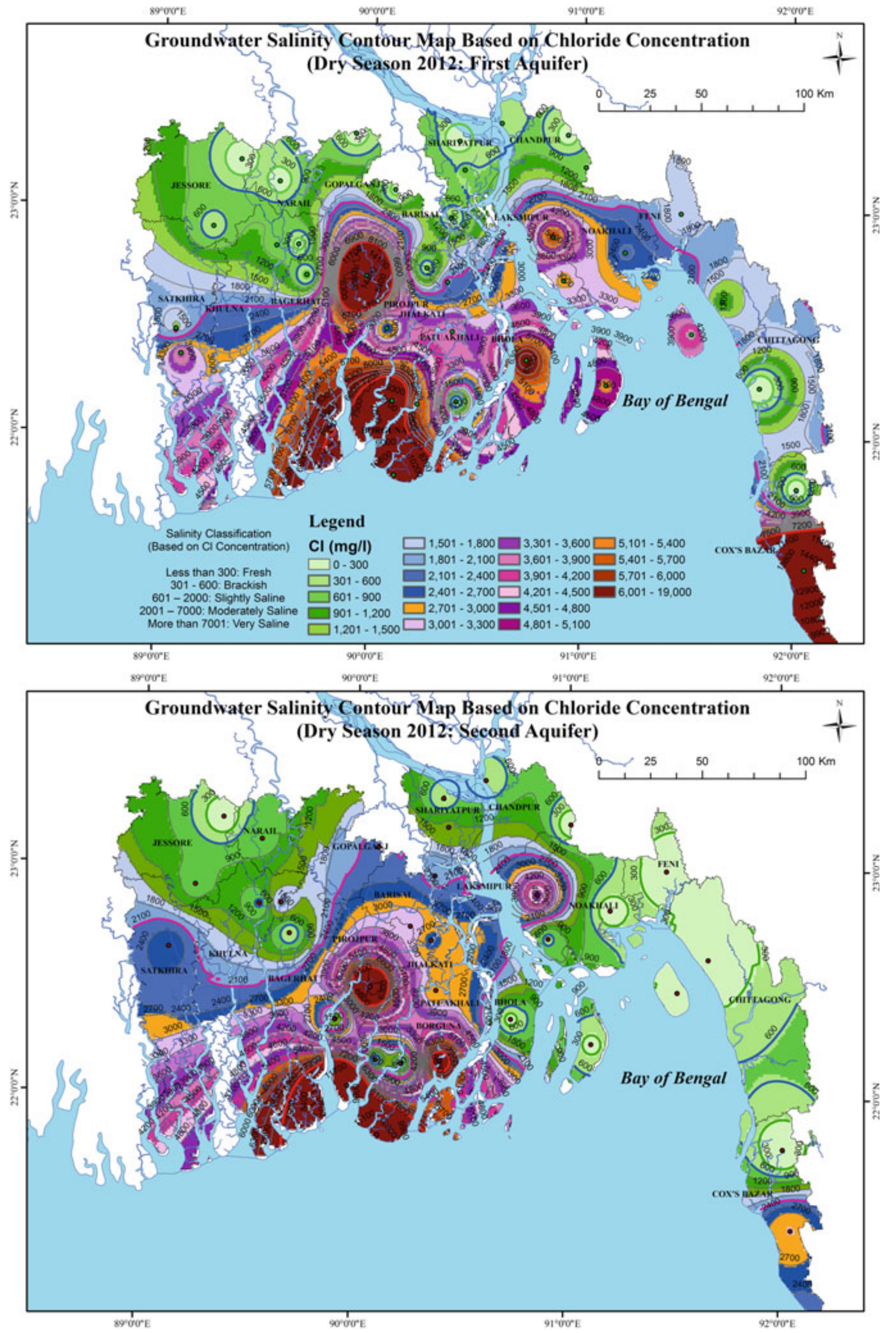


Fig. 26.6 Groundwater salinity maps of the shallow (first), intermediate depth (second), and deep (third) aquifer units in dry season based on chloride concentration (mg/l)

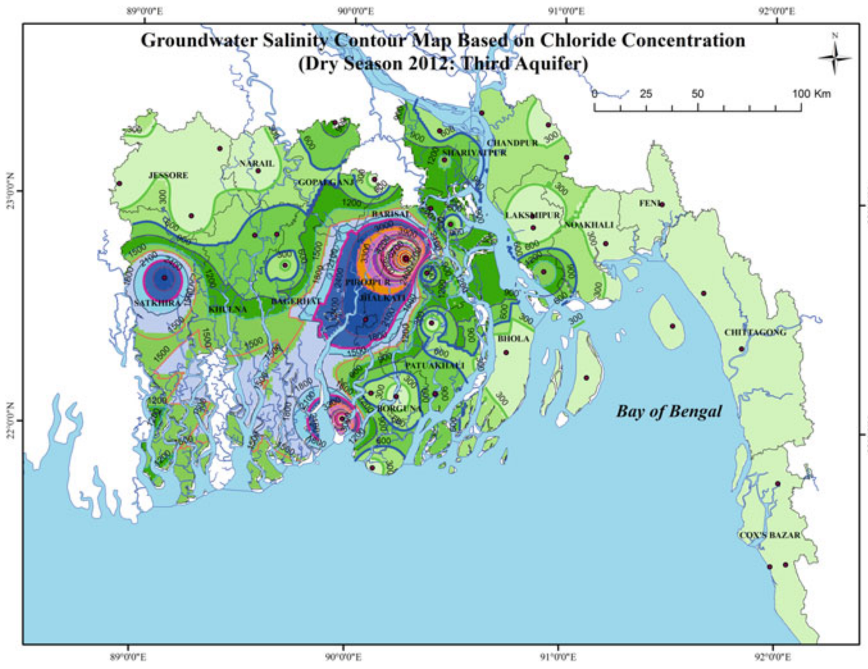


Fig. 26.6 (continued)

fresh groundwater ($Cl^- < 300$ mg/l) is noticed in areas of Patuakhali, Barishal, Satkhira, Jessore, and Narail districts while brackish water (Cl^- 300–600 mg/l) occurs at Shariatpur, Chandpur, and Gopalganj areas. Salinity ($Cl^- > 600$ mg/l) occurs in the aquifers of Shariatpur, Chandpur, Feni, Laksmipur, Noakhali, Cox's Bazar, Barguna, Barishal, Bhola, Pirojpur, and Jhalokathi district areas. Fresh water occurs in the main aquifers of Chandpur, Feni, Laksmipur, Cox's Bazar, Barguna, Patuakhali, Barisal, Bhola, Satkhira, and Jessore district areas. In the deep aquifer, fresh water occurs in Chandpur, Feni, Laksmipur, Chittagong, Cox's Bazar, Barguna, Patuakhali, Barisal, Bhola, Satkhira, Jessore, and Narail districts. Salinity occurs in the deep aquifers of Shariatpur, Barguna, Gopalganj, Khulna, and Cox's Bazar district areas. Seasonal variability of salinity is also noticed, and generally, dry season Cl^- is higher than wet season Cl^- in groundwater of all aquifer units. In the upper aquifers, down to 100 m depths, the salinity level is significantly variable. The shallow fresh water pockets are found, recharged by the recent precipitation, but changes to brackish or saline during dry period. Groundwater Cl^- values vary from 9 to 13,000 and 11.5 to 13,800 mg/l in dry and wet seasons, respectively, in the first aquifer. The maximum Cl^- value of dry and wet seasons were measured 13,000 and 13,800 mg/l, respectively, at Patharghata and Barguna. In the second aquifer, it ranges from 92.5 to 11,200 mg/l in dry season and in wet season 33 to 10,200 mg/l. Maximum Cl^- concentrations of dry season and wet season were detected 11,190 and 10,230 mg/l at Patharghata. The deep or third aquifer shows groundwater Cl^- values between 69 and 11,100 mg/l in dry season and 21.5 and 3,100 mg/l in wet season. Maximum Cl^- content of 11,100 mg/l was observed in dry season at Kalapara and Patuakhali, and maximum value of 3,100 mg/l was observed in wet season at Bhandaria and Pirojpur.

The salinity appears closely connected to the flooding intensity of saline and fresh water from estuarine due to tidal effects. However, saline water of sufficient flushing has taken place at many locations in the shallow aquifer. The salinity distribution pattern in the deep aquifer (>225 m) is more uniform on a regional basis, as is the continuity of the aquifer. Factors suggest that the fresh water—saline water interface is still moving.

Periodic storm surge flooding significantly influences the vertical infiltration of saltwater, generally where clay layers are absent above the pumping aquifers (World Bank-USGS 2010). Due to sea-level rise, liability to lateral saltwater movement depends on aquifer hydraulic properties. The regions with high permeability of the aquifer are more vulnerable than less permeable aquifer, but the process of this salinization is very slow. Liability to pumping-induced combination of pre-existing fresh and saline groundwater or increasing transportation rates of saltwater may be everywhere, mostly where abstraction occurs from freshwater pockets bounded by saltwater. The aquifers are more vulnerable in areas with lower topographic relief (central delta) than the aquifers in higher-relief (eastern delta) areas to all three intrusion pathways.

In the coastal aquifers, fresh groundwater pumping accelerates saltwater intrusion and water quality degradation along both vertical and horizontal salinization paths. This indicates a clear need for hydrogeologic characterization, management of pumping, and hydrologic and geochemical monitoring of the coastal aquifers in Bangladesh—irrespective of future climate change. Any future sea-level rise will accelerate the adverse impact of the already existing salinization mechanisms. Within the current coastal zone, the primary impact of sea transgression on coastal groundwater resources is the direct loss of land area (assuming a net balance between deposition and subsidence of sediment) and loss of the possibility to easily pump any fresh groundwater that remains below the areas covered by the sea. Moreover, an increased frequency of storm surges, or storm surges that cover a greater area of the land surface due to the higher sea stand, will increase the likelihood of vertical downward intrusion of saltwater to wells that currently produce fresh groundwater, wherever the saline floodwater is able to infiltrate.

As the density of fresh water (1,000 kg/m^3) is less than the density of saline water (1,004 kg/m^3 for a chloride content of 3,000 mg/l); therefore, deep freshwater would normally be expected to rise above, or mix with, saline water (DPHE-DANIDA 2001). During the Holocene (the last 10,000 years), the sea level gradually rose, the gradient of the major rivers decreased, and river sediments accumulated. The sea water encroachment via tidal rivers causes the elevated salt content in the shallow groundwater. Due to fresh and saline water density difference, the shallow brackish/saline water could penetrate into the deep aquifer layers, except where the deep fresh water was protected by more or less continuous clay layers. In many areas, saline or brackish water is noticed in deep aquifers. The BWDB (2013) and DPHE-DANIDA (2001) studies indicate that the fresh water pockets at variable depths is reported all over the coast. The fresh bodies do not seem to be connected locally with each other, which would be the case if they have been built up by groundwater flow from the hinterland. The protective clay layers are leaky or even absent in some places, so it does not provide the closed conduit necessary for flushing saline aquifers at a large distance from the recharge area. The saline water in the coastal fresh water environment could occur by a variety of mechanisms, such as lateral penetration through relatively high permeability layers, upcoming of saline water underneath the fresh water, and down coning (leakage through the overlying clay layers).

26.4 Conclusion and Recommendation

To obtain the target for the sustainable groundwater resource planning, balancing abstraction of groundwater to recharge is required. Managing the water balance of discharge and recharge is crucial for mitigating developing stresses on water and environmental resources. Wise groundwater resources management and governance, projecting the possibilities of future development and climate change impact, can be achieved by aquifer mapping and zoning for various uses considering long-term available hydrometeorological and hydrogeological data. In coastal area, regular monitoring and evaluation of water quality and storage have to be ensured by means of established monitoring network. In other parts of the country, expansion of present groundwater monitoring network is required by installing multi-layered piezometers down to the depths of 350–400 m based on the areas of recharge and discharge, flow area, surface water regime, etc. This will support for recharge estimation, monitoring groundwater table fluctuation to pumping, quality of water, and groundwater flow patterns. Regular monitoring of groundwater table and quality data will lead to preparing zone/area-wise water budget and water allocation plans considering water demand for different sectors, water resource availability (surface water, groundwater, and precipitation), and water needed for environment preservation.

Even without climate change, pumping in the coastal zone and it’s vicinity is a significant factor of salinization processes. The discharge-induced salinization rate is reliant on the pattern of hydrostratigraphy and sediment properties that compose the aquifers. The straight impact to the rise of sea level, i.e., coastal flood and storm surges, is of bigger threat for groundwater situation than horizontal sea water intrusion. The availability of the fresh groundwater in the present coast may shorten due to rising sea level. However, this impact may not noticeably increase the rate of salinization.

As groundwater in the upper shallow aquifers is unsuitable due to arsenic contamination and saline water, the deep and fresh groundwater may serve as prospective and sustainable sources for safe drinking water supply. Deep groundwater must not be used for irrigation, without proper study and investigation. Studying and monitoring the behavior and mobility of arsenic and salinity need to be done carefully, as the investigated aquifers are hydraulically linked regionally. About coastal groundwater resources, deep concerns already exist, and in some areas, substitutes for freshwater supplies are needed. A critical need for improved management and governance is required that can be achieved by better understanding of aquifer system, properties of aquifer sediments, controlled use of scarce fresh water resources and assessing water quality i.e. salinity distribution trends. To characterize these aquifers, which are highly heterogeneous and vary regionally, an extensive network of observation wells, installed for the specific purpose of hydrogeologic and geochemical data collection and monitor on a regular basis, is required. Stable and carbon isotope data of groundwater would clarify the age, origin of both fresh groundwater and saline groundwater, and recharge volume and velocity.

The salinization processes that have occurred since the last glacial maximum (long-term sea-level rise) and that occur at present within the coastal zone (saline water flooding from storm surges and groundwater abstraction) will continue to occur. Today's study, understanding, and management will offer the insight and guideline required to govern a future coastal zone.

Acknowledgments Bangladesh Water Development Board (BWDB) under the Ministry of Water Resources, Bangladesh Climate Change Trust (BCCT) under the Ministry of Environment and Forest and Institute of Water Modeling (IWM) are highly acknowledged for supporting the research on assessment and monitoring of coastal water resources. Professionals and officials involved in the research project activities are also acknowledged for their valuable contribution.

References

Ahmed AU, Alam M (1999) Development of climate change scenarios with general circulation models. In: Huq S, Karim Z, Asaduzzaman M, Mahtab F (eds) Vulnerability and adaptation to climate change for Bangladesh. Kluwer Academic Publishers, 147 pp

Appelo CAJ, Postma D (1999) Geochemistry, groundwater and pollution. A.A. Balkema, Rotterdam, p 535

Bhattacharya P, Chatterjee D, Jacks G (1997) Occurrence of arsenic contaminated groundwater in alluvial aquifers from the delta plains, eastern India: options for safe drinking water supply. Water Resour Develop 13:79–92

BADC (2011) Forecasting saline water intrusion, irrigation water quality and water logging program in Southern Area. Ministry of Agriculture, Government of Bangladesh

Burgess WG, Shamsudduha M, Taylor RG, Zahid A, Ahmed KM, Mukherjee A, Lapworth DJ, Bense VF (Unpublished) Terrestrial water load and groundwater fluctuation in the Bengal Basin. University College London, Bangladesh Water Development Board and others

BWDB (2013) Establishment of monitoring network and mathematical model study to assess saline water intrusion in groundwater in the coastal area of Bangladesh due to climate change. Final Report, Bangladesh Water Development Board and Institute of Water Modelling, p 2300p

BWDB (1979) Ground water in the coastal zone and offshore islands of Bangladesh. BWDB Water Supply Paper entitled, 1979

BWDB-UNDP (1982) Groundwater survey: the hydrogeological conditions of Bangladesh. UNDP Technical Report DP/UN/BGD-74-009/1, 113 pp

DPHE-BGS (2001) Arsenic contamination of groundwater in Bangladesh. British Geological Survey and Department of Public Health Engineering, Govt. of Bangladesh; Technical report, WC/00/19

DPHE-DANIDA (2001) Hydrogeology summary report. Department of Public Health Engineering—Danish International Development Water Supply and Sanitation Components, Ministry of Foreign Affairs, Government of Bangladesh, 129 pp

Hem JD (1992) Study and interpretation of the chemical characteristics of natural water (3rd edn). US geological Survey Water Supply Paper 2254, 263 pp

IPCC (2001) Climate change 2001: impacts, adaptation, and vulnerability. In: McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds) Contribution of working group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 1032 pp

IPCC (2008) Climate change and water. Technical paper VI, Intergovernmental Panel on Climate Change, WMO, UNEP, 200 pp

Karmakar S, Shrestha ML (2000) Recent climate changes in Bangladesh. SMRC-No.4, SMRC publication, Dhaka, Bangladesh, 43 pp

Nickson R, McArthur J, Burgess W, Ahmed KM, Ravenscroft P, Rahman M (1998) Arsenic poisoning of Bangladesh groundwater. Nature 395:338

Ravenscroft P (2003) Overview of the hydrogeology of Bangladesh. In: Atiq Rahman A, Revenscroft P (eds) Groundwater resources development in Bangladesh: background to the arsenic crisis, agricultural potential and the environment. The University Press Limited, Bangladesh, pp 43–86

UNESCO-IHP (2006) Groundwater resources assessment under the pressures of humanity and climate changes (GRAPHIC). UNESCO-IHP Intergovernmental Hydrological Program

WARPO (2000) Draft development strategy (DDS), estimation of groundwater resources, Annex-C, Appendix 6. National Water Management Plan, WARPO

Woodworth PL, Blackman DL (2004) Evidence for systematic changes in extreme high waters since the mid-1970s. J Climate 17:1190–1197

World Bank-USGS (2010) Implications of climate change for fresh groundwater resources in coastal aquifers in Bangladesh. The World Bank, South Asia Region, Sustainable Development Department, 105 pp

Zahid A, Ali MH, Islam F, Hassan MR, Islam K, Ahmed N (Unpublished) Analysis of the aquifer pumping test data to determine the deep groundwater security in the southeastern Bangladesh

Zahid A, Ali MH, Hassan MR, Islam K, Ahmed N, Sultana N (2017) Assessment of the deep groundwater security in the Bengal Delta by conducting aquifer pumping tests. Water Utility J 15:29–43

Zahid A, Hassan MQ, Ahmed KMU (2015) Simulation of flowpaths and travel time of groundwater through arsenic contaminated zone in the multi-layered aquifer system of Bengal Basin. J Environ Earth Sci. https://doi.org/10.1007/s12665-014-3447-7

Zahid A, Hassan MQ, Balke, K-D, Flegr M, Clark DW (2008) Groundwater chemistry and occurrence of arsenic in the Meghna floodplain aquifer, southeastern Bangladesh. J Environ Geol 54:1247–1260

Zahid A, Hassan MQ, Imes JL, Clark DW (2009) Hydraulic characterization of aquifer(s) and pump test data analysis of deep aquifer in the arsenic affected Meghna river floodplain of Bangladesh. Environ Res J 3(2/3):325–355

Chapter 27

Investigations on Groundwater Buffering in Khulna-Satkhira Coastal Belt Using Managed Aquifer Recharge

M. M. Hasan, Kazi Matin Ahmed, S. Sultana,
M. S. Rahman, S. K. Ghosh and P. Ravenscroft

Abstract The Khulna-Satkhira coastal belt is one of the most vulnerable areas in Bangladesh in terms of access to safe drinking water, mostly because of salinity problem. In order to cope with the ever-increasing demand of fresh water in this area, managed aquifer recharge (MAR) has been proposed as an alternative, cost-effective, and disaster resilient option for fresh water supply particularly during the dry period. GIS analysis has been conducted to identify the areas suitable for MAR. Different physical, physicochemical, hydrogeological, geochemical, social, and economic criteria have been investigated in the field for designing and construction of test sites. Four injection wells of 22 or 12 inches diameter have been drilled to a depth of 60–75 ft at the infiltration sites using locally available materials and drillers. Pond water has been pumped or rooftop rainwater has been channelized to an infiltration tank set with a sand filter to remove turbidity and to provide a total head of about 3 ft above the shallow water level. Water has been distributed to various wells through PVC pipe network fitted with stop valves and water flow

---

M. M. Hasan · K. M. Ahmed (✉) · S. Sultana
Department of Geology, Faculty of Earth and Environmental Sciences,
University of Dhaka, Dhaka-1000, Bangladesh
e-mail: kazimatin@yahoo.com

M. M. Hasan
e-mail: sohel_87@yahoo.com

S. Sultana
e-mail: sarmin@du.ac.bd

M. S. Rahman · S. K. Ghosh
Groundwater Circle, Department of Public Health and Engineering,
DPHE Bhaban, Kakrail, Dhaka-1000, Bangladesh
e-mail: sagor70@gmail.com

S. K. Ghosh
e-mail: skg_rddphe@yahoo.com

P. Ravenscroft
Water, Sanitation and Health Section, UNICEF, Hotel Ruposhi Bangla
Compound, 1 Mintoo Road, Dhaka-1000, Bangladesh
e-mail: ravenscroftp@aol.com

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_27

meter. Water has been allowed to infiltrate into the wells using gravity. Significant reduction of groundwater electrical conductivity and major dissolved constituents of concern such as chloride, arsenic, and manganese have been documented after the infiltration of fresh water into the shallow brackish aquifer. The findings of this study clearly demonstrate that MAR is feasible in the coastal belt of Bangladesh.

27.1 Introduction

The Khulna-Satkhira coastal belt is one of the most vulnerable areas in Bangladesh in terms of access to safe drinking water mostly because of salinity problem. There is no available deep ground and shallow groundwater as the ambient groundwater is mostly saline or brackish. Local communities rely mostly on rainwater during the monsoon, and for the rest of the year, they rely on pond water. It is of great concern that these existing surface water options, which serve as the reliable source of fresh water during the dry period, are becoming saline or brackish due to frequent storm surges with higher intensity and magnitude like the cyclone Aila. The groundwater is also vulnerable to climate changes (Ahmed et al. 2010) such as inundation due to sea level rise, decreasing monsoon rainfall, and reduced surface water flux from the upstream. Moreover, brackish water aquaculture is also responsible for the increased salinity of shallow groundwater. As a result, access to fresh water options is very limited and is the main concern of this region. Different NGOs and government agencies are currently supplying fresh water to the local communities which is insufficient against the actual demand. To meet this ever-increasing demand of fresh water, rooftop rainwater- or pond water-induced managed aquifer recharge has been proposed as an alternative, cost-effective, and disaster resilient option to ensure fresh water supply during the dry period. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

27.2 Study Area

The study area is situated in the southwestern part of Bangladesh (Chap. 1, Fig. 1.1) including three coastal districts viz. Khulna, Satkhira, and Bagerhat. In this region, about 1500–2000 mm rainfall occurs annually of which about 70% rainfall occurs during the monsoon period. Based on the geomorphic feature, the study area belongs to the western region (NPA 2007) characterized by dense Mangrove forest and deeply scoured tidal channels. Geologically, the area belongs to the tidal delta and partly of both active and inactive Ganges delta and is composed of floodplain deposits mainly consisting of sand, silt, clay, silty clay, and sandy clay (Hassan and Pekdeger 1998) of the Quaternary age (Woobaidullah 1998). The depositional pattern is very complex and doesn't follow any regular trend and is characterized by frequent lateral and vertical facies change within very short distances. This region is characterized by multilayer prolific aquifers composed of deltaic sediments. According to Ahmed (2005), the sandy sediments of the Holocene coastal plain forms the aquifer system in this region. These aquifers are not continuous, but rather sand lenses interbedded with silt and clay occurring at various depth ranging from 1.5 to 335 m. Groundwater quality is poor and is beyond the potable limit. The shallow aquifer is either saline or brackish with high chloride concentration or has high arsenic level (Ahmed 2011).

27.3 Site Selection and Exploration

Integrated GIS and RS mapping along with field investigations are essential and have been reported as an effective and proven method to identify suitable sites for MAR (Ahmed et al. 2010; Chowdhury et al. 2010, Ghayomian et al. 2007, Balachander et al. 2012). GIS analysis has been conducted to identify the suitable sites based on the available existing safe water options like shallow tube wells (STW) and deep tube wells (DTW) since these are the main source of fresh water. Firstly, the whole study area has been divided into classes based on the density of STWs and DTWs to identify the areas with limited safe water options. Secondly, areas with STW density less than 5 have been identified for implementation of MAR. Finally, the existence of other safe water options like shallow shrouded tube wells (SST), very shallow shrouded tube wells (VSST), pond sand filter (PSF), and rainwater harvesting (RWH) have been taken into consideration to identify the areas where fresh water crisis is most severe. The GIS analysis identifies 28 unions of 11 Upazilas for field investigation (Fig. 27.1).

After the GIS analysis, different physical, physicochemical, hydrogeological, geochemical, social, and economic criteria have been investigated in the field. Easily accessible areas with significant size of roof and pond were the first criteria for selecting sites. The thickness of top confining bed and the shallow aquifer has been measured, and the aquifer material and property such as porosity and hydraulic conductivity have been determined by grain-size analysis using sediment samples collected during exploratory drilling. Electrical conductivity, arsenic and iron concentrations of groundwater have been determined to identify areas with high salinity and less arsenic contamination. Other social and economic criteria like population density and their economic condition, social acceptance, community participation, and the cost and use of land required for the infiltration system have also been taken into consideration. Based on the set of criteria, two test sites have been selected: one at Assasuni union of Assasuni Upazila of Satkhira district and the other at Gangarampur union of Batiaghata Upazila of Khulna district for piloting the technology.

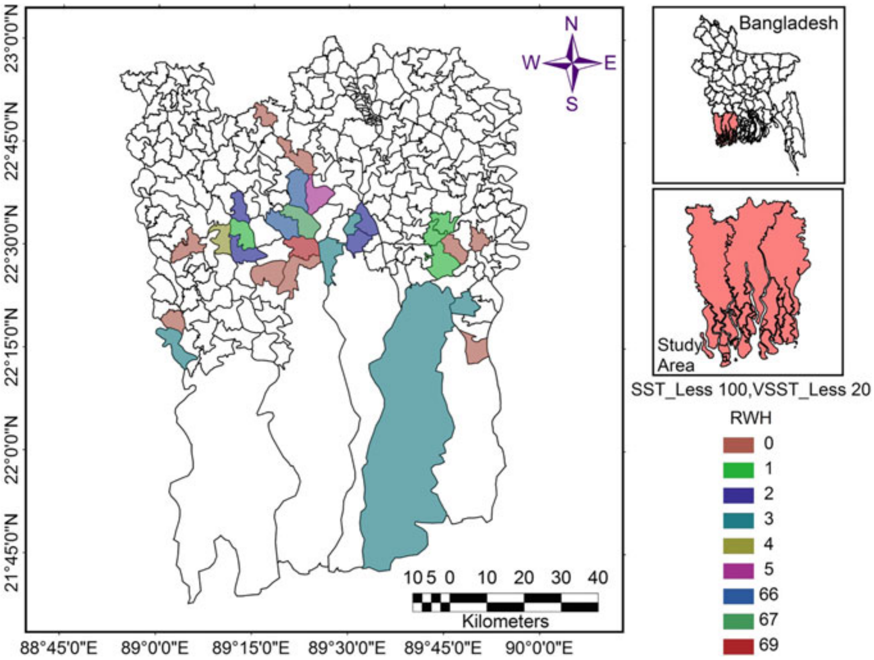


Fig. 27.1 Map representing areas with less than 100 SST and 20 VSST and with different numbers of RWH

27.4 Well Design and Construction

Following the completion of final site selection, innovative well design and construction has been carried out. The conceptual design of the Assasuni site consists of the collection of source water from both roof and pond (Fig. 27.2) whereas in Gangarampur site, source water will be collected only from the pond and primary accumulation in a storage tank (Fig. 27.2).

The design of the infiltration scheme can be simply divided into the following systems viz. collection system, filtration system, distribution system, infiltration system, monitoring system, and the abstraction well. The collection system consists of collection of source water either from the roof or pond and delivery to the filtration system through delivery pipes. The filtration system or storage tank is of two chambered, namely filtration tank and infiltration tank (Figs. 27.2 and 27.3).

The filtration tank is fitted with a sand filter to remove turbidity of pond water and to prevent infiltration wells from clogging. The filtered water passes from the filtration tank to the infiltration tank which stores the filtered water and provides a head of about 3 ft. From the infiltration tank, water is distributed to the infiltration wells through the distribution system made up of PVC pipe network. The distribution system is fitted with stop valve to control the flow of water and flow meter to

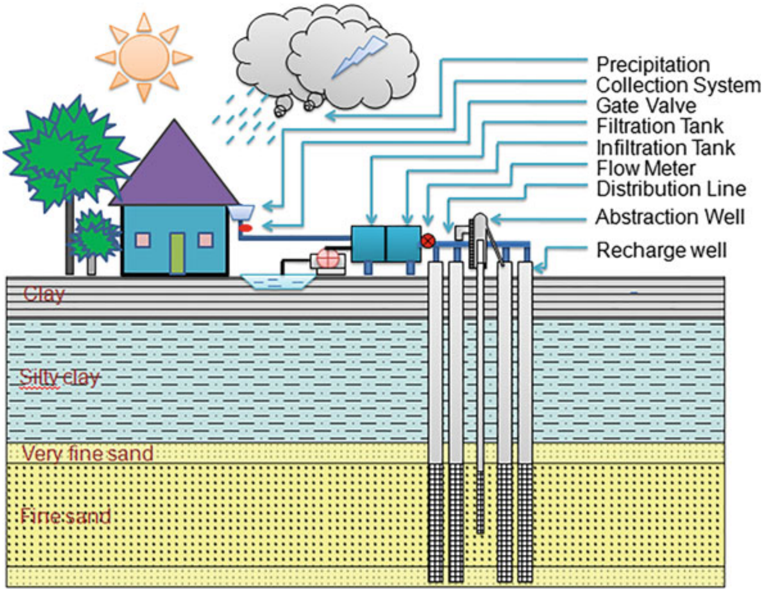


Fig. 27.2 Conceptual design of the infiltration scheme for Assasuni

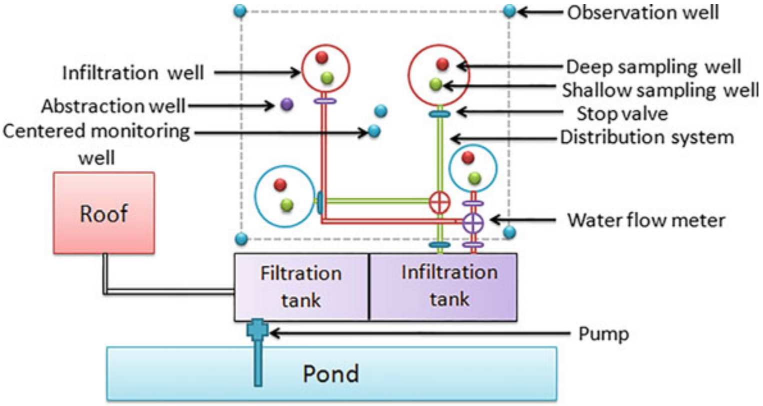


Fig. 27.3 Plan view of the infiltration scheme

measure the amount of injected water. The infiltration system consists of infiltration wells. Infiltration wells can be divided into two parts: the upper part and the lower part. The upper part consists of PVC casing for the clayey section and the reducing socket. The lower part only consists of the screen to allow the injected water to spread in the shallow brackish aquifer to create fresh water bubble. Unlike the traditional production well, the screen diameter is greater than the casing. The monitoring system includes the piezometers installed in and around the infiltration wells to observe changes of different physicochemical parameters and for sampling. The piezometers have been installed at the perimeter of a circle of radius of 3 m within which the infiltration wells are situated. The abstraction well has been designed to install at the center of the infiltration wells and includes No. 6 pump to draw water.

Four injection wells of 22 or 12 inches diameter have been drilled to a depth of 60 (Gangarampur) to 75 (Assasuni) feet using the locally available direct circulation rotary drilling method. A 12 inch diameter PVC casing has been used for the clayey section while the lower part was left open. The screen has been made manually using locally available MS rod and chicken mesh. The lower part of the well has been filled with gravel, and the upper part has been filled with locally withdrawn sand. The inner part of the wells has been filled with fine gravel. The whole construction phase has been carried out using locally available materials and by the local drillers. Water has been allowed to infiltrate into the wells using gravity.

27.5 Monitoring

A systematic monitoring scheme has been developed (Table 27.1) to monitor the interaction of injecting fresh water with the brackish ambient groundwater through measuring a number of physicochemical parameters. Field data sheet has been prepared for documentation. Local NGO partners have been trained and assigned to take daily measurements and provided with necessary equipment. Amount of daily rainfall and injected water, electrical conductivity, temperature, pH, turbidity, and water level have been measured twice daily while arsenic and iron concentrations have been measured once a week. Baseline sampling and sampling at the end of the infiltration period have been performed to observe the change in hydrochemical facies due to recharge.

Table 27.1 Monitoring scheme

Frequency	Daily						Weekly	
Items	Parameters							
	EC	Temperature	pH	Turbidity	Water level	Amount	As	Fe
Infiltration wells	*	*	*		*	*	*	*
Monitoring wells	*	*	*		*		*	*
Pond	*	*	*	*				
Tank	*	*	*	*				
Rain	*	*	*			*		

27.6 Results and Discussions

27.6.1 Infiltration Rate

A total of 392 m^3 of water has been injected at the Assasuni site with the average of 2.93 m^3/day. The maximum rate of infiltration has been found to be 12.4 m^3/day when both rainwater and pond water have been injected simultaneously during the monsoon of 2011. At the Gangarampur site, 827 m^3 of water has been injected. At this site, the average rate of infiltration found to be 6.95 m^3/day with the maximum of 25 m^3/day.

27.6.1.1 Source Water Quality

Pond water has been injected at both the sites which is characterized by high turbidity fluctuating between 29 and 52 ntu. But the filtration system has been found to be effective as about 97% turbidity is removed after filtration (Fig. 27.4).

The electrical conductivity of pond water ranges from 4.0 to 0.8 mS/cm. But during the monsoon due to the addition of rainwater, pond water becomes fresh enough to be injected into the shallow brackish aquifer.

27.6.2 Ground Water Quality

27.6.2.1 Electrical Conductivity

A positive impact of infiltration on groundwater electrical conductivity has been found (Fig. 27.5). Initially, the electrical conductivity of the central monitoring well at Assasuni and Gangarampur were 5.82 and 1.79 mS/cm respectively. At the end of the infiltration, the electrical conductivity has been lowered to 0.82 mS/cm at Assasuni and 0.79 ms/cm at Gangarampur, respectively.

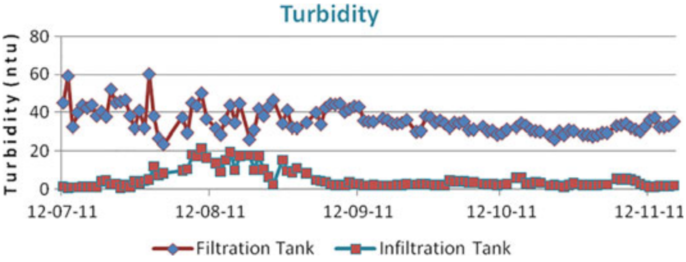


Fig. 27.4 Turbidity of pond water

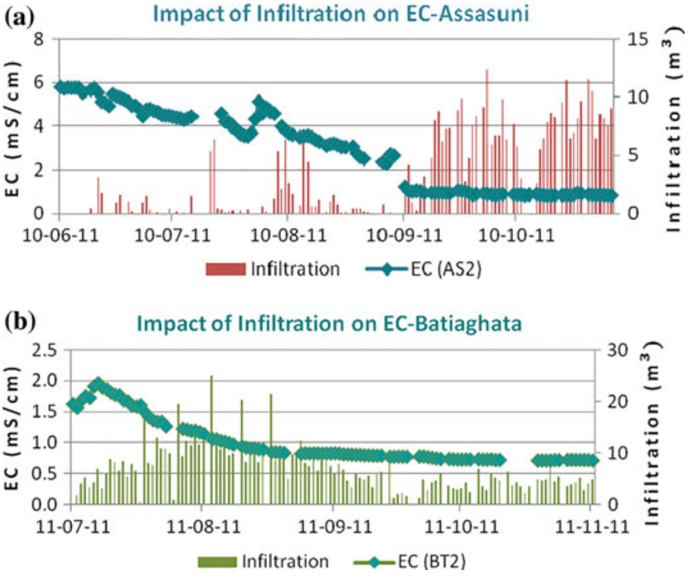


Fig. 27.5 Impacts of infiltration on groundwater electrical conductivity, **a** Assasuni, **b** Gangarampur

27.6.2.2 Trace Elements

Improvement of groundwater quality is evident from the reduction of the concentration of toxic metals such as arsenic and manganese. At Assasuni, the initial arsenic, iron, and manganese concentrations were 0.1, 9.2, and 0.6 mg/L respectively but after the infiltration, their concentrations have been reduced by 90, 91, and 76% respectively (Fig. 27.6). Though the arsenic concentration at Gangarampur remains more or less same, after infiltration, the manganese and iron concentrations have been reduced from 0.2 to 0.1 mg/L and 2.3 to 0.3 mg/L. It is

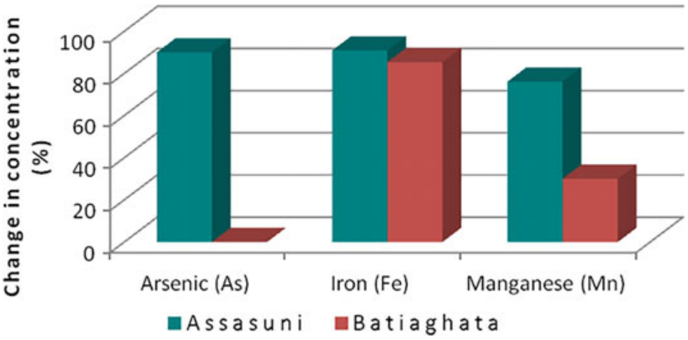


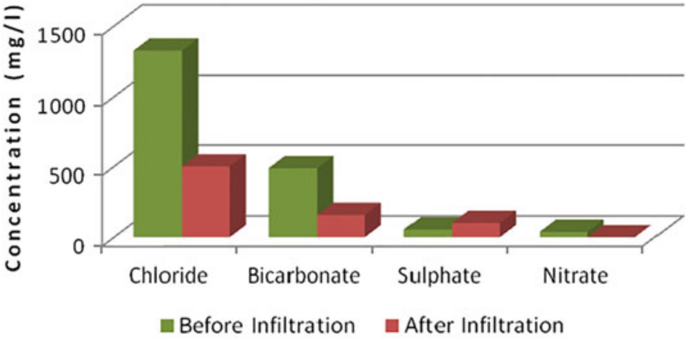
Fig. 27.6 Change in concentration of trace elements due to infiltration

important to note that the reduction in concentration is higher at Assasuni than Gangarampur since both rainwater and pond water have been injected in Assasuni.

27.6.2.3 Major Constituents

The concentration of major cations and anions has also been reduced significantly after infiltration. The chloride concentration has been reduced from 1324 to 500 mg/L at Assasuni and 450–140 mg/L at Gangarampur, respectively (Fig. 27.7). Though the sulfate concentration has been increased slightly at Assasuni, bicarbonate and nitrate concentrations have been decreased from 488 to 160 mg/L and 39.1 to 1.3 mg/L. At Gangarampur, bicarbonate, nitrate, and sulfate concentrations have been reduced from 275 to 168 mg/L, 5.2 to 0.1 mg/L, and 79 to 18 mg/L respectively.

(a) Major Anions-Assasuni



(b) Major Anions-Batiaghata

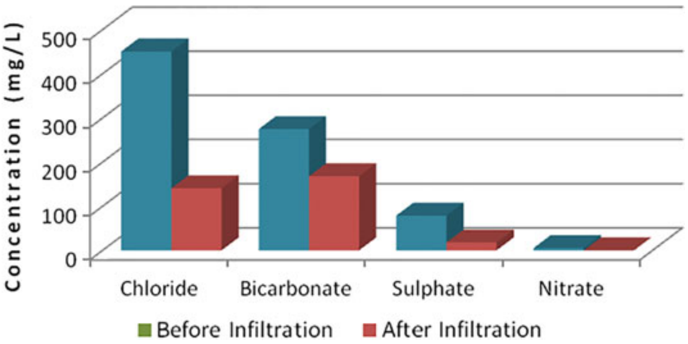


Fig. 27.7 Change in concentration of major anions due to infiltration, **a** Assasuni, **b** Gangarampur

27.7 Conclusions

Systematic GIS analysis and determinations of field criteria have been found to be successful in identifying suitable sites for MAR. Site-specific and innovative well designs have been performed at both sites. Four injection wells of 22 or 12 inches diameter have been drilled to a depth of 60–75 ft. The whole construction phase has been carried out using locally available materials and drillers. A total of 392 and 827 m^3 of water has been injected at the Assasuni and Gangarampur sites respectively, where both rainwater and pond water have been injected in Assasuni simultaneously. Significant reduction of groundwater electrical conductivity and concentrations of dissolved constituents of concern indicate the improvement of groundwater quality due to recharge, and simultaneous infiltrations of both rainwater and pond water showed better performance. The findings of this study clearly demonstrate that rooftop rainwater- and pond water-induced MAR is feasible in the coastal belt of Bangladesh.

References

Ahmed KM (2005) Management of the groundwater arsenic disaster in Bangladesh. In: Bundschun J, Bhattacharya P, Chandrashekharam D (eds) Natural arsenic in groundwater: occurrence, remediation, and management. Taylor & Francis Group, London

Ahmed KM, Sultana S, Hasan K, Groen K, Tuinhof A, Spruijt H, Patra L, Ghosh SK, Huq I (2010) Artificial recharge to manage groundwater quantity and quality in Bangladesh: GIS mapping and other investigations. Alternative recharge systems. ISMAR7, Abu Dhabi

Ahmed KM (2011) Groundwater contamination in Bangladesh (Chap. 25). In: Quentin Grafton R, Hussey K (eds) Water resources planning and management. Cambridge University Press, pp 527–560

Balachander D, Alaguraja P, Rutharvelmurthy K, Kumaraswamy K (2012) Application of remote sensing and GIS for artificial recharge zone in Sivaganga District, Tamil Nadu, India. Int J Geomat Geosci 1(1):84–97

Chowdhury A, Jha MK, Chowdary VM (2010) Delineation of groundwater recharge zones and identification of artificial recharge sites in west Madanipur district, West Bengal using RS, GIS and MCDM techniques. Environ Earth Sci 59:1209–1222

Ghayomian J, Saravi MM, Feiznia S, Nouri B, Malekian A (2007) Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran. J Asian Earth Sci 30:364–374

Hassan MQ, Pekdeger A (1998) Aquifer parameters for groundwater modeling application: a study from Southwest Bangladesh. Dhaka Univ J Sci 46(1):25–35

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

NPA (National Program of Action) (2007) Bangladesh National Program of Action for Protection of the Coastal and Marine. Environment from Land Based Activities, Department of Environment, Ministry of Environment and Forests, Government of the Peoples Republic of Bangladesh

Woobaidullah ASM (1998) Application of surface resistivity method to groundwater exploration in the coastal belt of Bangladesh. In: Proceedings of 20th Bangladesh science conference, Part-2, pp 349–357

Chapter 28
Groundwater Discharge to the Bay of Bengal: Hydrological, Societal, and Environmental Implication to the Ocean

Palash Debnath and Abhijit Mukherjee

Abstract The interaction of two of the largest hydrological systems, groundwater and seawater, takes place along the coast, either by seawater intrusion to land (SWI) or submarine groundwater discharges (SGD). Groundwater discharge from the coastal aquifers to the oceans takes place when the elevation of the water table of coastal aquifers is higher than the mean sea level, varying seasonally and tidally. SGD provides a route for escape of a large portion of the usable groundwater resource, solutes, and contaminants to sea. The chemical evolution and redox transformation of SGD are poorly understood, especially at the subsurface freshwater discharge zone. Globally, there have been several studies to understand the coastal hydrodynamics of the SGD; however, there is a serious lack of such knowledge from the coastal aquifers of the Indian subcontinent. The present chapter demonstrates the details of groundwater discharge to the Bay of Bengal, India (BOB). Our study result shows that SGD can add a huge amount of solutes and nutrients to the BOB, which is likely to have a great impact on BOB ecosystem. Hence, understanding the dynamics of SGD in coastal parts of India is an extremely interesting scientific question along with its societal importance and environmental

---

P. Debnath · A. Mukherjee (✉)
Department of Geology and Geophysics, Institute of Technology (IIT)—Kharagpur,
Kharagpur 721302, West Bengal, India
e-mail: amukh2@gmail.com; abhijit@gg.iitkgp.ernet.in

P. Debnath
e-mail: palashdeb.d@gmail.com

P. Debnath
National Institute of Hydrology Roorkee, Roorkee 247667, Uttarakhand, India

A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee
Applied Policy Advisory to Hydrogeosciences Group, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_28

implications. It is expected that the knowledge and information provided in this chapter would enhance the understanding of the coastal hydrodynamics in site-specific scales and extrapolated, larger scales along the BOB and would be useful in making regional coastal management plan or integrated coastal management plan.

Keywords Submarine groundwater discharge · Bay of Bengal
Coastal hydrodynamics · Solutes and nutrients · Ecosystem

28.1 Significance of SGD in Context of India

Groundwater discharge is the most important pathway connecting two largest hydrological systems, groundwater (GW) and seawater (SW). Surface water mainly river and stream inputs to the ocean is visible and also added a large amount of solutes to the ocean (Mulligan and Charette 2009). Hence, over the last years the influences of surface water discharge have been well studied along with its geochemical importance and the influences on the marine ecosystem. The second pathway connecting land and ocean directly is a direct groundwater flow from land side which is also termed as submarine groundwater discharge (SGD). The term "submarine groundwater discharge (SGD)" can be defined as "any and all flow of water on continental margins from the seabed to the coastal ocean, regardless of fluid composition or driving force" (Burnett et al. 2003). While the terrestrial-sourced SGD (T-SGD) would be discharged from continental groundwater, the marine-sourced SGD (M-SGD) results from seawater recirculation at various spatiotemporal scales.

In India, GW–SW interactions are continuously taking place along the >6000 km coastline and within coastal zone hydrological systems (Chap. 1, Fig. 28.1). Out of which more than 50% of the discharge probably accounts to the coast of BOB. It has been reported that in Indian hydrologic system more than 50% of the annually hydrological input (>4000 billion m^3) are losing due to various unaccounted processes, including escape flow path by SGD to the ocean (Verma and Phansalkar 2007). Hence, understanding the various phenomenon of SGD in coastal India is very important along with its societal importance and environmental implications. In Indian context, there is a dearth of studies on coastal hydrogeology, among which the interaction of groundwater discharge with seawater is hardly reported. Most of the studies and published literatures focus on degradation of groundwater quality by seawater intrusion, its geochemical aspects, and management. There are very few SGD studies or related studies that have been reported in the Indian coastal areas. Among notable studies, Jacob et al. (2009) have conducted a monitoring of ^{222}Rn in the coastal waters of Vizhinjam, Thiruvananthapuram, to investigate the existence of SGD. Another study was carried out for coastal aquifer management purpose in Cuddalore, India, using geophysical methods by Chidambaram and Ramanathan (2008). Mukherjee et al. (2007a) reported enhancement of SWI in most of the coastal aquifers in southern West Bengal

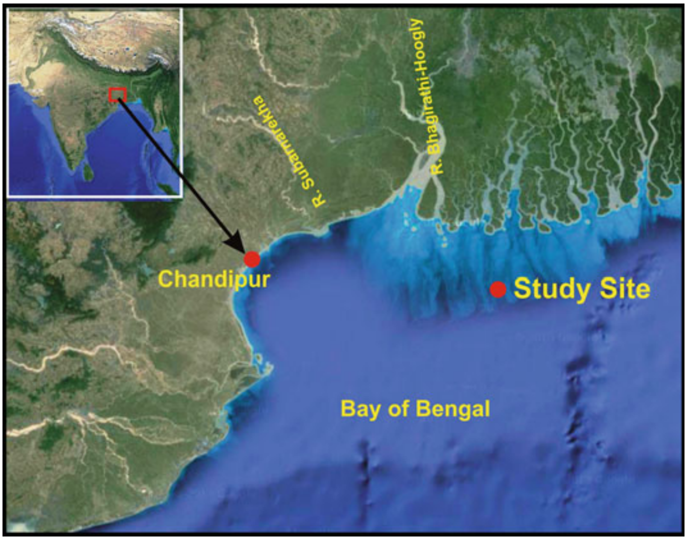


Fig. 28.1 Aerial view of the study area (modified after Debnath et al. 2015a, b)

caused by irrigational pumping. These observations are in agreement to the results obtained from geochemical modeling of the area by Mukherjee and Fryar (2008) and isotope results from coastal aquifers (Mukherjee et al. 2007b). Rejani et al. (2008) noted that artificial recharge is required in dry season in an aquifer to protect groundwater from SWI in the coastal aquifers near Balasore, Orissa. Also, pumping of brackish water from the dispersion zone may provide a mechanism for mitigation and retardation of SWI in coastal aquifers (Khaled and Mohsen 2001).

This chapter provides documentation of summary of one of the first comprehensive studies of the submarine groundwater discharge (SGD) in a micro-tidal coast of eastern India adjoining Bay of Bengal (Chandipur, Balasore district, Odisha) (Fig. 28.1). The general purpose of this proposed research is to initiate an integrated study to elucidate the chemical nature and physical processes involved in groundwater discharge of groundwater to seawater in Bay of Bengal from the eastern Indian coastal aquifers by using geochemical and geophysical techniques. More related information regarding groundwater of South Asia is available in Mukherjee et al. (2018).

28.2 Delineation and Quantification of the Nature of Groundwater Discharge Zones to Bay of Bengal (BOB)

In last few decades, a number of research studies have addressed the method of quantification of SGD and delineation of the SGD zone. Very recently, Debnath et al. (2015a) and Debnath and Mukherjee (2016) have conducted a numerical modeling and seepage meter experimental study in a micro-tidal coast adjoining BOB to delineate different SGD zones and to quantify SGD toward BOB. In numerical modeling studies, a high-resolution thermal mapping and chemical profiling of porewater were done to identify the zones of SGD for different seasons in a hydrologic year (Debnath et al. 2013, 2015a, b). Using this technique, several focused and diffused discharge points have been identified, which have been found to be enriched with algal mats (an indicator of nutrient-solute-enriched SGD). High-resolution, 3D thermal models (Fig. 28.2) have also been constructed for immediate identification of T-SGD and M-SGD along the study transects, which reveals the 3D overview of GW–SW interaction and seasonal hydrodynamics. Assuming the vertical flow of the discharged groundwater, the SGD rates toward the BOB are further measured in present-day condition. The calculated total average annual SGD to BOB is reported to be 1.16 × 10^7 m^3/m/year.

Debnath and Mukherjee (2016) have reported the quantity and seasonal variability of SGD toward BOB through a high-resolution spatiotemporal lunar-tidal cycle-scale seepage meter experiment. The total annual SGD to the BOB is quantified as ~8.98 ± 0.6 × 108 m^3/year, which is about 0.9% of global SGD flux, which is probably the first documentation of an in-field measurement of tidally influenced SGD toward BOB. Here, we have presented a general comparison between estimated SGD to BOB and the global SGD input using several different, commonly used approaches in Table 28.1.

28.3 Nature and Variation of SGD

The SGD to the BOB has been found to be a mixture of terrestrially derived groundwater and marine component of the discharged groundwater, which varies seasonally and governed by the tidal set up the coastal areas (Debnath and Mukherjee 2016).

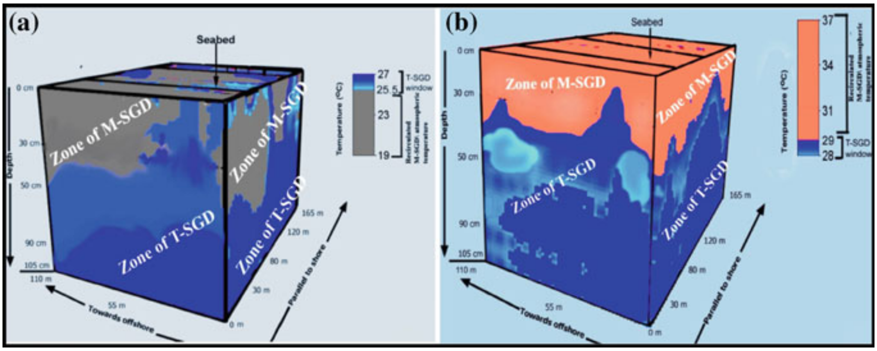


Fig. 28.2 Thermal map (3D) of the discharging groundwater at micro-tidal coastal area adjoining BOB for **a** post-monsoon season and **b** pre-monsoon season. The image also distinguishes the temperature of T-SGD and M-SGD, respectively (modified after Debnath et al. 2015a, b)

Table 28.1 A general overview of measured SGD fluxes to ocean in different coastal areas across world and in and around the Bay of Bengal (modified after Debnath et al. 2015a, b)

Adjoining coastal area	Methodology used	SGD fluxes to ocean	Source
Bengal basin (India–Bangladesh)	Water balance study	$1.5 \pm 5.9 \times 10^7$ m^3/year	Dowling et al. (2003)
Western Bengal basin, India	Water balance study	5.9×10^7 m^3/year	Mukherjee et al. (2007a, b)
Bay of Bengal, India	Numerical modeling	1.16×10^7 m^3/m/year	Debnath et al. (2015a, b), Debnath and Mukherjee (2016)
	Seepage meter study	$8.98 \pm 0.6 \times 10^8$ m^3/year	
Global SGD flux	Simulated	1×10^{11} m^3/year	Burentt et al. (2003)
Osaka Bay, Japan	Seepage meter	8.3–34.9 cm/day	Taniguchi (2002)
Cockburn Sound, Western Australia	Seepage meter	2.5–3.7 m^3/m/day	Burnett and Turner (2001), Smith and Nield (2003), Burnett et al. (2006)
	Simulated	2.5–4.8 m^3/m/day	Burnett and Turner (2001), Smith and Nield (2003), Burnett et al. (2006)
Mauritius lagoon spring	Seepage meter	0.4–120 m^3/m/day	Burnett et al. (2006), Rapaglia et al. (2006)
	Radon	26–56 m^3/m/day	Burnett et al. (2006), Rapaglia et al. (2006)
Mauritius lagoon South Beach	Seepage meter	1–8.8 m^3/m/day	Burnett et al. (2006); Rapaglia et al. (2006)
	Radon	5.2–9.2 m^3/m/day	Burnett et al. (2006), Rapaglia et al. (2006)
Florida Bay (USA)	Seepage meter	3–35 m^3/m/day	Burnett et al. (2002), Cable et al. (1997), DiLorenzo and Ram (1991)
Shelter Island, New York (U.S.A.)	Seepage meter	0.4–17.5 m^3/m/day	Burnett et al. (2006), DiLorenzo and Ram (1991)
	Simulated	0.23–1.4 m^3/m/day	Burnett et al. (2006), Schubert (1998)
Donnalucata, Sicily	Seepage meter	10–30 m^3/m^2/day	Burnett and Dulaliova (2006), Taniguchi et al. (2006)
	Radon	30–200 m^3/m^2/day	Burnett and Dulaliova (2006), Taniguchi et al. (2006)
Ubatuba, Brazil	Seepage meter	5–270 cm/day	Burnett et al. (2006)
	Continuous radon	1–29 cm/day	

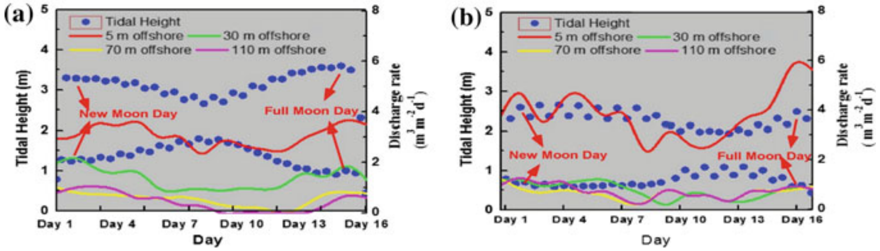


Fig. 28.3 Patterns of tidally influenced SGD rates at micro-tidal coastal areas adjoining Bay of Bengal for **a** pre-monsoon and **b** post-monsoon (modified after Debnath and Mukherjee 2016)

The experimental study demonstrated that the tide heights related to lunar tidal cycles have a substantial influence on SGD, especially on new moon and full moon day, and may also lead to tidally induced enhanced recirculation of seawater that influence the SGD chemistry and reactions along flow paths. It has also been explained that the tidal force of the coastal hydrodynamic system is a prominent governing process that can control the SGD within the lunar tidal cycles. As a result, diurnal variation of physicochemical characters of seepage can be observed within the lunar tidal cycle, mainly due to the changes in the mixing patterns of discharge of T-SGD and M-SGD component (Fig. 28.3).

Bengal basin is considered as one of the largest freshwater sources to the ocean (Harvey 2002; Mukherjee et al. 2007a). Thus, freshwater fluxes via SGD have also been found to be greater in this zone, but have been found to seasonally variable. Debnath and Mukherjee (2016) have summarized an overview of T-SGD and M-SGD input to the ocean for micro-tidal coast adjoining BOB (Fig. 28.4). The result shows that during pre-monsoon and post-monsoon season the T-SGD input may vary between 42–86% and 53–96% of the total SGD, respectively. It clearly reveals that within the nearshore zone the T-SGD appears to be the direct freshwater input to the ocean and the primary flow path of freshwater flux from the landward zone. However, the magnitude of the T-SGD input in a hydrologic year depends on the amount of precipitation and evapotranspiration for the respective coastal areas (Martin et al. 2006, 2007).

28.4 Stable Isotopic Characterization of SGD to the Bay of Bengal

Stable isotopes of oxygen (δO^{18}) and hydrogen (δD) are widely used for fingerprinting the sources of water. The stable isotope composition of the porewater, groundwater, and surface water can be used to delineate the seasonal and temporal patterns of discharging terrestrial-sourced groundwater to the sea. The comparison

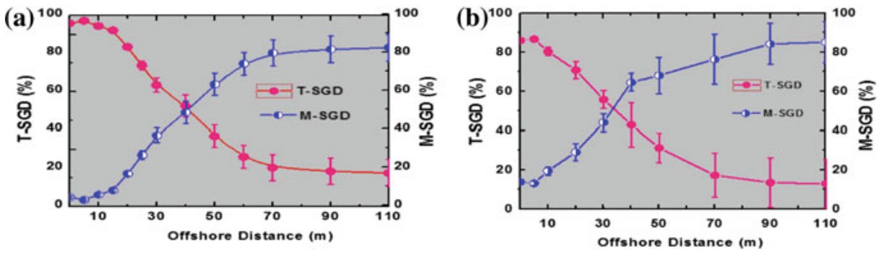


Fig. 28.4 Patterns of calculated T-SGD and M-SGD input at micro-tidal coastal areas adjoining BOB for **a** pre-monsoon and **b** post-monsoon (modified after Debnath and Mukherjee 2016)

of seasonal isotope signature within different hydrological scenario in a coastal area can be used to distinguish SGD end-member and their contributions to the ocean within the system. In this article, we will show a general overview of the stable isotopic signature of the discharging groundwater of a micro-tidal coast adjoining BOB and their variation in different end-member composition of SGD (Debnath et al. 2014a, b, 2015a). The bivariate plot of δ^{18}O versus δD (Fig. 28.5) provided insights into the sources of the discharging porewater and the regional hydrological influence in SGD. This study also explains that SGD mechanism of the study is controlled by tidal setup of the area with M-SGD input to the ocean through tidal pumping, which is also occasionally subject to seasonal variation.

The seawater salinity at the study area in monsoon season (16.33 ppT) is observed to be relatively lowered as compared to the other seasons. The regional map of the study site is showing that this area is subjected to a huge volume discharge of the monsoonal freshwater to BOB during monsoon season (accounted as river freshwater flux to the BOB). The annual discharge rate through the GBM basin and Bhagirathi-Hooghly was

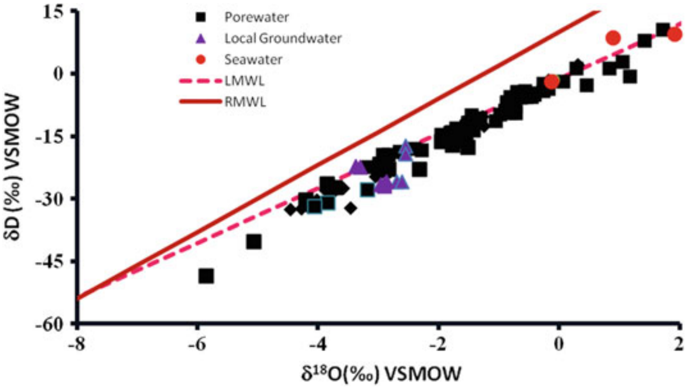


Fig. 28.5 Figure representing the bivariate plot of δ^{18}O versus δD for all porewater, local groundwater, and seawater with a comparison to the local meteoric line (LMWL: Debnath 2016) and regional meteoric line (RMWL; Mukherjee et al. 2007b)

found as ~2200 km^3/year (Datta and Subramanian 1997) in which ~75% of the discharge occurs during monsoon season (Sarin et al. 1989; Milliman et al. 1995; Datta and Subramanian 1997). The addition of this huge amount of monsoonal freshwater can dilute the seawater salinity from its expected concentration; as a result, relatively low salinity in BOB during monsoon season was observed. The monsoonal porewater isotopic composition demonstrated that most of the low-saline porewater are close to groundwater regime and rest of the porewater (salinity >4 ppT) resides near to monsoonal seawater regime. This implies that monsoonal seawater recirculation and its mixing with groundwater at the intertidal zone followed by its discharge to the ocean through the intertidal zone. Thus, such depleted isotopic signatures of monsoonal porewater demonstrate that monsoonal porewater isotopic signature is dominated by the regional hydrologic influence.

28.5 SGD-Associated Nutrients Flux Toward Bay of Bengal (BOB)

The nutrient dynamics of BOB are still unknown; increases in algal bloom events in the BOB indicating that the marine ecosystem of BOB is changing with the increased anthropogenic activities. As many of the coastal areas of the eastern coast adjoining BOB is well known for tourism and entertainment industry, the marine ecosystem of BOB may also face drastic modifications in near future. As a result, it can turn into a nutrient-limited ecosystem. In that case, SGD will play a major role in the nutrient dynamics and the nutrient budget of BOB. In our one of the ongoing studies at Chandipur (a micro-tidal coast adjoining BOB), we found that the nutrient concentration in seawater is lower than that in the SGD samples, and seasonal differences have also been observed in nutrient concentration similar to SGD samples (Debnath 2016). Our high-resolution, spatiotemporal, and lunar-tidal cycle-scale seepage meter and multi-depth porewater experiment during pre-monsoon and post-monsoon seasons of 2014–15 reveals that seawater NH_4^+ was highest during pre-monsoon (0.67 μM), while both NO_3^- and PO_4^{3-} were found as below the detectable limit. In post-monsoon season seawater, NO_3^- concentration was found to be 1.3 μM, while NO_2^- and PO_4^{3-} were found to be below the detection limit. NO_3^- budget of the respective study site have been described in our study from direct field investigation. This is very important as the discharge of N-dominated groundwater is considered as a typical biogeochemical phenomenon for the nutrient cycling as described in the recent SGD studies over the world (Santos et al. 2009; Tao et al. 2013; Beck et al. 2015). The average rate of (NO_3^-)-discharge was estimated to be 112 and 180 mM m^{-2} d^{-1} for pre-monsoon and post-monsoon seasons, respectively. The annual flux of Fe_{tot} has been estimated as 224 ± 1.8 mM m^{-2} d^{-1} for the study site. Concentration of PO_4^{3-} was found to be below detection level for both seasons. The SGD-associated solute and nutrient flux may change the nutrient dynamics in the study area. This is important for the solute and nutrient budget of the coastal and marine ecosystem of BOB. This assessment of solute and nutrient flux via groundwater discharge to BOB may provide vital information for probable future changes in marine ecological system and its environmental implications to BOB.

28.6 SGD-Associated Contaminant Flux Toward Bay of Bengal

SGD from coastal aquifers are one of the important links between marine and terrestrial biogeochemical cycles. Hence, SGD-associated solute may influence the marine ecosystems and associated biota, which further pronounced at the GW–SW mixing zone of a coastal hydrodynamic system. By analogy to surface estuary, this mixing zone is termed as “subterranean estuaries” (Moore 2010). Several studies have also showed that SGD affects coastal trace metal budgets with its associated contaminated flux. Out of which As is one of the major concern. The sources, major occurrences, geochemistry, and fate of the arsenic have been well studied over the last few decades in natural waters (Nordstrom and Archer) and in the aquifers of the regional area of study, e.g., for Bengal basin and Ganga-Brahmaputra-Meghna (GBM) basin (Mukherjee et al. 2011). In regional scale, most of the studies have been focused on the biogeochemical process and release of the arsenic in Bengal basin aquifer and GBM basin (Mukherjee et al. 2008, 2011), but there are very little information about the fate and transport of the arsenic from the coastal aquifers to BOB (Datta et al. 2009). Recent field and numerical investigation on the fate and transport of arsenic in coastal aquifers (like Waquoit Bay, MA, and Brazilian coast) demonstrated that the mobility of the arsenic near the GW–SW interaction zone is controlled by the geochemical reaction of iron (Fe) and manganese (Mn). Terrestrially sourced groundwater is mixed with oxic seawater in seepage face which acts as a reactive barrier for movement of arsenic reached water. Our continued study of SGD in the Chandipur coastal site has aimed to investigate the different biogeochemical processes that control arsenic (As) discharge and cycling toward the BOB, India. For this purpose, a series of porewater samples were collected from different multi-depth observational wells from February 2012 to September 2014. Measured total dissolved As concentrations were found in the range of 1–71 µg/L, where more than 40% of the studied samples having concentrations greater than 10 µg/L (World Health Organization (WHO) guideline value for As) (Debnath et al. 2014a, b). In last few years, different researchers (Bone et al. 2006; Plant et al. 2004) have studied porewater As concentrations in different coastal hydrodynamic system and have observed the porewater As concentrations in the above portion of discharging groundwater columns.

28.7 Conclusion

The above discussion and detailed overview of the groundwater discharge studies across BOB inferred that still SGD research is underdeveloped in Asia. Researchers need more focus to develop the current level of knowledge of SGD in India, as it is very important for the coastal water resource management. In addition, decision makers and water resource managers need to be aware of SGD, because due to the lack of knowledge of SGD we are losing a huge amount of fresh groundwater toward the ocean. In this study, we have already shown that SGD can add a huge amount solutes and nutrients to the BOB, which is likely to have a great impact on ecosystem of BOB. Hence, understanding the different phenomenon of SGD in coastal areas across the BOB would be an extremely interesting research question along with its environmental implication and societal importance. The manuscript also provides the detailed overview estimated and modeled value of the discharged groundwater, nutrient flux toward the BOB, which will be helpful for future SGD-related studies.

References

Beck AJ, Alex AK, Jena LL, Michele CA (2015) Chemical flux associated with spatially and temporally variable submarine groundwater discharge, and chemical modification in the subterranean estuary at gloucester point, VA (USA). Estuaries Coasts. https://doi.org/10.1007/s12237-015-9972-0

Bone SE, Eagle M, Charette MA (2006) Geochemical cycling of arsenic in a coastal aquifer. Envi Sci Tech 40:3273–3278

Burnett WC, Dulaiova H (2006) Radon as a tracer of submarine groundwater discharge into a boat basin in Donnalucata, Sicily. Conti Shel Res 26:862–873

Burnett WC, Turner J (2001) LOICZ group investigates groundwater discharge in Australia. LOICZ Newslett 18:1–4

Burnett WC, Bokuniewicz H, Huettel M, Moore WS, Taniguchi M (2003) Groundwater and pore water inputs to coastal zones. Biogeochemistry 66(1–2):3–33

Burnett WC, Chanton J, Christoff J, Kontar E, Krupa S, Lambert M, Moore W, O'Rourke D, Paulsen R, Smith C, Smith L, Taniguchi M (2002) Assessing methodologies for measuring groundwater discharge to the ocean. EOS 83:117–123

Burnett WC, Aggarwal PK, Aureli A, Bokuniewicz H, Cable JE, Charette WC, Kontar E, Kulkarni KM, Loveless A, Moore WS, Oberdorfer JA, Oliveira J, Ozyurt N, Povinec P, Privitera AM, Rajar R (2006) Quantifying submarine groundwater discharge in the coastal zone via multiple methods. Sci Total Environ 367:498–543

Cable JE, Burnett WC, Chanton JP (1997) Magnitudes and variations of groundwater seepage into shallow waters of the Gulf of Mexico. Biogeochemistry 38:189–205

Chidambaram S, Ramanathan AL (2008) Comparison of subsurface ground water discharge in east and west coast of India (DST- ILTP project Progress report 2007–2008, Govt of India, 32 p, Unpublished)

Datta DK, Subramanian V (1997) Nature of solute loads in the rivers of the Bengal drainage basin, Bangladesh. J Hydrol 198:196–208

Datta S, Mailloux B, Jung HB, Hoque MA, Stute M, Ahmed KM, Zheng Y (2009) Redox trapping of arsenic during groundwater discharge in sediments from the Meghna riverbank in Bangladesh. Proc Natl Acad Sci U.S.A 106(40) (Oct 6, 2009):16930–16935

Debnath P (2016) Hydrogeochemical dynamics of discharging groundwater from a coastal aquifer to the Bay of Bengal. Unpublished thesis, Indian Institute of Technology Kharagpur

Debnath P, Mukherjee A (2016) Quantification of tidally-influenced seasonal groundwater discharge to the Bay of Bengal by seepage meter study. J Hydrol 537:106–116

Debnath P, Mukherjee A, Singh HK (2013, October) Delineation of submarine groundwater discharge zones in a micro-tidal coast of the Bay of Bengal by thermal imaging and hydrogeochemistry. In: 2013 GSA annual meeting in Denver

Debnath P, Mukherjee A, Roy M, Joshi G, McManus J (2014a) Arsenic enriched groundwater discharge from a micro-tidal subterranean estuary, at the Bay of Bengal, India. In: 2014 GSA annual meeting in Vancuver, British Columbia, Canada 19–22 Oct 2014, vol 46, no 6. Geological Society of America, Abstracts with Programs, p 689

Debnath P, Mukherjee A, Rao S, Krishan G (2014b) Stable isotope signature of groundwater-seawater interaction in a microtidal coast of the Bay of Bengal. In: 2014 AGU fall meeting, in San Francisco, California 15–19 Dec 2014. Abstracts with Programs. Paper Id-H3Q8 and Abstract Id: 25373

Debnath P, Mukherjee A, Rokade P, Joshi G, Rao S, Krishan G (2015a) Stable isotopes and major ion chemistry of discharging groundwater to the Bay of Bengal: implications to strontium flux. In: 2015 Goldschmidt Conference, 16–21 Aug 2015, Prague, Czech Republic. Abstract with programs. Abstract id-3080

Debnath P, Mukherjee A, Singh HK, Mondal S (2015b) Delineating seasonal porewater displacement on a tidal flat in the Bay of Bengal by thermal signature: implications for submarine groundwater discharge. J Hydrol 29(3):1185–1197

DiLorenzo JL, Ram RV (1991) Flushing-time estimates for West Neck Harbor: a small tidal embayment of the Peconic Bays, New York. Report—Najarian Associates, L.P. Eatontown, New Jersey, pp 1–44

Dowling TI, Summerell GK, Walker J (2003) Soil wetness as an indicator of stream salinity, Environ Manage Softw 18:587–593

Harvey CF (2002) Groundwater flow in the Ganges delta. Science 296:1563

Jacob N, Babu SSD, Shivanna K (2009) Radon as an indicator of submarine groundwater discharge in coastal regions. Curr Sci 97(9)

Khaled IH, Mohsen MS (2001) Mitigation of seawater intrusion by pumping brackish water. Transp Porous Media 43:29–44

Martin JB, Cable JE, Jaeger J, Hartl K, Smith CG (2006) Thermal and chemical evidence for rapid water exchange across the sediment-water interface by bioirrigation in the Indian River Lagoon, Florida. Limnol Oceanogr 51:1332–134

Martin JB, Cable JE, Smith C, Roy M, Cherrier J (2007) Magnitudes of submarine groundwater discharge from marine and terrestrial sources: Indian River Lagoon, Florida. Water Resour Res 43:W05440

Milliman JD, Rutkowski C, Meybeck M (1995) River Discharges to the Sea: a global river index (GLORI). NIOZ, Texel, pp 125

Moore WS (2010) The effect of submarine groundwater discharge on the ocean. Annu Rev Mar Sci 2:345–374

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Mukherjee A, Fryar AE (2008) Deeper groundwater chemistry and geochemical modeling of the arsenic affected western Bengal basin, West Bengal. India Appl Geochem 23:863–892

Mukherjee A, Fryar AE, Howell P (2007a) Regional hydrostratigraphy and groundwater flow modeling of the arsenic contaminated aquifers of the western Bengal basin, West Bengal. India Hydrol J 15:1397–1418

Mukherjee A, Fryar AE, Rowe HD (2007b) Regional scale stable isotopic signature and recharge of the deep water of the arsenic affected areas of West Bengal, India. J Hydrol 334:151–161

Mukherjee A, Fryar AE, Scanlon BR, Bhattacharya P, Bhattacharya A (2011) Elevated arsenic in deeper groundwater of western Bengal basin, India: extents and controls from regional to local-scale. Appl Geochem 26:600–613

Mulligan AE, Charette MA (2009) Groundwater flow to the coastal ocean. In: Steele JH, Thorpe SA, Turekian KK (eds) The coastal ocean. The United Kingdom, Oxford, pp 143–152

Plant JA, Kinniburgh DG, Smedley PL, Fordyce FM, Klinck BA (2004) Arsenic and Selenium. In: Lollar BS, Holland HD, Turekian KK (eds) Treatise on Geochemistry. Elsevier Ltd, San Diego, CA, vol 9, pp 17–6

Rejani R, Jha MK, Panda SN, Mull R (2008) Simulation modeling for efficient groundwater management in Balassore coastal basin. Water Resour Manag 22:23–50

Rapaglia J, Beck A, Stieglitz T, Bokuniewicz H, Kontar E (2006) Submarine groundwater discharge patterns through volcanic fractured rock. Submarine groundwater discharge assessment intercomparison experiment, Mauritius; Report to UNESCO

Santos IR, Burnett WC, Dittmar T, Suryaputra NA, Chanton J (2009) Tidal pumping drives nutrient and dissolved organic matter dynamics in a Gulf of Mexico subterranean estuary. Geochim Cosmochim Acta 73:1325–1339

Sarin MM, Krishnaswami S, Dilli K, Somayajulu BLK, Moore WS (1989) Major ion chemistry of the Ganges–Brahmaputra river system: weathering processes and fluxes to the Bay of Bengal. Geochim Cosmochim Acta 53:997–1009

Schubert CE (1998) Areas contributing ground water to the Peconic estuary, and ground-water budgets for the North and South forks and Shelter Island, Eastern Suffolk County, New York. U.S. Geological Survey, Water Resources Investigations Report, pp 97–4136

Smith VH (2003) Eutrophication of freshwater and coastal marine ecosystems—a global problem. Environ Sci Pollut R 10:126–139

Taniguchi M, Burnett WC, Cable JE, Turner JV (2002) Investigations of submarine groundwater discharge. Hydrol Process 16:2115–2129

Taniguchi M, Ishitobi T, Shimada J (2006) Dynamics of submarine groundwater discharge and freshwater–seawater interface. J Geophys Res 111. https://doi.org/10.1029/2005JC002924

Tao J, Du J, Moore WS, Zhang G, Su N, Zhang J (2013) Nutrient inputs to a Lagoon through submarine groundwater discharge: the case of Laoye Lagoon, Hainan, China. J Marine Syst 111–112: 253–262

Verma S, Phansalkar SJ (2007) India's water future 2050: potential deviations from "Business-as-usual". Int J Rural Manag 3(1):149–179

Chapter 29
Characterization of Coastal Aquifers in SE Coast of India

S. Chidambaram, C. Thivya, A. L. Ramanathan, R. Thilagavathi and M. V. Prasanna

Abstract India has a very long coastline compared to other countries in the world and is considered as the backbone of our national economy. One-fourth of the country's population lies in this region; the most fertile agricultural land is situated in this area, and it occupies the most potential aquifer systems of the country which faces multifaceted complex problems like seawater intrusion, land use/land cover changes, climate change, and human-induced anthropogenic problems like discharge of sewage effluents, agricultural, salt pan, and aquacultural activities. It is also highly vulnerable to extreme events, such as storms, which impose substantial costs on coastal communities. Numerous rivers enter to the coast that tends to form estuaries and mixes with sea which includes a huge complex ecosystem. The population density increases the risks and vulnerability of the coastal states. The anticipated sea level rise by climate changes affects the coastal aquifers which push the freshwater–seawater interface and makes the shallow aquifers saline. Rivers are the major contributory of the pollution in the coast whereas all rivers are polluted due to industrial effluents and sewage disposal. The various studies on different aspects of hydrogeochemical approach explain the degradation of coastal regions and also various mitigations to overcome these problems.

S. Chidambaram (✉) · C. Thivya · R. Thilagavathi
Department of Earth Sciences, Annamalai University, Annamalai Nagar, India
e-mail: chidambaram_s@rediffmail.com

A. L. Ramanathan
School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India

M. V. Prasanna
Faculty of Engineering and Science, Department of Applied Geology, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_29

29.1 Introduction

Coastal regions are the densely populated areas in the world (Small and Nicholls 2003; Post 2005). These regions are affected by hydrological problems such as cyclones, flooding, freshwater scarcity due to overexploitation which ultimately results in saline water intrusion. Indirectly, it is also affected by industrial, agricultural, and land use practices. Coastal aquifers are different when compared to other aquifers because these aquifers are affected by tidal effects which cause the complication in groundwater flow. More related information regarding groundwater of south Asia is available in Mukherjee et al. (2008).

The quality of coastal aquifers is contaminated by the release of sewage effluents, industrial wastages directly into the ground or into the subsurface which pollutes the underlying aquifers which reaches the oceans. The contaminated groundwater can have significant modifications on coastal ecosystems as the quantity of freshwater is high of submarine groundwater discharge (SGD) in the aquifers (Gallagher et al. 1996). There are different techniques used for the coastal aquifers to overcome saline water intrusion, anthropogenic activities, and overexploitation. The geochemical technique characterizes the ionic concentration of groundwater which is saline in nature (Thilagavathi et al. 2012; Prasanna et al. 2010a, b; Singaraja et al. 2013a). Isotopic techniques help in identifying the sources of salinization and other processes. In order to manage groundwater in coastal areas, mostly δD, $\delta^{18}O$, environmental Tritium, Carbon-13, and Carbon-14 are used in conjunction with hydrogeological data and water chemistry to understand the origin and history of groundwater, surface water and groundwater interaction, and dynamics of aquifers. All groundwater of economic interest originates as precipitation. But, depending upon the residence time, we can classify the groundwater as recent, young, and old (paleo-water) groundwater. The stable isotopic methods are used to know the source of groundwater by its recharge processes and also based on variability of isotopes in water. Hence, in this study, an attempt has been made on hydrogeochemical processes, isotopic techniques, and climate changes to overcome the problems in coastal aquifers.

29.2 Hydrogeochemical Techniques

Hydrochemical facies are the suitable tools for identifying the chemical characteristics of groundwater (Piper 1953). Piper plot comprises the plotting of major ionic concentrations of various water samples (Piper 1953). The two triangles at the base of the plot demonstrate the cation (Ca^{2+} + Mg^{2+}, Na^+, K^+) and anion (Cl^-, SO_4^{2-}, HCO_3^-) dominance, whereas the central diamond field illustrates various sources and processes associated with the groundwater system. The geochemical processes can be determined from the piper plot (Fig. 29.1), which has been divided into six sub-fields, viz. 1 (Ca–HCO_3 type); 2 (Na–Cl type); 3 (mixed Ca–Na–HCO_3

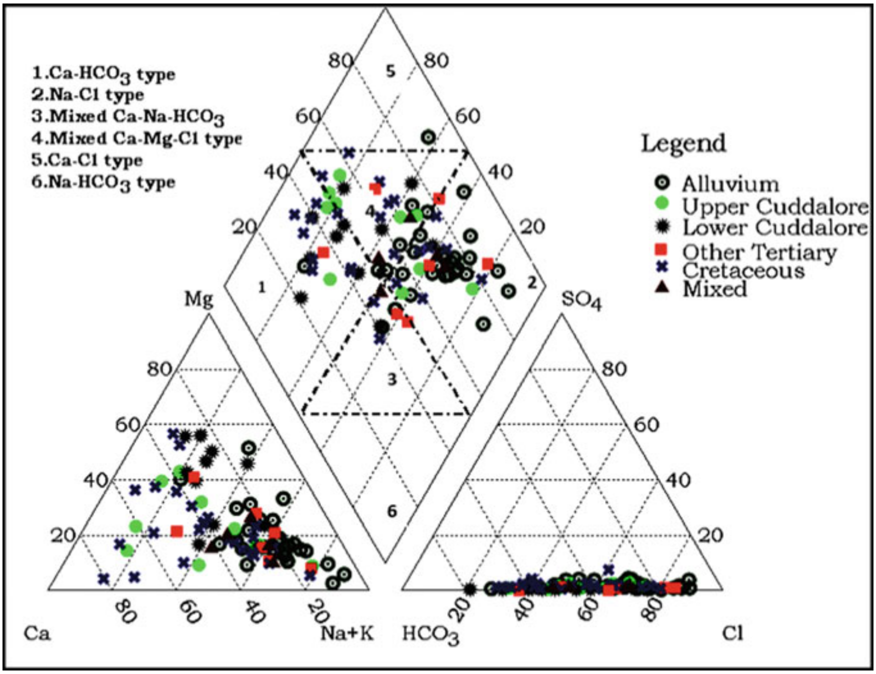


Fig. 29.1 Piper plot for groundwater samples of Pondicherry region (Thilagavathi 2015)

type); 4 (mixed Ca–Mg–Cl type); 5 (Ca–Cl type); and 6 (Na–HCO_3 type) (Thilagavathi et al. 2012).

The samples have been collected from pre-monsoon (PRM) season from the Pondicherry region, and it is dominated by the fields of 1, 2, and 4. Most of the samples from Alluvial formations and few samples from other formation fall in field 2, reflecting high sodium and chloride. These are inferred to be obtained by either adsorption or precipitation processes (Chidambaram et al. 2007a, b). Due to the saturation, they can also be understood as the discharge region (Thilagavathi et al. 2012) and migration of the samples from transition zone of mixed type of Ca–Mg–Cl and Na–Cl facies which resembles the seawater composition, and these samples also shows the long residence time of shallow groundwater (Prasanna et al. 2010a, b) where Na exceeds Ca and Mg, Cl exceeds HCO_3 and SO_4 (Prasanna et al. 2008). Na + Cl water type in discharge zone shows the saline nature (Prasanna et al. 2008). Maximum number of samples from Cretaceous and few from the Upper Cuddalore and Lower Cuddalore formations are representing the recharging field 1 of Ca + HCO_3 water type (Thilagavathi et al. 2012). Samples irrespective of formations are represented in field 4.

29.3 A Case Studies on Seawater Intrusion Using Ionic Ratios

A study on the coastal aquifers of Kalpakkam region of Tamilnadu has been carried out by the Karmegam (2012). The study categorizes the seawater intrusion using Na/Cl ratio and also calculates using several ionic ratios in coastal groundwater (Sanchez Martos et al. 1999; Vengosh et al. 2002). The molar ratios of Na^+/Cl^- versus Cl^- (mg/l) concentrations have been explained in Fig. 29.2. Fresh groundwater contaminated with sea water indicate the linear mixing trend between two end variables. This is predominantly observed in Na-Cl type more near the seawater ratio (0.86) (Sanchez Martos et al. 1999). The ratios from 0.35 to 3.26 during POM, 0.46 to 1.54 during NEM, 0.48 to 6.09 during SUM, and SWM ranges from 0.53 to 1.63 were noted; hence, most of the samples were observed in the contamination region. The ratio of Cl^- with Na^+ and Mg^{2+} indicates a predominantly evaporated water source for these ions.

In general, Na is added to the groundwater by weathering of feldspar which seems to be lesser when compared to the rainfall that occurs in coastal region which contributes more Na and it gets diluted to the groundwater with Na^+/Cl^- greater than 1. The Na^+/Cl^- ratio shows that 66, 63, 53, and 40% of samples during POM, NEM, SUM, and SWM (Fig. 29.2) were above the seawater ratio, indicating most

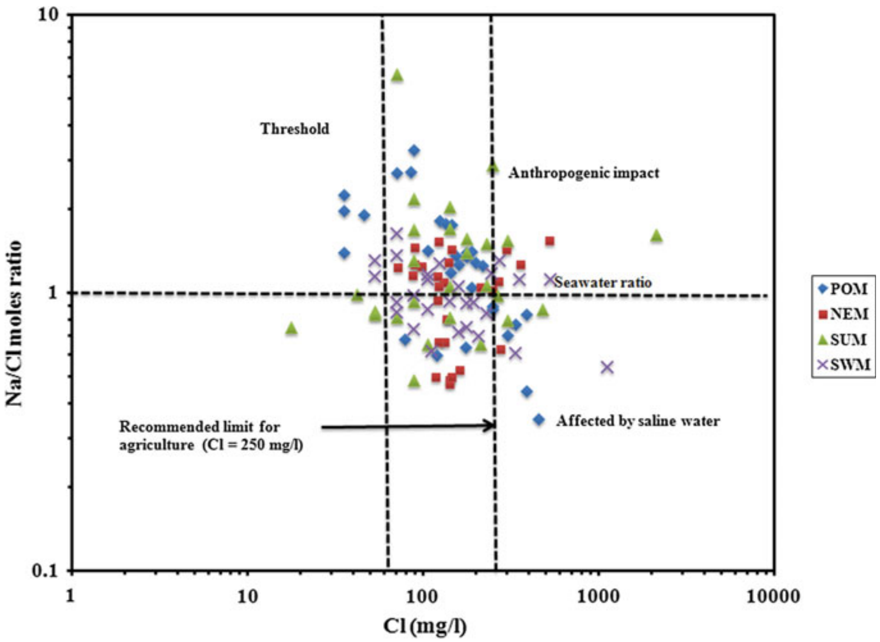


Fig. 29.2 Relationship between Na/Cl and Cl for groundwater samples of different seasons (after Karmegam 2012)

of the samples were affected by saline water intrusion to certain degrees. This may be due to the brackish water recharge as the higher EC falls near the coastal water bodies. The values closer to the ratio indicates the fresh mixing of groundwaters with saline water (Mercado 1985). The higher concentration of Na^+/Cl^- ratios also indicates the anthropogenic contamination, such as impact of fertilizers (Jones et al. 1999) and the similar results were observed by Singaraja et al. (2013a) of costal aquifers of Thoothukudi district of Tamilnadu.

The conservative Cl^- ion and the HCO_3^- ions mixed with groundwater which is due to the leaching and mineral weathering in the aquifers. Bicarbonate is introduced to the groundwater in lesser amount due to the organic matter which oxidates as a byproduct of SO_4^{2-} reduction (Last 1990; Compton 1988). In seawater composition, Cl is the dominant ion and HCO_3 is only in minor amount. $Cl/(Cl/HCO_3)$ ratio is used to identify the seawater intrusion called Simpson's ratio (Todd 1959). A study by Singaraja (2014) attempts the seawater intrusion by this ratio in coastal aquifers of Thoothukudi district, Tamilnadu.

According to Simpson classification, five classes have been proposed such as: <0.5—good quality water, 0.5–1.3—slightly contaminated water, 1.3–2.8—moderately for contaminated water, 2.8–6.6—injuriously contaminated, and >15.5 for highly contaminated water. As the threshold value of Cl^- is noted to be 63 mg l^{-1}, it is observed that about 32, 16, 11, and 12% of groundwater is extremely affected by the saline water during PRM, SWM, NEM, and POM, respectively. 56% were slightly or moderately affected in SWM and NEM and 61, 29% during POM and PRM seasons (Fig. 29.3). 35, 17, 22, and 12% of the groundwater samples fall on

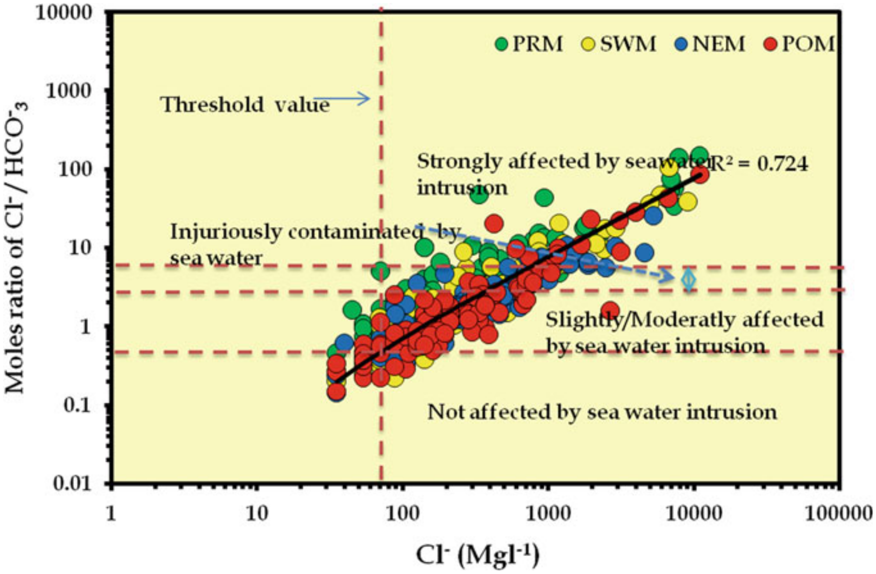


Fig. 29.3 Molar ratios of Cl^-/HCO_3^- versus Cl^- concentration for four seasons (after Singaraja 2014)

injuriously contaminated zone, and 11% of samples were not affected by seawater intrusion during SWM and NEM then 15 and 4% in POM and PRM, respectively.

Cl^-/HCO_3^- ratios range from 0.14 to 152.50, and it shows positive linear relation with Cl^- ions with an R^2 value of 0.72 (Fig. 29.3). It specifies the mixing of saline water with groundwater. At the lower range of ratios, the slight deviation occurs by the variations of HCO_3 ions in groundwater. Increase of Cl/HCO_3 and decrease of HCO_3 at the lower values are noted in X-axis due to change in land use pattern along the coastal region.

Seawater composition has distinctive ionic ratios such as $Na^+/Cl^- = 0.86$, $SO_4^{2-}/Cl^- = 0.05$, $Ca^{2+}/(HCO_3^- + SO_4^{2-})$, and $Mg^{2+}/Ca^{2+} = 5.2$ (Vengosh et al. 2002; Vengosh and Rosenthal 1994). The Na/Cl ratio of the coastal aquifers of Nagapattinam district is greater than unity in all seasons (Johnsonbabu 2011). The Na^+/Cl^- molar ratio reaches the unity which might be due to the mixing of saline water with freshwater (Vengosh and Rosenthal 1994). By comparing seawater, the saline groundwater possesses low Na^+/Cl^- (0.5–0.8) and Mg^{2+}/Ca^{2+} ratios and also high $Ca^{2+}/(HCO_3^- + SO_4^{2-})$ ratios (greater than unity) (Vengosh et al. 2002).

The probable source of salinization is characterized by various chemical parameters of the groundwater. If seawater intrusion in the aquifers occurs only by the source of salinization, then the Mg^{2+}/Ca^{2+} ionic ratio should be greater than 5, and it is a direct indicator of seawater contamination (Metcalf and Eddy 2000; Thilagavathi et al. 2012). $Ca^{2+}/(HCO_3^- + SO_4^{2-})$ ratio indicates the seawater intrusion process in both seasons due to occurrence of complex reactions in the aquifer (Kumar et al. 2006) (Table 29.1).

29.4 Geophysical Techniques

29.4.1 Resistivity 3D Interpretation

Geophysical techniques such as resistivity measures help in the identification of saline water intrusion in coastal aquifers. An attempt on Pondicherry region by Thilagavathi (2015) studied the spatial distribution of the subsurface resistivity in different bore-holes in 3D. The resistivity cross section shows that lesser resistivity zone is noted in southeastern part which is thicker than the northern region at Nallavadu. The depth below 100 m from the groundwater level tends to show high resistivity. There exists a difference in deeper aquifer of northern and southwestern part as it shows lesser and higher resistivities, respectively. An intervening impermeable clay layer is inferred from the lithology with a lignite seam (Thilagavathi et al. 2013). Lower resistivity values are noted in recent alluvium, due to intervening clay layers or saline intrusion present in southeastern regions.

Table 29.1 Comparison of ionic ratio for identification of sources for potential salinization and chemical constituents of groundwater for seawater intrusion in study area (after Johnsonbabu 2011)

Parameter	Seawater intrusion	Deep saline up coning	Agriculture return flows	Waste water infiltration	SPRM	SPOM	DPRM	DPOM
Na^+/Cl^-	0.86–1[a]	<0.8[b]	–	1.1[c]	0.8	0.8	1.9	1.1
SO_4^{2-}/Cl^-	0.05[a,c]	0.05[c,d]	≫0.05[e]	0.09[d]	0.1	0.1	0.3	0.36
K^+/Cl^-	0.019	<0.019	–	≫0.02	0.3	0.3	0.1	0.2
Mg^{2+}/Ca^{2+}	<5b	<1a	–	–	1.1	0.8	0.8	0.7
$Ca^{2+}/(HCO_3^- + SO_4^{2-})$	0.35–<1	<1a	–	–	0.3	0.13	0.1	0.1

[a] Vengosh and Rosenthal (1994)
[b] Vengosh and Ben-Zvi (1994)
[c] Vengosh et al. (1994)
[d] Mercado (1985)
[e] Vengosh et al. (2002)

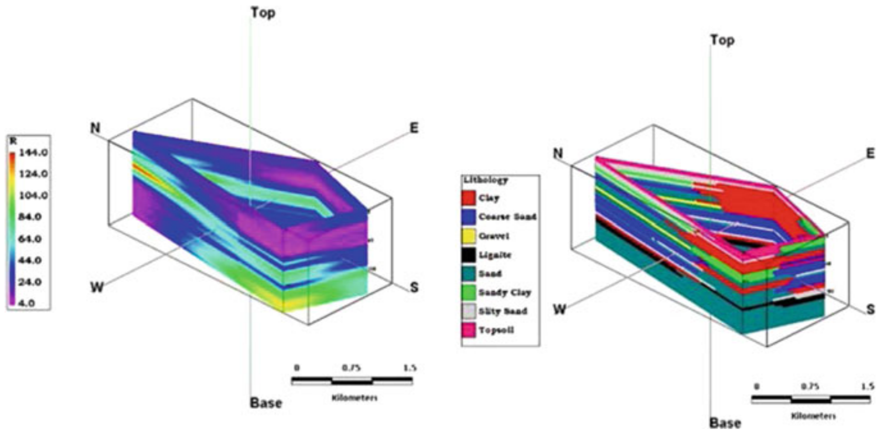


Fig. 29.4 Variation of resistivity (Ωm) in 3D sections for four locations in the Pondicherry region (after Thilagavathi et al. 2016)

Nallavadu region is represented by low resistivity of about 50 m due to the presence of coarse sand with saline groundwater (Fig. 29.4). This has not been observed in the lower aquifer due to the presence of clay layer. Increase of resistivity is noted in the deeper aquifers of Upper Cuddalore (Mio-Pliocene) formation due to the presence of lignite in Muthaliyarpettai and Nallavadu. This is also witnessed from the hydrogeochemical studies (Pethaperumal et al. 2008) whereas the deeper aquifer is fresh compared to shallow aquifers (Thilagavathi et al. 2012).

29.5 Environmental Isotopes Techniques

29.5.1 δ^2H–δ^{18}O Relationship in Groundwater

Stable isotopes of H and O (i.e., ^{2}H and ^{18}O) being fundamental parts of water molecules are perfect tracers to understand the movement of water (evaporation, mixing, and dispersion) (Clark and Fritz 1997; Sharp 2007). Isotopic study from Pondicherry coastal region (Thilagavathi et al. 2016) reveals that depleted isotopes are similar to the global meteoric water line (GMWL). It is understood that most of the recharge mechanism held by the process of infiltration and the groundwater should reflect the isotopic composition of the surrounding river or lake or that of local precipitation (Aggarwal et al. 2004). The enrichment of heavier isotopes occurs mainly through the process of evaporation or due to anthropogenic activities like aquaculture, and indicative of evaporative enrichment/seawater intrusion is observed in Cuddalore and Pondicherry region (Fig. 29.5). A regional study on the stable isotope was carried out to find the impact of recharge on deeper aquifers in

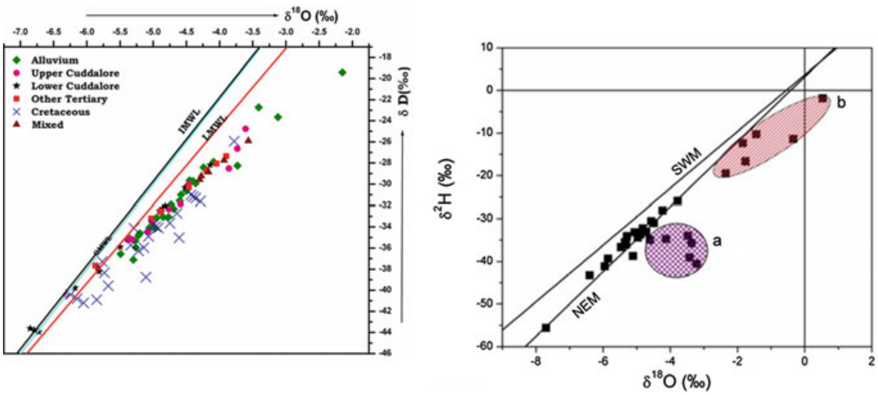


Fig. 29.5 Plot for d-excess versus $\delta^{18}O$ permil data of groundwater samples with dominant recharge sources identified (after Thilagavathi et al. 2016; Johnson 2011)

Cuddalore to Nagapattinam (Chidambaram et al. 2010) and Tuticorin coast (Singaraja 2014). The study showed enrichment of heavier isotopes indicates salt pan activities in these regions.

Alternately, substantial re-evaporation of surface waters in the local regions under low humidity creates vapor mass with high d-excess, and it mixes with atmospheric reservoir then it re-condenses, as the resultant precipitation will have high d-excess (Clark and Fritz 1997). Lower d-excess values (<10) signifies the evaporation of rainwater and leaving the residual groundwater with lower d-excess values. Another geographic effect on the stable isotope content that can be applied effectively is the shift in the D-^{18}O relationship. Signature of d-excess in layered aquifers from Pondicherry (Thilagavathi et al 2016) and Cuddalore (Chidambaram et al. 2010) reveals that the recharging of evaporated sources by the influence of lateral infiltration or through surface runoff recollected by tanks/ponds. A study from Kalpakkam region of Tamilnadu, India, shows that d-excess is due to evaporation processes from surface water bodies (Fig. 29.6). A different trend is observed in samples representing the Cuddalore to Nagapattinam and Kalpakkam coast, due to seawater intrusion. The enriched part (encircled values) also shows lower d-excess, which again points to the evaporated water from tanks or agricultural return flow which are the common practices along the coastal alluvium. These aquifers are dominantly recharged by evaporated rainwater/surface waters, recharged by direct precipitation by rivers and backwaters.

$\delta^{18}O$ and EC relationship brought out by few studies along Tuticorin (Singaraja 2014) and Cuddalore coastal (Chidambaram et al. 2010) region indicates the mixing processes. Its also reveals the fact there is a linear relationship observed with respect to the proportion of the mixing waters (Fig. 29.7). Salt water intrusion is evident from the higher concentration of EC (Singaraja et al. 2013b).

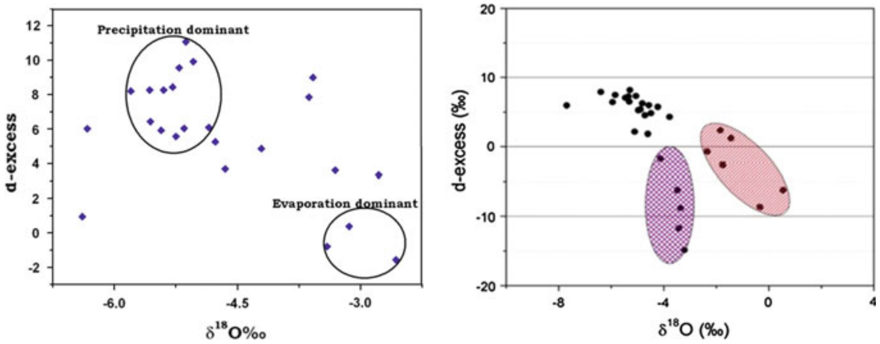
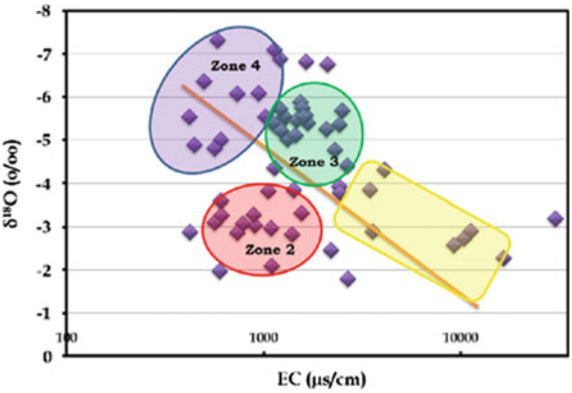


Fig. 29.6 Bivariate plot for d-excess versus δ^{18}O (‰) of groundwater samples with dominant recharge sources identified (after Thilagavathi et al. 2016)

Fig. 29.7 Plot for EC versus δ^{18}O for groundwater samples (after Singaraja 2014)



The influence of seawater/saltpan is observed by the interrelationship between Cl^-–δ^{18}O along the coastal regions of Tuticorin and Cuddalore to Nagapattinam (Singaraja et al. 2013a; Chidambaram et al. 2014) (Fig. 29.8). High chloride with enriched δ^{18}O shows the samples are recharged rarely from the precipitation and also evolved from the evaporated waters from surrounding tanks. This concentration is also attributed by the leaching processes of secondary salts from the formations underlain in the coastal aquifers (Chidambaram et al. 2007a, b) or due to seawater intrusion (Singaraja et al. 2013a) or due to salt pan activity.

Based on Cl^-–δ^{18}O distribution in Pondicherry to Nagapattinam coast and Kalpakkam (Thilagavathi et al. 2016; Chidambaram et al. 2014; Karmegam 2012), groundwater is saline due to the influence of seawater/backwater; therefore, it can be concluded that these locations are affected by saline waters.

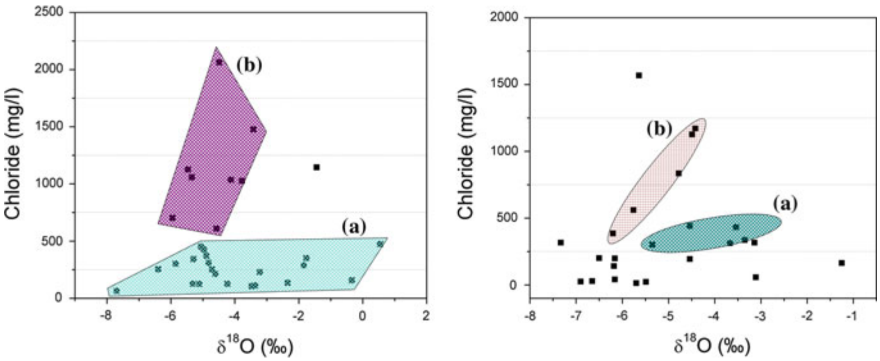


Fig. 29.8 Relationship between δ^{18}O-chloride correlations for groundwater samples (After Johnsonbabu 2011)

29.6 Climatic Changes with Groundwater Dating with ^{3}H

The study on the isotopes in groundwater also helps to understand the environment of paleo recharge and climatic changes. The classification of Tritium for dating is as follows:

<0.8 TU	Sub-modern-recharged prior to 1952
0.8 to ~2 TU	Mixture between sub-modern and recent recharge
2–8	Modern (<5–10 year)
10–20	Residual “bomb” ^{3}H present
>20 TU	Considerable component of recharge from 1960s or 1970s

A study on the tritium in shallow alluvial groundwater of Oman suggests that recharge in that region taken place primarily by infiltration of flash flood events and interchannel areas receives direct infiltration and sub-surface flow (Clark and Fritz 1997). Tritium is of special value in detecting recent recharge because of its short half-life of 12.32 years. Tritium values for groundwater along the Cuddalore to Nagapattinam coast falls in the range of 2–5 TU. The tritium values <1 TU indicate the old groundwater. These findings infer that these groundwaters are probably recharged from distant areas.

Chidambaram et al. (2010) found that the ^{3}H and Cl distribution showed (Fig. 29.9) the rain dominated area. The source of salinity in Cuddalore to Nagapattinam coast is mostly surface water sources like backwater. Old groundwater shows depleted isotopic values indicating distant recharge. Enriched isotopic composition as well as high tritium indicating the source of salinity in these regions is surface water that has undergone evaporation and backwaters (Chidambaram et al. 2010).

The inferences based on tritium values of Pondicherry (Pethaperumal 2010) (Fig. 29.9) indicates the different nature of groundwater. These are inferred as old

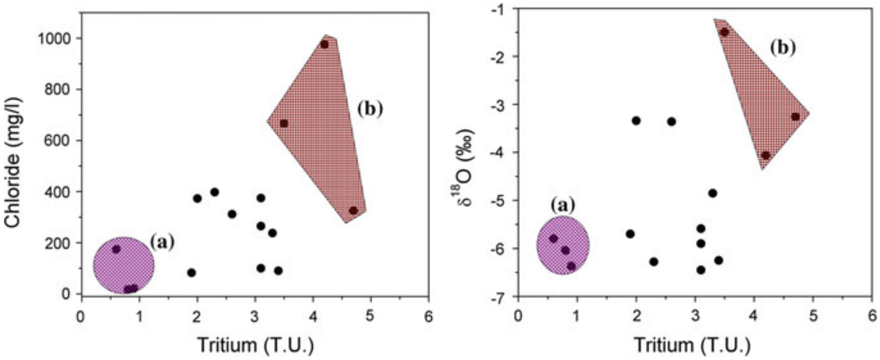


Fig. 29.9 Variation of tritium versus chloride and $\delta^{18}O$ (after Johnsonbabu 2011)

groundwater with lower electrical conductivity which reveals recharge process of the region is less active and also have lesser interaction between groundwater and aquifer matrix. Modern groundwater with high electrical conductivity reveals that the residence time of the groundwater was estimated to be relatively short/less after infiltration. Moreover, groundwater flow system in this region is thought to be active. Chidambaram et al. (2010) studied the variation of climate conditions in the recent recharge of the coastal aquifers by using isotopes. The study found that the sub-modern water is noted to be fresh and modern type water is saline in nature. It is also observed a wide variation in climate was noted in the modern recharge waters.

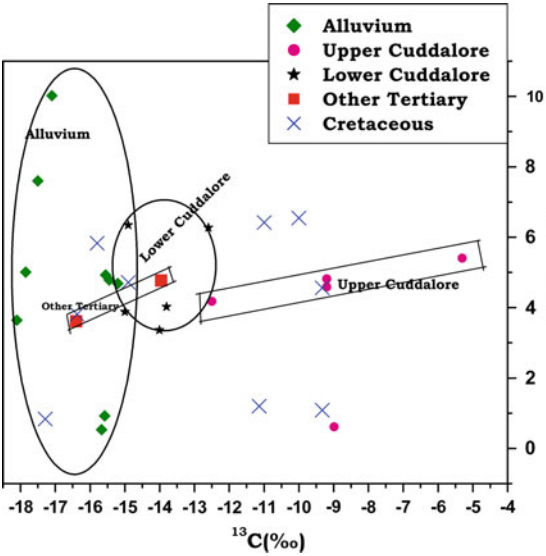
29.7 Relationship of $\delta^{13}C$ in Groundwater

Pethaperumal (2010) discussed the groundwater in Pondicherry coast recharges at higher elevations with high vegetation cover has more negative $\delta^{13}C$ values because root zone contributes a greater proportion of CO_2 (Fig. 29.10) compared to recharges taking place at lower elevations. In addition to depleted $\delta^{13}C$ composition, recharge at higher elevations also contains less total inorganic carbon, because the duration that open system conditions prevail is shorter. At lower elevations, a greater proportion of atmospheric CO_2 is incorporated into the infiltrating waters, because of increased atmospheric contact.

29.8 Saturation Index of Carbonate Minerals

The Thermodynamic stability of groundwater is characterized by the condition of saturation index (SI) to a particular mineral. If the value of log IAP is $\geq$ log *Ksp* (>0), the natural water is saturated or supersaturated with respect to the mineral.

Fig. 29.10 Variation of ^{13}C in groundwater (after Thilagavathi et al. 2016)



If IAP is <*Ksp* (>0), the solution is undersaturated with respect to the mineral. If indices log(IAP/*Ksp*) = 0, it inferred to be in equilibrium state (Trusdell and Jones 1973).

Saturation index of zero indicates equilibrium. This condition is affected by CO_2 out gassing and errors in pH and alkalinity (Sprinkle 1989). The saturation state of carbonate minerals is in the following order: $SI_C > SI_M > SI_A > SI_D$, and they were plotted against HCO_3 (in mg/l). During the POM, an increasing trend of SI is noted with the increasing HCO_3 (Fig. 29.11). More number of groundwater samples were found fall between saturation to oversaturation during POM. The magnesite and aragonite minerals are near the state of equilibrium showing an increasing trend with $HCO_{3.}$ During POM, the saturation index of the carbonate minerals in almost 80% of the sample is saturated by the carbonate minerals. When HCO_3 concentration increases, there is an increase of SI of all the carbonate minerals and they

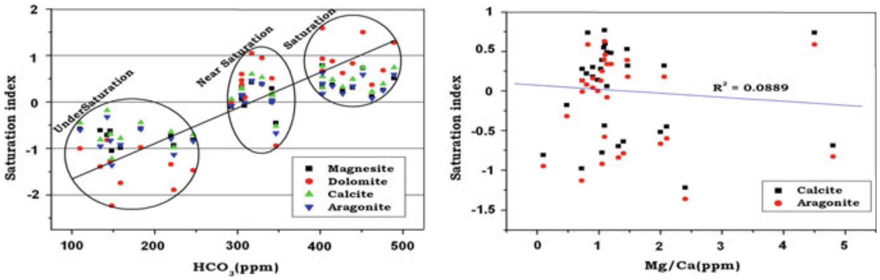


Fig. 29.11 Variation of Saturation index of different Carbonate minerals with dissolved HCO_3 and Mg/Ca ratio for samples collected during POM (after Karmegam 2012)

form near saturation to saturation state. Few samples show undersaturation though with high HCO_3, may be due to non-availability of cations (Ca and Mg) which might have been removed from the aqueous system due to process of cation exchange (Gomez et al. 2006). The carbonate minerals generally attain saturation when the concentration of HCO_3 reaches nearly 300 mg/l. It is interesting to note that there is one group of samples i.e., around 150–200 mg/l attain saturation before this concentration.

Since the Mg^{2+}/Ca^{2+} ratio of these samples is >1, it is possible that re-precipitated mineral is impure calcite i.e., Mg-calcite. Reports on this observation by Drever (1988) proposed that if the Mg^{2+}/Ca^{2+} ratio is near seawater value (5.2), the precipitated calcite can contain up to 20% Mg-carbonate. During calcite precipitation, CO_2 is evolved leading to increase in partial pressure, and the equilibrium reaction can be written as follows:

$$Ca^{2+} + HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O$$

In this case, most of the groundwater samples during POM show oversaturation with respect to calcite and aragonite, reflecting a good chance of calcite re-precipitation. Even in these samples, the Mg^{2+}/Ca^{2+} ratio is >1, indicating formation of Mg-calcite as noticed. Few of the fluvio-marine samples in POM show undersaturation (Fig. 29.11).

29.9 Comparison of Groundwater Samples to Seawater Composition

The similarity coefficient between groundwater samples (including pre- and post-monsoon) with the seawater of the Nagapattinam regions is calculated by linear regression logarithm. The samples which are observed to be similar in correlation coefficients were considered rather than the absolute values. Therefore, samples that are diluted by precipitation still have a correlation coefficient with its original composition even though the dissolved minerals are very different in composition. The difference in absolute concentration is expressed by the Euclidean distance.

$$D_{ij} = \frac{\sum nk - 1\left(X_{ik} - \mathrm{X_{jk}}\right)}{n}$$

where X_{ik} denotes the Kth variable measured on samples i and X_{jk} is the Kth variable measured on sample j, in all 'n' variables are measured on each sample and D_{ij} is the distance between sample i and sample j.

This is calculated by comparing seven parameters such as Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, HCO_3^-, and SO_4^{2-} of coastal aquifers of Nagapattinam district, where the

Table 29.2 Comparison of all groundwater samples to seawater composition (used parameters Na, Ca, Mg, Cl, HCO_3, and SO_4)

Index	Sample	Correlation coefficients	Euclidean distance	Points used for correlation
866	DPRM16	1	0	6
776	ASPM32	0.997	4683.447	6
794	BSRM5	0.995	4687.879	6
760	ASPM16	0.991	4050.54	6
811	BSRM22	0.991	4429.89	6
812	BSRM23	0.991	4698.964	6
793	BSRM4	0.982	4248.636	6
792	BSRM3	0.98	4671	6
778	ASPM34	0.972	3917.975	6
774	ASPM30	0.97	3979.507	6

correlation coefficient values of the samples are greater than 0.97 (Table 29.2) (Johnsonbabu 2011). The comparison is done with all the samples, first with that of seawater. It is to be noted that in samples of both the seasons and of different depths, sample 31 falls in the central part of the study region which is noted near the coast, also it has the closest correlation to seawater composition of the region (Palayar seawater). The pre-monsoon season shows salt precipitation along the pore spaces, and during the post-monsoon, the salts precipitated in these spaces are leached to the groundwater. This results in more correlation of this sample during post-monsoon to seawater. Hence, it is evident that the process altered the groundwater is not only due to the direct infiltration but also due to precipitation and dissolution of salts entrapped from seawater (Karmegam et al. 2010). Pre-monsoon season shows more extraction of groundwater along the coast. It is also evident that the location is subjected to backwater recharge during pre-monsoon period as there is less river water flow in Coleroon and the influence of seawater dominates in the river mouth (Chidambaram et al. 2008). The study also reveals that the shallow groundwater is more contaminated with seawater than the deeper aquifers, and it is more prominent during pre-monsoon than the post-monsoon.

29.10 Calculation of Percentage of Mixing of Seawater

The chemical compositions of groundwater and composition of seawater samples were compared in the coastal aquifers of Nagapattinam (Xue et al. 2000). The same samples of different seasons were selected to identify the mixing proportion in groundwater. This was done by using the following formula:

$$\text{SPRM 31} + \text{Sea Water composition } (\% \text{ in question}) \rightarrow \text{SPOM 31}$$

The sample SPRM 31 was attempted to mix with the seawater composition of the Palayar (Chidambaram et al. 2008) to obtain the composition of SPOM 31, as SPOM 31 has very good correlation to seawater. It was found that only 7–8% mixture of seawater with the SPRM 31 (Table 29.2) would result in the SPOM 31 composition. This post-monsoon sample shows higher correlation to that of the seawater composition, due to the dissolution of the precipitated salts during the pre-monsoon period.

29.11 Statistical Techniques

Multivariate statistical methods help to understand and identify the process of groundwater flow in complex aquifer systems (Farnham et al. 2003). The Pearson's correlation coefficient value ranges from +1 to −1, if the correlation coefficient value is near +1 is said to be perfect correlation. Values ranging between +0.75 and +1 resembles the high degree of correlation, similarly moderate degree of correlation for values between +0.25 and +0.75 and lower degree of correlation for the values between 0 and +0.25 (Olobaniyi and Owoyemi 2006).

In PRM, good correlation exists between Cl–Ca, Cl–Mg, Cl–Na, Cl–K, Cl–SO_4, Mg–Ca, Na–Ca, Mg, SO_4, and K–Ca (Table 29.3). Significant correlation of HCO_3–F, NO_3–Na, Cl, SO_4, SO_4^- Ca, and Mg indicates chemical weathering (Chidambaram et al. 2008). Most of the ions that are positively correlated with Cl^-, particularly Na^+, Mg^{2+}, K, and SO_4^{2-} (Table 29.3), indicate the same source of saline waters (Kim et al. 2003) and also leaching of secondary salts (Chidambaram et al. 2009; Prasanna et al. 2010a, b). It is also indicating the influence of evaporation processes, agricultural activities, poor drainage conditions, and marine sources on the groundwater system (Subba Rao et al. 2012).

Good to moderate correlation of Cl and SO_4 with Ca, Mg, Na, K is mainly due to the seawater intrusion (Singaraja et al. 2012), saltpan (Smith et al. 2004) in coastal region, and precipitation of secondary salts (Chidambaram et al. 2009). Good correlation between NO_3 and other ions in PRM indicates the anthropogenic influence. The negative correlation of pH with Mg^{2+} indicates ion exchange process (Chapelle and Knobel 1983).

Table 29.3 Correlation analysis of groundwater samples collected during PRM (after Singaraja 2014)

	pH	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	HCO_3^-	NO_3^-	PO_4^{3-}	F^-	SO_4^{2-}	H_4SiO_4
pH	1.00											
Ca^{2+}	−0.30	1.00										
Mg^{2+}	−0.28	0.75	1.00									
Na^+	−0.31	0.47	0.73	1.00								
K^+	−0.34	0.67	0.38	0.32	1.00							
Cl^-	−0.33	0.70	0.88	0.94	0.46	1.00						
HCO_3^-	−0.07	0.12	0.11	0.24	0.16	0.18	1.00					
NO_3^-	−0.18	0.05	0.17	0.39	0.20	0.32	0.13	1.00				
PO_4^{3-}	−0.10	0.00	−0.01	0.02	0.12	0.00	0.04	0.08	1.00			
F^-	0.21	−0.14	−0.08	−0.08	−0.10	−0.13	0.41	−0.06	−0.06	1.00		
SO_4^{2-}	−0.25	0.37	0.38	0.53	0.18	0.47	0.14	0.33	0.08	0.13	1.00	
H_4SiO_4	−0.05	0.17	0.10	−0.13	0.01	−0.03	−0.12	−0.08	−0.15	0.01	−0.04	1.00

29.12 Conclusion

Coast is considered to be important economy center where the populations are highly concentrated in these regions. It is the complex ecosystems and highly vulnerable to storms, cyclones, seawater intrusion, anthropogenic activities, and climatic changes. Various techniques are followed in this study to overcome the problems in coastal aquifers of Tamilnadu. In the hydrogeochemical techniques, piper plot suggests that samples that fall in Na–Cl facies is influenced by the seawater intrusion in the coastal aquifers of Pondicherry and Nagapattinam regions. Using ionic ratios and simpson classification, it is observed that the regions of Kalpakkam, Nagapattinam, and Thoothukudi district of Tamilnadu are affected by the saline water intrusion. The geophysical techniques which are carried out in Pondicherry region noted higher resistivity in deeper layers of Upper Cuddalore formations and lower resistivity in alluvial aquifers. The inverse trend between the d-excess and $\delta^{18}O$ indicates that kinetic evaporation of the water underwent before the recharge in Nagapattinam and Kalpakkam coast. Enrichment of stable isotopes also indicates the salt pan activities in coastal aquifers. In the study of climatic changes in coastal aquifers based on tritium, it explains that sub-modern water is noted to be fresh and modern water are saline in nature. Based on the saturation index of carbonate minerals, it is noted that they are near saturation to saturation state. In the percentage of mixing of seawater, it is observed that 7–8% mixes with groundwater in Nagapattinam district. In the statistical techniques, various ions like Na–Cl and $Cl–SO_4$ explains that saline water intrusion is due to natural and also due to human-induced processes. This study suggests the proper management plans that have to be implemented in order to solve these problems in coastal aquifers.

References

Aggarwal PK, Frohlich K, Kulkarni KM, Gourcy LL (2004) Stable isotope evidence for moisture sources in the Asian summer monsoon under present and past climate regimes. Geophys Res Lett 31:L08203

Chapelle FH, Knobel (1983) Groundwater geochemistry and calcite cementation of the Aquia aquifer in Southern Maryland. Water Resour 19(2):545–548

Chidambaram S, Ramanathan AL, Prasanna MV, Anandhan P, Srinivasamoorthy K, Vasudevan S (2007a) Identification of hydrogeochemically active regimes in ground waters of Erode district, Tamilnadu—a statistical approach. Asian J Water Environ Pollut 5(3):93–102

Chidambaram S, Prasanna MV, Vasu K, Shahul Hameed A, Unnikrishna Warrier C, Srinivasamoorthy K (2007b) Study on the stable isotope signatures in groundwater of Gadilam river basin, Tamilnadu, India. Indian J Geochem V 22(2):209–221

Chidambaram S, Ramanathan AL, Prasanna MV, Loganatan D, Badrinarayanan TS, Srinivasamoorthy K, Anandhan P (2008) Study on the impact of tsunami on shallow groundwater from portnova to pumpuhar, using geoelectrical technique—south east coast of India. Indian J Mar Sci 37(2):121–131

Chidambaram S, Senthil Kumar G, Prasanna MV, John Peter A, Ramanthan AL, Srinivasamoorthy K (2009) A study on the hydrogeology and hydrogeochemistry of groundwater from different depths in a coastal aquifer Annamalai Nagar Tamilnadu India. Environ Geol 57:59–73

Chidambaram S, Ramanathan AL, Prasanna MV, Karmegam U, Dheivanayagi V, Ramesh R, Johnsonbabu G, Premchander B, Manikandan S (2010) Study on the hydrogeochemical characteristics in groundwater, post- and pre- tsunami scenario, from Portnova to Pumpuhar, southeast coast of India. Environ Monit Assess 169(1):553–568

Chidambaram S, Tirumalesh K, Prasanna MV, Thilagavathi R, Pethaperumal S, Johnson Babu G, Paramaguru P (2014) Stable isotopic signatures for hydrogeochemical characterisation of ground water from Pondicherry to Nagapattinam, Tamil Nadu. In: Management of water, energy and bio-resources in the era of climate change: emerging issues and challenges. Springer, Berlin, pp 97–112

Clark ID, Fritz P (1997) Environmental isotopes in hydrogeology. Lewis Publishers, New York

Compton JS (1988) Degree of supersaturation and precipitation of organogenic dolomite. Geology (Boulder) 16:318–321

Drever IJ (1988) The geochemistry of natural waters, 2nd edn. Prentice Hall, Englewood Cliffs, p 388

Farnham IM, Johannesson KH, Singh AK, Hodge VF, Stetzenbach KJ (2003) Factor analytical approaches for evaluating groundwater trace element chemistry data. Anal Chim Acta 123–138

Gallagher DL, Dietrich AM, Reay WG, Hayes MC, Simmons GM Jr (1996) Ground water discharge of agricultural pesticides and nutrients to estuarine surface water. Ground Water Monit Rem 16(1):118–129

Gomez P, Garralón A, Buil B, Turrero MJ, Sánchez L, De La Cruz B (2006) Modeling of geochemical processes related to uranium mobilization in the groundwater of a uranium mine. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2005.06.024

Johnsonbabu G (2011) Hydrogeochemical study on coastal groundwaters in parts of Nagapattinam district. Ph.D. thesis, Annamalai University, India

Jones BF, Vengosh A, Rosenthal E, Yechieli Y (1999) Geochemical investigations. In: Seawater intrusion in coastal aquifers: concepts, methods, and practices. Kluwer, Dordrecht, pp 51–71

Karmegam U (2012) A study on the hydrogeochemical modeling of coastal aquifers in and around Kalpakkam. Unpublished Ph. D thesis, Department of Earth Sciences, Annamalai University, India

Karmegam U, Chidambaram S, Prasanna MV, Sasidhar P, Manikandan S, Johnsonbabu G, Dheivanayaki V, Paramaguru P, Manivannan R, Srinivasamoorthy K, Anandhan P (2010) An study on the mixing proportion in groundwater samples by using Piper diagram and Phreeqc model. Chin J Geochem 30:490–495

Kim JH, Yum BW, Kim RH, Koh DC, Cheong TJ, Lee J, Chang HW (2003) Application of cluster analysis for the hydrogeochemical factors of saline groundwater in Kimje, Korea. Geosci J 7(4):313–322

Kumar M, Ramanathan AL, Rao MS, Kumar B (2006) Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi. India Environ geology 50:1025–1039

Last WM (1990) Lacustrine dolomite—an overview of modern, Holocene, and Pleistocene occurrences. Earth Sci Rev 27:221–263

Mercado A (1985) The use of hydrogeochemical patterns in carbonate sand and sandstone aquifers to identify intrusion and flushing of saline water. Groundwater 23:635–645

Metcalf & Eddy Inc. (2000) Integrated aquifer management plan: final report. Gaza coastal aquifer management program, USAID Contract No. 294-C-00-99-00038-00

Mukherjee A, von Brömssen M, Scanlon BR, Bhattacharya P, Fryar AE, Hasan MA, Ahmed KM, Jacks G, Chatterjee D, Sracek O (2008) Hydrogeochemical comparison and effects of overlapping redox zones on groundwater arsenic near the western (Bhagirathi sub-basin, India) and eastern (Meghna sub-basin Bangladesh) of the Bengal basin. J Contam Hydrol 99:31–48

Olobaniyi SB, Owoyemi FB (2006) Characterization by factor analysis of the chemical facies of groundwater in the deltaic plain-sands aquifer of Warri, Western Niger Delta Nigeria. Afr J Sci Tech 7(1):73–81

Pethaperumal S (2010) Study on groundwater chemistry in the Pondicherry region. Ph.D. thesis, Annamalai University, India

Pethaperumal S, Chidambaram S, Prasanna MV, Verma VN, Balaji K, Ramesh R, Karmegam U, Paramaguru P (2008) A study on groundwater quality in the Pondicherry region. Eco-Chronicle 3(2):85–90

Piper AM (1953) A graphic procedure I the geo-chemical interpretation of water analysis. USGS Groundwater Note no. 12

Post VEA (2005) Fresh and saline groundwater interaction in coastal aquifers: is our technology ready for the problems ahead? Hydrogeol J 13:120–123

Prasanna MV, Chidambaram S, Pethaperumal S, Srinivasamoorthy K, John Peter A, Anandhan P, Vasanthavigar M (2008) Integrated geophysical and chemical study in the lower sub basin of Gadilam River, Tamilnadu, India. Environ Geosci 15(4):145–152

Prasanna MV, Chidambaram S, Shahul Hameed A, Srinivasamoorthy K (2010a) Study of evaluation of groundwater in Gadilam basin using hydrogeochemical and isotope data. Environ Monit Assess 168:63–90

Prasanna MV, Chidambaram S, Srinivasamoorthy K (2010b) Statistical analysis of the hydrogeochemical evolution of groundwater in hard and sedimentary aquifers system of Gadilam river basin, South India. J King Saud Univ Sci 22(3):133–145

Sanchez Martos F, Pulido Bosch A, Calaforra JM (1999) Hydrogeochemical processes in an arid region of Europe (Almeria, SE Spain). Appl Geochem 14:735–745

Sanchez Martos F, Pulido Bosch A, Molina Sanchez L, Vallejos Izquierdo A (2002) Identification of the origin of salinization in groundwater using minor ions (Lower Andarax, Southeast Spain). Sci Total Environ 297:43–58

Singaraja C (2014) A study on the geochemistry of groundwater in Tuticorin district of Tamil Nadu, India. Ph.D. thesis, Annamalai University, India

Sharp Z (2007) Principles of stable isotope geochemistry. Pearson Prentice Hall, New Jersey, p 344

Singaraja C, Chidambaram S, Anandhan P, Prasanna MV, Thivya C, Thilagavathi R (2012) A study on the status of fluoride ion in groundwater of coastal hard rock aquifers of south India. Arabian J Earth Sci 6:4167–4177

Singaraja C, Chidambaram S, Anandhan P, Prasanna MV, Thivya C, Thilagavathi R, Sarathidasan J (2013a) Hydrochemistry of groundwater in a coastal region and its repercussion on quality, a case study—Thoothukudi district, Tamilnadu, India. Arab J Geosci 7:939–950. https://doi.org/10.1007/s12517-012-0794-0

Singaraja C, Chidambaram S, Prasanna MV, Thivya C, Thilagavathi R (2013b) Statistical analysis of the hydrogeochemical evolution of groundwater in hard rock coastal aquifers of Thoothukudi district in Tamil Nadu, India. Environ Earth Sci. https://doi.org/10.1007/s12665-013-2453-5

Small C, Nicholls RJ (2003) A global analysis of human settlement in coastal zones. J Coast Res 19:584–599

Smith SJ, Andres R, Conception E, Lurz J (2004) Sulfur dioxide emissions: 1850–2000. JGCRI Report. PNNL-14537

Sprinkle CL (1989) Geochemistry of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama. USGS Professional Paper 1403-1

Stetzenbach KJ, Hodge VF, Guo C, Farnham IM, Johannesson KH (2001) Geochemical and statistical evidence of deep carbonate groundwater within overlying volcanic rock aquifers/aquitards of southern Neveda, USA. J Hydrol 243:254–271

Subba Rao N, Surya Rao P, Venktram Reddy G, Nagamani M, Vidyasagar G, Satyanarayana NL (2012) Chemical characteristics of groundwater and assessment of groundwater quality in Varaha River Basin, Visakhapatnam District, Andhra Pradesh, India. Environ Monit Assess 184:5189–5214

Thilagavathi R (2015) Hydrogeochemistry of organic carbon in groundwater of Pondicherry region. Ph.D. thesis, Annamalai University, India

Thilagavathi R, Chidambaram S, Prasanna MV, Thivya C, Singaraja C (2012) A study on groundwater geochemistry and water quality in layered aquifers system of Pondicherry region, southeast India. Appl Water Sci 2:253–269. https://doi.org/10.1007/s13201-012-0045-2

Thilagavathi R, Chidambaram S, Prasanna MV, Pethaperumal S (2013) A study on the interpretation of spontaneous potential and resistivity logs in layered aquifers sequence of Pondicherry Region, South India. Arabian J Geosci AJGS-D-13-00121

Thilagavathi R, Chidambaram S, Pethaperuamal S, Thivya C, Rao MS, Tirumalesh K, Prasanna MV (2016) An attempt to understand the behaviour of dissolved organic carbon in coastal aquifers of Pondicherry region, South India. Environ Earth Sci 75:235

Todd DK (1959) Ground water hydrology. Wiley, New York

Trusdell AH, Jones BF (1973) WATEQ: A computer program for calculating chemical equlibria of natural waters. J Res US Geol Surv 2(2):233–248

Vengosh A, Ben-Zvi A (1994) Formation of a salt plume in the coastal plain aquifer of Israel: the Be’er Toviyya region. J Hydrol 160:21–52

Vengosh A, Heumann KG, Juraski S, Kasher R (1994) Boron isotope application for tracing sources of contamination in groundwater. Environ Sci Technol 28(11):1968–1974

Vengosh A, Rosenthal E (1994) Saline groundwater in Israel: its bearing on the water crisis in the country. J Hydrol 156:389–430

Vengosh A, Gill J, Davisson ML, Hudson GB (2002) A multi isotope (B, Sr, O, H, and C) and age dating study of groundwater from Salinas Valley, California: hydrochemistry, dynamics, and contamination process. Water Resour Res 38(1):1–17

Xue YQ, Wu JC, Ye SJ, Zhang YX (2000) Hydrogeological and hydro geochemical studies for salt water intrusion on the South Coast of Laizhou Bay, China. Ground Water 38:38–45

Chapter 30
Groundwater System of Sundarbans (Basanti), West Bengal, India

Moritz Kopmann, Philip John Binning and Henrik Bregnhøj

Abstract In Basanti, a rural block in the Sundarbans, West Bengal, the water availability is vital for its inhabitants. Groundwater levels are decreasing, and a proper understanding of key factors influencing the water resource is required. In the following, a social review of Basanti is given followed by a geologic and hydrostratigraphic analysis. The main hydrologic flows, a water balance, and the trend of salinity in the groundwater are presented. Finally, available long- and short-term drawdown data of South 24 Parganas and Basanti to determine groundwater level and annual recharge trends. The assessment shows that Basanti's groundwater resource is under stress because of increased groundwater irrigation. The critical state of groundwater reservoirs increases the danger of saltwater intrusion and raises the need for mitigation strategies.

Keywords Groundwater level · Hydrostratigraphy · Saltwater intrusion

30.1 Introduction

The Bengal Delta Plain (BDP) is the world's largest fluvial, deltaic system and is drained by the Ganges, Meghna and Brahmaputra rivers (Alam et al. 2003; Dowling et al. 2003) (Chap. 1, Figs. 1.1, 1.3). The western part of the BDP covers West Bengal from Murshidabad over Nadia to North- and South 24 Parganas. (Mukherjee et al. 2007), see Fig. 30.1.

In North and South 24 Parganas, a project by the *Danish Association for Sustainable Development* (UBU) and a local community-based organization

---

M. Kopmann (✉)
Department of Environmental Engineering, TUM, Munich, Germany
e-mail: mkopmann07@gmail.com

P. J. Binning
DTU, Copenhagen, Denmark

H. Bregnhøj
COBL, University of Copenhagen, Copenhagen, Denmark

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_30

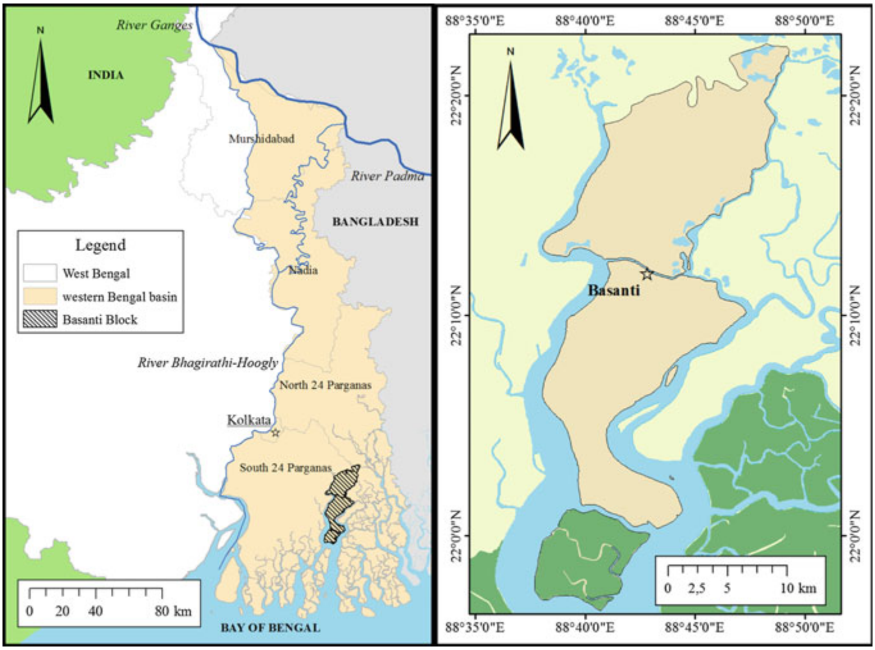


Fig. 30.1 Left: location of Basanti within the western Bengal basin, West Bengal. Right: map of Basanti. Black line illustrates the boundary of Basanti block

Joygopalpur Gram Vikash Kendra (JGVK) aims to improve the resilience to future climate and water-related problems of some rural communities (UBU 2015). One of the project's communities is in Basanti which is a development block in Canning subdivision of the district South 24 Parganas. Basanti block has a total area of 389 km^2 (measured by ArcGIS) and consists of three land parts: Basanti mainland, i.e. 46% of the total area; Basanti Island (41%); and an island of reserved forest (12%). The block is surrounded and drained by rivers Matla from the west and Bidyadhari from the east, flowing into the Bay of Bengal.

Currently, Basanti satisfies the needs of its growing population and irrigated agriculture mainly by means of groundwater of different qualities. Over the past years, the project's studies have shown that groundwater resources are becoming scarcer in the region and fear of water scarcity is increasing (UBU 2015).

Although West Bengal includes the rivers Ganges (81% of area), Brahmaputra (12%) and Subarnarekha (4%), the water availability in the southern districts is considered to be scarce (Bandyopadhyay et al. 2014; Sharma and Paithankar 2014). In the past, the increasing pollution of water streams made West Bengal's surface water, which includes large numbers of private and public ponds in the area, undrinkable. Harmful pathogenic microorganisms were a major reason for the water policy for West Bengal being shifted from surface water usage towards groundwater abstraction starting in the early 1970s. Subsequently, a high number of tube wells have been installed to meet agricultural and domestic water demands. However, strongly increasing pumping in West Bengal has put pressure on the whole freshwater resource (Mukherjee 2006; Winter et al. 1998). A previous regional scale groundwater modelling study of Michael and Voss (2009a) outlined a substantially changed shallow groundwater budget in the Bengal basin due to pumping. Based on Mukherjee et al. (2007), the impact on pumping led to the formation of cones of depression that have highly disturbed natural flow paths in all examined districts of the western Bengal basin, except the southern half of South 24 Parganas. Here, a flow reversal has developed with inflow from the Bay of Bengal leading to saltwater intrusion.

Future population growth with its resulting food and water demand is likely to increase the pressure on present water resources and will limit the availability of water downstream in Basanti (HDRCC 2009). The understanding of key influence factors on the groundwater resource is crucial in order to formulate sustainable management strategies to meet the increasing demand. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

30.2 Cultivation and Irrigation

Basanti block is governed by 13 local self-government organizations *Gram Panchayats* (GPs), which further comprise smaller villages (Ashur and Rasmussen 2012; GOWB 2012). In 2011, Basanti's total population was 336,717 with 70,818 families, i.e. about 5 persons per household. The ratio of male and female is 51/49, and 58% of the total population is literate (Census 2011).

In Basanti, agriculture is crucial for local people as it ensures food- and income security (Maharana 2016). People are mainly living of subsistence farming on small plots. The latest data from the agricultural block office in Basanti indicated a total cultivated area of 20,050 ha land, i.e. 0.29 ha/household (ABO 2016). It fits well with a recent socio-economic survey by Sharma and Chauhan (2014), where 350 households in Jharkhali GP had been interviewed resulting in an average land holding of 0.5 ha per household of which 70% is agricultural land, i.e. 0.35 ha per household. Our interviews confirm that households that own land grow as much as they can of mainly rice such as Aman, Aus or Boro paddy (see below).

The agricultural system in Basanti is based on two main cultivating seasons: the kharif or wet season (June–October), where the monsoon takes place, and the rabi or dry season (November–June) with only minor rainfall (Maharana 2016). In Basanti, agricultural fields are classified into single-cropped land and double/multi-cropped land (Maharana 2016; Subirdas 2014). Single-cropped land is cultivated with Aman paddy, whereas farmers with double-cropped fields grow Boro paddy in the additional rabi season. Small amounts of Aus paddy or vegetables are also cultivated (multi-cropped land). Based on information from local farmers, the various cultivation schemes are described in Table 30.1.

Generally, irrigation takes place only during the rabi/dry season with water sourced from freshwater canals, stored rainwater in ponds and tanks, and deep groundwater tube wells.

The calculation of tube well densities over the land surface of Basanti Island and mainland, i.e. 0.018 pumps/ha, in combination with the norm "3 ha of irrigated land per pump" (CGWB 2009b), led to an irrigated land area by groundwater of 1,845 ha. Moreover, the latest data from Khush (2016) describe a total irrigated land area for Boro paddy of 4,500 ha. The irrigated land area of vegetables varies seasonally from 280 to 880 ha (ABO 2016). After processing data of Agricultural Census (2011), the irrigated land area ratio for Boro paddy/vegetable was 84/16 in 2010 and thus led to an irrigated land area for vegetables of 857 ha. The resultant dry season irrigated land is therefore comprised of a total area of 5,357 ha, see Table 30.2.

However, trends in cultivation and irrigation are affecting the groundwater source in Basanti in terms of both quantity and quality.

In terms of quantity, Basanti's population has increased by 2.1% annually, based on population data of 2001 (278,592) and 2011 from Census (2011). In the last three decades, population pressure and the need for cultivatable land have driven partial deforestation in Basanti leaving only minor areas of forest, i.e. 680.6 ha (Samanta and Hazra 2012). Agricultural lands have also increased at the cost of tree cover, which is now found only on the borders of rivers and creeks (Das and Das 2016). According to GOWB (2012), the share of double-cropped cultivation in blocks of South 24 Parganas had been on average 16.2 and 21.2% between 2004–2006 and 2006–2009, respectively. In Table 30.2, we have estimated that irrigated areas in Basanti were roughly 27% in 2015. Irrigated areas in Basanti (mostly from surface water) have increased on average by 62% from the years 1995–2000 to 2005–2010 (Agricultural Census 2011).

Based on the Irrigation Department Basanti IDB (2016), the first groundwater irrigation pumps were installed by Basanti's farmers sometime between 2005 and

Table 30.1 Cultivation schemes of main crops in Basanti

Main crops	Cultivation period	Irrigation time	Harvest	Water sources	Total water demand (mm)[a]
Boro paddy	January–April	3 months	April	Groundwater, canals, ponds	1,000–1,750
Aus paddy	April–July	3 months	July	Rainfall, canals, ponds	400–450
Aman paddy	June–September	3 months	September	Rainfall	300–600
Vegetables	February–May/ October–January	3 months	May/ January	Rainfall, canals, ponds	100–500

[a] Total crop water demand was based on Guruprasad (2009), Harvey et al. (2006), Mishra (2013), Mitra et al. (2015), and Rudra (2007)

Table 30.2 Irrigated area (ha) by crop, season and water source

Season	Kharif/monsoon			Rabi/summer		
Cultivated crops	Aman paddy	Vegetables	Total	Boro paddy	Vegetables	Total
Irrigated area by GW	–	–	–	1,845	–	1,845
Irrigated area by SW	19,193	857	20,050	2,655	857	3,512
Total irrigated area	19,193	857	20,050	4,500[a]	857	5,357

GW groundwater, *SW* surface water. Aus paddy was not considered as it is only less cultivated. Shown values based on own calculations and [a]Kush (2016)

2009, about 10 years ago. Main drivers have been the additional income from dry season cultivation as well as secured water availability for dry season cultivation as the occurrence of rainfall is unstable and inland freshwater ponds/reservoirs are sometimes subject to saltwater intrusion from flooding. In order to pay for the expensive installation of an irrigation pump, people tend to migrate to bigger cities for higher income and send money back to their rural communities. However, the lack of access to electricity is the main reason for having only small irrigation facilities and resultant minor but increasing dry season cultivation (Danda and Sriskanthan 2011; HDRCC 2009).

As can be seen from Table 30.2, it shows that today less than 10% of agricultural land is irrigated by groundwater, and there is thus a potential demand of about 10 times as much.

In terms of quality, the groundwater may be affected by increasing saltwater aquaculture. Between 1986 and 2004, 3,737 ha of aquaculture had been added in total in Basanti out of which 69% are from former paddy fields (Chopra et al. 2006). High demand, frequent cyclones and seasonal flooding causing embankment breaches and saltwater flooding have led to the increased transformation of agriculture fields. According to Das and Das (2016), population density has also influenced this transformation and indicated that annually for every 1% increase in population per km^2 a corresponding conversion of 0.4% of agricultural land to aquaculture takes place.

From an economic point of view, aquaculture can be attractive. One study in Jharkhali showed that the net income was Rs. 10,600 per household, whereas households doing agriculture only earned Rs 6,607/year/ha (Sharma and Chauhan 2014).

30.3 Geology and Hydrostratigraphy

30.3.1 Geology of the Western Bengal Basin

In Basanti, water resources are vital for its inhabitants. The community block lies within a complex hydrogeological region characterized by depositional processes, tidal fluctuations and a heterogenic subsurface of variable sediments. The topography of the western Bengal basin is flat and decreases southward with a gradient of only ~0.1 m/km from a maximum elevation of 35 m in the northern district Murshidabad (Mukherjee et al. 2009). The vegetation is characterized by a monotonous surface and occasionally crossed by channels and rivers (Bandyopadhyay et al. 2014; Sharma and Paithankar 2014). The subsurface consists of alluvial formations of sand and gravel, representing the main aquifer (Rajmohan and Prathapar 2013; Roy 2015). From the southern part of South 24 Parganas up to the Sundarbans, the subsurface consists of quaternary deltaic sediments such as clay, silt, gravel, sand of various grades which are underlain by a Tertiary alluvium (CGWB 2009a). In Basanti, the first two meter of topsoil is characterized by an average and maximum clay fraction of 27 and 40%, respectively (Bandyopadhyay et al. 2003). It is similar to found soil properties in the database of HWSD (2012) indicating fractions of clay (27–40%), sand (25%) and silt (35%).

30.3.2 Hydrostratigraphy in the Western Bengal Basin

Due to depositional processes in the delta of Ganges-Brahmaputra, a granular zone under unconfined conditions, called Golden Bengal aquifer, is formed over the Murshidabad aquitard with an initial thickness of 150–250 m in the district of Murshidabad and Nadia, see Fig. 30.2. It acts as a recharge zone for confined, deeper aquifers farther south. From North 24 Parganas, a top clay layer of up to 60 mbgl extends south to Kolkata and continues with 12–25 mbgl towards southern South 24 Parganas. This surficial aquitard substantially reduces direct rainfall recharge into the aquifers below and also protects the aquifer from surface water recharge. From latitude 22.7°N (in the vicinity of Kolkata), the Ichamati-Bhagirathi aquitard spreads southward at a depth of 150 mbgl with an initial thickness of 20–30 m and increases to 50–60 m farther south. It divides the main aquifer into a shallow and deeper aquifer (Mukherjee 2006; Sharma and Paithankar 2014). Additionally, alternating sequences of sand and clay layers of different thicknesses occur in the coastal areas down to a depth of about 300 mbgl (Pal and Mukherjee 2009; Rajmohan and Prathapar 2013; Roy 2015) (Fig. 30.2).

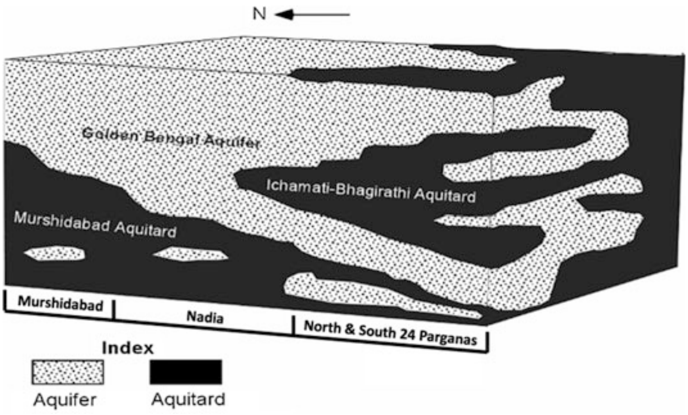


Fig. 30.2 Conceptual block model showing the possible hydrostratigraphy of the western Bengal basin. An edited version of Mukherjee (2006)

30.3.3 Hydrostratigraphy of Basanti's Subsurface

The aquifer–aquitard framework of Basanti was analysed by using gathered borehole log data from a local driller and Dr. Abhijit Mukherjee. In total, 32 lithologs of Basanti's subsurface were collected having depths of 144–432 mbgl. The lithologs contained detailed information about composition and texture of subsurface sediment samples that were collected every 3 m along the borehole. From a hydrogeological point of view, layers of fine sand were considered as aquifer whereas layers of clay, sandstone and poli form aquitards. Poli is a powdery sediment of very fine sand and silt, and sandstone is a sedimentary rock type (Mukherjee 2016; Naskar 2016).

Based on collected lithologs, a hydrostratigraphic model of Basanti was developed by the geologic modelling software GeoScene3D (I-GIS 2015). Thereby, subsurface layers were interpolated by a 2D "Inverse Distance Weighting" algorithm.

In Fig. 30.3, the N–S profile indicates the presence of alternating sequences of clay and sand layers which are in accordance with studies by Mukherjee (2006). In total, five potential aquifers and five aquitards varying in thickness were discovered in the subsurface. A similar number of aquifers and aquitards were also found in all East–West profiles (not shown). The top is marked by a 15–30 m thick clay layer present throughout Basanti. The first aquifer layer has an average thickness of 15 m and is constantly enclosed by an upper and a lower clay layer. Also, connections between aquifers occur and are observed between the second and the third aquifer in the North–South profile. Both profiles indicate the largest aquifer in a depth range between 260 and 320 mbgl.

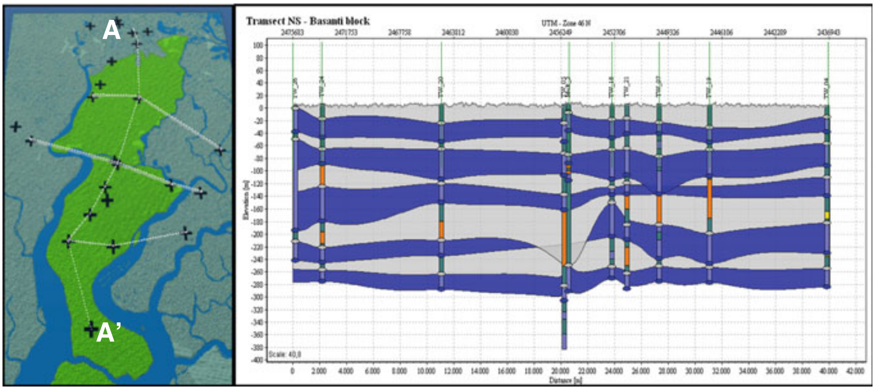


Fig. 30.3 Left: layout of Basanti. Crosses indicate the location of lithologs. Right: A–A′ north-south (NS) profile of Basanti block. Layer colours: grey = aquitard, blue = aquifer. The colour of lithologs: dark gray = clay, light blue = fine sand, orange = very fine sand and silt

30.3.4 Aquifer Response Analysis

Tidally driven rivers surround Basanti and may be connected to the aquifer system below. Tide waves can communicate with water pressures below clay layers by changes of weight on top of the aquitard skeleton (called effective stress). The resulting wave migration from loading and unloading leads to a response of water levels in tube wells installed in the aquifer (Voss 2016). Shallow and deep aquifer systems in the western Bengal basin are likely to be connected with each other in some areas due to cross-cuttings (Mukherjee et al. 2007). Moreover, representative aquifer tests for the Bengal basin, performed by the British Geological Survey in Bangladesh, reported a leaky confined response on a short-term basis, whereas showed unconfined or semi-confined behaviour for longer periods (i.e. months) (BGS and DPHE 2001).

By means of a field study, the interaction of aquifers with the top surface was analysed from short-term direct water level measurements at tide gauges (TG), nearby hand pumps (HP), as well as, irrigation pumps (IG) in Bermajur I and Goranbose. The measurements were taken every 30 min. The aim was to point out possible aquifer responses to tidal waves and thus detect the existence of hydraulic connections between the top and the deep aquifers.

The measured drawdowns in Basanti area follow the movement of river heads and show direct response to changes in river head over time with a certain attenuation of the river amplitude, see Fig. 30.4.

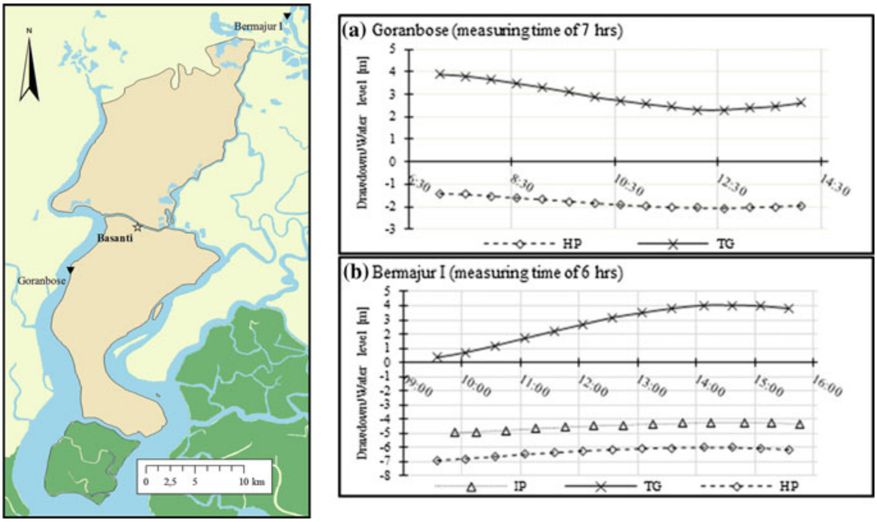


Fig. 30.4 Left: locations of aquifer-river-tests. Measured drawdown/water levels in **a** Goranbose and **b** Bermajur 1. Water levels of HP and IP are corrected to ground level

In another approach, the response of measured water levels was evaluated by a method of Townley which efficiently computes analytical solutions for periodic flow and gives insight into spatial variations of amplitudes of head fluctuations (Townley 1995). By adjusting the storage coefficient S_{fitted} and the aquifer transmissivity T_{fitted}, the degree of confinement of present aquifers in the subsurface can be determined. The resulting amplitude was plotted in MATLAB and fitted to measured water heads. The fitted storativity S_{fitted} ranged from 0.002 up to 0.012 thus showing confined/semi-confined behaviour. The resulting specific storage accounted for values of dense sand/sandy gravel with a mean value of 0.00038 l/m. Moreover, a low transmissivity T_{fitted} of 240–768 m^2/day may demonstrate slow groundwater flows in the subsurface due to smaller interconnected pore spaces in very fine and dense sand sediments. The hydraulic conductivity was determined to range between 10 and 21 m/day, which is equivalent with very fine sand to sand. Finally, an aquifer diffusivity from 10,286 to 160,000 m^2/day and a non-dimensional response time of maximal 1.05 indicate a quick response of the aquifers to the occurring flood wave from the river. All values showed good correlations to groundwater flow model studies of Michael and Voss (2009b) and Mukherjee et al. (2007).

30.4 Flow of Natural Water Resources

30.4.1 Character of Groundwater Flow in the Western Bengal Basin

The depositional history of the BDP has formed a complicated inter-layering of coarse and fine-grained sediments in the delta which resulted in an equally complex groundwater flow (Dowling et al. 2003). According to Ravenscroft et al. (2005), groundwater flow occurs at three distinct scales. On the village scale, the local flow system predominantly discharges groundwater only several kilometres from recharge zones and has residence times in the order of decades. Groundwater flows on an intermediate scale and basin/regional scale have lateral flow paths around 10 km and up to hundreds of kilometres, respectively. Intermediate and regional scale flows likely remain undisturbed from anthropogenic influences and have groundwater residence times of 10^2–10^3 and greater than 10^4 years, respectively (Harvey et al. 2006).

According to Mukherjee (2009), regional groundwater flow occurs from the Ganges southward to the Bay of Bengal, see Fig. 30.5. Despite a low natural gradient, the reduction in effective vertical hydraulic conductivity by the layering of fine and coarse sediments makes large-scale semi-regional and regional flow systems at depths of 100 m and greater possible (Michael and Voss 2009a). At the regional scale, the Ganges area and several wetlands, e.g. those in the east of Kolkata and those spread over the western Bengal basin, act as recharge zones for the southern areas. Previous regional flow modelling studies suggested that vertical recharge and discharge of water at depths below 200 m are minimal. For the Bengal basin, Michael and Voss (2009a) proposed that 95% of surface recharge flows past 10 mbgl, 7% passes 100 mbgl and only 2% reaches 350 mbgl. The low vertical recharge and outflow are synonymous with relatively long residence times and thus negligible flushing (Mukherjee 2009).

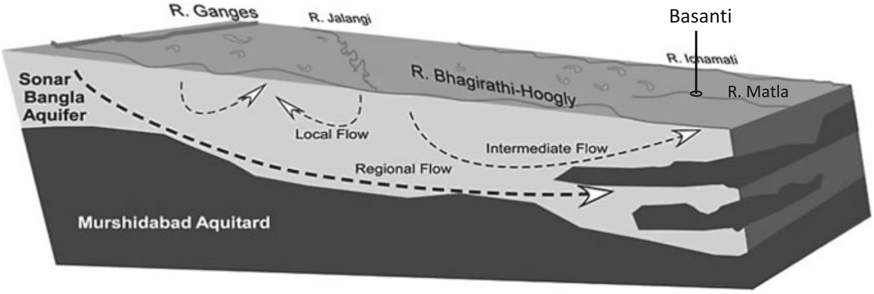


Fig. 30.5 Conceptual hydrostratigraphy and groundwater flow of the western Bengal basin. An edited version of Mukherjee (2009)

30.4.2 The Influence of Saltwater

In general, aquifers in the BDP area are highly productive as the water table is within 15 mbgl (Mukherjee et al. 2007). But the possibility of saltwater intrusion is high in coastal regions. Freshwater recharge is essential for maintaining groundwater levels to prevent saltwater intrusion into the aquifer. However, natural heterogeneity in the subsurface and extensive pumping may diminish the effect and raise the danger of saltwater intrusion (Mukherjee 2016). According to Mukherjee et al. (2007), Mukherjee (2016), the multiple clay layers in the delta of the western Bengal basin subdivide the aquifer into fresh-brackish-freshwater aquifers, and form a vertically bell-shaped saltwater intrusion, see Fig. 30.6.

Groundwater flows are high near the surface and may prevent saltwater from intrusion. High vertical recharge, i.e. 95% of surface recharge (Michael and Voss 2009a) and evidence presented by Mukherjee (2016) and Nasker (2016), suggests that the top aquifer is likely to contain freshwater. In intermediate aquifers, high heterogeneity and partly disconnected aquifers may have resulted in a deceleration of groundwater flow. The low flows through these intermediate layers may have resulted in saltwater intrusion (Mukherjee 2016). Additional evidence was obtained from local drillers who reported the presence of brackish water layers at depths between 50 and 250 mbgl. Although flow is low in the bottom aquifer, freshwater pressure from total water mass extending landward to the recharge zones is high and has the same effect as flows in the top aquifer. Here, the bottom aquifer (260–320 mbgl) contains freshwater. According to Mukherjee (2016), freshwater can only be extracted from a maximum depth of 350 mbgl, and everything deeper is reportedly brackish water.

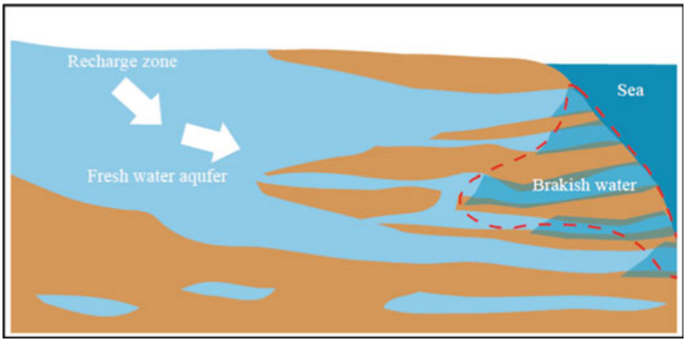


Fig. 30.6 Conceptual map of fresh- and saltwater interaction in the western Bengal basin. Not to scale

30.4.2.1 Trend in Electronic Conductivity on Basanti Island

Salinity is the most critical water quality parameter for the region and levels are quite high in some places because of salt water intrusion. Groundwater salinity was analysed by electric conductivity measurements on Basanti Island. Measurements from a field study in April/May 2016 were compared with previous data collected by Ashur and Rasmussen (2012) in July/August 2012. The locations, as well as the interpolated distribution of results, are shown in Fig. 30.7.

The field study measured the electrical conductivity of samples collected from hand pumps which are installed in the bottom aquifer at depths of 280–320 mbgl. Measurements showed that the conductivity varied between 1,000 and 1,400 µS/cm. According to Agriculture Victoria (2015), good drinking water has a conductivity between 0 and 800 µS/cm but water having 800–2,500 µS/cm can still be consumed by humans. A comparison with measurements by Ashur and Rasmussen (2012) indicated only minor changes in electric conductivity of less than ±200 µS/cm over the past four years, indicating that significant saltwater intrusion has not occurred in the deep aquifer over the four year period.

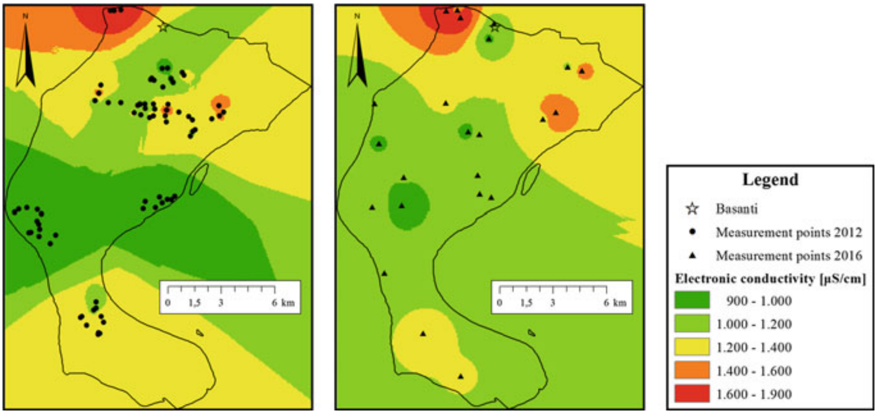


Fig. 30.7 Electrical conductivity (µS/cm) on Basanti Island at depths of 280–320 mbgl mapped using borehole measurement data and the inverse distance weighted interpolation method in ArcGIS (ESRI 2012). Left: measurements taken July/August 2012 by Ashur and Rasmussen (2012). Right: measurements taken April/May 2016

30.4.3 Hydrologic Cycle of Basanti

The climate of the coastal region is warm and hot (Falkenmark and Chapman 1989), with an average monthly temperature varying from a maximum of 38 °C in June to a minimum of 13.5 °C in January (Harris et al. 2014). The relative humidity ranges between 62 and 88% (Ashur and Rasmussen 2012). The seasonal climate in Basanti is driven by an annual southwest monsoon from June until September/October, i.e. 4–5 months (CGWB 2009a; Mukherjee 2006; Prasari 2011). Based on monthly climate observations from 2001 to 2015, the monsoonal period accounted for approximately 85% of the annual, average precipitation of 1800 mm. Residual rainfall is distributed over post-monsoon (2%), from November until December, and pre-monsoon (13%), from January until May, see Fig. 30.8. Due to high seasonal fluctuations, rainfall peaks of 500–700 mm/month can occur during monsoon season (Harris et al. 2014; JGVK 2016).

The South Asian monsoon governs the natural hydrology of the Bengal basin affecting surface- and groundwater flow dynamics (Michael and Voss 2009a), see Fig. 30.9.

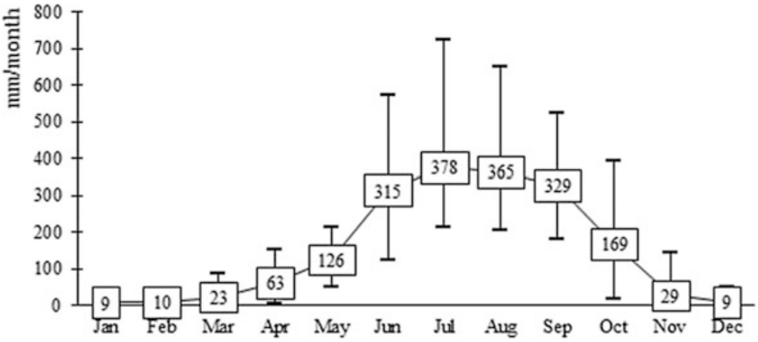


Fig. 30.8 Average annual rainfall distribution over Basanti include maximum/minimum fluctuations

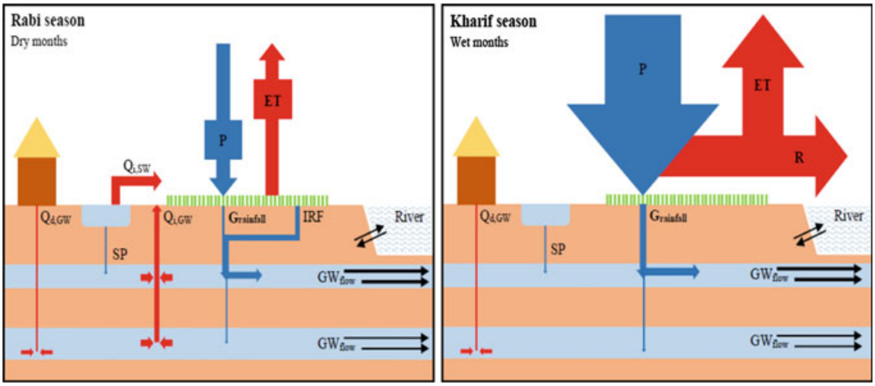


Fig. 30.9 Water flows in the dry Rabi season (left) and wet Kharif season (right). Water flows coloured in blue/red/black indicate inflow/outflow/no data of water volumes. Active flow arrows are *only as indications* sized according to their share of total rainfall. GW_{flow} groundwater flow in the aquifers, *SP* seepage and *IRF* irrigation return flow

A water balance can be written as Eq. (30.1), where input rainfall P is balanced by outputs in the form of actual evapotranspiration ET, annual (net) recharge G_{rainfall} and surface runoff R:

$$P = \text{ET} + G_{\text{rainfall}} + R + \Delta S \tag{30.1}$$

Some assumptions on meteorological parameters are needed to estimate the water outflows. By applying the methods of Malmstrom (1969) and Pike (1964), actual evapotranspiration ET is accounted for 58.5% of annual precipitation P, synonymous to studies of Mishra (2013), Mukherjee et al. (2007), and CSIRO (2014). As Basanti's topography has a low gradient, recharge rate G_{rainfall} takes over as a primary controlling factor for groundwater flow in the top aquifer (Mukherjee et al. 2007). Basanti's topsoil is classified as light clay with poor drainage characteristics (HWSD 2012). This soil type is dominant along the West Bengal coast and extends eastward to Bangladesh. Based on reports in the Purba and Paschim district (west of Basanti) by Mitra et al. (2015) and in tidal regions southwest of Bangladesh by Shamsudduha et al. (2011), a recharge-rainfall ratio of 7% was assumed. Over a long-time period, the soil storage changes ΔS in Eq. (30.1) are zero and surface runoff R can be estimated to account for 34.5% of the mean annual rainfall which is similar to studies of Shamsudduha et al. (2011) and Michael and Voss (2009a) stating 20–40%. Horizontal groundwater flow is supposed to decrease by depth. Both the influence of horizontal groundwater flow below Basanti and water exchanges with the river are unknown and need to be studied in future.

30.4.4 Water Supply

For drinking water, 68.5% of Basanti's residents depend on hand/suction pumps and 22.7% are supplied by wells with electric submersible pumps. The remaining population, i.e. 8.8%, obtains tap water from treated and untreated surface water sources (Agricultural Census 2011). According to Sahu et al. (2013), Ashur and Rasmussen (2012) and personal interviews with locals, a domestic water consumption rate of 10 l/capita/day can be applied to the area in 24-Parganas (North and South) and Basanti resulting in an annual domestic water consumption $Q_{d,GW}$ of 1.4 million m^3/year in 2016 (with 372,072 residents) (Kopmann 2016).

Irrigation pumps extract brackish water from approximately 150–200 mbgl, whereas domestic hand pumps are placed at depths of 280–320 mbgl in freshwater reservoirs (Naskar 2016; UBU 2015). Since 2012/2013, an increasing number of irrigation tube wells have been installed at depths of $\sim$300 mbgl in order to increase water quality and thus cultivation yields. In general, irrigation tube wells in Basanti are driven by either electric or diesel pumps with capacities of up to 62 m^3/h (Kopmann 2016; Maharana 2016). The average duration of irrigation pumping is 10 h/day over an average irrigation period of three months for Boro paddy (30 days/month). By including a pump efficiency of 80% due to capacity reductions from power cuts, the groundwater irrigation volume $Q_{i,GW}$ of 615 pumps can be estimated to be 27.4 million m^3/year. In another approach, the water demand of crops of Boro paddy and vegetables in the dry season can be used to estimate irrigated water use. Based on Table 30.2, the water demand of these crops was estimated to be 15,000 m^3/(ha * irrigated period) and 4,000 m^3/(ha * period), respectively. Employing the estimated irrigated area of Boro paddy ($A_{GW,Boro}$), a groundwater withdrawal of 27.6 million m^3/year is calculated and thus, similar to the aforementioned irrigation discharge.

These results show that groundwater pumping for irrigation purposes has risen to a level 20 times higher than domestic consumption within the last 10–15 years.

Surface water from nearby canals and ponds is also used for irrigation, washing and bathing. Surface water consumption for irrigation purposes was calculated by multiplying surface water irrigated areas by the associated total water demands of Boro paddy and vegetables. For the dry period, the resultant surface water discharge $Q_{i,SW}$ of Boro paddy and vegetables were 39.8 and 5.7 million m^3, respectively. Available surface water resources are limited because water from canals and ponds is either abstracted for irrigation, seeped through the bottom layer, evaporated or polluted by saltwater.

30.5 Trend Analysis of Groundwater Levels

30.5.1 Short-Term Trend in Basanti and South 24 Parganas

In the entire basin, pumping combined with the region's monsoonal climate is the principal controls on groundwater levels (Michael and Voss 2009a). Short-term analysis of drawdown data from Basanti Island can be used to detect the aquifer recharge behaviour in the region. The data describes monthly drawdown measurements of 20 hand pumps, taken by JGVK staff between 2015 and 2016, and covers 75% of Basanti Island, i.e. Jyotishpur, Bharatgarh, Nafarganj and Jharkhali GPs, see Fig. 30.10.

The number of irrigation tube wells found in Jharkhali, Nafarganj, Bharatgarh and Jyotishpur is 1, 22, 34 and 161, respectively. The majority of domestic and irrigation pumps are installed between 260 and 320 m, which is the range of Basanti's largest and deepest freshwater aquifer.

Drawdown in the area is high in the summer period with water levels increasing to the previous year's level with the monsoonal period, see Fig. 30.11. The water storage tends to be refilled from April until the onset of pumping in December/ January. Moreover, the gram panchayats Jotishpur, Bharatgarh and Nafarganj showed higher annual groundwater variation than Jharkhali. This higher variation can be explained by a greater number of tube wells in the gram panchayats. The annual recovery of groundwater levels can be attributed to several factors. Firstly, increased pumping leads to increased vertical gradients which may lead to increased recharge. Secondly, groundwater depletion also increases horizontal gradients

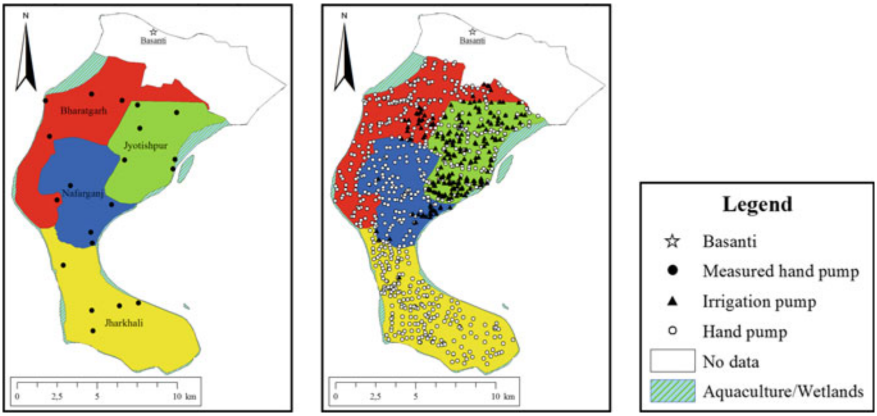


Fig. 30.10 Left: locations of measured hand pumps in Basanti Island. Right: distribution of hand- and irrigation pumps over parts of Basanti Island. Map produced using raw data provided by JGVK

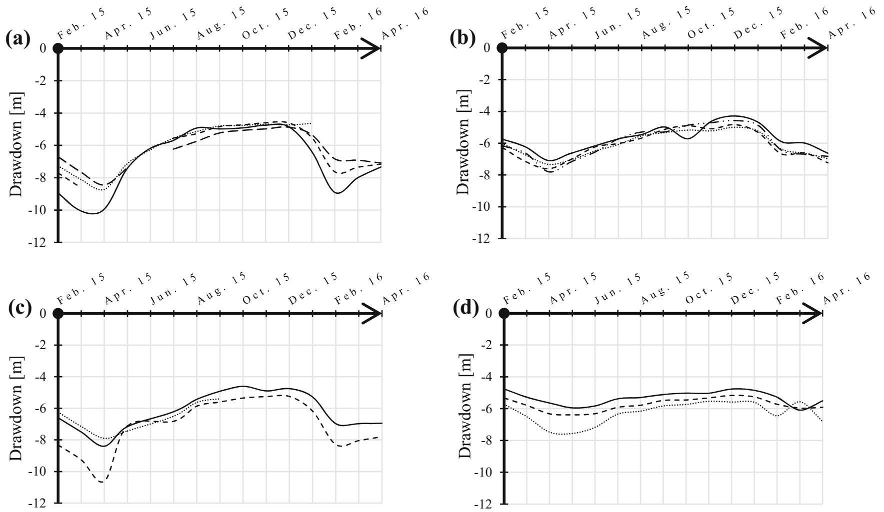


Fig. 30.11 Water head development in **a** Jyotishpur (4× HP), **b** Nafarganj (4× HP), **c** Bharatgarh (3× HP) and **d** Jharkhali (3× HP) from February 2015 to April 2016. Obtained drawdown data are not corrected to the land surface. Drawdowns are measured from tube well aperture to water table

causing increased regional groundwater flow to Basanti. Finally, local groundwater depletion increases infiltration to the aquifers from the delta river systems. These three water inputs are similar to current groundwater withdrawals leading to an annual recovery of groundwater levels each year. However, surface water inputs from delta rivers are often brackish, leading to a risk of increased groundwater salinity.

On a regional scale, water level distributions throughout South 24 Parganas can be analysed to determine annual fluctuations and the direction of groundwater flow. For this purpose, quarterly water level data from 2013 from the Water Resources Information System of India WRIS (2015) was examined. Only locations were used where water level data were available over a longer measurement period, i.e. 19 years. By subtracting obtained water level data from a processed 30 × 30 m m DEM of South 24 Parganas (Jarvis et al. 2008), water head distributions above mean sea level (a.m.s.l) for January, March/April, August, and November 2013 were created by IDW interpolation in ArcGIS (ESRI 2012), see Fig. 30.12.

Results indicate a south-eastward hydraulic gradient leading to a groundwater flow from Kolkata to Basanti area. The gradient is present throughout the year, increasing in dry months and decreasing in wet months. Moreover, groundwater levels show high fluctuations in the course of the year, especially in the south-eastern areas. In wet months, groundwater heads increased suggesting that

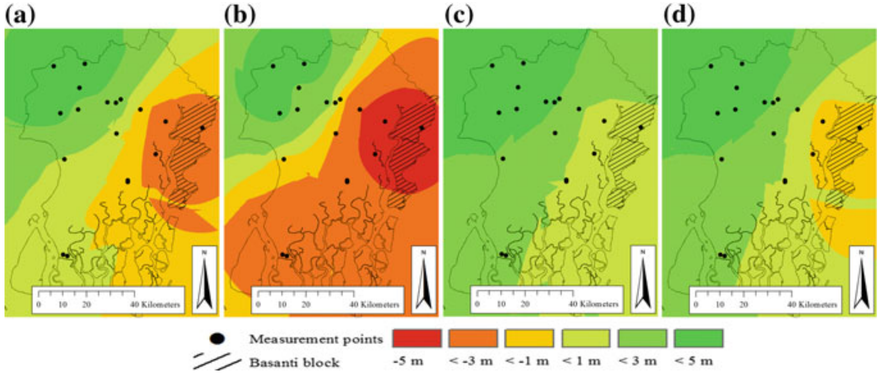


Fig. 30.12 Water level (a.m.s.l) distribution over South 24 Parganas in **a** January, **b** April, **c** August and **d** November 2013

recharge occurs in the area. Interpolated water levels of Basanti region were negative from November until March, with March being worst. Negative head values may indicate overuse of groundwater resources.

30.5.2 *Long-Term Trend in South 24 Parganas*

High pressure on the water resource in the Bengal basin was also suggested by a gravimetric study of the lower Ganges basin by Khan et al. (2013). Khan et al. (2013) analysed data from environmental satellite (ENVISAT) mission, as well as, microgravity data from Gravity Recovery and Climate Experiment (GRACE) mission and observed a decrease in the equivalent water thickness, which includes groundwater-, soil moisture- and surface water storage, between the year 2003 and 2007. The decreasing net water storage is synonymous with a trend of total water depletion (Khan et al. 2013). As the lower Ganges Basin is the major draining system for coastal areas, it may affect the situation downstream and lead to smaller inflows to the Basanti area.

To examine long-term trends in water storage, quarterly water level measurements in South 24 Parganas from 1996 until 2014 (≈19 years) are shown in Fig. 30.13. In the figure, the district was separated along the groundwater flow into four zones between Kolkata and Basanti, i.e. Kolkata region, Northwest South 24 Parganas (S24P), Central S24P and Southeast S24P.

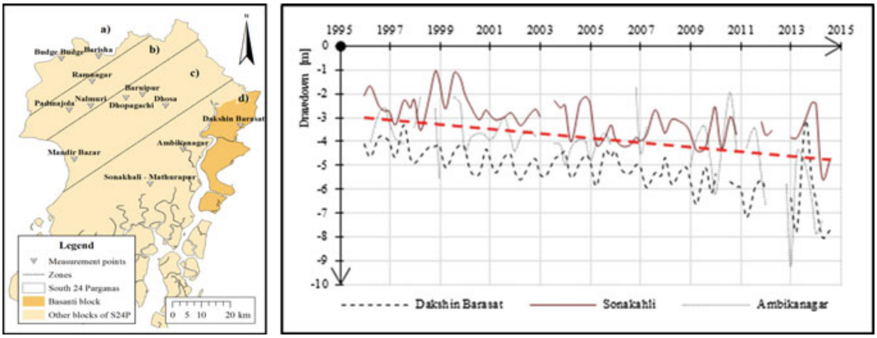


Fig. 30.13 Left: selected measurement zones for analysis. (**a**–**d**) Illustrate chosen zones. **a** Kolkata region. **b** Northwest S24P. **c** Central S24P. **d** Southeast 24P. Right: water head development in the zone SE South 24 Parganas (**d**) from 1996 to 2014. Dashed red line indicates the long-term trend of water tables

The occurrence of water trend decline is dependent on the distance to Kolkata region. No decline was found in Kolkata region (a). A decrease in water levels of 0.25 m per year from 2009 and 0.6 m per year by from 2006 was found in northwest S24P (b) and Central S24P (c), respectively. In the most southern-east zone, i.e. Basanti area (d), measurements recorded a steady decline of 0.1 m per year in the 19 year period. The south-eastern decline may have several causes: first, in the last decades, there has been a large increase in the installation of tube wells. Moreover, regional groundwater inflow may have declined as a result of decreases in the net water storage in the lower Ganges region.

To conclude, deep groundwater storage in Basanti region is annually replenished but insufficiently to stop a long-term decline in water levels. This long-term decline may affect future groundwater supplies in Basanti. A further decline in water levels will have severe consequences by increasing saltwater intrusion in the villages downstream.

30.6 Mitigation Strategies to Reduce Stress on Groundwater Resource

Groundwater depletion is most likely due to increased demand, mainly from expanding irrigation practices. In Basanti, irrigation is 95% of total groundwater withdrawal and groundwater irrigation is 37.7% of the total dry period irrigation. In the following, two possible strategies are suggested: a change in the cropping pattern and the use of surface water.

The dominating summer crop is Boro paddy, i.e. 84%, and consumes three times the amount of water than for an equivalent vegetable cultivation. An alternative cropping pattern could benefit both groundwater resources and the farmer by

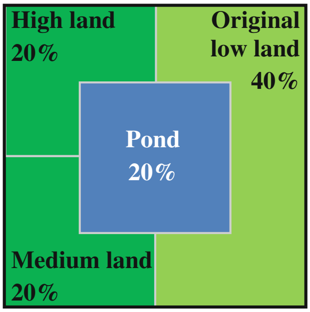


Fig. 30.14 Advanced pond farming scheme (CSSRI 2016)

increasing their income (Sudansu 2016). An adjustment of cropping patterns only requires a change of seeds and land preparation; no further investments need be made. Despite saline soil conditions, a variety of vegetables can be cultivated such as bitter guard, tomato, cucumber, sunflower, cotton, beetroot and spinach (Bhandari 2016). As farmers in the Sundarbans region used to cultivate paddy, lack of knowledge about growing alternatives, awareness and teaching programs have been introduced by several NGO's (Maharana 2016). These programs may lead farmers to rethink and to make changes in their cultivation patterns and thus reduce the pressure on the groundwater.

Moreover, introducing new techniques, e.g. in multiple crop cultivation and diversification through land shaping, to the farmers may reduce groundwater irrigation demand. The advanced pond farming scheme improves productivity and runoff by partly raising the land. A pond covering 20% of an area is excavated. The dugout material is used to elevate 20% of the area by 1 m into highland and 20% of the area by 0.4 m into medium land. About 40% of the area remains on the original level (original lowland), see Fig. 30.14.

The rise in land into medium and highland benefits agricultural productivity due to better runoff towards lowland in the monsoon season and less salinity in the dry season. Better runoff also prevents water logging and allows growth of vegetables on the highland, even in the monsoon season. As the growth of vegetables is more profitable and less water intensive, the amount of surface water from the pond would be sufficient for irrigation purposes in the dry season (CSSRI 2016).

30.7 Conclusion

Groundwater resources in Basanti are in a critical state due to high stress. Irrigation is the major groundwater demand and is expected to increase in the future, worsening the situation. Despite replenishment by recharge and groundwater flow towards Basanti, long-term water levels have indicated decreasing groundwater levels in the study area over the past 19 years. Lower groundwater levels raise the danger of saltwater intrusion. Water availability in the top aquifers is higher because recharge is high with the onset of monsoon. However, the deep aquifer is dependent on a deep vertical recharge and pumped water demand is similar to or exceeds inflows in the dry months. Future research on saltwater intrusion including regular monitoring of electric conductivity throughout Basanti is suggested. Finally, regional management strategies that decrease groundwater withdrawals and mitigate pressures on deep aquifer resources must be enacted.

Acknowledgements We are very grateful for the support provided by JGVK and its staff, including transportation, planning meetings with local people and for arranging various measurement sites.

We would also like to acknowledge Dr. Abhijit Mukherjee, Assistant Professor in the Department of Geology and Geophysics at the Indian Institute of Technology Kharagpur, West Bengal, who assisted in discussions of the hydrogeology of the western Bengal basin. The drilling contractor Mihir Naskar provided most of the borehole lithologs and thus made a hydrostratigraphic model possible.

Finally, we would like to acknowledge the people of Basanti for their assistance with the field work.

References

ABO Agricultural Block Office (2016) Irrigation and cultivated area of Basanti [Interview]. Basanti, West Bengal, India, 15 June 2016

Agricultural Census (2011) Agricultural census database [Online], 2011. http://agcensus.dacnet.nic.in/, 21 Mar 2016

Agriculture Victoria (2015) Agriculture Victoria [Online], 17 Nov 2015. http://agriculture.vic.gov.au/agriculture/farm-management/soil-and-water/salinity/measuring-the-salinity-of-water, 23 June 2016

Alam M, Curray J, Chowdhury M, Gani M (2003) An overview of the sedimentary geology of the Bengal Basin in relation to the regional tectonic framework and basin-fill history. Sediment Geol 155(3):179–208

Ashur HA, Rasmussen MN (2012) Water resources availability on the island of Basanti in West Bengal [Report/Bachelor's Thesis (not published)]. Technical University of Denmark, Department of Environmental Engineering, Kongens Lynby, Copenhagen, Denmark

Bandyopadhyay BK, Maji B, Sen HS, Tyagi NK (2003) Coastal Soils of West Bengal—Their nature, distribution and characteristics, vol Bulletin No. 1/2003. Central Soil Salinity Research Institute, Regional Research Station, Canning Town, West Bengal, India, p 62

Bandyopadhyay S, Kar NS, Das S, Sen J (2014) River systems and water resources of West Bengal: a review. In: Conference GSI, pp 63–84

BGS, DPHE (2001) Arsenic contamination of groundwater in Bangladesh. In: Kinniburgh DG, Smedley PL (eds). British Geological Survey Technical Rep. WC/00/19, Bangladesh

Bhandari N (2016) Questions on salt resistent vegetables and change in cropping pattern [Interview]. Basanti, West Bengal, India, 27 Apr 2016

Census (2011) District census handbook South 24 Parganas. Directorate of Census Operations, New Delhi, India

CGWB (2009a) Ground water information booklet. South 24 Parganas district, West Bengal—district at a glance. Central Ground Water Board, Ministry of Water Resources, Kolkata, West Bengal, India

CGWB (2009b) Ground water resource estimation methodology. Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi, India

Chopra K, Kumar P, Khan NA (2006) Identifying the economic drivers of landuse change in mangrove ecosystems: a case study of the Indian Sundarbans. In: Workshop on trade, environment and rural poverty

CSIRO WARPO, BWDB, IWM, BIDS, CEGIS (2014) Bangladesh integrated water resources assessment: final report. CSIRO, Australia

CSSRI (2016) Mitigation strategies in the Sundarbans [Interview]. Central Soil Salinity Research Institute, Canning Town, West Bengal, India, 02 June 2016

Danda AA, Sriskanthan G (2011) Indian sundarbans delta: a vision. WWF World Wide Fund for Nature-India, New Delhi, India

Das K, Das K (2016) Livelihood dynamics as a response to natural hazards: a case study of selected places of Basanti and Gosaba Blocks, West Bengal. Earth Sci 5(1):13–18

Dowling CB, Poreda RJ, Basu AR (2003) The groundwater geochemistry of the Bengal Basin: weathering, chemsorption, and trace metal flux to the oceans. Geochim Cosmochim Acta 67(12):2117–2136

ESRI (2012) Software—ArcGIS for desktop advanced version 10.1. Esri, Redlands, CA

Falkenmark M, Chapman T (1989) Comparative hydrology: an ecological approach to land and water resources. UNESCO, Paris, France

GOWB (2012) District statistical handbook South 24-Parganas 2009. Bureau of Applied Economics and Statistics, Government of West Bengal, Kolkata, West Bengal, India

Guruprasad (2009) Shodhganga. Groundwater irrigation and its impact on hydrology and morphology [Online]. 04 Aug 2009: http://shodhganga.inflibnet.ac.in/bitstream/10603/28039/10/10_chapter-5.pdf. 23 May 2016

Harris IPDJ, Jones PD, Osborn TJ, Lister DH (2014) Updated high resolution grids of monthly climatic observations—the CRU TS3. 10 dataset. Int J Climatol 34(4):623–642

Harvey CF, Ashfaque K, Yu W, Badruzzaman A, Ali M, Oates P, Ahmed M (2006) Groundwater dynamics and arsenic contamination in Bangladesh. Chem Geol 228(1):112–136

HDRCC Human Development Coordination and Research Center (2009) District human development report South 24 Parganas. HDRCC, Development and Planning Department, Government of West Bengal, Kolkata, West Bengal, India

HWSD (2012) Software—Harmonized world soil database (version 1.2). FAO/IIASA/ISRIC/ISSCAS/JRC, Rome, Italy, Laxenburg, Austria

IDB (2016) Interview regarding irrigated area, installed pumps, and cultivated crops [Interview]. Irrigation Department Basanti, 19 June 2016

I-GIS (2015) I-gis.dk [Online]. http://i-gis.dk/GeoScene3D/tabid/62/language/en-GB/Default.aspx. 24 Mar 2016

Jarvis A, Reuter HI, Nelson A, Guevara E (2008) Hole-filled seamless SRTM data V4. Available from http://srtm.csi.cgiar.org. International Centre for Tropical Agriculture (CIAT)

JGVK (2016) Rainfall data from raingauge 2015, GIS water bodies 2016 [Interview]. Joygopalpur Gram Vikash Kendra, Basanti, West Bengal, India

Khan HH, Khan A, Ahmed S, Gennero MC, Do Minh K, Cazenave A (2013) Terrestrial water dynamics in the lower Ganges—estimates from ENVISAT and GRACE. Arab J Geosci 6(10):3693–3702

Khush A (2016) Agricultural Development Office. Development of irrigated land over the past years [Interview]. Basanti, West Bengal, India. 29 June 2016

Kopmann M (2016) Assessing the sustainability of the groundwater resource in Basanti, West Bengal [Report/Master's Thesis (not published)]. Technical University of Denmark (DTU) and Technical University of Munich (TUM), Copenhagen, Denmark

Maharana B (2016) Cultivation scheme in Basanti and tube well construction [Interview]. Apr–May 2016

Malmstrom VH (1969) A new approach to the classification of climate. J Geogr 68(6):351–357

Michael HA, Voss CI (2009a) Controls on groundwater flow in the Bengal Basin of India and Bangladesh: regional modeling analysis. Hydrogeol J 17(7):1561–1577

Michael HA, Voss CI (2009b) Estimation of regional-scale groundwater flow properties in the Bengal Basin of India and Bangladesh. Hydrogeol J 17(6):1329–1346

Mishra S (2013) Estimation of water resource: an essential input for its conservation in West Bengal. West Bengal Gov J. pp 47–53

Mitra S, Wright J, Santra A, Ghosh AR (2015) An integrated water balance model for assessing water scarcity in a data-sparse interfluve in eastern India. Hydrol Sci J 60(10):1813–1827

Mukherjee A (2006) Deeper groundwater flow and chemistry in the arsenic affected Western Bengal Basin, West Bengal, India. University of Kentucky, UKnowledge, Lexington, Kentucky, USA

Mukherjee A (2009) Some recent advances in understanding the groundwater resources of gangetic West Bengal. Bhu-Jal News Quart J Cent Ground Water Board 24(1):18–27

Mukherjee A (2016) Hydrogeologic situtation in the western Bengal Basin [Interview]. IIT Kharagpur, Kharagpur, West Bengal, India. 03 May 2016

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN: 978-981-10-3888-4

Mukherjee A, Fryar A, Howell P (2007) Regional hydrostratigraphy and groundwater flow modeling in the arsenic-affected areas of the western Bengal basin, West Bengal, India. Hydrogeol J 15(7):1397–1418

Mukherjee A, Fryar AE, Thomas WA (2009) Geologic, geomorphic and hydrologic framework and evolution of the Bengal basin, India and Bangladesh. J Asian Earth Sci 34(3):227–244

Naskar M (2016) Interview on drilling techniques, as well as, information about lithologs in and around Basanti. [Interview] Canning, South 24 Parganas, West Bengal, India. 04 May 2016

Pal T, Mukherjee P (2009) Study of subsurface geology in locating arsenic-free groundwater in Bengal delta, West Bengal, India. Environ Geol 56(6):1211–1225

Pike JG (1964) The estimation of annual run-off from meteorological data in a tropical climate. J Hydrol 2(2):116–123

Prasari R (2011) Livelihood zones analysis—a tool for planning agricultural water management investments—West Bengal. FAOWater, Kolkata, West Bengal, India

Rajmohan N, Prathapar SA (2013) Hydrogeology of the Eastern Ganges Basin: an overview, vol 157. International Water Management Institute (IWMI), Colombo, Sri Lanka

Ravenscroft P, Burgess WG, Ahmed KM, Burren M, Perrin J (2005) Arsenic in groundwater of the Bengal Basin, Bangladesh: distribution, field relations, and hydrogeological setting. Hydrogeol J 13(5–6):727–751

Roy MP (2015) Groundwater towards sustainable agriculture—a global challenge. Int J Ecosyst 5(3A):86–88

Rudra K (2007) The status of water resources in West Bengal (a brief report)

Sahu P, Michael HA, Voss CI, Sikdar PK (2013) Impacts on groundwater recharge areas of megacity pumping: analysis of potential contamination of Kolkata, India, water supply. Hydrol Sci J 58(6):1340–1360

Samanta K, Hazra S (2012) Landuse/landcover change study of Jharkhali Island Sundarbans, West Bengal using remote sensing and GIS. Int J Geomat Geosci 3(2):299–306

Shamsudduha M, Taylor RG, Ahmed KM, Zahid A (2011) The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. Hydrogeol J 19(4):901–916

Sharma JR, Paithankar Y (2014) Ganga Basin. Government of India, Ministry of Water Resources, National Remote Sensing Centre (ISRO), Central Water Commission, New Dehli, India

Sharma JV, Chauhan S (2014) Assessment for designing REDD plus projects in India. TERI—The Energy and Resources Insitute, New Delhi, India

Subirdas (2014) District profile of South 24 Parganas—16. Land Reforms Department, Government of West Bengal, West Bengal

Sudansu (2016) Information about the cultivation scheme, used irrigation pumps, situation of farmers [Interview]. Basanti, South 24 Parganas, West Bengal, India. Apr–May 2016

Townley LR (1995) The response of aquifers to periodic forcing. Adv Water Resour 18(3): 125–146 (Elsevier Science Limited, Wembley, Australia)

UBU (2015) UBU-Project Application: Resilience in North and South 24 Parganas, West Bengal —preparedness for future water related disasters. Danish Association for Sustainable Developement (UBU) and Joygopalpur Gram Vikash Kendra (JGVK), Copenhagen, Denmark

Voss Clifford I (2016) Informations about regional flow systems, influence of tides, and project related questions [Interview].

Winter TC, Harvey JW, Franke OL, Alley WM (1998) Ground water and surface water: a single resource. US Geological Survey, Denver, Colorado

WRIS (2015) Water resources information system of India, India-WRIS WebGIS [Online]. http://india-wris.nrsc.gov.in/wrpinfo/index.php?title=Ganga, 03 Jan 2016. Joint project between Central Water Commission (CWC), Ministry of Water Resources, Government of India, New Delhi and Indian Space Research Organization (ISRO), Department of Space, Government of India, Bangalore

Part V
Groundwater and Climate Change

Chapter 31
Impacts of Human Development and Climate Change on Groundwater Resources in Bangladesh

Mohammad Shamsudduha

Abstract Groundwater has been playing a central role in drinking and irrigation water supplies in Bangladesh for more than four decades. Today, nearly 97% of all drinking water supplies in Bangladesh come from groundwater via hand-operated tubewells that tap the shallow part (<150 m bgl) of the Bengal Aquifer System (BAS). Groundwater-fed irrigation, that currently meets 80% of irrigation water supplies, has been sustaining the dry-season high-yielding "Boro" rice cultivation since the 1970s that has made Bangladesh nearly self-sufficient in food production and led to major economic development. The shallow groundwater is, however, facing major challenges: (1) widespread, natural contamination of arsenic (As) and salinity in coastal areas and (2) rapid depletion of groundwater storage in intensely irrigated areas (e.g., Barind Tract) and major metropolitan cities like Dhaka City. Substantial declines in shallow groundwater levels are currently leading toward an "unsustainable" condition for low-cost pumping technologies (e.g., hand pumps, shallow irrigation wells) and threatening food security. In contrast, intensive dry-season abstraction has also led to increased groundwater recharge by enabling pumping-induced greater infiltrations of rain and surface water during the wet season in areas where surface geologies are permeable and potential recharge is high—realizing the idea of the Ganges Water Machine. Although the impacts of human development of groundwater resources are evident, it is unclear how changing climate will affect groundwater quality and quantity. In addition, recently, there is an increased focus on the development of deep groundwater in Bangladesh to mitigate As and salinity problems. However, little is known about recharge mechanisms and long-term security of the deep groundwater resource in Bangladesh.

Keywords Groundwater monitoring · Dry-season irrigation · Groundwater recharge · Climate change · Bengal Basin

---

M. Shamsudduha (✉)
Institute for Risk and Disaster Reduction, University College London, London, UK
e-mail: m.shamsudduha@ucl.ac.uk

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_31

31.1 Introduction

Groundwater represents ~30% of the Earth's total 2.5% freshwater resources (Shiklomanov 1993) and currently provides essential drinking water supplies to billions of people (Gleeson et al. 2012). Globally, groundwater accounts for one-third of all freshwater use including 42% domestic, 36% agriculture, and 27% industrial withdrawals (Taylor et al. 2013a). Approximately, one-fifth of the Earth's total freshwater resources can be found in South Asia—home to some 1.7 billion people (Shamsudduha 2013b). By proportion, Bangladesh is the largest (~80% of freshwater use comes from groundwater) consumer of groundwater resources in South Asia.

Groundwater is an essential part of public water supply, agricultural (e.g., irrigation), and industrial (e.g., garments manufacturing) activities in Bangladesh—home to some 160 million people. Groundwater-fed irrigation, which has been sustaining the dry-season (December to May) "Boro" rice cultivation in large parts of Bangladesh since the early 1970s, has made the country nearly self-sufficient in food grains (Rahman and Parvin 2009). Currently, the high-yielding Boro rice is grown (Fig. 31.1) in ~4 million hectares (ha) out of a total of 7.7 million ha of net cultivable land in the country that is primarily groundwater-fed (BBS 2008). The dry-season groundwater-fed irrigation represents ~80% of total groundwater use in Bangladesh. Groundwater also provides a year-round, pathogen-free drinking water supply to 97% population in the country. However, Bangladesh is currently facing two grave crises relating to the shallow (<150 m below ground level, bgl) groundwater resource: (1) widespread contamination of elevated levels of arsenic (As) concentrations and high salinity in the south and (2) rapid decline of shallow groundwater storage in many parts (e.g., Dhaka City, Barind Tract region) resulting from a long-term, intensive abstraction.

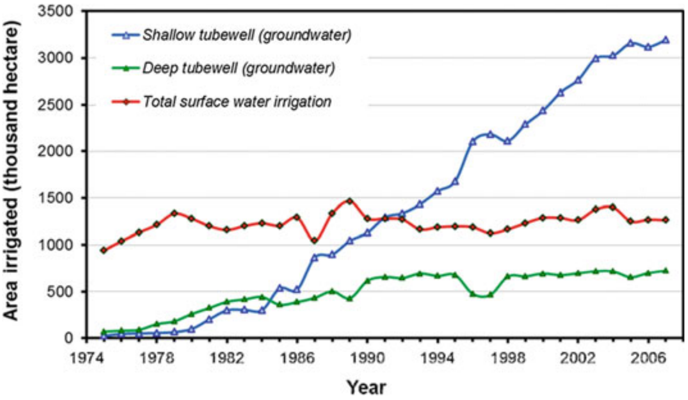


Fig. 31.1 Estimated land area under groundwater and surface water-fed dry-season irrigation in Bangladesh since the early 1970s (Shamsudduha et al. 2011)

A total of 77 million people of Bangladesh (Chap. 1, Fig. 1.1) is estimated to be exposed to toxic levels of As (WHO Standard of 10 μg/L) in their drinking water supply (Argos et al. 2010) that primarily comes from shallow groundwaters. A recent study (Flanagan et al. 2012) reports that over the next 20 years As-related mortality in Bangladesh (1 of every 18 deaths) could lead to a loss of US $12.5 billion assuming a steady economic growth and an unchanged population exposure to As contamination. The second issue is considered as an imminent threat to food security of Bangladesh as declining groundwater levels in shallow aquifers in the northwestern, north-central and southwestern parts of the country have already rendered many low-cost pumping technologies (e.g., shallow irrigation pumps, hand tubewells) inoperable, particularly, during the dry season when water table is too deep (>10 m bgl). Declining groundwater levels beneath Dhaka City is currently costing the city water supply authorities much greater than the previous years as the high-cost pumping technologies have now been utilized to provide domestic water supply to its 12 million people (Shamsudduha 2013a). This study presents a critical review of groundwater resources development in Bangladesh over the last four decades and highlights the current challenges in the face of ever-increasing human development, and climate variability and change in a warmer world. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

31.2 Development of Groundwater in Bangladesh

31.2.1 Groundwater-Fed Drinking Water Supply

Before 1970s, surface water (e.g., pond, river) was the main source of drinking and domestic water supplies in Bangladesh. Dug wells were also commonly used in many parts of the country except in coastal areas where near-surface (very shallow, depth <50 m bgl) groundwater is generally saline. During the late 1970s and early 1980s, in order to avoid surface water sources, which were mostly contaminated with pathogenic microorganisms, the use of groundwater was introduced in Bangladesh. Thousands of hand-operated tubewells were installed in rural areas of Bangladesh by the government aided by international donor agencies to provide pathogen-free groundwater-fed drinking water supply. During the International Drinking Water Decade (1980–1990), several millions of such hand-operated tubewells were installed to tap shallow (<150 m bgl) groundwater for domestic use. The current number of hand tubewells in Bangladesh is not precisely known but an estimated 10–12 million tubewells exit in the country. The vast majority of these tubewells are privately owned. These wells penetrate mainly the shallow part of the BAS down to a depth typically of 10–60 m bgl (BGS and DPHE 2001).

In large urban areas of Bangladesh, there are city/municipal water supply and sewerage authorities that are responsible for providing drinking water supplies to city dwellers. For instance, in Dhaka City, there is the Dhaka Water Supply and

Sewerage Authority (DWASA) that supplies water to the city dwellers. At present, DWASA has a network of ~700 deep (>150m bgl) groundwater wells and 4 surface water treatment plants. DWASA covers more than 360 km^2 service area with production of nearly 2,110 million l of water every day of which 87% comes from groundwater and the rest from surface water treatment plants. In addition to DWASA water supply wells, there exist several hundreds to a thousand, essentially unlicensed groundwater abstraction boreholes in Dhaka City. There are similar water supply and sewerage authorities operating in other big cities in Bangladesh such as the Chittagong Water supply and Sewerage Authority in Chittagong and the Khulna Water Supply and Sewerage Authority in Khulna. Like DWASA, these water supply authorities are also heavily dependent upon groundwater resources for municipal, piped water supplies.

In many peri-urban, provincial towns throughout Bangladesh there are local water supply and sanitation authorities, known as municipalities, that are responsible for providing public water supply through pipe networks. These municipal water supply systems are mainly groundwater fed. The Department of Public Health Engineering (DPHE) and BWDB are the two government organizations that provide technical support to local municipality to setup their own water supply system. In addition to the government initiatives, many private sectors and NGOs also provide financial support and some technical assistants to develop water supply systems in many rural parts of Bangladesh.

31.2.2 Groundwater-Fed Irrigation Water Supply

Groundwater is essential for food production. Irrigated agriculture is the largest consumer of groundwater in Bangladesh. Nearly 80% of all irrigation water supplies come of groundwater in which shallow groundwater-fed irrigation dominates (Fig. 31.1). Small-scale groundwater-fed irrigation (known as the minor irrigation) has been sustaining the high-yielding Boro rice cultivation in Bangladesh since the 1970s. Boro rice is grown during the dry season (December to May) throughout Bangladesh except some areas in the south (Fig. 31.2).

Besides Boro rice cultivation, groundwater-fed irrigation is applied to other non-dry season rice (e.g., Aman) in drought-prone parts of northwestern Bangladesh.

Groundwater-fed irrigation first started during a period of 1963–1966 in the former East Pakistan with installation of a few hundred deep irrigation wells. Although these wells were installed at a depth ranging from 75 to 100 m bgl, they are popularly known as "deep" wells as the pump (submersible) is set below the static water table. A good description to the development of groundwater-fed irrigation is Bangladesh can be found in several literatures (e.g., Rahman and Ravenscroft 2003; Ahmed et al. 2012).

Currently, nearly 90% of the total irrigation in Bangladesh is operated under "minor irrigation" or small-scale irrigation scheme primarily involving

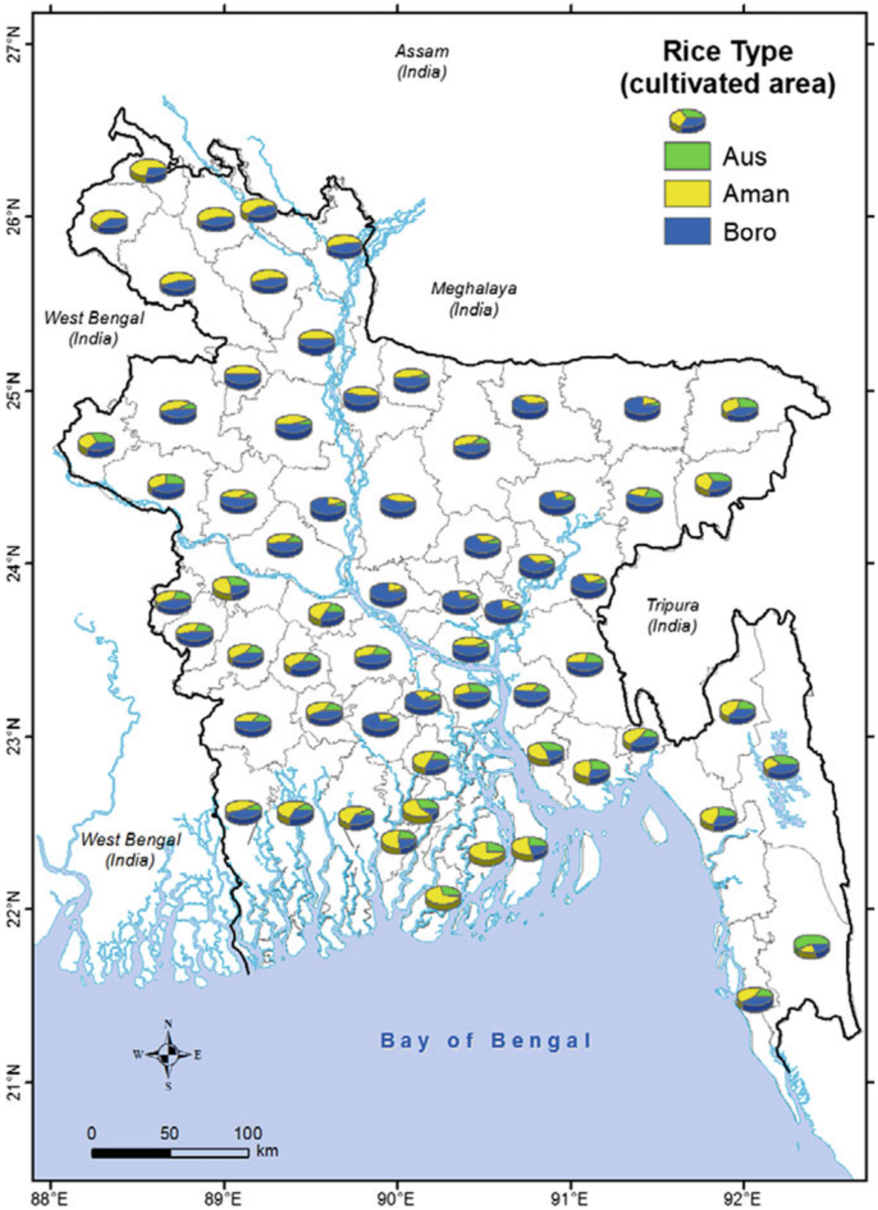


Fig. 31.2 District-wise summary of cultivated area (percentage of net cultivated land) under three main rice in three main seasons (summer: Aus, rainy: Aman, dry: Boro) in Bangladesh (data from BBS Agricultural Census 2008)

groundwater-fed shallow tubewell (STW), deep-set shallow tubewell (DSSTW), deep tubewell (DTW), and force mode tubewell (FMTW), and surface water-fed low lift pumps (LLT). According to BADC irrigation statistics, a total of 1.2 million STW, nearly 30,000 DTW, and 50,000 LLP operated during the Boro rice season in 2007. It is clear from Fig. 31.1 that STW-based irrigation has dramatically increased over the last three decades in Bangladesh.

31.3 Monitoring of Groundwater Resources

31.3.1 Development of Groundwater-Level Monitoring Network

There are several organizations that have established national scale groundwater-level monitoring networks throughout in Bangladesh. These organizations are the Bangladesh Water Development Board (BWDB), the Department of Public Health Engineering (DPHE), and the Bangladesh Agricultural Development Corporation (BADC). Amongst these three national organizations, BWDB is the key organization responsible for monitoring both surface water and groundwater resources and implementation of drainage and flood control, and water-related development projects in Bangladesh. To monitor water resources of the region, the Water and Power Development Agency (EPWAPDA) was established in the former East Pakistan in the late 1950s. Subsequently, BWDB emerged following the independence of Bangladesh in 1971 replacing the former EPWAPDA. Currently, there are well-established monitoring networks of groundwater, surface water levels and chemistry. A detailed account of the development history of groundwater-level monitoring in Bangladesh can be found in several literatures (e.g., Nishat et al. 2003; Zahid and Ahmed 2006).

Currently, BWDB manages a total of about 1250 monitoring boreholes or piezometers across the entire Bangladesh. Most of these boreholes are shallow (depth <50 m bgl); only a few boreholes in the southern Bangladesh are deep (>150 m bgl). The depth to groundwater levels is measured manually once a week (i.e., every Monday). Depth from the wellhead (also known as parapet) to groundwater level at each station is referenced to a common horizontal datum known as the Public Works Datum (PWD), originally set approximately at the mean sea level (msl) with a vertical error of ±0.45 m (Shamsudduha et al. 2009).

In the early 1970s, BWDB started their monitoring with a few hundred boreholes mostly inherited from the former EPWAPDA. During the 1960s, most of these monitoring points were dug wells; many of these were subsequently replaced by piezometers. The total number of monitoring wells that operated from 1961 to 2006 is 2154; 735 were dug wells and 1419 were boreholes (Fig. 31.3). Most dug wells have been replaced by boreholes at the same location; faulty boreholes have

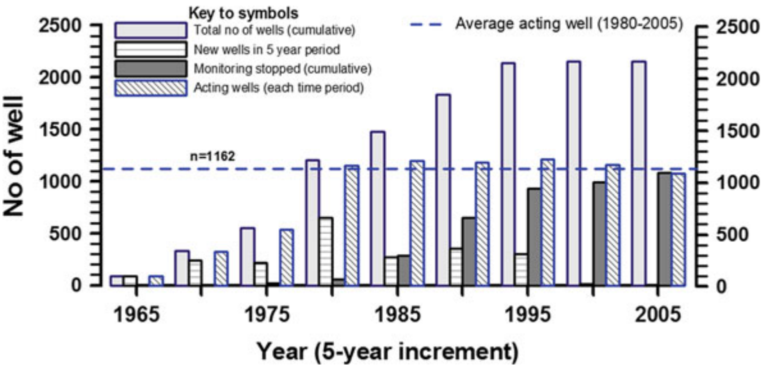


Fig. 31.3 Development of groundwater-level monitoring network by the Bangladesh Water Development Board (BWDB) (Shamsudduha et al. 2009)

also been replaced throughout the recording period. In some cases, newly installed boreholes were drilled deeper or shallower than those they replaced.

The total number of active piezometers in the BWDB database is ~1250 (Fig. 31.4) (Shamsudduha et al. 2009).

DPHE has its own network of about 4500 monitoring wells throughout Bangladesh. However, DPHE only measures the depth to the dry-season groundwater levels once a year that generally corresponds to the deepest annual groundwater levels in most locations in Bangladesh. BADC has a network of more than 3000 monitoring wells throughout Bangladesh. However, little is known about their monitoring frequency and observation techniques as these organizations do not regularly publish their monitoring records and data are not easily accessible for analysis. For example, BADC has published groundwater-level maps known as "Groundwater Zoning" maps for two seasons (2004 and 2010) (Alam 2011).

31.3.2 Long-Term Trends in Shallow Groundwater Levels

Long-term trends in shallow groundwater levels reflect the sustainability of abstraction abstractions primarily used for dry-season irrigation in Bangladesh. This study has estimated that nearly 30 km^3 of groundwater was abstracted for irrigation throughout Bangladesh during the Boro rice season in 2006. Considering an average daily groundwater use of 50 L per person for both drinking and domestic uses (total population of 150 million in 2006) an estimated domestic groundwater use is approximately 3 km^3 which is an order of magnitude less than annual irrigation abstraction in Bangladesh. Irrigation water supplies predominantly come from shallow groundwater mainly through private irrigation wells owned by smallholder farmers that have superseded so-called deep irrigation tubewells (Fig. 31.1) operated by the Bangladesh Agricultural Development Corporation.

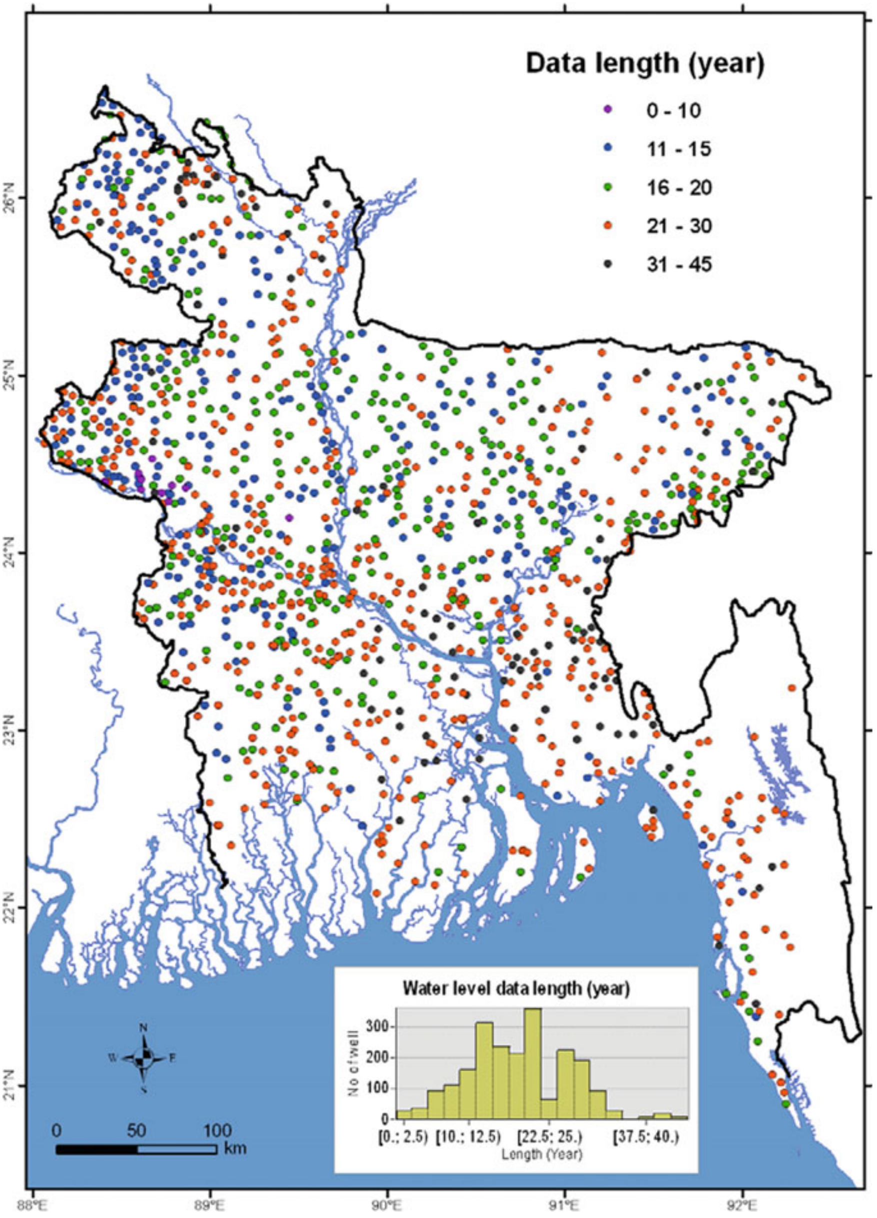


Fig. 31.4 Map showing the spatial distribution of BWDB groundwater-level monitoring boreholes in Bangladesh. The histogram at the bottom of the figure shows distribution of the lenghth of data of BWDB boreholes

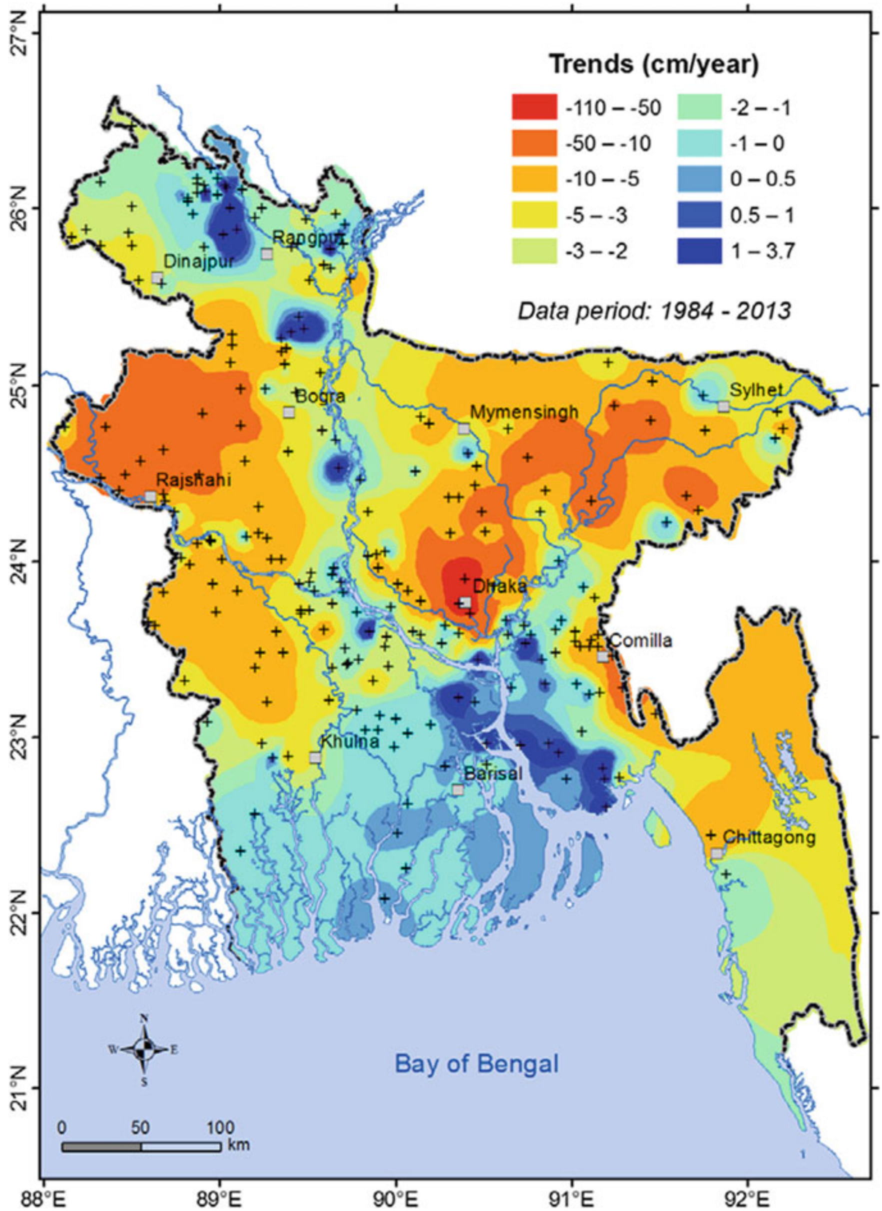


Fig. 31.5 Long-term (1984–2013) linear trends in shallow groundwater levels in Bangladesh. Groundwater levels are declining over areas that are marked in orange-red colors but stable to slightly rising in areas that are marked in cyan-blue colors

During each Boro rice season in Bangladesh, about a million shallow tubewells operate that withdraw a substantial amount of groundwater from shallow aquifers that are not fully recharged during the following monsoon season. As a result of this, "unsustained" groundwater abstraction for irrigation and municipal water supplies shallow groundwater levels are declining at high rates in many areas of Bangladesh.

Using weekly monitoring records of groundwater levels from a network of 454 boreholes throughout Bangladesh Shamsudduha et al. (2009) showed that shallow groundwater levels are declining in recent time (1985–2005) throughout the country. Declining rates are the highest (exceeding −0.5 m/year) in and around Dhaka City and Barind Tract region, and moderate (0 to −0.05 m/year) in areas south of the River Ganges (Fig. 31.5). In the coastal areas, shallow groundwater levels are, however, showing relatively stable to slightly rising (0 to +0.1 m/year) over the same period.

31.3.3 Long-Term Trends in Deep Groundwater Levels

Unlike a dense monitoring network of shallow groundwater levels throughout Bangladesh, monitoring of deep (>100 m bgl) groundwater levels is very limited. A total of 13 deep monitoring piezometers are identified in the BWDB weekly groundwater-level monitoring database of which monitoring has stopped in 7 boreholes. Time series of deep groundwater levels from three continuously monitored boreholes in southern Bangladesh are shown in Fig. 31.6. BA025 is a deep (281 m bgl) monitoring piezometer located in Mathabaria Upazila of Pirojpur District of southern Bangladesh. Long-term (1994–2014) time series data show a declining trend in the records. A relatively shallower piezometer BA026 (152 m bgl) from the same district, however, shows more or less stable to a sharply rising trends since 2010. Piezometer CT012 (108 m bgl) from Chittagong district shows a steadily declining trend. It is difficult to derive any consistent story on the long-term changes in deep groundwater in coastal Bangladesh from a limited number of deep piezometers. However, the lack of deep groundwater monitoring has made the authority wary about being in dark about any negative consequences of deep groundwater development in the country. Under a new initiative taken by BWDB, a number of deep monitoring piezometric sites ($\sim$40 stations) has already been installed in several coastal districts in Bangladesh by BWDB (Zahid et al. 2012).

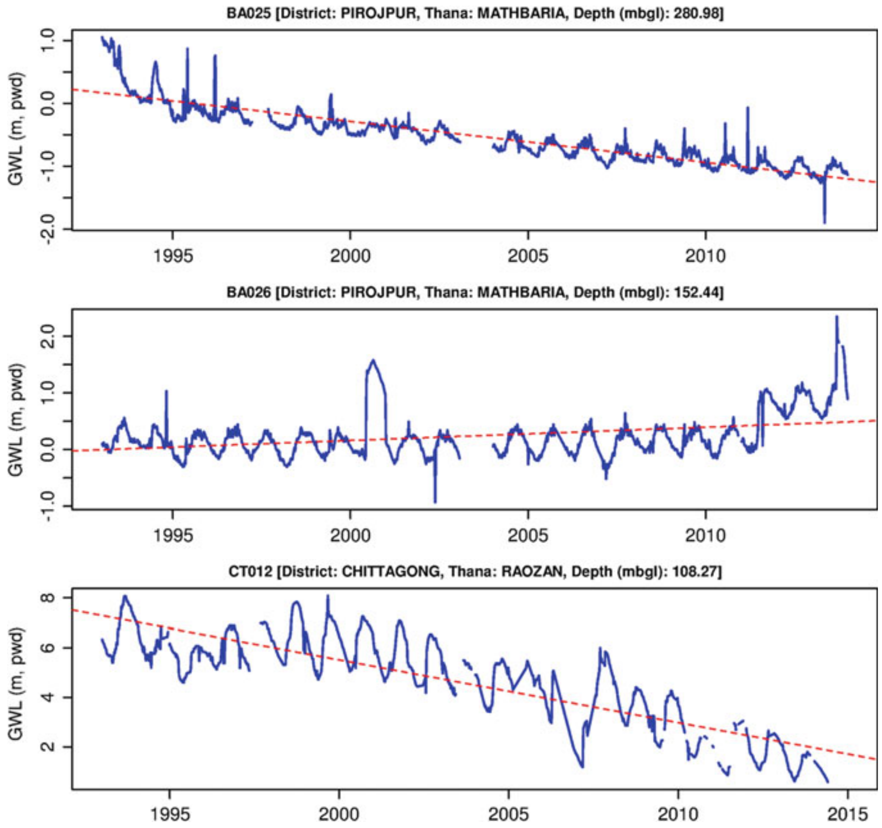


Fig. 31.6 Long-term (1994–2014) monitoring of deep groundwater levels in coastal Bangladesh and linear trends through the time series records

31.4 Groundwater Recharge and Storage Change

31.4.1 Groundwater Recharge in Bangladesh: Long-Term Trends

Groundwater recharge is influenced not only by climate variability but also human influences including groundwater abstraction. A recent study (Shamsudduha et al. 2011) has estimated net actual groundwater recharge to shallow aquifers in Bangladesh using BWDB monitoring hydrographs and applying the water table fluctuation method. The national scale estimate of groundwater recharge shows that mean annual recharge is higher (300–700 mm) in northwestern and southwestern areas of Bangladesh than in southeastern and northeastern regions (<100 mm) where rainfall and potential recharge are greater. Net groundwater recharge in many parts of Bangladesh has increased substantially (5–15 mm/year) between since

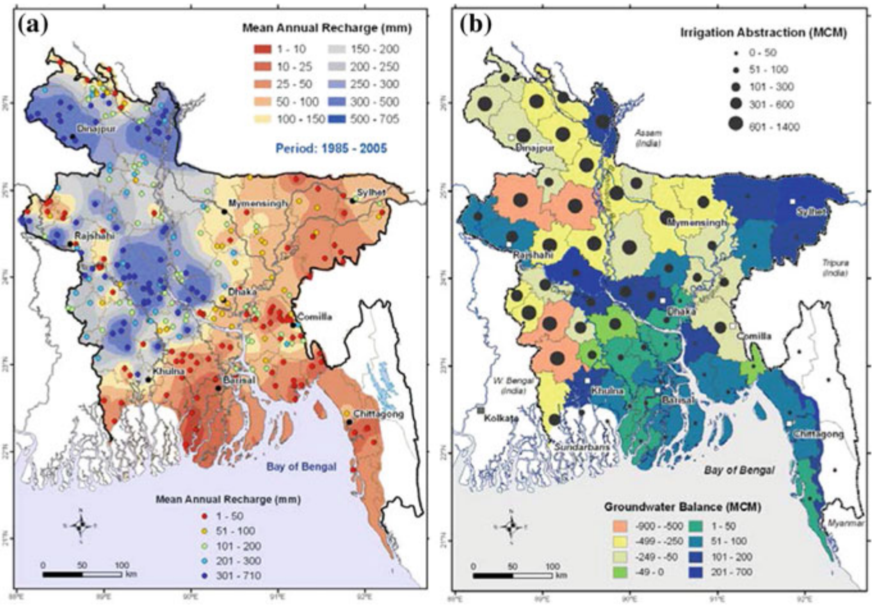


Fig. 31.7 **a** Mean annual (mean period 1985–2005) net groundwater recharge in Bangladesh; **b** estimates of simple groundwater balance (recharge—abstraction) at district level in Bangladesh. Groundwater-fed irrigation is shown as graduated solid circles at the center of each district. Negative balance in groundwater storage is observed in northwestern, southwestern, and north-central parts of the country where groundwater-fed irrigation has been intensive over the last 4 decades

early 1980s in response to increased groundwater abstraction for irrigation and urban water supplies (Fig. 31.7) (Shamsudduha et al. 2011).

More specifically, actual recharge has increased substantially (5–15 mm/year) in northwestern and western districts (Bogra, Dinajpur, Gaibandha, Jessore, Jhenaidah, Rangpur, and Rajshahi), north-central districts (Dhaka, Jamalpur, Mymensingh, Tangail districts), and Comilla district in the east, but has slightly decreased (−0.5 to −1 mm/year) or remained unchanged in the rest of Bangladesh (Shamsudduha et al. 2011). Furthermore, net groundwater recharge in many places has increased by 100–350 mm between pre-development (before 1980) and development of groundwater-fed irrigation (after 2000) periods. A reduction in the net groundwater recharge (10–50 mm) is observed mainly in the tidal Ganges-Brahmaputra-Meghna Delta and some parts of northeastern Sylhet region in Bangladesh (Fig. 31.8).

Increasing trends in net groundwater recharge in many areas of Bangladesh since the 1980s is positively associated with intensive dry-season irrigation for Boro rice cultivation. In northwestern Bangladesh where net recharge has increased substantially groundwater is used to irrigate not only Boro but also transplanted Aman

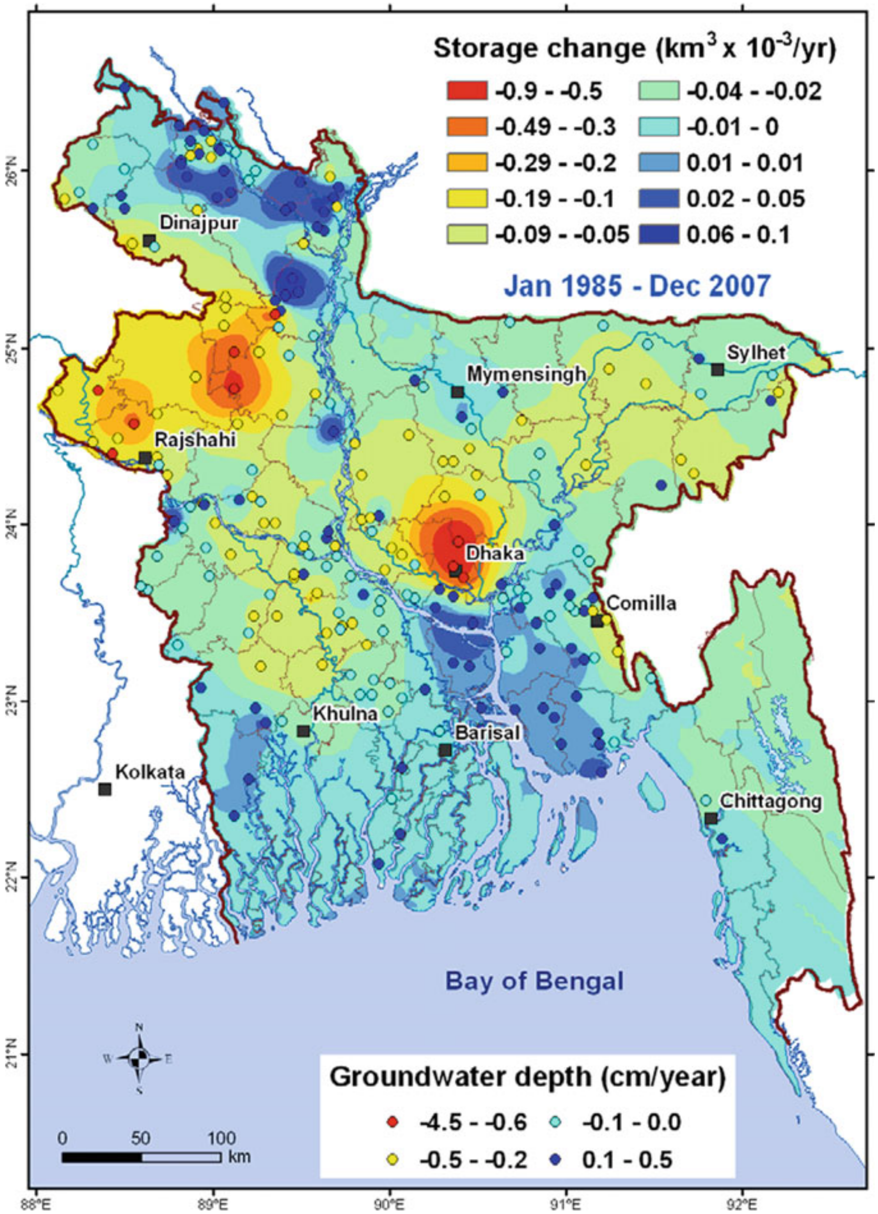


Fig. 31.8 Calculated spatiotemporal changes in shallow groundwater storage (mean period 1985–2007) in Bangladesh using borehole records

rice that grows during the monsoon season. The Barind region is considered as a drought-prone area in Bangladesh where the mean annual rainfall is less than 1500 mm, whereas the country-wide average is 2500 mm.

Supplementary groundwater-fed irrigation is, therefore, necessary during the transplanted Aman rice cultivation in the Barind region where Aman is grown in >60% land area.

Groundwater recharge to regionally unconfined shallow aquifers in Bangladesh is primarily controlled by the permeability of surficial geology (i.e., hydraulic conductivity), storage property (i.e., specific yield), and abstraction. Greater abstraction enables increased recharge in shallow aquifers that are underlain by permeable soil and sand-silt type of unconsolidated sediments by lowering the long-term mean water table and, essentially, by increasing storage space in the aquifer. This long-term increase in groundwater recharge induced through irrigation pumping has clearly demonstrated the idea of the “Ganges Water Machine” proposed by Revelle and Lakshminarayana (1975). The estimate of net recharge shows that mean groundwater recharge to shallow aquifers in Bangladesh has increased from ~130 to ~190 mm/year over a period from 1975–1980 (pre-development irrigation) to 2002–2007 (developed irrigation) (Shamsudduha et al. 2011).

Evidence of greater groundwater recharge in Bangladesh as a result of increased human-driven abstractions (i.e., anthropogenic impact) is clearly evident as suggested by the analysis of observational records and groundwater modeling studies (Michael and Voss 2009; Shamsudduha et al. 2011). On the other hand, influence of climate variability and change on groundwater recharge is not clear. A few studies (Owor et al. 2009; Taylor et al. 2013b) in the sub-Saharan Africa show that under deeply weathered crystalline basement aquifers, shallow groundwater recharge occurs disproportionately (i.e., episodic as opposed to regular intervals). These studies have found statistically significant associations between heavier rainfalls and individual recharge events and a nonlinear relationship between recharge and rainfall. Episodic large recharge events due to heavy rainfall events (e.g., El Niño-Southern Oscillation or ENSO-driven rainfall) in semiarid central Tanzania are observed to raise lowered groundwater levels resulted from intensive abstraction for municipal water supplies (Taylor et al. 2013b).

Groundwater recharge in Bangladesh generally occurs primarily through infiltration of monsoon rainfall and small amount recharge is expected to take place from irrigation return flow and through focused recharge from river channels, particularly in areas that are (i) in close proximity to river channels and (ii) occupied by Plio-Pleistocene aquifers with low-permeable surface geology and incised drainage channels that cut through the aquifer (WARPO 2000; BGS and DPHE 2001). Aquifers in the northwest and southwest, where monsoon rainfall is far less than the country average of 2500 mm and dry-season groundwater-fed irrigation is intensive, recharge takes place slowly with peak groundwater levels appearing in September–October months or even in November. This is because dry-season groundwater levels are generally deeper in these intensely irrigated, dry areas in Bangladesh.

31.4.2 Groundwater Storage Change

Recent groundwater storage changes in the Bengal Basin of Bangladesh have been estimated using both long-term groundwater-level hydrographs and gravity satellites, GRACE (Gravity Recovery and Climate Experiment) and land surface models (Shamsudduha et al. 2012). A summary of the borehole-derived estimates for long-term (1985–2007) groundwater storage changes is provided below.

Weekly time series records of BWDB borehole hydrographs from a subset of 236 shallow boreholes with a mean depth of 30 m bgl (below ground level) were used to assess changes in groundwater storage over the period of January 1985 to December 2007 (Shamsudduha et al. 2012). This data period represents the longest period of groundwater storage changes in Bangladesh for which observational records of high density and high quality (missing record <4.3%) are available.

The annual fluctuation (annual maxima − annual minima) in observed groundwater levels or hydraulic heads (Δh) in the regionally unconfined shallow aquifer (<100 m bgl) in the Bengal Basin of Bangladesh is translated into an equivalent groundwater depth (GWD) to derive in situ ΔGWS (Shamsudduha et al. 2012). Shallow groundwater levels in Bangladesh generally reach the peak level around September following rain-fed recharge throughout monsoon season following their deepest levels observed toward the end of dry season (Shamsudduha et al. 2011). Estimates of in situ ΔGWS are compared with GRACE satellite-derived estimates according to Eq. (31.1) where $S_{\text{gw}}(t)$ is the linear trend in GWD and A is area of the grid cells (Shamsudduha et al. 2012).

$$\Delta \text{GWS}_t = \sum_{i=1}^{n} \left(S_{\text{gw}}(t) \times A_i \right) \tag{31.1}$$

S_{gw} is calculated at each BWDB monitoring location (n = 236) using specific yield value (S_y) and annual groundwater-level fluctuations according to Eq. (32.2).

$$S_{\text{gw}} = \Delta h \times S_y \tag{32.2}$$

Spatially distributed S_y values derive from 279 pumping test records (Shamsudduha et al. 2011) are applied across Bangladesh. The mean value of the estimated S_y in Bangladesh is 0.06 (range 0.01–0.2) with a standard deviation of 0.04.

31.5 Impacts of Climate Change on Groundwater

31.5.1 Projected Changes in Temperature in Bangladesh

According to the IPCC's (Intergovernmental Panel on Climate Change) assessment reports (AR4 and AR5), the global average surface temperature has increased especially since 1950s (IPCC 2007, 2013). The rate of global warming averaged over the last 50 years (0.13 °C ± 0.03 °C per decade) is nearly twice that for the last 100 years. Based on AR4 multi-model ensemble, an increase is projected in global mean air temperature of 1.8, 2.8, and 3.4 °C in various climate change scenarios (e.g., B1, A1B, and A2) by 2090–2099 relative to 1980–1999. Climate models have been improved substantially since AR4. IPCC's AR5 (IPCC 2013) multi-model ensemble projects rise in global surface temperature with maximum ranging from 1.2, 2.4, to 5.4 °C in various scenarios (RCP2.6, RCP4.5, and RCP8.5); the corresponding rise in minimum temperature ranges from 1.7, 3.2, and 6.2 °C in the above-mentioned scenarios (Kharin et al. 2013).

An analysis of historical surface temperature data from the Bangladesh Meteorological Department shows an increase in observed surface temperature of approximately 1 °C from 1976 to 2008 (Basak et al. 2013). According to the CMIP5 (Coupled Model Intercomparison Project Phase 5) climate models the surface air temperature in Bangladesh is going to increase substantially in 2071–2095 compared to a period of 1980–2004 (Fig. 31.9) (Hostetler et al. 2011; Alder et al. 2013).

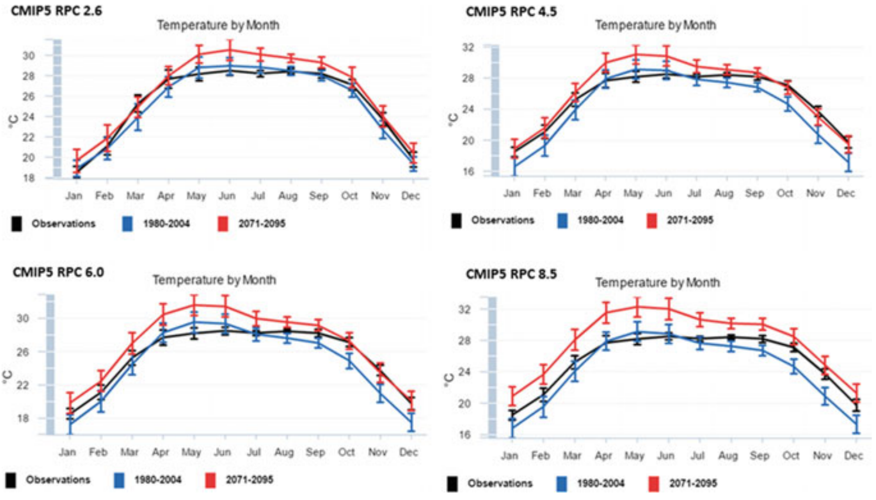


Fig. 31.9 Projected rise in seasonal surface temperature in Bangladesh in 2071–2095 compared to a period of 1980–2004 using a CMIP5 multi-model ensemble under various representative concentration pathways (RCPs) greenhouse gas concentrations scenarios

31.5.2 Rainfall Variability and Groundwater Recharge

An increase in precipitation (i.e., rainfall) intensity due to global warming and climate change is clearly evident (Meehl et al. 2005). The global mean precipitation may increase by several percent within the next hundred years. Climate models predict an increase of approximately 7% until 2100 (IPCC AR4 emission scenario A1B). The spatial and temporal distribution of the rainfall is also going to change (Fig. 31.10). In Bangladesh, both volume and intensity of monsoon rainfall are going to increase in the future. An increase in heavy rainfall events has already been observed during monsoon seasons in the recent past (Shahid, 2010).

There is a consensus that changes in projected precipitation and temperature extremes will intensify global hydrological system (Taylor et al. 2013a). An analysis of recently compiled groundwater-level observations in an aquifer of

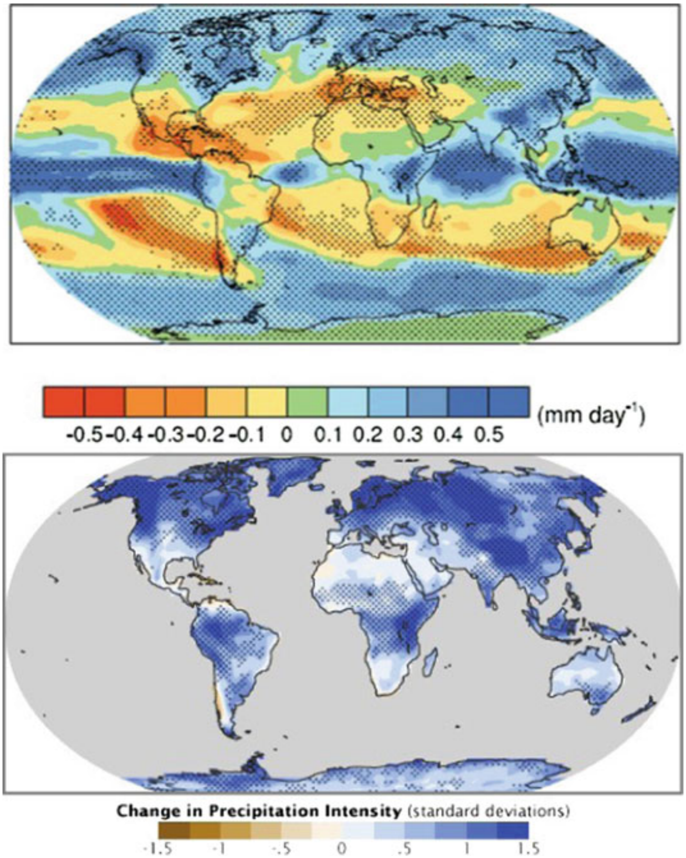


Fig. 31.10 Projected changes in global rainfall amount (left) and intensity (right) according to the IPCC fourth assessment report (IPCC 2007)

central Tanzania reveals that groundwater recharge is highly episodic and closely associated with anomalously intense seasonal rainfall (Taylor et al. 2013b). However, how changes in magnitude and intensity of the monsoonal rainfall will impact groundwater recharge in the Bengal Basin is not fully understood. Shallow groundwater recharge in Bangladesh is largely controlled by soil properties and surface geology, and the timing and magnitude of groundwater recharge have been greatly modified by human influences (i.e., intensive pumping for irrigation and municipal water supplies) (Shamsudduha et al. 2011). Under a changing climate, with shortened monsoon season and fewer rainfalls during the dry season, these drought-prone areas are likely to face increased abstraction to meet growing demand for dry-season rice cultivation but reduction in induced recharge. In the eastern and north-central Bangladesh, heavy rainfall events under a warmer climate may facilitate increased recharge to shallow aquifers. It already appeared that greater recharge took place during the exceptionally wet years (e.g., 1988, 1998, 2007) when ENSO-driven flooding was prolonged and widespread in Bangladesh.

31.5.3 Sea-Level Rise and Salinity Intrusion in Coastal Aquifers

Recent sea-level rise in the Bay of Bengal is going to affect coastal ecosystems and influence salinity intrusion in coastal shallow aquifers in Bangladesh. Rising sea levels will also affect salinity-sensitive coastal bionetworks and aquatic ecosystems including the world's largest mangrove forest—the Sundarbans located in south-western Bangladesh and West Bengal of India. Rising sea levels forces ground-water levels to rise in shallow aquifers within low-lying and flat deltaic environments (Barlow 2003). Shamsudduha et al. (2009) reported long-term (1985–2005) rising trends (0.5–5.0 cm/year) in shallow groundwater levels in coastal Bangladesh. Monthly tidal gauge records (1980–2000) at four locations in coastal Bangladesh also show rising trends (0.4–1.7 cm/year) that are higher than the average global sea-level rise of 0.2 and 0.3 cm/year over the period of 1961–2003 and 1993–2003, respectively (IPCC 2007).

How will climate change (i.e., sea-level rise, coastal storm surges) impact shallow groundwater in coastal Bangladesh? The precise mechanisms are currently unknown partly due to lack of long-term monitoring records of groundwater salinity in coastal aquifers and lack of integration of groundwater and sea-level monitoring records. However, there are several pathways through which saline water can intrude shallow groundwater in the coastal region as a result of rising sea levels under a warmer global climate. These potential pathways are: (1) an increased groundwater salinity by raising the freshwater–saltwater interface (current position is unclear) in the shallow aquifer can raise shallow water levels; (2) groundwater salinity in coastal river channels can increase groundwater salinity through indirect recharge to shallow coastal aquifers; (3) an increase in coastal storm surges and tropical cyclones that can frequently flood coastal region including the areas that are currently protected by polders or embankments that can ultimately cause salinity rise in groundwater; (4) localized recharge to shallow aquifers from brackish water-based shrimp farms can further increase salinity in shallow groundwater; and (5) intensive pumping of fresh groundwater in the coastal aquifer that can accelerate saltwater intrusion and degradation of groundwater quality (Yu et al. 2010).

31.6 Concluding Remarks

Managing groundwater resources is critical for sustaining long-term, safe public water supply and food security in Bangladesh. For continuing social and economic development, there is no alternative to sustainable development of groundwater resources. Currently, nearly one-fourth of the national Gross Domestic Product (GDP) comes from the agricultural sector that largely dependents on groundwater resources. However, declining water storage in many parts of Bangladesh is posing a threat to its economic development contributed by the agriculture sector. Municipal and public water supplies are also affected by the shortage of groundwater storage at shallow depth as water levels are declining at faster rates (e.g., Dhaka City). In contrast, intensive abstractions over the last few decades have induced both direct or diffuse (i.e., rain-fed) and indirect or focused (i.e., capture of surface and floodwater) groundwater recharge in areas where potential recharge is substantial and surface geology and soils favor greater recharge to shallow aquifers. This human development led to induced groundwater recharge suggesting that the idea of the Ganges Water Machine can be realized as a possible mechanism to increase capture of surface water (i.e., flood water during monsoon) in major river catchments.

In contrast to shallow groundwater, little is known about the recharge mechanisms of the deep (>150 m bgl) groundwater environment in Bangladesh. Understanding the deep groundwater is critical as this resource has already been recognized and used as the most popular and economic mitigation measure for arsenic and salinity contaminations in recent time. Deep groundwater, however, has long been used in the coastal region to provide fresh drinking water as shallow groundwater is mostly saline. In the last decade, thousands of deep tubewells have been installed in southern Bangladesh to provide As-safe water supply.

Studies using both time series data on groundwater chemistry from coastal areas (Ravenscroft et al. 2013) and numerical groundwater modeling (Michael and Voss 2008; UCL 2013) show that deep groundwater in most places is safe to develop for domestic water supply for >100 years. However, this critical resource needs to be safeguarded. Thus, there is no alternative to regular monitoring of groundwater levels and chemistry of both shallow and deep groundwaters. Thanks to large government initiatives (e.g., BWDB Climate Change Trust Fund Project) for establishing monitoring network of groundwater levels and salinity in several coastal districts of Bangladesh (BWDB 2013).

Acknowledgements The author likes to acknowledge the support from the Bangladesh Water Development Board for providing weekly groundwater-level monitoring records. The author acknowledges the USGS's Global Climate Change Viewer (http://regclim.coas.oregonstate.edu/visualization/) for providing the downscaled Coupled Model Intercomparison Project Phase 5 (CMIP5) temperature data for Bangladesh.

References

Ahmed N, Zahid A, Kabir MA, Islam MS, Haque MA (2012) Evolution of irrigation system and requirements of water saving technology in Bangladesh to mitigate climate change impact. In: Zahid A et al (eds) Impact of climate change on water resources and food security of Bangladesh. Alumni Association of German Universities in Bangladesh, Dhaka, pp 63–78

Alam E (2011) The updated groundwater zoning map of Bangladesh, Bangladesh Agricultural Development Corporation, Dhaka. http://www.badc.gov.bd/files/map/water_zoning_map_small.pdf. Access date 19 May 2012

Alder JR, Hostetler SW, Williams D (2013) An interactive web application for visualizing climate data. EOS Trans AGU 94:197–198

Argos M et al (2010) Arsenic exposure from drinking water, and all-cause and chronic-disease mortalities in Bangladesh (HEALS): a prospective cohort study. Lancet 376:252–258

Barlow PM (2003) Ground water in freshwater-saltwater environments of the Atlantic coast, U.S. Geological Survey, circular 1262. U.S. Geological Survey, Reston, Virginia

Basak JK, Titumir RAM, Dey NC (2013) Climate change in Bangladesh: a historical analysis of temperature and rainfall data. J Environ 2:41–46

BBS (2008) Census of agriculture 2008. Bangladesh Bureau of Statistics (BBS), Ministry of Planning, GoB, Dhaka

BGS, DPHE (2001) Arsenic contamination of groundwater in Bangladesh. In: Kinniburgh DG, Smedley PL (eds) BGS technical report WC/00/19. British Geological Survey, Keyworth, p 267

BWDB (2013) Hydrogeological study and mathematical modelling to identify sites for installation of observation well nest. Final report "establishment of monitoring network and mathematical model study to assess salinity intrusion in groundwater in coastal area of Bangladesh due to climate change". Bangladesh Water Development Board (BWDB) and Institute of Water Modelling (IWM), Dhaka

Flanagan SV, Johnston RB, Zheng Y (2012) Arsenic in tube well water in Bangladesh: health and economic impacts and implications for arsenic mitigation. Bull World Health Organ 90:839–846

Gleeson T, Wada Y, Bierkens MFP, Beek LPHv (2012) Water balance of global aquifers revealed by groundwater footprint. Nature 488:197–200

Hostetler SW, Alder JR, Allan AM (2011) Dynamically downscaled climate simulations over North America: methods, evaluation and supporting documentation for users. Geol Surv, U.S, p 64

IPCC (2007) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC (2013) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Kharin VV, Zwiers FW, Zhang X, Wehner M (2013) Changes in temperature and precipitation extremes in the CMIP5 ensemble. Clim Change. https://doi.org/10.1007/s10584-013-0705-8

Meehl GA, Arblaster JM, Tebaldi C (2005) Understanding future patterns of increased precipitation intensity in climate model simulations. Geophys Res Lett 32:L18719

Michael HA, Voss CI (2008) Evaluation of the sustainability of deep groundwater as an arsenic-safe resource in the Bengal Basin. PNAS 105:8531–8536

Michael H, Voss C (2009) Controls on groundwater flow in the Bengal Basin of India and Bangladesh: regional modeling analysis. Hydrogeol J 17:1561–1577

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN: 978-981-10-3888-4

Nishat A, Bhuiyan MA, Saleh FM (2003) Assessment of the groundwater resources of Bangladesh. In: Rahman AA Ravenscroft P (eds) Groundwater resources and development in Bangladesh—background to the arsenic crisis, agricultural potential and the environment. Bangladesh Centre for Advanced Studies, University Press Ltd., Dhaka, pp 87–114

Owor M, Taylor RG, Tindimugaya C, Mwesigwa D (2009) Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin. Environ Res Lett, pp 1–6

Rahman MW, Parvin L (2009) Impact of irrigation on food security in Bangladesh for the past three decades. J Environ Prot 1:40–49

Rahman AA, Ravenscroft P (2003) Groundwater resources and development in Bangladesh. The University Press Limited, Dhaka, p 446

Ravenscroft P, McArthur JM, Hoque MA (2013) Stable groundwater quality in deep aquifers of Southern Bangladesh: the case against sustainable abstraction. Sci Total Environ 454–455:627–638

Revelle R, Lakshminarayana V (1975) The Ganges water machine. Science 188:611–616

Shahid S (2010) Rainfall variability and the trends of wet and dry periods in Bangladesh. Int J Climatol 30:2299–2313

Shamsudduha M (2013a) Groundwater-fed irrigation and drinking water supply in Bangladesh: challenges and opportunities. In: Zahid A et al (eds) Adaptation to the impact of climate change on socio-economic conditions of Bangladesh. Alumni Association of German Universities in Bangladesh, German Academic Exchange Service (DAAD), Dhaka, pp 150–169

Shamsudduha M (2013b) Groundwater resilience to human development and climate change in South Asia, GWF discussion paper 1332. Global Water Forum, Canberra, Australia

Shamsudduha M, Chandler RE, Taylor RG, Ahmed KM (2009) Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. Hydrol Earth Syst Sci 13:2373–2385

Shamsudduha M, Taylor RG, Ahmed KM, Zahid A (2011) The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. Hydrogeol J 19:901–916

Shamsudduha M, Taylor RG, Longuevergne L (2012) Monitoring groundwater storage changes in the highly seasonal humid tropics: validation of GRACE measurements in the Bengal Basin. Water Resour Res 48:W02508

Shiklomanov IA (1993) World fresh water resources. In: Gleick PH (ed) Water in crisis: a guide to the world's fresh water resources. Oxford University Press, New York, pp 13–25

Taylor RG et al (2013a) Ground water and climate change. Nat Clim Change 3:322–329

Taylor RG, Todd MC, Kongola L, Maurice L, Nahozya E, Sanga H, MacDonald AM (2013b) Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. Nat Clim Change 3:374–378

UCL (2013) The security of deep groundwater in southeast Bangladesh: recommendations for policy to safeguard against arsenic and salinity invasion. University College London, London, p 78

WARPO (2000) National water management plan (NWMP)—draft development strategy report, Water Resources Planning Organization (WARPO). Ministry of Water Resources, GoB, Dhaka

Yu W, Voss CI, Michael HA, Ahmed KM, Feinson L, Khan MMR, Tuinhof A (2010) Implications of climate change on fresh groundwater resources in coastal aquifers in Bangladesh. Report No. 56556, The World Bank, South Asia Region, Dhaka, p 105

Zahid A, Ahmed SR (2006) Groundwater resources development in Bangladesh: contribution to irrigation for food security and constraints to sustainability. In: Sharma, BR et al (eds) Groundwater research and management: integrating science into management decisions. Groundwater governance in Asia series-1. International Water Management Institute, Colombo, Sri Lanka, pp 27–46

Zahid A, Hassan MQ, Islam K, Islam MS (2012) Strengthening of monitoring network to assess the impacts of climate change on groundwater resources of Bangladesh. In: Zahid A et al (eds) Impact of climate change on water resources and food security of Bangladesh. Alumni Association of German Universities in Bangladesh, Dhaka, pp 22–43

Chapter 32
Model Impact of Climate Change on the Groundwater Flow and Salinity Encroachment in the Coastal Areas of Bangladesh

Anwar Zahid, A. F. M. Afzal Hossain, Gautam C. Mridha, M. Rezaul Hasan, Kamrul Islam and M. Salah Uddin Abbassi

Abstract The coastal population of Bangladesh has already been suffering from the salinity encroachment both in groundwater and surface water regime. Reduced river discharge, coastal surges, shrimp farming, lowering of groundwater table due to dry season irrigation in a large part of the country accelerate the rate of saline water distribution. In addition, sea level rise, due to the impact of climate change, may contribute to salinity encroachment on coastal freshwater resources, particularly in the shallow alluvial aquifers. Though the groundwater table is within 2–5 m below ground surface, availability of fresh and safe water in the coast is very limited in upper aquifers because of the arsenic contamination and water salinity. For the coastal population, deep (>250 m) tube wells are the main source of drinking water and irrigation water supply is mostly restricted to surface water including rainwater. In monsoon, freshwater pockets are available at the shallow depth (<8 m) from seasonal precipitation but mostly turn to brackish condition during dry period. Therefore, assessment and monitoring of development stress and probable impact of climate change on freshwater resource are utmost important. The main purpose of the study is to assess the impact of climate change and development stresses on the availability of fresh water resources in the coastal area. For that purpose, integrated hydrological model has been prepared describing the subsurface condition both the saturated and unsaturated zone together with the influence of various water components of the hydrological cycle. Groundwater salinity models are developed to simulate salinity transport in the sea, river and through the porous medium of aquifer for a range of existing and possible future

---

A. Zahid (✉)
Directorate of Ground Water Hydrology, Bangladesh
Water Development Board, Dhaka, Bangladesh
e-mail: anwarzahidb@gmail.com

A. F. M. Afzal Hossain · G. C. Mridha · M. Rezaul Hasan · K. Islam
Institute of Water Modelling (IWM), Dhaka, Bangladesh

A. Zahid · M. S. U. Abbassi
Center for Water and Environment (CWE), Dhaka, Bangladesh

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_32

conditions. It has been seen from the simulation result of the model that under climate change condition during the month of March and April, the salinity level is highest for all river system within the study area and significant during period from December to June. The climate change scenario illustrates that the groundwater level increases within the range of 0.6–0.8 m under climate change scenario. Movement of salinity is found insignificant from the river to the aquifer. Major rivers in the south central coast there is a considerable interaction between surface water and groundwater due to the tidal effect. On the other hand, there is negligible interaction between the aquifer and adjacent river in the south-eastern coastal plain.

32.1 Introduction

The climate change, one of the greatest environmental challenges today the earth is facing. The weather pattern is changing due to the rising global temperatures. Bangladesh has very little role in greenhouse gas emissions which are causing climate change, but this country is the most vulnerable to the changes. The most direct impact of climate change is sea level rise (SLR) which contributes to saline water intrusion or inundation of coastal freshwater resources, particularly in the shallow alluvial aquifers. In Bangladesh coast, few studies depict the range of sea level rise by 2,100 as 30 to 100 cm, while the IPCC gives a global average range between 9 and 88 cm (IPCC 2008). Groundwater equilibrium is also vulnerable to changes in recharge and discharge which are connected with climate change. The population in the coastal belt may grow to about 60 million by 2050, and securing provision of safe drinking water for this growing population is needed. Ensuring the availability of freshwater for dry irrigation season to meet changing food demands will also be critical (World Bank-USGS 2010).

The shallow and the main aquifers (BWDB-UNDP 1982) are generally productive those can yield large quantities of water, but human consumption is susceptible in many areas because of water quality problems like contamination of arsenic in shallow groundwater and saline water encroachment in the coastal belt (Zahid et al. 2013; BWDB 2013; Zahid et al. 2009a; van Geen et al. 2003; DPHE-BGS 2001; Ravenscroft et al. 2001; Yan et al. 2000; Nickson et al. 1998; Bhattacharya et al. 1997). Therefore, a comprehensive data collection program to monitor SLR and groundwater level has been considered. Study on the measurement of groundwater level and salinity has been carried out. A mathematical model has been developed for this study to allow for simulation of both groundwater flow and the encroachment of saltwater in the subsurface. The models will help in understanding and assessment of the salinity intrusion process for present conditions and then evaluate changes due to increased groundwater uses and sea level rise.

The principal target of the water model study is to evaluate Upazila (sub-district)-wise surface water and groundwater resources and trends of water level fluctuation due to groundwater abstraction as well as to assess salinity intrusion, salinity level and movement of salinity considering the impact of climate change under two pilot areas, i.e. south central coast (study area-1) and south-eastern coastal plain (study area-2) of Bangladesh. The specific objectives are given below.

- Assessment of surface water resource in the selected rivers using surface water model.
- Determination of Upazila-wise groundwater resources by simulating groundwater model.
- Evaluation of the changes in groundwater table due to the increased withdrawal of groundwater.
- Assessment of the present extent of salinity encroachment in the rivers system as well as in groundwater aquifers.
- Study the impacts of sea level rise due to climate change on the surface water as well as groundwater salinity distribution.

32.2 Study Area

32.2.1 Study Area-1

The study area-1 is of 4,867 km^2 and consists of 15 Upazilas of the districts of Barisal, Patuakhali, Barguna, Pirojpur and Jhalokathi (Fig. 32.1). The area lies

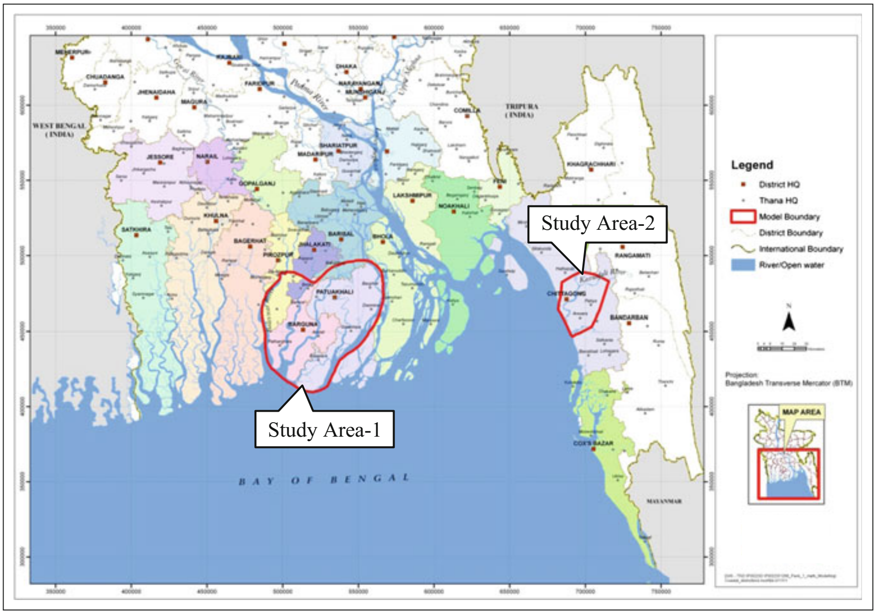


Fig. 32.1 Location map of the study areas in the coastal belt of southern Bangladesh

approximately between 89° 51′ 3.61″E and 90° 39′ 38.93″E longitudes and 21° 46′ 59.61″N and 22° 36′ 2.78″N latitudes. The area is bordered by Baleswar River system on the west, Tentulia River on the east and the Bay of Bengal on the south.

32.2.2 Study Area-2

The study area-2 lies approximately between 91° 45′ 5.03″E and 92° 6′ 5.90″E longitudes and 22° 6′ 14.67″N and 22° 30′ 29.93″N latitudes. This area is of about 946 km^2 covering entire Chittagong district of south-east Bangladesh (Fig. 32.1). Three major rivers namely Karnaphuli, Sangu and Halda surround this area.

32.2.3 River System

For its wide and complex drainage and tributary system, the Bengal delta covers a unique position among the larger deltas of the world. Numerous big and tiny channels criss-cross the delta of which some are active while some are decaying. The Sundarbans, world’s largest mangrove forest situated in the south-western portion of the Ganges delta, is completely a maze of tidal creeks and channels. The river channels carry a considerable amount of water through its distributaries which join tidal channels and estuarine creeks. Plenteous lakes, marshes and low-lying swamps are also present in the delta.

Frequent shifting of courses is another remarkable feature of the delta rivers. The Ganges–Padma and many other rivers have been ceaselessly changing their courses or migrating and occupying new locations. These deltaic rivers have common flow trend and generally direction is north–south. In the western part of the delta, most of the rivers such as the Ichamati and Kuttiganga follow a rather south-easterly direction while some of the eastern rivers show a south-westerly tendency (viz. the Arial Khan, Bishkhali). The flow tendencies of the deltaic rivers have a linkage to the regional geotectonic features. The main outlet of the Ganges–Padma has long been maintaining a south-easterly direction. In the Chittagong coastal plain, the river basins are characterized by hilly terrain and foothills with a long strip of lowland coastal plains along the Bay of Bengal. Besides the river systems, there are innumerable small streams which drain the foothills to the sea.

Most of the rivers of study area-1 lie in south-west region are dominated by the tide. Many rivers carry very little freshwater flow, but instead act as tidal channels for tides originating in the Bay of Bengal. The southern rivers mainly comprise tidal estuary systems, the largest being the Baleswar, Bishkhali, Buriswar and Tentulia. There are huge numbers of small tidal channels, which interconnect these large rivers. The Baleswar River is a part of the Gorai-Madhumati–Kocha–Baleswar system, and other important river system Arial Khan–Kirtonkhola–Uzirpur–Bishkhali–Buriswar lies also inside the south-west region. The River Tetulia lies on the Lower Meghna system.

The Karnafuli River originates in the Lushai Hills of Mizoram in India. Downstream of the Kaptai Dam that was constructed over the Karnafuli receives its tributaries named the Ichhamati River and the Halda River on its right bank and the Boalkhali on its left bank. However, The Halda River originates from the highlands of Khagrachhari. The Karnafuli River is tidal for about 80 km length from its outfall to the downstream of Kaptai Dam. The Sangu River originates in the Arakan hills of Myanmar and its total length up to outfall is about 160 km. Before its outfall, it meets with several hilly streams and khals. The river is tidal for about 30 km length.

32.3 Model Simulations

In order to achieve the study objectives, mathematical modelling supported by comprehensive data collection program has been carried out. Major activities of the study include cross-sectional survey, hydrometric data collection, computation of water demand, model calibration and validation. In this study, surface water models are simulated using MIKE 11 and groundwater models are developed using MIKE-SHE programs. The surface water model set-up has been included existing river systems and updated topographical features while in groundwater models, hydrogeological setting, aquifer properties, DEM, land use pattern, etc., are incorporated. The coupled model has been calibrated using the data for the period of 2000–2005 and validated for the period of 2006–2009. The validated model was simulated for base condition and climate change conditions. In some key locations, surface water resources have been assessed based on average year. Groundwater resources have been assessed considering yield criteria of 6 and 7 m depth from ground surface, and potential recharge. Usable recharge is considered as 75% of the potential recharge; however, various uncertainties inherent in different assumptions.

32.3.1 Model Set-up for the Study

Model set-up includes identification of the area model domain (area to be modelled), river system that would be included in the model, delineation of catchment area, identification of hydraulic structures, identification of geological layers and their hydraulic properties, identification of boundary stations and conditions, land use and preparation various hydro-meteorological input data. A brief description of the model set-up activities is presented in the following sections.

32.3.1.1 Simulation Specification

For the whole simulation period, the time step and computational control parameters for overland flow, saturated and unsaturated zone have been considered. The periods of simulation of the calibration, validation and prediction models were user-specified and different.

32.3.1.2 Model Domain and Grid Size

Two study areas have been discretized into 1,000 m square grids. For south central coast, the model has 5,127 grid cells, where 4,878 grids are the computational cells and the rest are boundary cells. For Chittagong, i.e. south-eastern coastal plain, the model has 1,052 grid cells where 109 grids are the boundary cells. The basic units, i.e. grid cells, provide all the spatial and temporal data as input and to obtain corresponding data as output.

32.3.1.3 Topography

A well-prepared DEM is prerequisite for visualizing the floodplain topography and for accurate modelling. A DEM of 300 m resolution has been used to define the topography of the study area. Elevation of the area varies from 0.72 to 3.0 m PWD.

32.3.2 Coupling of Surface Water and Groundwater Model

The coupling of surface water with groundwater model involves a number of provisions. The coupling of river reaches has been specified in river model. Groundwater system has been coupled with all the major rivers and canals within the study area. The flooding and variety of river-aquifer exchange condition have been also defined. The interaction of flow between the saturated zone and the river component is due to hydraulic gradient, properties of riverbed substance such as leakage coefficient. For river-aquifer interaction, leakage coefficients along with the hydraulic conductivity of the saturated zone are taken into consideration for most of the river reaches.

32.3.3 Main Calibration Parameters

Two pilot areas are very different from other areas of the country as the groundwater flow and available water resource to a large extent are controlled by the relatively impermeable clay layer and the limited aquifer extent in the area.

For the south-west coastal region, the presence of the clay layer and the transmissivity of the clay layer are very crucial for the simulation of both groundwater flow and its dynamics. Hence, the geological model is one of the major components in the calibration of the numerical model. As the geological model is not a direct calibration parameter, any uncertainties in the geological model have to be reflected in the calibrated parameters (mainly conductivity and storage terms) for the numerical model. Although many of the parameters have been collected through field surveys, some minor adjustments have been needed during the model calibration. During this process, the emphasis has been given on maintaining these adjustments within a realistic range.

32.3.4 Formulation of Options for Groundwater Level Model

The calibrated and verified models are simulated for a number of development options or alternatives, and the results are analysed to evaluate the performance to achieve the objectives for the study area. Technicalities of some probable options are:

Option I: Existing Situation, i.e. Base Condition

- Hydrological situation considered as average situation based on proposed year selected from long-term data and information.
- All active features including crop coverage, domestic, irrigation and industrial demand, etc.

Option II: Climate Change Option with Rise of Sea Level

- Hydrological situation considered as average situation for the years 2030 and 2050 for the selected design year.
- Future condition of ea level rise for the years 2030 and 2050 has been adopted from the results of IPCC model.

Option III: Climate Change Option with Predicted Sea Level Rise and Increased Groundwater Withdrawal due to Human Consumption

- Hydrological situation considered as average situation in the years 2030 and 2050 using relevant climate change parameters.
- Increased future demand of groundwater for household, irrigation and industrial water supply.

32.3.5 Salinity Intrusion Model

Salinity model has been used to assess the salinity intrusion towards upstream due to the increase of human activity, reduction of dry period flow and climate change within the study area using existing Bay of Bengal model of IWM and south-east regional salinity model. Peak salinity maps have been produced to assess the change in salinity distribution pattern for base and different scenarios. Salinity modelling aids to assess the salinity intrusion under known boundary conditions without detailed measurements throughout the entire coastal region. To model the salinity variation in the estuary, it is very important to have a well-calibrated water flow model. The salinity model, based on this hydrodynamic model, will describe the transport and advection of salinity.

The 1-D salinity model consists of three different modules: rainfall-runoff, hydrodynamic (HD) and salinity model (AD). The salinity intrusion in the river system is very much dependent on the freshwater flow from the upstream, tidal dynamics of the coastal river system and surface water runoff as a result of rainfall events. This is why the salinity model needs the results from the rainfall-runoff model and the hydrodynamic model.

To estimate the runoff generated from rainfall occurring in the catchments of the model area, the rainfall-runoff model (NAM) is applied. In the catchments, the model considers the basin characteristics including specific yield, initial soil moisture contents and irrigation/water extraction from the surface or groundwater sources. In the model, used rainfall and evaporation data have been collected from secondary sources (Bangladesh Water Development Board and Bangladesh Meteorological Department). Evaporation, percolation and other losses including catchment runoff are considered as outputs in the model.

The 1-D hydrodynamic model calculates water flow and water level using the runoff generated from the catchments (output of NAM model) as well as taking input of flow from the upstream rivers. It incorporates water flow data at upstream boundaries and water level data at downstream boundaries. The 2-D Bay of Bengal (BoB) model uses the water flow generated from the 1-D HD model as its upstream boundary and water level boundary from Global Tide Model as its downstream boundary. The salinity measurements are used as the upstream boundaries of the BoB salinity model and constant 32 ppt constant as its downstream boundary in the boundary. The BoB model gives the downstream salinity boundary for the 1-D salinity models. Usually the salinity at the upstream of the regional 1-D salinity models is taken from salinity measurements (zero salinity most of the times).

The available salinity models for the coastal area of Bangladesh has been developed based on MIKE 11 and MIKE 21 FM modelling system and applied to a number of projects over the last 20 years, to find the spatial and temporal variation of salinity level over a year, and also to examine the effect of climate change on landward movement of salinity front and to assess the freshwater availability. This model follows the one-dimensional (vertically and laterally integrated) equation for the preservation of mass of objects in a solution, i.e. the one-dimensional advection-dispersion equation. Two transport mechanisms are reflected in the equation:

- The mean flow advective or convective transport.
- Dispersive transport because of concentrations gradients.

The study to understand the salinity intrusion process in the coastal aquifer has been conducted using FEFLOW density-dependent groundwater modelling tool which is coupled with MIKE 11 hydrodynamic modelling tool.

32.3.6 Aquifer System

BWDB-UNDP (1982) study defines three aquifers, i.e. the shallow, the main and the deep aquifers on a regional basis. Based on isotopic studies, a three-tier division with four types of the aquifers has been classified by Aggarwal et al. (2000). With slight adjustments of the BWDB-UNDP (1982) study, DPHE-BGS (1999, 2001) also divides the aquifer zones as three-tier. In the coastal delta, these aquifers are named based on lithology (Zahid et al. 2009b) and are described in this section. The shallow, i.e. the 1st aquifer, that is the upper Holocene aquifer, extends down to 50 to over 100 m depth, below a considerably thick upper clay and silt unit in many places. Sediments of the aquifer are composed of fine sand with clay lenses. This 1st aquifer is dated by Aggarwal et al. (2000) and Zahid et al. (2015) as about 40–135 years old. The main or the 2nd water-bearing zone is generally underlain and overlain by silty clay bed. This aquifer is encountered down to 250–300 m depths and composed mainly of fine-to-very fine sand, at some places inter-bedded with clay lenses. These Mid-Holocene aquifers can be compared with the main aquifer (BWDB-UNDP 1982), the 2nd aquifer or the lower shallow aquifer (BGS-DPHE 2001) of the floodplain aquifers of the country. Age of water from this aquifer is dated as about 2300–3000 years old (Aggarwal et al. 2000; Zahid et al. 2015). The deep, i.e. the 3rd aquifer, has been encountered to depths of 300–350 m, generally below a silty clay aquitard. This aquifer is composed of grey to dark grey fine sand that in places inter-bedded with thin silty clay or clay lenses. Appearance of clay or silty clay aquitards is not common in all locations. Regionally, aquifers down to the investigated depth of 350 m seem hydraulically connected. However, in many places 3–4 aquifer units are encountered separated by aquitards and limited scale abstraction of groundwater from any aquifer depth does not affect the others. These Late Pleistocene-Early Holocene aquifers to some extent correspond to the deep aquifer (BWDB-UNDP 1982; BGS-DPHE 2001) and the 3rd aquifer (Aggarwal et al. 2000) by different studies. This aquifer water is dated as about 1,400–20,000 years old (Aggarwal et al. 2000; Zahid et al. 2015). For model simulations, aquifer unit has been defined as follows.

32.3.6.1 Upper Shallow Aquifer (1st Aquifer)

Water table aquifers generally exist within 50 m below ground level consisting mostly of heterogeneous assemblage of sand, silt and clay. In the coastal areas, this aquifer contain saline water in most places. Freshwater pockets are encountered in places, generally within 5–10 m depths.

32.3.6.2 Lower Shallow Aquifer (2nd Aquifer)

Lower aquifer systems in coastal area exist 50–150 m which contains saline water.

32.3.6.3 Deeper Aquifer (3rd Aquifer)

This aquifer is deeper more than 250 m. It generally consists of fine-to-medium sands and mostly of confined to semi-confined in nature. It contains potable water and the aquifer is sandwiched by saline water layer at the top and bottom (Fig. 32.2).

The groundwater level fluctuation trend indicates the hydraulic connectivity of these aquifers (Zahid et al. 2009b). Regionally aquitards separating aquifers are not continuous. Deep aquifers may cause leakage of arsenic or any other contaminant from the shallow depths to aquifers below because of uncontrolled development. Where clay layers above pumping wells are absent, vertical infiltration of saltwater due to periodic storm surge flooding is also significant (World Bank-USGS 2010). Vulnerability to lateral saltwater migration due to sea level rise depends on aquifer

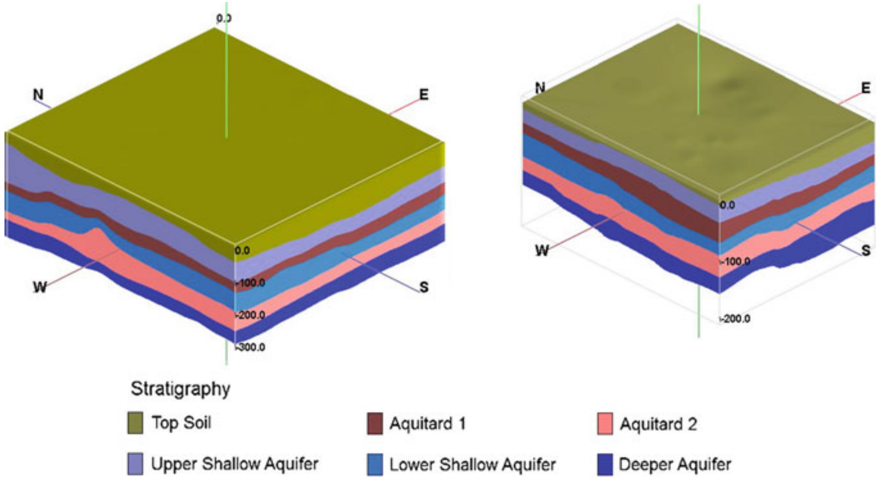


Fig. 32.2 3-D stratigraphic model of the study area-1 (left) and study area-2 (right)

hydraulic properties. The occurrences of paleo-brackish water entrapped inland during rapid regressive events between 12,000 and 10,000 years after transgression period between 18,000 and 12,000 years cause salinization in small areas (Acharyya 1999).

32.4 Study Findings

Major findings of the study are summarized below.

32.4.1 Surface Water

Availability of surface water resources has been assessed at upstream and downstream of four major rivers of the study area for base condition and year 2030 and 2050. Surface water salinity has also been assessed at the same locations for the present condition. Out of eight locations in four rivers where surface water availability have been assessed, surface water salinity remains below around 1.00 ppt in three rivers, namely Biskhali, Bureswar and Tetulia. In Baleswar River at the downstream location, salinity becomes more than 1.00 ppt during the dry season and reaches to about 6.50 ppt. At the upstream location, however the salinity remains below 1.00 ppt in both seasons. It is noticed that at the upstream locations of all the rivers both seaward (flow towards sea) and inward (flow towards inland) flow increase in year 2030 and 2050 compared to base case.

32.4.2 Groundwater

The potential recharge in south central coast varies from 183 mm at Bhandaria Upazila to 291 mm at Kalapara Upazila and from 396 mm at Patia Upazila to 522 mm of Panchlaish under average hydrological condition. In south central coast, during dry season, groundwater salinity remains below 1.00 ppt only in a small part of Bamna, Amtali and Kalapara Upazilas, and in rest of the area salinity remains above 1.00 ppt. In the wet season, this situation noticeably improves. Only in few Upazilas, e.g. Patharghata, Mathbaria, Bhandaria and Khantalia, the groundwater salinity remains above 1.00 ppt. In Chittagong, i.e. south-eastern coast, in general the groundwater salinity situation is better compared to south central coast. In the wet season only in a small localized area in Chittagong city, the presence of salinity greater than 1.00 ppt is noticed. Except this pocket, in other parts of Chittagong groundwater, salinity is well below 1.00 ppt. On the other hand in the dry season, the 1.00 ppt salinity range extends over a larger area extending from the seaside up to the eastern side of the pilot area following a narrow strip along the middle part of the area.

Maximum depth to groundwater table in south central coast is 3.00 m during post-monsoon season and 4.00 m during the dry season at present condition. No significant change in maximum depth-to-groundwater table in the pre-monsoon season is seen under climate change condition. On the other hand under climate change condition, compared to the base case, there will be a noticeable increase in post-monsoon recharge. Study indicates that groundwater flow paths and travel time are primarily controlled by hydrogeologic characteristics (Zahid et al. 2015).

32.4.2.1 Recharge Characteristics

Recharge means the replenishment of groundwater storage that is depleted by withdrawal of groundwater with the tube wells and by natural processes. The sources of groundwater replenishment of the study area are deep percolation of rainwater and irrigated water from the crop fields, seepage from the rivers, khals, ponds and other waterbodies, and horizontal flow of groundwater from the surrounding areas. The hydrographs rise steadily until the levels are within about 1–2 m of the surface during monsoon when a dynamic equilibrium is reached among the water table, surface waterbodies and deep-rooted vegetation (Ravenscroft 2003). Recharge to groundwater depends on different physical and climatic conditions as well as hydraulic properties related to soil, aquifer and water. Recharge to groundwater rainfall begins with the rainfall from late May and continues up to October while recharge from irrigated field occurs from December to the end of March.

The aquifer becomes full in the months of August or September but excess rains are available to recharge till October if there is room for recharge. By creating additional storing space, the magnitude of annual replenishment of groundwater may be increased but it depends on the availability of water and the percolation rate of soil. Direct percolation occurs during the rains from naturally submerged fields and unsubmerged lands. Excess rainwater is also stored within the bund that surrounds the paddy field. This water is also available for recharging the groundwater after meeting the demand of evapotranspiration. The long-term average of annual replenishment of groundwater may be considered as safe yield. Groundwater storage reduces due to withdrawal for irrigation, domestic and industrial uses and outflow to rivers, canals, ditches, ponds and other waterbodies. The loss of groundwater due to evaporation from water table and transpiration by plants also attributes to depletion of groundwater storage.

32.4.2.2 Potential Recharge

Potential recharge is the actual recharge plus rejected recharge. The main source of groundwater is rainfall in the study area. In the study area, generally recharge to groundwater starts from the 1st decade of May or June and continues till the end of October when aquifer becomes full in average hydrological condition. During October, there is still some rainfall, which goes straightway as runoff because aquifer is full. Excess rainfall for the month of October could have been recharged to groundwater if there were room for recharge. Sometimes the water table attains this highest elevation before September or August. After that there is no room to recharge to groundwater but excess rainfall is available, which is mainly lost by surface runoff. This water is termed as rejected recharge. This rejected recharge can be included to the actual recharge to estimate the potential recharge. The potential recharge can be estimated as (Eq. 32.1).

$$V_{\mathrm{p}} = K_{\mathrm{v}} \times t \tag{32.1}$$

where V_{p} is the potential recharge volume (mm), K_{v} is the deep percolation rate (mm/day), and t is the time of recharge in days. The term t is considered from the start date of recharge (May or June) till the end of October when rainfall virtually ceases.

Under the present study, Upazila-wise potential recharge has also been estimated from model results simulated for the study areas during monsoon period of 2006 and 1998, respectively. For south central coast, Potential Recharge = 224 mm (for SZ-Storage Change) + 22 mm (for UZ-Storage Change) = 246 mm. In estimating potential recharge, the components of irrigation by DTW and STW shown in unsaturated zone have not been considered because there is no irrigation after 1st June. For Chittagong area, Potential Recharge = 356 mm (for SZ-Storage Change) + 40 mm (for UZ-Storage Change) = 396 mm. In estimating potential recharge, the components of irrigation by DTW and STW shown in unsaturated zone have not been considered because there is no irrigation after 1st May. Overland flow storage change and unsaturated storage change have also not been considered because these changes do not contribute to groundwater storage change in saturated zone.

32.4.2.3 Safe Yield Criteria for the Assessment of Groundwater Resources

Because of the availability of good aquifer and limited scope of surface water development, groundwater in the study area is being used to meet the irrigation as well as potable and industrial demands. DTWs and STWs are being used for abstracting irrigation water; HTWs are being used for drinking water supply in the rural areas; and DTWs are being used to meet the drinking and industrial water demands in the municipal areas. As HTWs and STWs operate under suction mode, these become completely inoperable condition when depth-to-groundwater table goes below suction limit, i.e. 7 m from ground surface. Wetlands, ponds and small streams also dry out when groundwater table goes below 7 m. On the other hand, HTWs and STWs can operate with full efficiency when groundwater table remains within 6 m from ground surface. If water table remains within 6–7 m depth, HTWs and STWs still can abstract water but efficiency will be less and more energy will be required.

Considering these facts, to ensure the drinking and irrigation water supply through HTWs and STWs with full operational efficiency, 6 m depth of groundwater table from ground surface has been considered as safe yield limit. The 7 m depth of groundwater table has also been estimated considering for the preservation of wetlands, ponds, dug wells and in-stream flow during dry period.

32.4.2.4 Groundwater Resources Assessment

In general, dry period crops HYV Boro in particular require maximum amount of irrigation from groundwater source because during this period practically there is almost no rainfall. Normally, dry season irrigation starts in the 1st decade of December. As such available groundwater resources in 1st decade of December would help in determining the area coverage of dry season irrigation. On the other hand, for assessing the potential recharge of an area, which is one of the main objectives of the present study, it is justified to assess the groundwater resources on that period when the groundwater table attains its peak. Under the present study, it is found that groundwater table attains its peak during the period of September or October. Considering this, 1st November has been chosen under the study for the assessment of groundwater resources. The values of specific yield of the saturated thickness of the corresponding layers have been taken from the calibrated model.

Based on saturated thickness up to the 6 and 7 m depths, the availability of groundwater resources are estimated 6 and 7 m multiplied by specific yield and the area (volume of water = area × Δh × S_Y, where Δh is the saturated thickness within 6 and 7 m depths). Model grid-wise groundwater availability on 1st November has been estimated following the procedure. Only single geological layers exist within 7 m depth from data analysis. Saturated thicknesses of these two layers have been calculated based on following considerations:

- Case-1: Entire saturated thickness lies only in 1st layer, if thickness of 1st layer exceeds 6 or 7 m.
- Case-2: Entire saturated thickness lies only in 2nd layer, if thickness of 1st layer remains above the groundwater table.
- Case-3: Saturated thickness lies in both 1st and 2nd layers, if case 1 and case 2 do not occur. To find out the saturated thickness of 1st layer, simply depth of water table is subtracted from the 1st layer thickness. To find out the saturated thickness of 2nd layer, part of 1st layer within the saturated thickness is subtracted from the entire saturated thickness.

To obtain groundwater level simulation of the monsoon period, it is necessary to simulate the model from a certain time prior to the period of interest. Since in this case monsoon period was the period of interest, the model was simulated from previous dry season and as such the lowest groundwater level of the dry season was chosen as the initial head. The BWDB (2013) and DPHE-DANIDA (2001) studies indicate that the erratic occurrence of small freshwater pockets at depth is reported all over the coastal belt. The density of freshwater (1,000 kg/m^3) is less than the density of saline water (1,004 kg/m^3 for a chloride content of 3,000 mg/l); therefore, deep freshwater would normally be expected to rise above, or mix with, saline water (DPHE-DANIDA 2001). There is a strong correlation of Na^+ and Cl^- with TDS (r^2 = 0.9175–0.9908 and r^2 = 0.8469–0.9765, respectively) depicting that these ions have originated from the same saline water source (Zahid et al. 2008). Na^+ shows a strong correlation with Cl^- (r^2 = 0.8299–0.9956) also, indicating that the same source of saline waters is the origin of these ions. The fresh groundwater and seawater mixing are also supported by the relationship between $Cl^-:HCO_3^-$ ratios and Cl^-. Few water samples show lower ratios of $Cl^-:HCO_3^-$ ratios and Cl^- and can be considered as freshwater.

32.4.2.5 Spatial Distribution Map of Depth-to-Groundwater Table

For option I, spatial distribution maps of maximum and minimum depth-to-groundwater tables were prepared for 01.04.2006 and 01.12.2006 to see the depth-to-groundwater table and range of fluctuation of groundwater table. Maximum depth-to-groundwater table remains in the range between 0 and 4.0 m in most of the areas, whereas minimum depth-to-groundwater table remains in the range of 0–3.0 m. The fluctuation of groundwater table in south central coast is in the range of 0.5–1.0 m. In Chittagong coastal plain, the maximum depth-to-groundwater table remains in the range between 2.0 and 15.0 m in most of the areas, whereas minimum depth-to-groundwater table remains in the range of 1–2 m. The fluctuation of groundwater table in south central tidal plain is in the range of 2–3 m. Due to pumping at the model surface, the hydraulic head cannot be reduced because of providing an unlimited source of water (Michael and Voss 2008). Since the irrigation pumping has a short-range sequence, neither model input nor results differ in time.

Like option I, maximum and minimum depth-to-groundwater table and range of water table fluctuation have been evaluated under option II. A comparison of depth-to-groundwater table on 1st April of 2006 and 2030 shows that there is significant change in the depth-to-groundwater table between these two years. In the year 2030, the area under depth range 0–2 m as observed in 2006 almost totally disappears and most of the area transfers to depth range of 2–4 m. Subsequently area under greater depths also increases in 2030 compared to 2006. A comparison of depth-to-groundwater table of 1st April 2030 and 2050 shows no appreciable change. A comparison of the minimum depth-to-groundwater table of 2006, 2030 and 2050 shows that there is no appreciable change in the minimum of those values in three years which imply that the groundwater table returns to the original position at the end of the monsoon season.

Like option I and II, for option III, spatial distribution maps of maximum and minimum depth-to-groundwater tables were prepared for year 2030 and 2050 for the study areas to see the depth-to-groundwater table and range of fluctuation of groundwater table (Figs. 32.3 and 32.4). For south central coast, it can be seen that there are insignificant changes in the distribution of groundwater table both in pre- and post-monsoon season in the year 2030 and 2050 (Fig. 32.3). For Chittagong coastal plain, where water abstraction has been considered in all options, from a comparison of the groundwater table distribution in pre- and post-monsoon seasons of base year, 2030 and 2050, a nominal change is noticed (Fig. 32.4).

Model study for multi-level aquifers of south-east Bengal delta, down to 350 m, shows that, under the present situation the average travel time or age of water for the upper and the lower parts of the 1st and the 2nd and the upper part of the 3rd aquifers are 37, 133, 2,485, 2,454 and 2,297 years, respectively (Zahid et al. 2015).

32.4.3 Water Demand

Consumptive water demand for agriculture, domestic and industrial, forestry and fishery sector has been estimated for present, 2030 and 2050 under climate change condition. Agricultural water demand is significantly higher compared to other sectoral demands. Agricultural demand in PA-1 increases from 1,743 Mm under base condition to 1,815 and 1,860 Mm in 2030 and 2050, respectively. In PA-2, it increases from 304 Mm under base condition to 327 and 319 Mm in 2030 and 2050, respectively.

32.4.4 Groundwater Salinity

Three major modelling activities such as BoB salinity model, hydrodynamic salinity model, groundwater model have been developed and calibrated to achieve the study objectives. Due to the lack of data, there was lot of uncertainties in the model development.

Groundwater salinity for upper shallow aquifer varies from 12,000 to 1,000 mg/l. The maximum salinity is found to be in Kalapara Upazila which is near to coast for south central tidal plain. The dry period salinity for the major rivers, namely Baleshwar, Bishkhali, Burishwar, Tentulia, Khaprabhanga and Andarmanik, has been assessed under this study for the present condition (year 2012). As Andarmanik River is close to the Bay of Bengal, higher salinities have been observed (maximum concentration 20,000 mg/l), whereas the minimum salinities are found to be in Baleshwar River. It is seen from the simulation result of hydrodynamic salinity model that during the month of March and April, the salinity variation of salinity concentration is maximum for all river system within the project area. At Balesware river, difference of salinity for climate change scenario varies from 0.1 to 1.3 ppt;

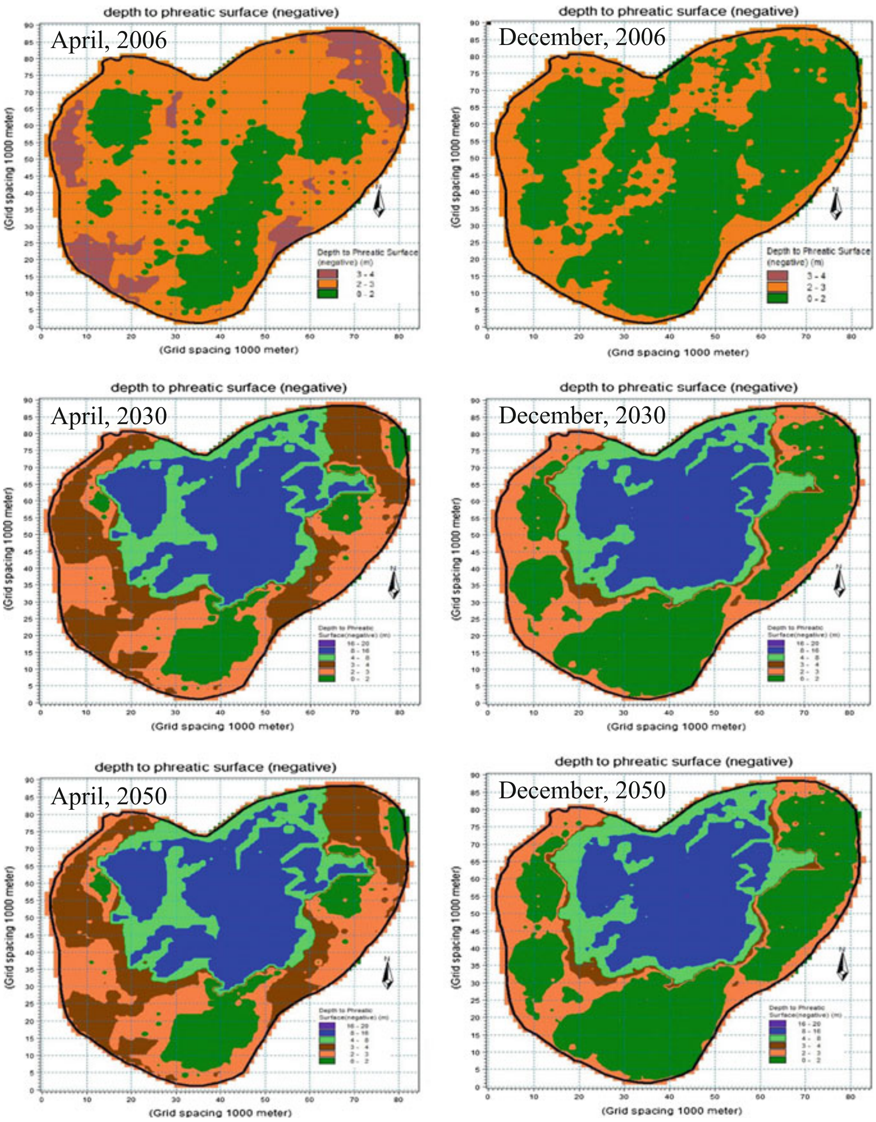


Fig. 32.3 Option III, maximum depth-to-groundwater table on April (left), and minimum on December (right) in the years 2006 (current scenario), 2030 and 2050 for the study area-1

Biskhali 0 to 1.7 ppt; Buriswar 0 to 1.5 ppt; and Tentulia 0 to 2 ppt during period from December to June. In the tidal delta, the scenario of climate change narrates that there is significant impact on groundwater level but less impact on distribution of salinity (Figs. 32.5, 32.6 and 32.7). The increase in range of groundwater level is 0.6–0.8 m because of less abstraction due to salinity. The uncertainties involved in

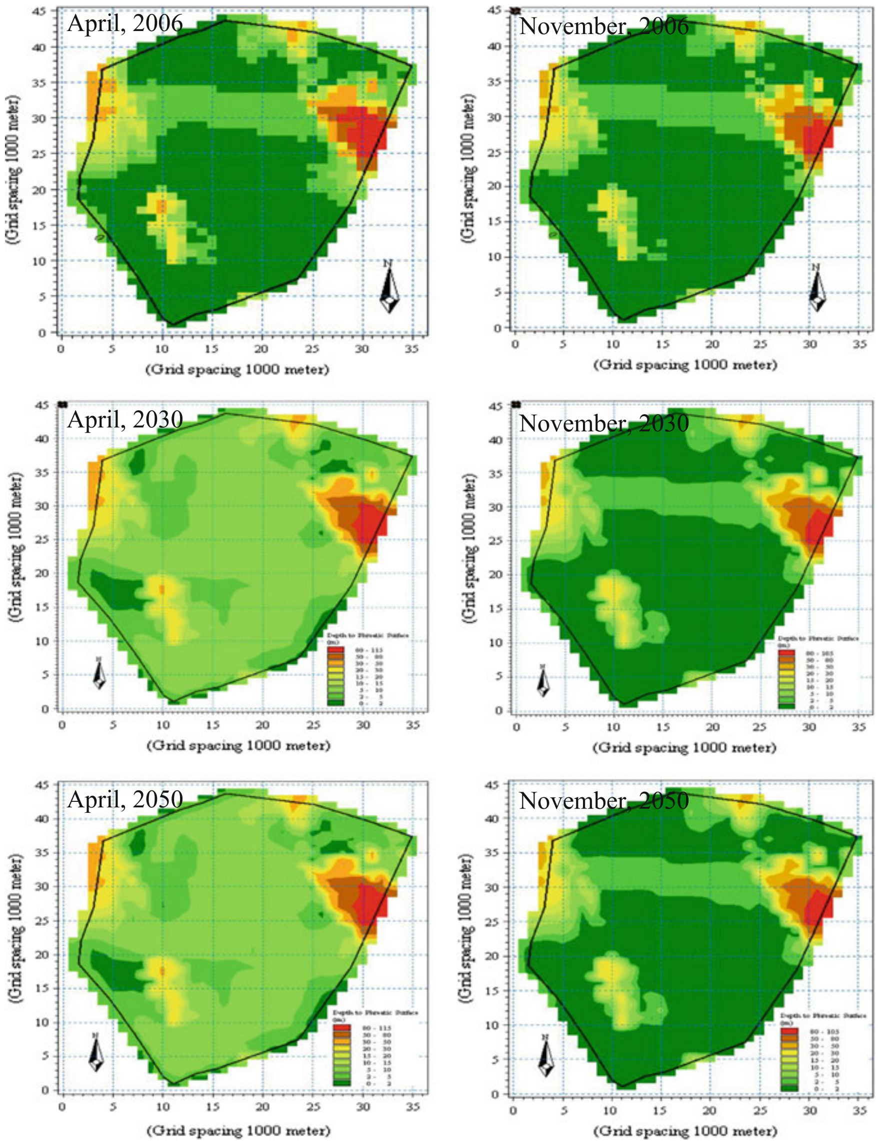
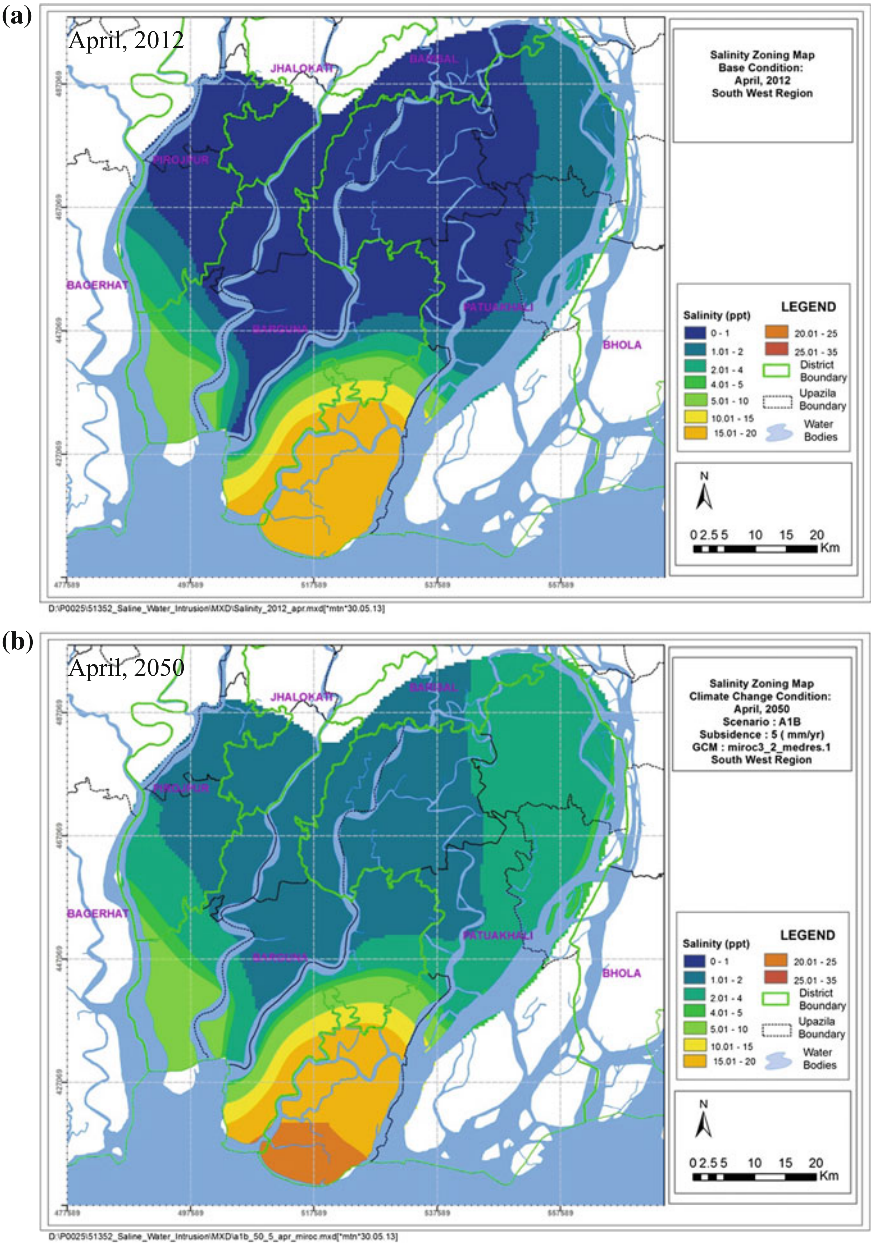


Fig. 32.4 Option III, maximum depth-to-groundwater table on April (left), and minimum on November (right) in the years 2006 (current scenario), 2030 and 2050 for the study area-2

the salinity model mainly the dispersion rate and mass transfer rate which could not be correctly addressed. The movement of salinity from river to aquifer is not significant, indicated by the long-term simulation for climate change options which may depend on the high velocity of river water, the groundwater flow direction, surface water–groundwater interactions and the seasonal variation of salinity concentration of



D:\P0025\51352_Saline_Water_Intrusion\MXD\Salinity_2012_apr.mxd[*mtn*30.05.13]

D:\P0025\51352_Saline_Water_Intrusion\MXD\a1b_50_5_apr_miroc.mxd[*mtn*30.05.13]

Fig. 32.5 Salinity zoning maps of base condition in 2012 (**a**) and impact of climate change in 2050 (**b**) rivers. This hypothesis should be verified with long-term data and also with sufficient primary data on aquifer properties. The Andharmanik river's salinity level is 17,000 mg/l for 2050 which dispersed into the aquifer up to the distance of 2.5 km from the river bank. The salinity concentration in groundwater is detected to be 1,000 mg/l.

The major sources of the salinity concentration are not only the river but also may from other sources such as local depression during different geological formation year, soil salinity due to leaching problem which also reflects the understanding of the 2010 study results of World Bank-USGS. Soil salinity has been increasing over time due to processes such as seawater inundation, tidal flooding and saline groundwater flow (Harun-ur-Rashid and Islam 2007). The coastal and offshore areas of about 14,000 km^2 have saline soils and are vulnerable to tidal flooding (MPO 1987). Michael and Voss (2009) mention that the regional ratio of horizontal to vertical hydraulic conductivity is about 10,000:1. Cyclones and associated storm surges are also predicted to increase in severity and perhaps frequency in the coastal zone of Bangladesh (Ali 1996).

Due to the tidal effect of major rivers for the south central coast, there is a considerable interaction between surface water and groundwater. For Chittagong area, there is less interaction between the aquifer and Karnafuli River. The water budget study reveals that river plays an important role to balance inflow and

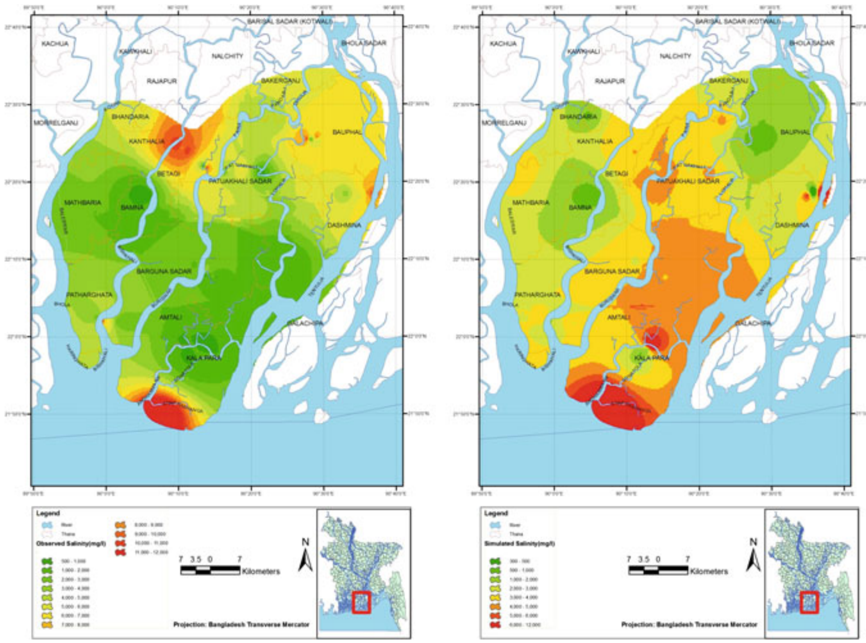


Fig. 32.6 Spatial distribution map of observed groundwater salinity (mg/l) on wet (left) and dry seasons for 2012 for upper shallow aquifer of study area-1 (right)

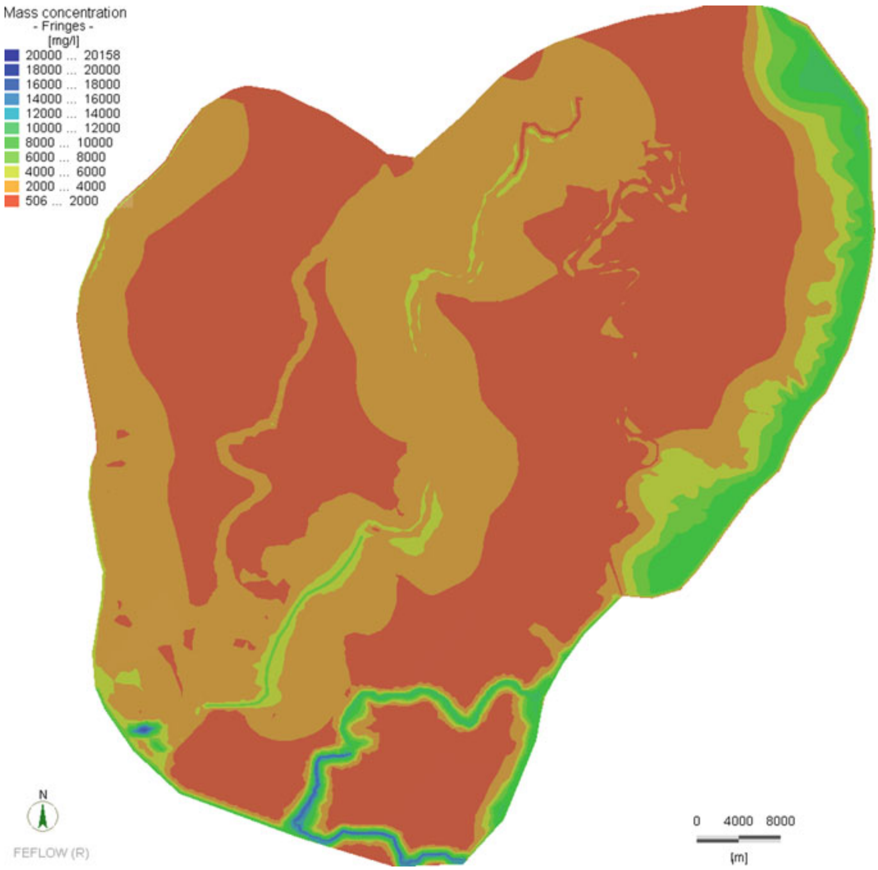


Fig. 32.7 Spatial distribution of groundwater salinity for climate change condition for upper shallow aquifer of study area-1

outflow which means there is an interconnection between the river and aquifer. Therefore, coastal zone also provides evidence of both flushing (more widespread) and saltwater intrusion in shallow zones (Ravenscroft and McArthur 2004). The study finds some lack of awareness about climate change among the stakeholders. However, the household survey indicates that many people have heard or are aware about climate change. The general conclusion is to increase capacity building among the stakeholders and to raise their awareness about the impact of climate change.

32.5 Summary

No significant change in maximum depth-to-groundwater table in the pre-monsoon season is noticed from the model simulations under climate change condition. However, in comparison to the current base condition, there will be a considerable increase in post-monsoon recharge. The water budget study shows that river plays a significant role to adjust inflow and outflow which means there is an interconnection between the river and the aquifer. The salinity movement from river to aquifer is not so significant in climate change condition but mostly depends on the subsurface lithology, velocity of river water, the groundwater flow direction and the seasonal variations of salinity concentration of rivers. The major sources of the groundwater salinity are not only the tidal rivers through which seawater mixes with fresh groundwater but also other causes like storm surges, shrimp farming might accelerate salinity in soil and water. The study reveals that the Andharmanik river's salinity concentration would be 17,000 mg/l in 2050 which is dispersed in the aquifer up to 2.5 km distance from the river bank. The salinity level of 1,000 mg/l was found in groundwater from the model simulations.

In order to properly and effectively monitor and evaluate the effect of climate change on the water resources of coastal region, the following recommendations are made.

- The climate change models used under the present study are of regional in nature. To address local issues under climate change condition, localized climate change models are needed.
- Groundwater flow model has been developed using limited data for short duration. Data scarcity was more acute in the coastal region compared to other parts of the country. Comprehensive data collection is essential to address and monitor future climate change aspects.
- Detail investigations for deeper aquifer using more number of deep test boring, aquifer test and monitoring well are necessary to have clear idea about the areal extent, thickness and potential resources in the deeper strata.
- In order to monitor the surface water and groundwater levels in an efficient way, sufficient number of auto-level recorders may be installed in the coastal area since the surface water and groundwater levels change are rapidly compared to non-tidal areas.
- In order to identify the sources of recharge of groundwater in deeper aquifer, more studies on isotope analysis of groundwater may be undertaken.

The salinity intrusion process is very difficult to identify as because of the complexity of hydrogeology of the coastal aquifer here in Bangladesh. The dynamics of saline water movement depends on a lot of parameters which are not adequately available. This study has been initiated which needs to be continued for understanding the dynamics with the regularly updated data. Long-duration time-series data of water table, water quality, i.e. salinity and aquifer hydraulic and physical properties, are needed to achieve the more reliable results. Besides hydrogeologic complexity, the climate change scenario itself contains a lot of uncertainties which may bias the model results. Calibration parameters for salinity model such as dispersion rate, density ratio are still needed to be justified with field measured data.

The model gives a preliminary idea about the groundwater level and salinity distribution which needs to be further clarified with sufficient data. Geophysical survey should be carried out in near future to clearly identify the saltwater–freshwater interface. Management Information System developed under this study should be updated regularly. Proper management of the coastal groundwater is a precondition to govern and mitigate future salinization problems caused by possible sea level rise. The deep, currently fresh coastal groundwater is likely not a permanent resource, even with no sea level rise, but careful management may enable use of the resource for very long periods of time.

Acknowledgements Bangladesh Water Development Board (BWDB), Bangladesh Climate Change Trust (BCCT) and Institute of Water Modelling (IWM) are highly acknowledged for supporting the research on assessment of coastal water resources. Professionals and officials involved in the project activities are also acknowledged for their valuable contribution.

References

Acharyya SK, Chakraborty P, Lahiri S, Raymahashay BC, Guha S, Bhowmik A (1999) Arsenic poisoning in the Ganges delta. Nature 401:545

Aggarwal PK, Basu AR, Kulkarni KM, Froehlich K, Tarafdar SA, Ali M, Ahmed N, Hussain A, Rahman M, Ahmed SR (2000) A report on isotope hydrology of groundwater in Bangladesh: implications for characterization and mitigation of arsenic in groundwater. Work performed within an IAEA–TC project (BGD/8/016), 61p

Ali A (1996) Vulnerability of Bangladesh to climate change and sea level rise through tropical cyclones and storm surges. Water Air Soil Pollut 92:171–9

Bhattacharya P, Chatterjee D, Jacks G (1997) Occurrence of arsenic contaminated groundwater in alluvial aquifers from the delta plains, eastern India: options for safe drinking water supply. Water Resour Dev 13:79–92

BWDB (2013) Establishment of monitoring network and mathematical model study to assess saline water intrusion in groundwater in the coastal area of Bangladesh due to climate change. Final report, Bangladesh Water Development Board and Institute of Water Modelling, 2500p

BWDB-UNDP (1982) Groundwater survey: the hydrogeological conditions of Bangladesh. UNDP technical report DP/UN/BGD-74-009/1, 113p

DPHE-BGS (1999) Groundwater studies for arsenic contamination in Bangladesh. Final report, rapid investigation phase. Department of Public Health Engineering, Government of Bangladesh. Mott MacDonald and British Geological Survey

DPHE-BGS (2001) Arsenic contamination of groundwater in Bangladesh. British Geological Survey and Department of Public Health Engineering, Govt. of Bangladesh; Technical Report, WC/00/19

DPHE-DANIDA (2001) Hydrogeology summary report. Department of Public Health Engineering–Danish International Development Water Supply and Sanitation Components, Ministry of Foreign Affairs, Government of Bangladesh, 129p

Harun-ur-Rashid M, Islam MS (2007) Adaptation to climate change for sustainable development of Bangladesh agriculture. Presentation at third session of the Technical Committee of the

Asian and Pacific Center for Agricultural Engineering and Machinery (APCAEM), November 20–21, Beijing, China

IPCC (2008) Climate change and water, Technical paper VI, Intergovernmental Panel on Climate Change, WMO, UNEP, 200p

Michael HA, Voss CI (2008) Evaluation of the sustainability of deep groundwater as an arsenic-safe resource in the Bengal Basin. PNAS 105(25):8531–8536

Michael HA, Voss CI (2009) Controls on groundwater flow in the Bengal Basin of India and Bangladesh: regional modeling analysis. Hydrogeol J 17:1561–1577

MPO (1987) Technical report no. 5, the groundwater resource and its availability for development, Ministry of Irrigation and Flood Control, Dhaka

Nickson R, McArthur J, Burgess W, Ahmed KM, Ravenscroft P, Rahman M (1998) Arsenic poisoning of Bangladesh groundwater. Nature 395:338

Ravenscroft P (2003) Overview of the hydrogeology of Bangladesh. In: Atiq Rahman A, Revenscroft P (eds) Groundwater resources development in Bangladesh: background to the arsenic crisis, agricultural potential and the environment. The University Press Limited, Bangladesh, pp 43–86

Ravenscroft P, McArthur JM (2004) Mechanism of regional pollution of groundwater by Boron: the examples of Bangladesh and Michigan, USA. Appl Geochem 19:1413–1430

Ravenscroft P, McArthur JM, Hoque BA (2001) Geochemical and palaeohydrological controls on pollution of groundwater by arsenic. In: Chappell WR, Abernathy CO, Calderon RL (eds) Arsenic exposure and health effects, IV edn. Elsevier, Oxford, pp 53–77

Van Geen A, Zheng Y, Versteeg R, Stute M, Horneman A, Dhar R, Steckler M, Gelman A, Small C, Ahsan H, Graziano JH, Hussain I, Ahmed KM (2003) Spacial variability of arsenic in 6000 tubewells in a 25 km^2 area of Bangladesh. Water Resour Res 39(art no 1140)

World Bank-USGS (2010) Implications of climate change for fresh groundwater resources in coastal aquifers in Bangladesh. The World Bank, South Asia Region, Sustainable Development Department, 105p

Yan X-P, Kerrich R, Hendry MJ (2000) Distribution of arsenic (3), arsenic (5) and total inorganic arsenic in pore waters from a thick till and clay rich aquitard sequence, Saskatchewan, Canada. Geochim Cosmochim Acta 62:2637–2648

Zahid A, Hassan MQ, Balke, K-D, Flegr M, Clark DW (2008) Groundwater chemistry and occurrence of arsenic in the Meghna floodplain aquifer, southeastern Bangladesh. J Environ Geol 54:1247–1260

Zahid A, Hassan MQ, Breit GN, Balke KD, Flegr M (2009a) Accumulations of iron and arsenic in the Chandina Alluvium of the lower delta plain, southeastern Bangladesh. J Environ Geochem Health 31:69–84

Zahid A, Hassan MQ, Imes JL, Clark DW (2009b) Hydraulic characterization of aquifer(s) and pump test data analysis of deep aquifer in the arsenic affected Meghna river floodplain of Bangladesh. Environ Res J 3(2/3):325–355

Zahid A, Jahan K, Ali MH, Ahmed N, Islam MK, Rahman A (2013) Distribution of groundwater salinity and its seasonal variability in the coastal aquifers of Bengal Delta. In: Zahid A, Hassan MQ, Islam R, Samad QA, Khan MS, Haque R (eds) Impact of climate change on socio-economic conditions of Bangladesh. German Academic Exchange Service, German Development Cooperation, Alexander von Humboldt Foundation and Alumni Association of German Universities in Bangladesh, pp 170–193

Zahid A, Hassan MQ, Ahmed KMU (2015) Simulation of Flowpaths and travel time of groundwater through arsenic contaminated zone in the multi-layered aquifer system of Bengal Basin. J Environ Earth Sci. https://doi.org/10.1007/s12665-014-3447-7

Chapter 33
Climate Change and Hydrological Perspective of Bhutan

Chandan Mahanta, Anirudha Mahagaonkar and Runti Choudhury

Abstract Climate change recognized as a reality has cast a formidable challenge to the human race in terms of coping with its commonly understood as well as uncertain impacts. Several studies around the globe have shown that climatic change is likely to impact significantly all major aspects of the environment and consequently human life. Bhutan, located in the rugged Eastern Himalayan Terrain, one of the most environmentally pristine regions, has been identified as exceptionally vulnerable to climate change-induced changes. Among the biggest impacts of these changes would be to the hydrological system of Bhutan, which remains the capital resource of the country. The three major drivers of Bhutan's economy, viz. agriculture, hydropower, and tourism, directly or indirectly rely on this capital resource for its sustenance. Hence, it remains important for Bhutan and countries alike, to safeguard and protect their hydrological resources. Bhutan's water resources that are being discussed in this paper are at serious threat due to projected climate change impacts. The region deserves urgent and an extensive study to understand the nature and magnitude of the impacts. Recognizing the imminent impacts, mitigation, and adaptation too has to go hand in hand. However, inadequate and partially accessible sensitive data has created a great setback for sound research. In this paper, an assessment of the impact of climate change on the different sectors in Bhutan has been made based on published literature, along with exploring possible ways of overcoming the hurdles in the way of finding potential mitigation and adaptation strategies that are realistic, affordable, and practicable for a region that can do even more in environmental governance with improved institutional mechanism.

Keywords Bhutan · Climate change · Hydrological future · Transboundary cooperation

---

C. Mahanta (✉) · A. Mahagaonkar · R. Choudhury
Indian Institute of Technology Guwahati, Guwahati 781039, India
e-mail: mahantaiit@gmail.com

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_33

33.1 Introduction

The fear of risks from climate change is looming high all across the world. While much of the world is experiencing patterns of warming atmosphere, some parts of the world are experiencing cooling, and hence, the concept of climate change emerged. Bhutan, a naturally rich country with a relatively huge stock of natural resources, has also started feeling the heat of climate change. The country boasts of the highest per capita freshwater availability in the region, offering Bhutan an upper hand in terms of managing water resources; but the future may be gloomy in this climate-changing scenario even for Bhutan.

Water resources are abundant in Bhutan. The landlocked country is also immensely rich in biodiversity and forests, hosting an array of endemic and endangered species of flora and fauna. With the help of these resources, Bhutan has been emerging from a least developed country (LDC) (GNHC 2013) to a middle-income country. The landscape of Bhutan comprises of 70.46% forest cover, 10.81% of shrubs, 2.93% of agricultural land, and 4.10% of meadows; the snow and ice cover accounts for 7.44% of land area in Bhutan (NSSC 2011). According to the same technical report NSSC (2011), the water bodies accounted for less than 1% of the land area. It is interesting to note that, in spite of such small area covered, the potential of water resources in Bhutan is enormous.

Bhutan (Chap. 1, Fig. 1.1) is located atop the range of Eastern Himalayas, making it a natural station to observe smallest of the smallest changes in climate and warming. These minute changes lead to significant changes in hydrological system of Bhutan. For the first time, Glaciers in Bhutan were mapped by ICIMOD in 2001 using topographic maps from the 1970s. During that period, glaciers covered an area of $\sim 1317 \text{ km}^2$ (Mool et al. 2001); but these findings were strongly criticized by Reynolds and Taylor (2004) for the methodologies adopted. Later, Rupper et al. (2012) estimated the glacier area cover to be $\sim 1930 \text{ km}^2$, which was higher than the ICIMOD estimate. The reason, as quoted by Rapper et al. (2012), was the discrepancies due to the perennial snow. ICIMOD again in 2011 mapped glacial area of Hindu Kush Himalaya, including Bhutan Himalaya, and estimated the area of Bhutan Glaciers as $\sim 642 \text{ km}^2$ (Bajracharya and Shrestha 2011; Bolch et al. 2012). In spite of the sparse data and limited number of studies in Bhutan, it is clear that glaciers have retreated remarkably in the past and the melt rate has been relatively huge in the recent decades (Bolch et al. 2012) (Fig 33.1).

It could be stated that glaciers are indirectly the drivers of Bhutan's economy, as they are the major sources of water in the region. And loss of these sensitive elements can lead to major changes to structure and livelihood of Bhutan. The Amochu, Wangchu, Punatsangchu, Manaschu, and Nyera Ama Chu are major rivers in Bhutan. As much of these rivers, except Amochu and Nyera Ama Chu, are glacier-fed (Bajracharya et al. 2014) and are majorly at threat. Water from these rivers altogether is utilized for irrigation and hydropower generation apart from other minor and domestic uses. As these two factors are among the major

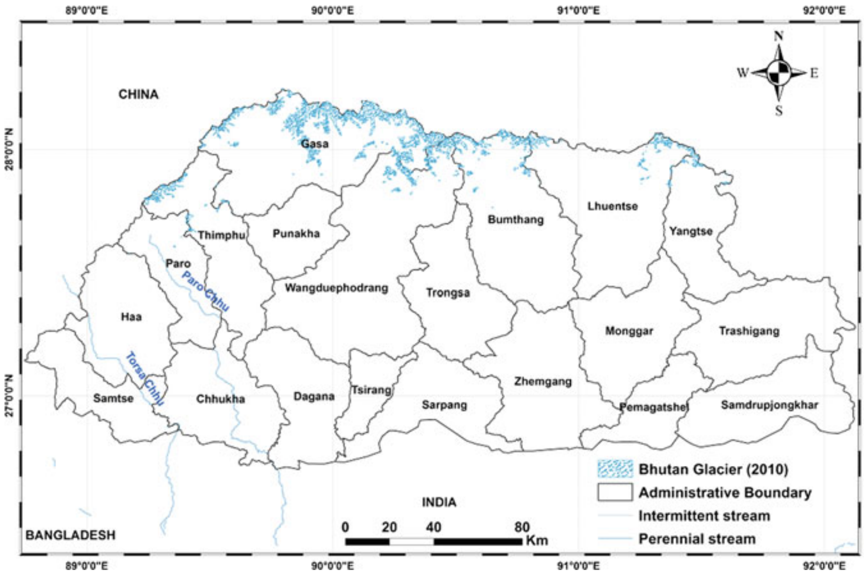


Fig. 33.1 Administrative map of Bhutan

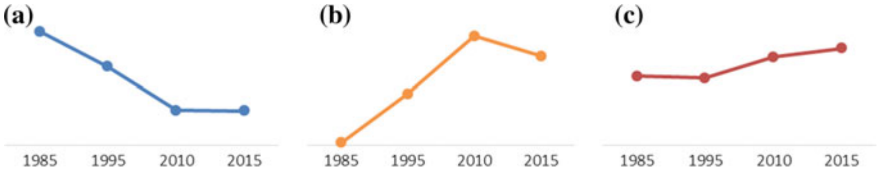


Fig. 33.2 Trends of sectoral contribution to GDP of Bhutan from 1985 to 2015. **a** Agriculture. **b** Electricity and water supply. **c** Construction

contributors to economy of Bhutan, climate change remains an evident threat to its future.

The strong forest cover of Bhutan helps in absorbing the erratic and frequent changes, thus helping the region in averting shocks from climate changes and lessen the impacts on glaciers and its water resources. Scrutinizing of development projects and rapid hydropower expansion is called for Katel et al. (2015), in their work, have also stressed that international cooperation in managing these transboundary water resources could possibly help in better management of the problem. Rivers that originate in Bhutan flow downward into India and further into Bangladesh before draining into Bay of Bengal, and this region hosts the largest population of poor in the world (Katel et al. 2015). Much more needs to be done to ensure security in all forms in the interest of healthier and happier future of Bhutan. More related information regarding groundwater of South Asia is available in Mukherjee et al. (2018).

33.2 Economy of Bhutan

With only 21% of the entire population living in the urban areas, Bhutan is one of the least urbanized countries in the world (ADB 2004). According to World Bank, Bhutan has a population density of 20.33 persons per km^2, compared to 172.6 persons per km^2 for Nepal (Zurick et al. 2006) and 382 persons per km^2 for India (Census 2011), and this has helped check societal pressure on land and resources (Zurick 2006).

The rugged topography of Bhutan has made development of roads and infrastructure difficult and expensive. This may have turned to be on the positive side for Bhutan, as it has helped them retain their resources in its best form. Among many values and policies that have helped Bhutan remain this way is the National Forestry Policy of Bhutan—of the total land cover, a minimum of 60% should be forest cover into perpetuity (RGOB 1974). With 70.5% under forest cover (tree canopy) currently, this policy has also been a major force for protection of forest resources in Bhutan. Maintaining forest cover to this extent has helped the environment of Bhutan trap more moisture from atmosphere and precipitation and recharge its water systems, which are critical to Bhutan's economy.

From the 1980s, Bhutan's economy has seen robust growth with complete transformation of agriculture-based economy (Frame 2005). Today, the state's GDP is governed by multiple sectors. Water, the capital resource of Bhutan, is one of the critical elements for the economy of Bhutan. The three major economic drivers of Bhutan's economy are—hydropower, agriculture, and tourism. Water plays an essential role in functioning of these three drivers of Bhutan's economy, making it an indispensable element of the state. WWF Bhutan and NEC (2016) reports that over 90% of water resources used in Bhutan is for agriculture. Agricultural sector of the state employs near about 50% of population and contributes to ~15% of GDP (Table 33.1).

From the graph shown in Fig. 33.3, it can be seen that the % of agricultural area (in relation to the total land area of Bhutan) has gone up from ~7% in the 1960s to ~14% in 2014. In spite of the considerable increase in the cultivated land,

Table 33.1 GDP of Bhutan—contribution from three sectors

Sectors	1985	1995	2010	2015
Agriculture, livestock, and forestry	54.9	38.0	16.8	16.67
Electricity and water supply	0.4	8.3	17.61	14.34
Construction	11.1	10.8	14.22	15.61
Source	Ministry of Planning (1996)		NSB (2014). % Share at prices of 2019–2013	NSB (2015). % Share at prices of 2011–2015

All values are mentioned as % of total GDP

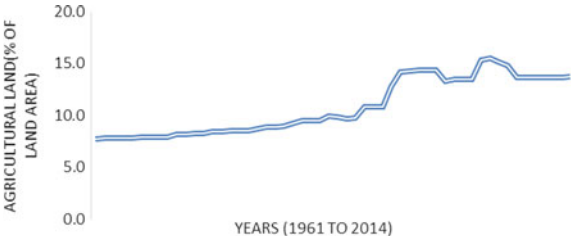


Fig. 33.3 Agricultural land (As % of total land area of Bhutan) from 1961 to 2014 (*Data source* World Bank 2017)

its contribution to GDP has dwindled (Fig. 33.2a). This clearly implies that other sectors have grown significantly to contribute to Bhutan's GDP. As the agriculture has still grown, its dependence on water has only increased with time. The energy sector of Bhutan, comprised mainly of Hydropower, also accounts for a major share of Bhutan's GDP. With negligible contribution in the 1980s (Fig. 33.2b), the hydropower industry has grown to such an extent that the sector contributes one-fifth of the GDP today. The construction activities have also grown considerably, owing to the construction of hydropower plants across different streams in Bhutan. Tourism in Bhutan is majorly driven by the culture and pristine natural landscapes, comprising of forests, lakes, glaciers, and mountain ecosystems, that offer an enchanting experience to visitors. Number of tourists since 1974 have considerably increased year after year (NSB 2014).

It is understood that all the three major contributors to Bhutan's economy directly or indirectly depend on water for their sustenance.

33.3 Climate Change in Bhutan

Climate impacts on pristine systems are regimes where implications are more visible than others. While the cumulative impacts of climate change are far too many, the impact on water resources would be significant. The aquifers composed of Himalayan fractured; crystalline rocks (Mukherjee et al. 2015) would be affected owing to the changes in precipitation and runoff patterns. Climate change-induced increased monsoon variability and loss of glacial meltwater will likely confront populations with ongoing and multiple challenges (Vinke et al. 2015). Rupper et al. (2012) suggested that even if climate remained at the mean values of the period 1980–2000, almost 10% of Bhutanese glacierized area would vanish and meltwater flux would drop by as much as 30%. This in turn would threaten hydropower development, including increasing risk of Glacial Lake Outburst Flooding (GLOF); variability of runoff and siltation from glacier melting and monsoon changes; and loss of reservoir water due to increased evaporation. Bajracharya et al. (2014), based on their study on status and decadal change of glaciers in Bhutan from the 1980s to 2010, report that glacier area loss in Bhutan from ~1980 to 2010 was 23.3 ± 0.9% (Table 33.2). This decreasing trend in glacier area will eventually have major impacts on ice storage and consequently on glacier runoff.

Table 33.2 Decadal glacial loss in different elevation ranges of Bhutan

Elevation range	Glacier area				Glacier area loss			
	~1980	1990	2000	2010	~1980–1990	1990–2000	2000–2010	~1980–2010
m a.s.l.	km^2	km^2	km^2	km^2	%	%	%	%
<5000	132.5 ± 16.1	115 ± 19.8	106.3 ± 16.5	101.6 ± 13.2	13.2 ± 5	7.5 ± 1.7	4.4 ± 2.6	23.3 ± 0.8
5000–5600	527.1 ± 11.6	477.5 ± 12.4	438.2 ± 4.8	405.4 ± 16.5	9.4 ± 0.4	8.2 ± 1.5	7.5 ± 3	23.1 ± 1.9
>5600	178 ± 11.5	148 ± 21.1	143.5 ± 7.3	134.8 ± 11.7	16.8 ± 7.8	3.1 ± 9.2	6 ± 3.6	24.3 ± 2.2
Total	837.6 ± 28.8	740.7 ± 16.7	688.2 ± 16.4	642.1 ± 16.12	11.6 ± 1.2	7.1 ± 0.1	6.7 ± 0.1	23.3 ± 0.9

Source Bajracharya et al. (2014)

33.3.1 Impact of Climate Change on Glaciers and Glacial Lakes

Small fluctuations in the temperature can turn snow and ice into water. Global warming and climate change are accelerating the melting of Himalayan glaciers, which are melting at rates higher than the global averages (Bajracharya et al. 2007; Dyurgerov and Meier 2005; Sharma et al. 2009). Glaciers of Bhutan are also at threat due to climate change.

A study by Bajracharya et al. (2014) on decadal changes in glaciers of Bhutan has reported a decrease in glacierized area by 23.3 ± 0.9% between 1977 and 2010. The authors also report that the loss was greater for clean ice glaciers when compared to debris-covered glaciers in Bhutan. From their study, it can be seen that number of glaciers has significantly increased from 771 glaciers in the late 1970s to 885 in 2010. This increase in number can be attributed to shrinkage and fragmentation of glaciers, which has also led to loss of glacier area. Change has been enormous in smaller glaciers due to their instability (Bajracharya et al. 2014). Karma et al. (2003) in their study reported that the retreat rates of glacier terminus during the recent times have been as twice faster than retreat rates that were observed by Asahi (1999) in the glaciers of eastern Nepal (Naito et al. 2012). Further, Asahi (1999) and Karma et al. (2003) suggest that this behavior may be due to enhanced influence of summer monsoon in Bhutan. These findings may suggest that glaciers in Bhutan are at higher risk than glaciers in Nepal or other regions of the Himalaya. Karma et al. (2003) also reported that in 30 years (between 1963 and 1993), glaciers in Bhutan have evacuated 8.1% of their area, while many smaller glaciers have even disappeared. Glaciers in the Lunana basin are cascading with high melt rates and expansion of glacial lakes (Ageta et al. 2000). IPCC in (2001), based on climate models, reported that by 2100 the global mean temperature could rise anywhere between 1.4 and 5.8 °C, depending on different emission scenarios. The projections for rise in temperature in the Indian subcontinent stand between 3.5 and 5.5 °C by 2100 (Lal 2002). If in the last few decades glacier melting has been at its high with just a rise of ~0.8 °C in average temperature, what could be the condition with rise in temperature by 3.5–5.5 °C? It is estimated that 25% of glacial mass could be lost by 2050 and almost 50% by 2100 (Kuhn 1993; Oerlemans 1994; and IPCC 1996), leading to formation and expansion of glacial lakes and thereby increased possibility of glacial lake outburst floods seriously affecting livelihood of mountain people.

Glacial lakes are reported to be more sensitive to climate change and affect outburst flood disasters more heavily than larger lakes or lakes located farther from glaciers (Zhang et al. 2015). Climate change-induced accelerated retreat of glaciers and enhanced precipitation have resulted in an increase in the number of lakes (>1 km^2), an expansion of lake area in the Tibetan Plateau (Zhang et al. 2015). Expansion of glacial lakes has been reported from the Northern Bhutan (Komori 2008; Fujita 2008). Choppel et al. (2011) reported a total of glacial 2674 lakes in Bhutan (Table 33.3), out of which 25 lakes have been identified as potentially

Table 33.3 Summary of glaciers and glacial lakes in Bhutan

S.No.	Sub-basins	Glaciers			Glacial lakes	
		Number	Area (km^2)	Ice reserves	Number	Area (km^2)
1	Amo Chhu*	0	0	0	71	1.83
2	Ha Chhu*	0	0	0	53	1.83
3	Pa Chhu	21	40.51	3.22	94	1.82
4	Thim Chhu	15	8.41	0.33	74	2.82
5	Mo Chhu	118	169.55	11.34	380	9.78
6	Pho Chhu	154	333.56	31.87	549	23.49
7	Dang Chhu*	0	0	0	51	1.81
8	Mangde Chhu	140	146.69	11.92	521	17.59
9	Chamkhar Chhu	94	104.1	8.11	557	21.03
10	Kuri Chhu	51	87.62	6.48	179	11.07
11	Drangme Chhu	25	38.54	2.26	126	5.82
12	Nyera Ama Chu	0	0	0	9	0.076
13	Northern basin	59	387.73	51.72	10	7.81
Total		677	1316.71	127.25	2674	106.776

* Sub-basins having no glaciers
Source Chhopel et al. (2011)

dangerous with high risk of bursting (Ageta and Iwata 1999; Mool et al. 2001), thus leading to glacial lake outburst floods. Many major settlements and infrastructural projects such as hydropower projects are located downstream these potentially dangerous lakes. This condition poses a huge threat to the downstream communities and their lives.

33.3.2 Impact of Climate Change on Agriculture and Food Security

Climate change will have huge impact on agriculture and food security in Bhutan. Agriculture directly depends on water for its sustenance and hence becomes specifically vulnerable (Hoy et al. 2016). The temperature rise due to regional changes in weather, triggered by climate change, has imparted heat stress upon farmers leading to change in agricultural practices. The change in precipitation patterns and intensity has impacted water sources and the crop yields (Kusters and Wangdi 2013), and this has led to increase in food costs impacting food security for the poor. In Bhutan, farming is majorly practiced in form of subsistence agriculture; these changes to farming will have a huge impact on the poor and small farmers, in turn affecting their health and livelihood. While projections for climate change also include changes in precipitation patterns, this is likely to increase crop failure events in the short run and decrease crop yield in the longer run (Nelson et al. 2009).

South Asia, which also includes Bhutan, will be hit hard due to impacts of climate change on agricultural sector (Nelson et al. 2009).

33.3.3 Impact of Climate Change on Hydropower

In Bhutan, there is huge demand for non-consumptive form of water from the hydropower industry. Keeping in view the proposed and upcoming hydropower projects, this demand, which was estimated to be 6,700 million m^3 for 2002, has been forecasted to grow to 26,900 million m^3 by 2022 (Chhopel et al. 2011). One of the primary facets contributing to Bhutan's economy is the run—of the river hydropower projects, with about 45% to national revenue and 12% to GDP growth (ADB 2004). Climate change-induced impacts have, however, raised concerns regarding the future of these projects vis-à-vis the overall economy of Bhutan. Excessive melting of glaciers in the higher reaches of the mountains could supply considerable amount of water for the hydropower projects in the shorter run, but as glacier mass is lost, the meltwater contribution to streams and rivers would decline, leading to reduced water flux, which may impact the hydropower sector in future. With Bhutan's ambitious plans of generating 10,000 MW with hydropower by year 2020, the future of these power plants remains gloomy. The list of ongoing and proposed hydropower projects in Bhutan is shown in Table 33.4. Rupper et al. (2012) report that even for a warming of 1 °C, almost 25% of the glacierized area will be lost accompanied by decrease in meltwater flux. South Asia would observe a warming of 2.5 °C, as projected by Christensen et al. (2007), and for this extent of warming, almost 50% of glacierized area will be lost, also reducing the annual meltwater flux to negligible levels (Rupper et al. 2012). Much of the rivers and streams in Bhutan are fed by glacier melt, and the melt from glaciers usually peaks in summer months after the spring snowpack melt. Such streams would go dry during summer months, and other streams would overflow with water contributing to flooding and breaching of dams (Bolch et al. 2012; Immerzeel et al. 2010) both being a consequence to hydropower. Bhutan's run of the river projects is accepted as safe, yet cascading impacts of climate change-induced glacial melts and storage issues are cause for concerns. As glaciers which act as natural reservoirs continue to melt, current planned hydropower development aims to incorporate reservoirs for water storage. Conceived as negative feedbacks, these hydropower reservoirs in turn contribute to GHG emission, particularly methane (Chhopel 2014).

33.3.4 Impact of Climate Change on Groundwater

While renewable surface water resources are an estimated 78 km^3, groundwater resources are rather limited owing to the country's rugged mountainous terrains (FAO 2012). The wider and flatter valleys of Paro, Punakha, Thimphu, Wangdue,

Table 33.4 Ongoing and proposed hydropower projects in Bhutan

S.No.	Project	Capacity (MW)	Start date	Completion date
1	Punatsangchhu—I	1200	2009	2015
2	Mangdechhu	720	2010	2017
3	Punatsangchhu—II	990	2010	2019
4	Sunkosh Reservoir	4060	2011	2020
5	Kuri-Gongri	1800	2012	2020
6	Amochhu Reservoir	620	2012	2018
7	Kholongchhu	650	2012	2018
8	Chamkharchhu—I	670	2012	2018
9	Wangchu	600	2012	2018
10	Bunakha Reservoir	180	2012	2018
11	Nikachhu	208	2012	2017
12	Khumachhu	327	2014	2017
13	Rotpashong	918	2012	2019
14	Gamri	102	2013	2017
15	Dagachhu	114	2009	2013
16	Nyera Ama Chu	473	2016	2021
	Total	13,632		

Source Katel et al. (2015)

and areas bordering the plains of India are, however, some areas that possibly have significant groundwater reserves (ADB 2016). Alluvial aquifer along the Indo-Bhutan border areas along Assam is an extension of the Bhabar–Tarai zone with moderate-to-high yield potentials (150–200 m^3/hr) (Dhiman and Jain 2010). The groundwater reservoirs play a critical role in meeting the water demands for domestic use, irrigation, industrial activities, and most importantly the sustenance of array of ecosystems (Green et al. 2011). Changes in precipitation patterns and amounts of precipitation, changes in temperature and glacier melt fluctuations are expected to affect the hydrological cycle, which will lead to alterations in surface water levels, thereby affecting groundwater recharge, with potential impacts on quality and quantity of groundwater (Zekster and Loaiciga 1993; Bear and Cheng 1999). The changes to the hydrological cycle from climate change will also likely affect the hydrological cycle in soil, vadose zone, and the subsurface reservoirs (Van Dijck et al. 2006). While some studies have projected reduced recharge to aquifers due to climate change (Herrera-Pantoja and Hiscock 2008), it may not be necessary that recharge in all aquifers across all periods of time be negative (Jyrkama and Sykes 2007; Döll 2009; Gurdak and Roe 2010). Groundwater quality may also be affected due to differential recharge patterns during the dry and wet periods (Sukhija et al. 1998). If the pumping of groundwater remains unchecked in highly populated areas, it may also affect the quality of groundwater due to poor freshwater recharge because of climate change, disrupting the balance that may cause intrusion from contaminated aquifers or saltwater systems (Green et al. 2011).

33.4 Hydrological Future of Bhutan

Although Bhutan has been carbon neutral and relatively clean with emissions, the country will not be spared for the impacts of climate change on its highly vulnerable hydrological resources. Taking into consideration the forest policy of Bhutan, which mandates at least 60% of total land area under forest cover, the hydrological system may seem secure for its ability to trap and hold moisture, but more needs to be done to ensure complete security of the system. The estimated hydropower potential of 30,000 MW of which 27,000 MW is feasible (Berkoff 2003; Biswas 2011; Bisht 2012; Dhakal and Jenkins 2013) can be well explored, but taking into consideration the environmental, social, technical, and financial aspects and consequences of development. A country like Bhutan may use its water resources for poverty alleviation and for pumping economic development, but it must keep in mind the future scenarios of climate change and projected trends of hydrological cycle, so that the investment matures long-term benefits. The hazard potential of the projects needs to be given a special attention as they can cause a catastrophe downstream in case of accident or breach. Out of the 10,000 MW generation of hydropower, 6000 MW has been planned in the Punatsangchhu basin which is downstream of the Lunana region (Chhopel et al. 2011) that typically holds some of the most dangerous glacial lakes of Bhutan. Such a development may be risky as a single episode of GLOF may turn out to be a nightmare in the region for the downstream communities. Dams and reservoirs need to be constructed in such a way that zero or very minimal damage is caused to the downstream hydrological system. It may not be a bad idea to decommission dams, which remains the best strategy to restore the river health (Chhopel 2014) in case it is understood at a later stage that the dam may be dangerous for the system. Maintaining the natural state and regime of the rivers and water bodies will be important to ensure security of hydrological system in future. People and organizations in Bhutan should take lead in enhancing watershed management. Tapping rainwater for agriculture and domestic usage should also be explored. Mitigation measures that can help minimize the impact of the changing climate are of utmost important, although the impacts of mitigation will only be felt in the long run by the future generations. Healthy rivers and sustainable strategies are now important to ensure high quotients of Gross National Happiness index in Bhutan.

33.5 A Need for Transboundary Cooperation

All the hydrological systems of Bhutan are transboundary in nature. The fact that many rivers of South Asia originate from the Himalayas provide a great opportunity to all the associated countries on transboundary water management and cooperation. Most of the rivers that originate in Bhutan drain southward into the Brahmaputra river in India that leads to the Bay of Bengal in Bangladesh. This itself remains a classic example for taking up joint-management of the hydrological system. India and Bhutan, for few decades now, have been successful in managing the hydropower sector successfully together, making it a story of success. Such cooperation will help not only the mountain ecosystems but also the downstream communities for sustainable development. Cooperation and sharing of information and technologies should be explored in the environmental protection front, apart from energy sector, technological knowledge, financial contracts, and watershed management. This kind of cooperation can help in poverty alleviation and environmental development on the whole for all the riparian and partner countries, ensuring a secure hydrological future.

References

ADB (2016) https://www.adb.org/countries/bhutan/main. Accessed 6 April 2017

Ageta Y, Iwata S (1999) Report of Japan-Bhutan joint research 1998 on the assessment of glacier lake outburst flood (GLOF) in Bhutan. Nagoya University, IHAS

Ageta Y, Iwata S, Yabuki H, Naito N, Sakai A, Narama CHIYUKI, Karma T (2000) Expansion of glacier lakes in recent decades in the Bhutan Himalayas. IAHS Publication, pp 165–176

Asahi K (1999) Data on inventoried glaciers and its distribution in eastern part of Nepal Himalaya. Data report 2 (1994–1998), Cryosphere Research in the Himalaya (CREH)

Asian Development Bank (ADB) (2004) Key indicators, of developing Asian and Pacific countries. ADB, Manila

Bajracharya S, Shrestha B (2011) The status of glaciers in the Hindu Kush-Himalayan region. International Centre for Mountain Development, Kathmandu

Bajracharya SR, Mool PK, Shrestha BR (2007) Impact of climate change on Himalayan glaciers and glacial lakes: case studies on GLOF and associated hazards in Nepal and Bhutan. International Centre for Integrated Mountain Development, Kathmandu

Bajracharya SR, Maharjan SB, Shrestha F (2014) The status and decadal change of glaciers in Bhutan from the 1980s to 2010 based on satellite data. Ann Glaciol 55(66):159–166

Bear J, Cheng AHD, Sorek S, Ouazar D, Herrera I (eds) (1999) Seawater intrusion in coastal aquifers: concepts, methods and practices, vol 14. Springer Science & Business Media

Berkoff J (2003) Hydropower in Bhutan and Nepal: why the difference? World Econ 4(3):121–142

Bisht M (2012) Bhutan-India power cooperation: benefits beyond bilateralism. Strateg Anal 36(5):787–803

Biswas AK (2011) Cooperation or conflict in transboundary water management: case study of South Asia. Hydrol Sci J 56(4):662–670

Bolch T, Kulkarni A, Kääb A, Huggel C, Paul F, Cogley JG, Frey H, Kargel JS, Fujita K, Scheel M, Bajracharya S (2012) The state and fate of Himalayan glaciers. Science 336(6079):310–314

Census (2011) http://censusindia.gov.in/. Accessed 6 April 2017

Chhopel GK (2014) Sustainability of Bhutan's hydropower. Hydro Nepal J Water Energy Environ 14:73–76

Chhopel GK, Dulal IR, Chhophel K, Wangchuk C, Rinzin U, Dupchu K, Kunzang TRK, Tshethar K, Dorji U, Wangchuk T, Lhamo T (2011) Securing the natural freshwater systems of the Bhutan Himalayas: climate change and adaptation measures on water resources in Bhutan. A climate summit for a living Himalaya

Christensen JH et al (2007) Regional climate projections, in climate change 2007: the Physical Science Bases. In: Solomon S et al (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, U. K, pp. 847–940

Dhakal DNS, Jenkins GP (2013) Risk sharing in hydropower development: case study of the Chukha Hydel Project in Bhutan. Water Policy 15(S1):109–125

Dhiman SC, Jain SK (2010) An overview of Transboundary aquifers of the Indian Sub-continent. Editorial Board 25(1&2):1

Döll P (2009) Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ Res Lett 4(3):035006

Dyurgerov MB, Meier MF (2005) Glaciers and the changing Earth system: a 2004 snapshot, vol 58. Institute of Arctic and Alpine Research, University of Colorado, Boulder

FAO (2012) The state of food and agriculture. http://www.fao.org/docrep/017/i3028e/i3028e.pdf. ISBN 978-92-5-107317-9

Frame B (2005) Bhutan: a review of its approach to sustainable development. Dev Pract 15(2): 216–221

Fujita K (2008) Effect of precipitation seasonality on climatic sensitivity of glacier mass balance. Earth Planet Sci Lett 276(1):14–19

Green TR, Taniguchi M, Kooi H, Gurdak JJ, Allen DM, Hiscock KM, Treidel H, Aureli A (2011) Beneath the surface of global change: impacts of climate change on groundwater. J Hydrol 405(3):532–560

Gross National Happiness Commission (2013) Eleventh Five Year plan document

Gurdak JJ, Roe CD (2010) Review: recharge rates and chemistry beneath playas of the High plains aquifer, USA. Hydrogeol J 18(8):1747–1772

Herrera-Pantoja M, Hiscock KM (2008) The effects of climate change on potential groundwater recharge in Great Britain. Hydrol Process 22(1):73–86

Hoy A, Katel O, Thapa P, Dendup N, Matschullat J (2016) Climatic changes and their impact on socio-economic sectors in the Bhutan Himalayas: an implementation strategy. Reg Environ Change 16(5):1401–1415

Immerzeel WW, Van Beek LP, Bierkens MF (2010) Climate change will affect the Asian water towers. Science 328(5984):1382–1385

IPCC (1996) Climate change 1995 impacts, adaptation and mitigation of climate change: scientific and technical analyses. Contribution of working group II to the second assessment report of the intergovernmental panel on climate change

IPCC (2001) IPCC Third assessment report—climate change 2001. Working Group II: impacts, adaptation and vulnerability. Summary for policy makers. Geneva, WMO and UNEP

Jyrkama MI, Sykes JF (2007) The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario). J Hydrol 338(3–4):237–250

Karma, Ageta Y, Naito N, Iwata S, Yabuki H (2003) Glacier distribution in the Himalayas and glacier shrinkage from 1963 to 1993 in the Bhutan Himalayas. Bull Glaciol Res 20:29–40

Katel ON, Schmidt-Vogt D, Dendup N (2015) Transboundary water resources management in the context of global environmental change: the case of Bhutan Himalaya. In: Managing water resources under climate uncertainty. Springer International Publishing, pp 269–290

Komori J (2008) Recent expansions of glacial lakes in the Bhutan Himalayas. Quat Int 184 (1):177–186

Kuhn M (1993) Possible future contribution to sea level change from small glaciers. In: Warrick RA et al (eds) Climate and sea level change: observations, projections and implications. Cambridge University press, Cambridge, UK, pp 134–143

Kusters K, Wangdi N (2013) The costs of adaptation: changes in water availability and farmers' responses in Punakha district, Bhutan. Int J Glob Warming 5(4):387–399

Lal M (2002) Possible impacts of global climate change on water availability in India. Report to global environment and energy in the 21st century

Ministry of Planning (1996) Eighth Five-Year Plan (1997–2002) vol 1, Main plan document. Royal Government of Bhutan, Thimphu

Mool PK, Wangda D, Bajracharya SR, Kunzang KARMA, Gurung DR, Joshi SP (2001) Inventory of glaciers, glacial lakes and glacial lake outburst floods. Monitoring and early warning systems in the Hindu Kush-Himalayan Region: Bhutan. In: Inventory of glaciers, glacial lakes and glacial lake outburst floods. Monitoring and early warning systems in the Hindu Kush-Himalayan Region, Bhutan

Mukherjee A (2018) Groundwater of South Asia. Springer, Singapore. ISBN 978–981-10-3888-4

Mukherjee A, Saha D, Harvey CF, Taylor G, Ahmed KM, Bhanjaa SN (2015) Groundwater systems of the Indian Sub-Continent. J Hydrol Reg Stud 4(2015):1–14

Naito N, Suzuki R, Komori J, Matsuda Y, Yamaguchi S, Sawagaki T, Tshering P, Ghalley KS (2012) Recent glacier shrinkages in the Lunana region, Bhutan Himalayas. Glob Environ Res 16(1):13–22

National Statistics Bureau (2014) Statistical yearbook of Bhutan 2014. National Statistics Bureau, Royal government of Bhutan, Thimphu, Bhutan

National Statistics Bureau (2015) Statistical Yearbook of Bhutan 2015. National Statistics Bureau, Royal government of Bhutan, Thimphu, Bhutan

Nelson GC, Rosegrant MW, Koo J, Robertson R, Sulser T, Zhu T, Magalhaes M (2009) Climate change: impact on agriculture and costs of adaptation, vol 21. International Food Policy Research Institution

NSSC P (2011) Bhutan land cover assessment 2010—technical report. National Soil and Services Centre and Policy and Planning Division. Ministry of Agriculture and Forests, Royal Government of Bhutan, Thimphu

Oerlemans J (1994) Quantifying global warming from the retreat of glaciers. In: Science-AAAS-weekly paper edition-including Guide to scientific information, 26

Reynolds JM, Taylor PJ (2004) Reviewed Work(s): inventory of glaciers, glacial lakes and glacial lake outburst floods, monitoring and early warning systems in the Hindu Kush-Himalaya Region: Nepal by Mool PK, Bajracharya SR, Joshi SP; Inventory of Glaciers, Glacial Lakes and Glacial Lake Outburst Floods, Monitoring and Early Warning Systems in the Hindu Kush-Himalaya Region: Bhutan by Mool PK, Wangda D, Bajracharya SR, Kunzang K, Gurung DR, Joshi SP. Mount Res Dev 24(3):272–274

Royal Government of Bhutan (RGOB) (1974) National Forest Policy. Department of Forestry, Ministry of Trade, Industry and Forests, Thimphu, Bhutan

Rupper S, Schaefer JM, Burgener LK, Koenig LS, Tsering K, Cook ER (2012) Sensitivity and response of Bhutanese glaciers to atmospheric warming. Geophys Res Lett 39(19)

Sharma E, Chettri N, Tse-Ring K, Shrestha AB, Jing F, Mool P, Eriksson M (2009) Climate change impacts and vulnerability in the Eastern Himalayas

Sukhija BS, Reddy DV, Nagabhushanam P (1998) Isotopic fingerprints of paleoclimates during the last 30,000 years in deep confined groundwaters of Southern India. Quat Res 50(3):252–260

Van Dijck SJE, Laouina A, Carvalho AV, Loos S, Schipper AM, Van der Kwast H, Nafaa R, Antari M, Rocha A, Borrego C, Ritsema CJ (2006) Desertification in northern Morocco due to effects of climate change on groundwater recharge. In: Kepner WG, Rubio JL, Mouat DA, Pedrazzini F (eds) Desertification in the Mediterranean region: a security issue. Springer, Dordrecht, The Netherlands, pp 549–577

Vinke K, Martin MA, Adams S, Baarsch F, Bondeau A, Coumou D, Donner RV, Menon A, Perrette M, Rehfeld K, Robinson A, Rocha M, Schaeffer M, Schwan S, Serdeczny O, Svirejeva-Hopk A (2015) Climatic risks and impacts in South Asia: extremes of water scarcity and excess. Reg Environ Change. https://doi.org/10.1007/s10113-015-0924-9

World Bank (2017) Link http://data.worldbank.org/country/bhutan. Data last accessed on 6 April 2017

WWF Bhutan, NEC Bhutan (2016) Bhutan—Water risk scenarios and opportunities for resilient development

Zektser IS, Loaiciga HA (1993) Groundwater fluxes in the global hydrologic cycle: past, present and future. J Hydrol 144(1–4):405–427

Zhang Y, Su F, Hao Z, Xu C, Yu Z, Wang L, Tong K (2015) Impact of projected climate change on the hydrology in the headwaters of the Yellow River basin. Hydrol Process 29(20):4379–4397

Zurick D (2006) Gross national happiness and environmental status in Bhutan. Geog Rev 657–681

Chapter 34

Potential Impact of Climate Change on Surface Water and Groundwater Interactions in Lower Reaches of Ganges River, India

Syed Aaquib Hussain, Kousik Das, Soumendra Nath Bhanja and Abhijit Mukherjee

Abstract Present projections of climate change scenario show an increase in global temperature and CO_2 content, which have indirect impacts on surface water flow, but rainfall has direct impacts on surface run-off and groundwater storage system. This study investigates the effect of climate change on aquifer storage and surface run-off, and interactions with the river Bhagirathi-Hooghly, the lowermost reach of Ganges River in Indian state of West Bengal, by considering changes in rainfall events from 1999 to 2013. From time series analyses, it has been shown that there is a linear decreasing trend of rainfall in the selected study area in Nadia district of West Bengal. It has been shown that baseflow to the river has an inverse relation with rainfall, which indicates that higher rainfall events relate to the low baseflow and lower rainfall will relate to the higher baseflow with a correlation coefficient of −0.74. The direct effect of climate change induced through precipitation indicates that the total run-off in the river is decreasing with time which causes stresses on groundwater.

Keywords Climate change · GW–SW interaction · Rainfall · Run-off
Sea level rise

S. A. Hussain · S. N. Bhanja · A. Mukherjee (✉)
Department of Geology and Geophysics, Institute of Technology (IIT)—Kharagpur,
Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

K. Das · A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee
Applied Policy Advisory to Hydrogeosciences Group, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_34

34.1 Introduction

According to the IPCC (2007a), climate change can significantly affect the groundwater and surface water bodies. It can cause a widespread sea level rise, inversions in precipitations, increase in temperature, ice and snow melting and increase in frequency and magnitude of extreme weather such as heat waves, floods and droughts (IPCC 2007a, b; USGS 2007; Bates et al. 2008; Gurdak et al. 2009; Ludwig et al. 2014). Increase in temperature and evapotranspiration, coupled with decreasing rainfall, prolonged and excruciating drought, causes a scarcity of water resources (Schewe et al. 2014). These worldwide changes of climate extremes are revealing the requirement of integrated water resource (both groundwater and surface water) management practices for future water security (Taylor et al. 2013).

Over the past decades, several studies have examined the potential impacts of global warming on surface water resources, but there is a paucity of studies do exists for assessing the interactions between groundwater and climate change. Change in pattern of climatic components can influence groundwater, both directly through replenishment by recharge and indirectly through change in groundwater use and interactions. Therefore, conjunctive management of groundwater–surface water in response to climate change is required that needs the understanding of the intricately linked groundwater and surface water processes. It also involves the exact quantification of baseflow (groundwater discharged to surface water bodies like rivers, streams) component. Groundwater is a vital water resource for global water and food security especially in regions with limited water supplies (Bovolo et al. 2009). Moreover, groundwater is relatively clean and more reliable than surface water as it can be extracted in period of dry seasons and is less polluted than surface water (Kundzewicz and Doll 2009).

The cyclic and noncyclic changes in the water level of surface water adjoining a permeable aquifer create a differential hydraulic gradient (e.g. wave, tidal and subtidal pumping) (Miller and Ullman 2004), which influences the flow dynamics of groundwater.

Groundwater–surface water interactions have been assessed experimentally in different physiographic settings such as mountain, riverine, coastal and karst terrains (Correll et al. 1992; Harte and Winter 1993; Smerdon et al. 2005; Stark et al. 1994; Winter and Rosenberry 1995), leading to development of conceptual models for groundwater–surface water exchange. Here, we have quantified the baseflow component in total river flow and tried to delineate the influence of change in rainfall pattern on baseflow component. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

34.2 Study Area

The study has been conducted in the river reach of Bhagirathi-Hooghly at Nadia district, West Bengal, India (Chap. 1, Fig. 1.1; Fig. 34.1). The river reach considered here has a length of approximately 150 km. Nadia is mostly located within fluvio-deltaic plain. The soil character along the flood plains is fine silt and loamy; especially along the river, it is fine to coarse loamy soil (C-DAP 2014). The geology of the Nadia district shows the presence of a major subsurface fault lying along the river's left bank from Krishnanagar to Kalyani (C-DAP 2014). The climate of Nadia is characterized by a hot summer, high humidity all around the year, well-distributed rainfall during the monsoon. The winter sets in the middle of November and continues till the end of February. The rainfall during the monsoon months from June to September constitutes about 78% of the annual rainfall (AFR 2014). Maximum rainfall occurs in the month of July–August. Temperature ranges from 27 to 42 °C (minimum to maximum) with a maximum humidity of 96% (C-DAP 2014).

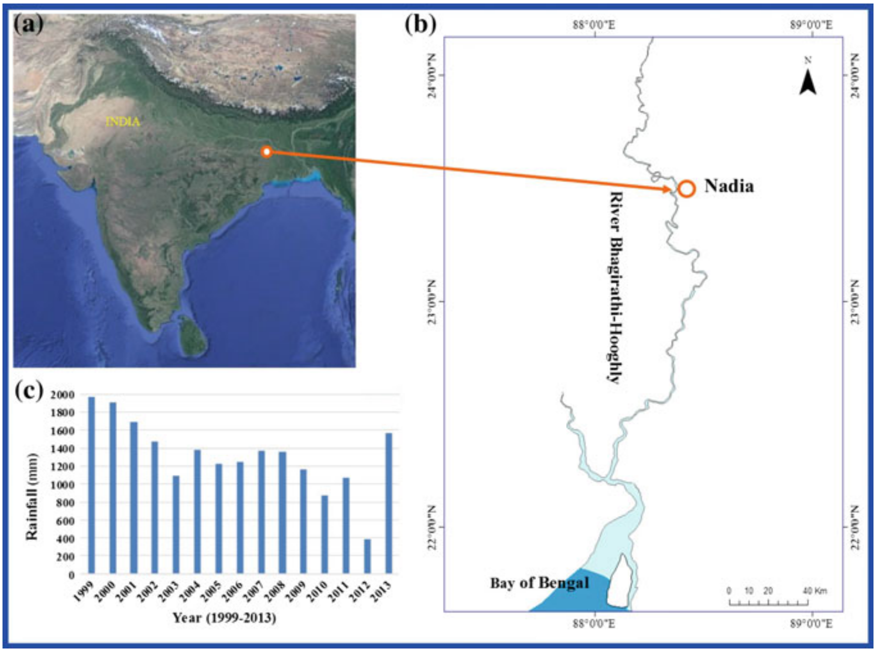


Fig. 34.1 **a** Depicts the terrain view of the study location of river Bhagirathi-Hooghly. **b** Represents the spatial location at river Bhagirathi-Hooghly at Nadia district where baseflow has been computed. **c** Represents the rainfall distribution pattern of Nadia district from 1999 to 2013

34.3 Methodology

34.3.1 Baseflow Calculation

The hydrograph separation method is used here for computing baseflow through the selection of analytical expression, derivation of the characteristic flood hydrograph and optimization of the run-off-related parameters. Using river stage data from the river reaches of Ganges over the period of 15 years (1999–2013), the annual run-off and baseflow components are computed. The baseflow is the component which is minutely affected by the seasonal variations that are taking place due to the changes in the amount of precipitation received over a period of time. To find the groundwater fraction (baseflow component) in the total river flow, the river geometry, flow velocity and the river stage data have been used. The discharge across the river cross-sectional area is being plotted against the Julian day to get the flood hydrograph curve and the technique of baseflow separation from the total streamflow component. Then, the area under the hydrograph and under the baseflow recession curve is separately calculated in MATLAB 2014b. The area fraction would provide the contribution from the baseflow component in the total river flow (Fig. 34.2).

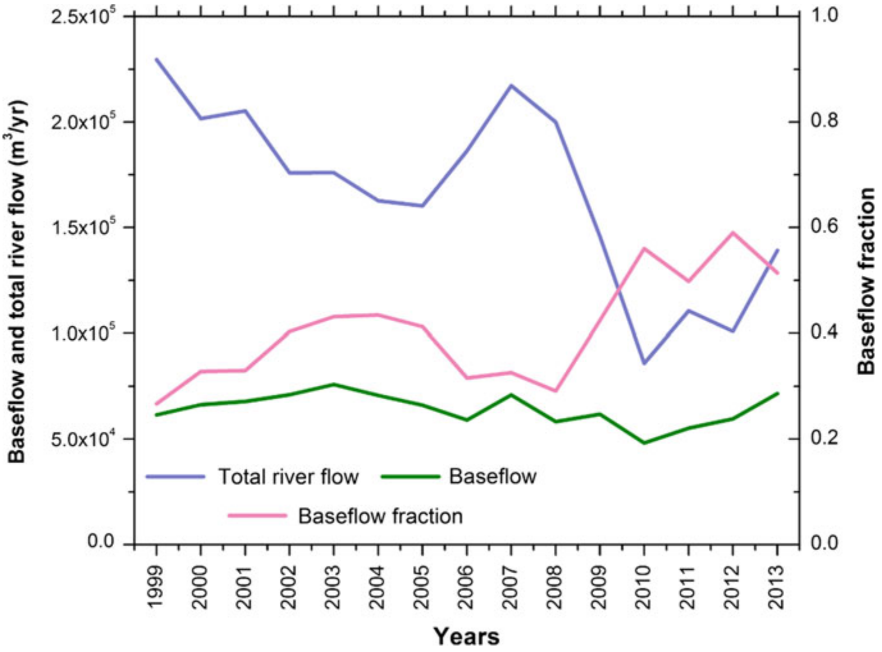


Fig. 34.2 Time series of total river flow and baseflow rates (m^3/yr)

34.4 Results and Discussions

34.4.1 Baseflow Variation

Baseflow component in selected river reaches is found to be highest (0.59) in 2012 with a mean value of 0.40 within the study period (Fig. 34.2). There is an approximate increasing linear trend of baseflow component for the selected time series of year 1999–2013. It is found that baseflow contributes 26–51% of total river water volume.

The groundwater fraction (baseflow) has also been plotted against rainfall for the period of 1999–2013 (Fig. 34.3). It was observed that the baseflow fraction in the total river flow is a bit high considering that the stream continues to receive the groundwater discharge even through the duration of the overland flow peak (Fetter 2000). Substantial amount of total run-off is comprised of interflow and rest of overland flow. Due to changes in precipitation and temperature, there is an overburden on the aquifers to meet the future water demands.

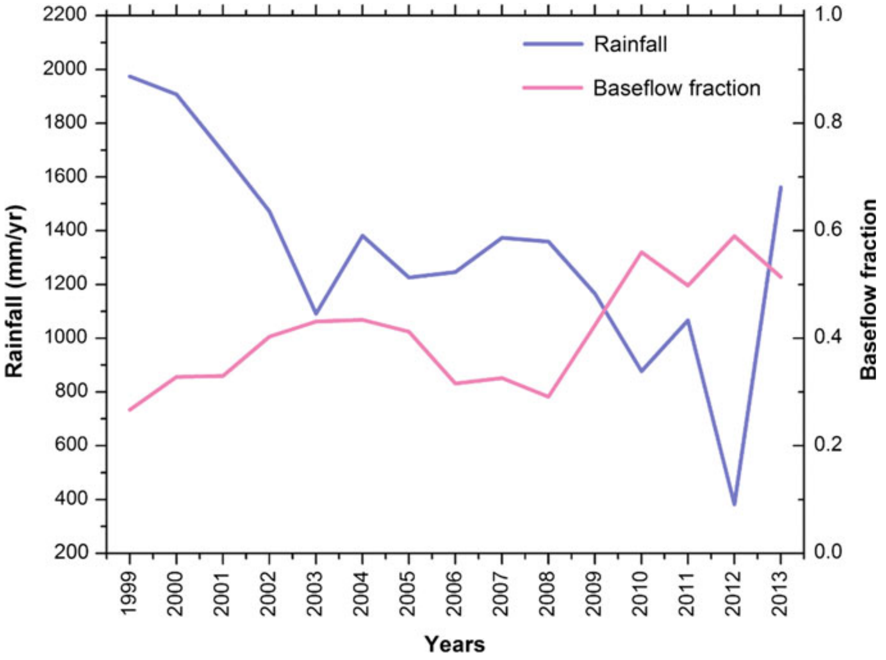


Fig. 34.3 Time series of mean annual rainfall and baseflow fraction

34.4.2 Rainfall Variation

The amount of rainfall received over the period of 15 years (1999–2013) in that particular river reach is shown in Fig. 34.3. Highest rainfall data was recorded as 1974.4 mm in 1999. The mean rainfall value for the study period is 1318.7 mm; it shows a linear decreasing trend for the selected time periods.

The year-wise data shows that the baseflow fraction in the river has an inverse relation with rainfall. It indicates that higher rainfall events are associated with the low baseflow fraction and vise versa. The correlation can also be obtained among the amount of rainfall received each year and the baseflow fraction in the river drainage flow. The correlation coefficient is calculated to be −0.74 (statistically significant with p values <0.01). The overlap is being plotted (Fig. 34.3) to show that rainfall received is inversely proportional to the amount of baseflow fraction each year. In 2012, with minimum annual rainfall of 381.3 mm, surface water in selected river reaches might be enriched from the groundwater discharge which indicates that besides withdrawal of groundwater for industrial, domestic and agricultural purposes, groundwater is also discharged to river stream as baseflow, which can create stress to groundwater storage.

It was also observed that with lower rainfall, the baseflow rate increases for the first 6 years from 1999–2004 showing a negative correlation of −0.96 and then for the next 9 years, with only exception in 2012, the baseflow rate more or less decreased with lower rainfall showing a positive correlation coefficient of 0.85 (Fig. 34.4).

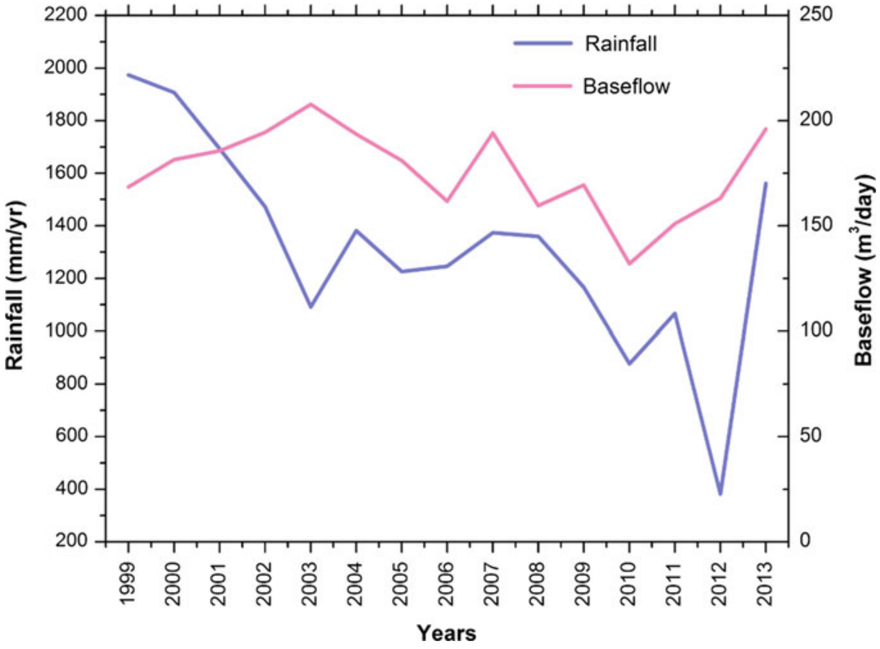


Fig. 34.4 Time series of mean annual rainfall and baseflow rate

In recent trends of global warming, water scarcity is affecting river water flow. According to the IPCC (2007a), temperature rising and atmospheric carbon dioxide affect river water directly, but rainfall is affecting the flow of river indirectly. Reduction in rainfall also affects the groundwater recharge. It gives an insight that there is a delegate balance between rainfall, groundwater recharge and baseflow to river.

34.4.3 Impact of Climate Change on Surface Water and Groundwater

The direct effects on the surface water through the changes of the long-term climate variables, such as precipitation, indicate that the total river flow in the river reaches of Bhagirathi-Hooghly at Nadia district is decreasing (total area under the flood hydrograph).

There was an intricate relationship between groundwater recharge and river water flow. The inverse relationship between rainfall event and baseflow fraction can be used as an effective predictor for change in groundwater storage. In previous studies, it has been reported that baseflow or groundwater fraction is also related to the atmospheric temperature change implicitly. It is also a fact that increase in temperature can increase the water vapour capacity of the air and the evaporation rate which in turn can reduce the groundwater recharge and baseflow as well (Cooper et al. 2015).

The contribution of groundwater to river flow can be identified from the stable isotopic compositions of water. At the global climate change scenario, sea level is rising up to 3.2 mm/year (IPCC 2007a). At different locations along the river reach in Nadia, the δ^{18}O values of groundwater samples range from −3.1 to −6.1‰, while in the river water samples of Bhagirathi-Hooghly, δ^{18}O values vary from −5.6 to −5.7‰ and are found to be more depleted than the Ichamati samples, with δ^{18}O values of −3.0 to −0.4‰ (Mukherjee et al. 2007). From the stable isotopic composition, it can be revealed that the groundwater is mixing with the surface water, as the δ^{18}O value of river water is moderately high that cannot be attained without having groundwater contribution from deep down subsurface. Also, the elevated heavier isotopic composition of groundwater might be attributed due to the salt water intrusion into the coastal aquifers that has resulted as an effect of sea level rise. But SLR trend in the Bay of Bengal (BoB), near the mouth of Bhagirathi-Hooghly river is 4.67 mm/year, which is higher than normal predicted rate or rise (NOAA: https://tidesandcurrents.noaa.gov/sltrends/sltrends_global_station.htm?stnid=500-131). These are some of the attributes of climatic variability leading to the disturbance at the entire land–water interface. The mouth of Bhagirathi-Hooghly River has been considered as one of the major sources of nutrient transport to the BoB, which may have major contribution to the ocean water ecosystem of BoB. Hence, climate change impacts and human interventions are causing reduction in groundwater storage and surface water discharge to the BoB which can disrupt the ocean ecosystem.

34.5 Conclusion

This study has explicitly demonstrated the impacts of climate change on groundwater stress and linked the yearly rainfall pattern to the groundwater–surface water interaction. The higher rainfall increased the surface run-off drastically but reduced the baseflow fraction and has an inverse, statistically significant relationship with baseflow fraction with a correlation coefficient of −0.74. Also, due to climate change, glaciers are melting that sustains the river water flow and reduces the baseflow rate into the river. It should be noted that increasing stress on groundwater due to climate change or due to anthropogenic activities may result in groundwater pollution and reduction of groundwater discharge.

References

AFR (Annual Flood Report) (2014) Irrigation and waterways directorate. Government of West Bengal

Bates BC, Kundzewicz ZW, Wu S, Palutikof J (eds) (2008) Climate change and water technical paper of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change Secretary, Geneva, Switzerland

Bovolo CI, Parkin G, Sophocleous M (2009) Groundwater resources, climate and vulnerability. Environ Res Lett 4:035001

C-DAP (2014) Comprehensive district agriculture plan for Nadia District, pp 1–10

Cooper DJ, Wolf EC, Ronayne MJ, Roche JW (2015) Effects of groundwater pumping on the sustainability of a mountain wetland complex, vol 3. Yosemite National Park, California, pp 87–105

Correll DL, Jordan TE, Weller DE (1992) Nutrient flux in a landscape: effects of coastal land use and terrestrial community mosaic on nutrient transport to coastal waters. Estuaries 15(4): 431–442

Fetter CW (2000) Applied hydrogeology, 4th edn, pp 37–48

Gurdak JJ, Hanson RT, Green TT (2009) Effects of climate variability and change on groundwater resources. U.S. Geological Survey, Fact sheet, Sept:3074

Harte PT, Winter TC (1993) Factors affecting recharge to crystalline rock in the Mirror Lake area, Grafton County, New Hampshire, paper presented at USGS toxic substances hydrology program—Proceedings of the technical meeting. Colorado Springs, Colorado, 20–24 Sept

IPCC (2007a) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the IPCC. Cambridge University Press, Cambridge, New York

IPCC (2007b) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press

Kundzewicz ZW, Doll P (2009) Will groundwater ease freshwater stress under climate change? Hydrogeological Sci J 54(4):665–675

Ludwig F, van Slobbe E, Cofino W (2014) Climate change adaptation and integrated water resource management in the water sector. J Hydrol 518:235–242

Miller DC, Ullman WJ (2004) Ecological consequences of groundwater discharge to Delaware Bay, United States. Ground Water 42:959–970

Mukherjee A (2018) Groundwater of South Asia. Springer, Singapore. ISBN 978-981-10-3888-4

Mukherjee A, Fryar AE, Rowe HD (2007) Regional-scale stable isotopic signatures of recharge and deep groundwater in the arsenic affected areas of West Bengal, India. 334:151–161

Schewe J, Heinke J, Gerten D, Haddeland I, Arnell NW, Clark DB et al (2014) Multimodel assessment of water scarcity under climate change. Proc Nat Acad Sci U.S.A. 111:3245–3250

Smerdon B, Devito K, Mendoza C (2005) Interaction of groundwater and shallow lakes on outwash sediments in the sub-humid Boreal Plains of Canada. J Hydrol 314(1):246–262

Stark J, Armstrong D, Zwilling D (1994) Stream-aquifer interactions in the straight river area, Becker and Hubbard Counties, Minnesota, US Geological Survey. Water-resources investigations report: 94-4009

Taylor RG et al (2013) Ground water and climate change. Nat Clim Change 3(4):322–329

USGS (2007) Climate variability and change. U.S. Geological Survey, Fact sheet 2007–3108

Winter TC, Rosenberry DO (1995) The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, East-Central North Dakota, 1979–1990. Wetlands 15(3): 193–211

Chapter 35
Monitoring Groundwater Flow Dynamics and Vulnerability to Climate Change in Chaj Doab, Indus Basin, Through Modeling Approach

Arshad Ashraf, Zulfiqar Ahmad and Gulraiz Akhter

Abstract The growing trend in global warming has impacted the hydrological system of the Indus River system. The variations in climate have influenced not only the local but also the regional behavior of groundwater system in the Indus River basin. It would also be crucial to investigate characteristics and behavior of this resource in order to ensure safe yield for irrigation, industry, and sustaining livelihood of millions of people of Indus area. A good knowledge of the problem and analysis of various components of the hydrological system are thus essential to achieve optimum groundwater management goals for sustaining agriculture development. The numerical groundwater flow model—Feflow—was calibrated to simulate groundwater flow behavior in upper Chaj Doab, Indus basin, during 1985–2005. The model had predicted an average decline of about 0.96 m in groundwater levels during the calibrated period and further reduction up to year 2020. A major breakthrough of groundwater depletion was observed in year 1999 when the last drought prevailed for over 3–4 years in this region. Major causative factors of watertable decline may include decrease in surface water for groundwater recharge, variability and change in rainfall pattern, and overexploitation of groundwater. The situation has resulted not only in exaggerating the cost of groundwater pumping, but also in abandoning existing wells. The integration of groundwater flow modeling and geoinformatic techniques proved helpful in analyzing the resource situation as well as vulnerability of the groundwater system to influential factors like climate change. As the country is already water stressed and predicted to face water

---

A. Ashraf (✉)
Climate, Energy and Water Research Institute,
National Agricultural Research Center, Islamabad, Pakistan
e-mail: mashr22@yahoo.com

Z. Ahmad
University of Wah, Wah, Pakistan
e-mail: fz97@hotmail.com

G. Akhter
Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan
e-mail: agulraiz@hotmail.com

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_35

scarcity in future, there is a need to monitor the groundwater system periodically on long-term basis to cope with food and water security issues in the Indus basin in future.

Keywords Groundwater flow modeling · Finite element · Waterlogging
Remote sensing · Indus basin

35.1 Introduction

Agriculture is the largest sector of groundwater use in the Indus basin. Global warming has been observed in the recent decades in the Hindu Kush Himalayas (Panday et al. 2011) and is expected to exaggerate further in the twenty-first century (IPCC 2013). Due to global warming, increased melting occurs, causing shrinkage of glaciers in the Hindu Kush Himalayas (Miller et al. 2012)—a situation that may effect the water supplies of Indus river system ultimately influencing a large number of people living in the downstream (Kanwar 2010). At present, the irrigation system in Pakistan is utilizing 129.7 billion cubic meter (BCM) of water for irrigating 17.2 M ha land and 59 BCM groundwater is pumped per year to supplement surface water supplies (WAPDA 2002). Tube wells are supplying more than 70% of irrigation water to the rice-growing areas (Qureshi et al. 2006). The tube wells not only provide additional water but also add flexibility of water supplies to match the crop water requirements. The excessive pumpage from tube wells had resulted in rapid decline in water table during the last drought of 1999–2002 (Ashraf and Ahmad 2008).

In low relief areas of Indus basin like Chaj Doab (a land within two rivers is locally called 'Doab'), the viability of irrigated agriculture is threatened by a multitude of factors, including seepage from the conveyance system and excessive irrigation in the fields; waterlogging and soil salinization; poor on-farm water management practices; insufficient canal water supplies; and use of poor-quality groundwater for irrigation (Qureshi 2011). Waterlogging and salinity often caused by accumulation of water affect ultimately the livelihood of farmers. A suitable model permits the evaluation of water resources and facilitates their management while valuing different choice consequences. Thus, a good knowledge of a problem and analysis of various components of the hydrological system are prerequisite to support groundwater management initiatives at various levels in any area.

In the present study, finite element model—Feflow 5.1 (WASY 2004)—was used to simulate groundwater flow behavior through establishing three-dimensional flow field in Chaj Doab, Indus basin. The remote sensing data were used to analyze potential recharge/discharge sources to conceptualize the groundwater flow model.

35.2 Study Area

The Chaj Doab belongs to the Punjab plains which form part of the Indo-Gangetic syncline, which has been filled up with a thick mass of alluvial material and now comprises the form of the immense alluvial plain (Soil Survey Report 1967; Wadia 1966) (Fig. 35.1). Quaternary alluvium has been deposited on semi-consolidated Tertiary rocks or on a basement of metamorphic and igneous rocks of Precambrian age. Except in a small area in northeastern Chaj Doab, the distribution of Tertiary rocks in the study area is unknown (Kidwai 1962). The Pabbi Hills, a range belonging to the Himalayan foothills, occur in the northern part of the Chaj Doab near the edge of the syncline. The upper portion of the rock formation is a part of the Siwalik System which is of Tertiary age. The oldest rocks exposed in the Chaj Doab, referred to as Kiranas, are of Precambrian age. This group of rocks has been named after the village of Kirana, in Chaj Doab, where the most conspicuous hills occur. The bedrock hills trend northwesterly and are part of a ridge within the Precambrian basement complex that is largely buried by the alluvium. The area is fairly level and slopes toward southwest with an average value of about 1.5 ft per mile (Ibrahim et al. 1972).

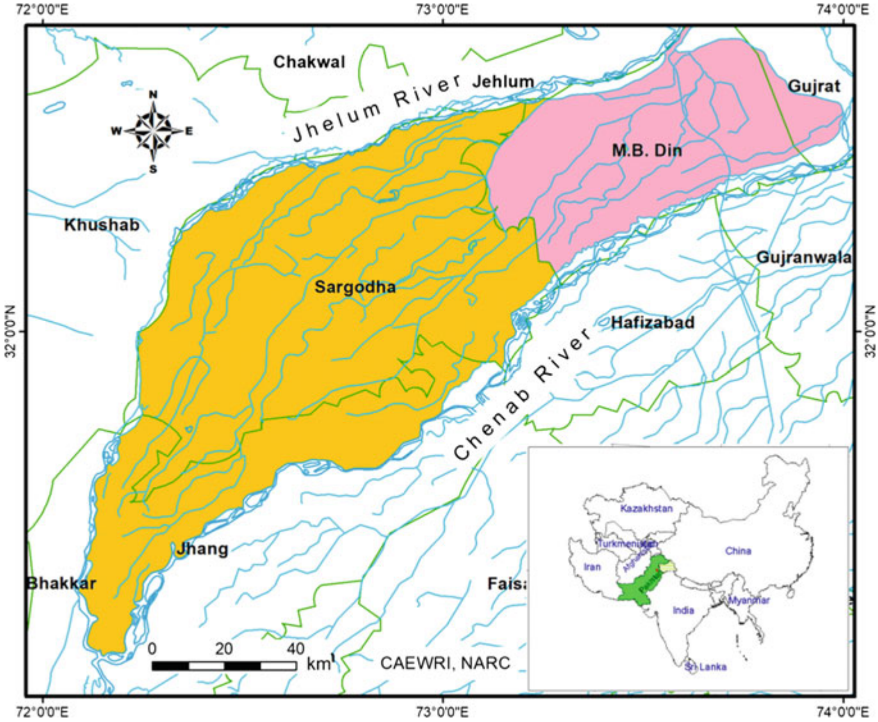


Fig. 35.1 Location of upper and lower Chaj Doab in Indus basin of Pakistan

The Jhelum and Chenab rivers have a profound influence on the hydrology of their respective floodplains. The flow of these rivers is quite variable with the seasons. The rivers have limited flows in winter since most of the precipitation is held up as snow in the high mountains, but in summer they rise due to monsoon rains and the water is released by melting of snow. High floods occur during the months of July, August, and September, and their duration is of a few days to about a week. Summer crops are sometimes damaged by these floods, but winter crops (Wheat and Gram) benefit from the extra moisture left in the soils. The groundwater hydrology of the area has been greatly affected by the seepage from large canals like upper and lower Jhelum canals and the Gujarat branch. The annual flows of Jhelum River vary between 11 and 33 million acre-feet (MAF), about 78% of which are received during summer (Fig. 35.2). The annual as well as seasonal flows of Jhelum River at Mangla have shown a slight positive trend—the situation that can be linked to increase in magnitude of climatic parameters, i.e., temperature and precipitation in the Jhelum catchment. Immerzeel et al. (2013) pointed toward increasing river flows from the Himalayas catchments in the twenty-first century; however, a decline in flows would be expected during mid-to-late century owing to loss in glacial coverage. The river flows are diverted to irrigate upper and lower Jhelum canal commands.

The study area lies in subhumid to semiarid region. The climate is extreme but healthy. Rainfall is erratic, and the mean annual is about 778 mm (1971–2001). As there was no historical climate data available of any meteorological station inside the study area, so the climate data of Jhelum station in the north and Sargodha station in the south of the area were used. Most of the area is irrigated by canal system. Wheat, rice, gram, cotton, sugarcane, and fodders are the main crops in the

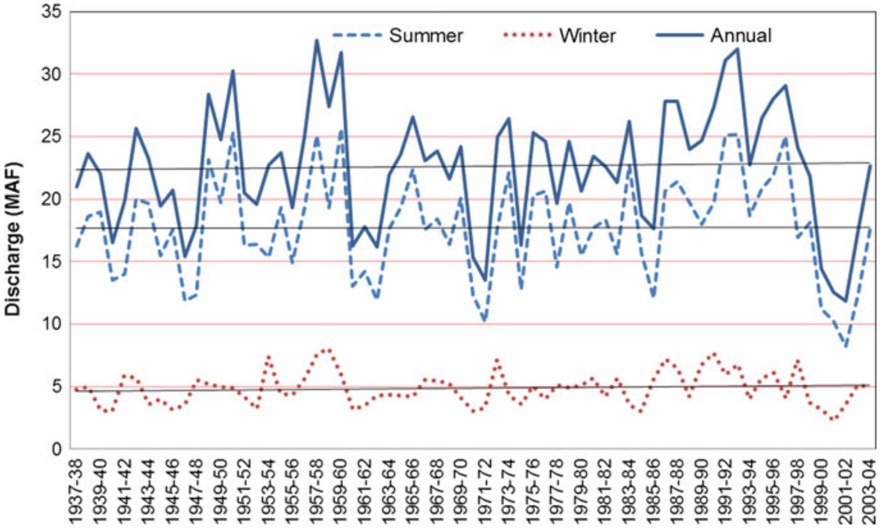


Fig. 35.2 Annual and seasonal trends in discharge of Jhelum River at Mangla Dam

irrigated area. Under irrigation by water wells, the main crops are wheat, tobacco, and fodder. In dry-farmed areas, major crops grown are wheat, gram, millet (bajra), and sorghum. The main fruit crops include citrus, mangoes, pomegranate, and guava.

35.2.1 Hydrogeology

In 1954, Punjab Irrigation Department in cooperation with US Geological Survey started a systematic study on soil and groundwater resources. During drilling of the formation, its samples were collected and analyzed. It was found to consist of sand, silt, and clay. Clay in particular was found to exist in small lenses which were not too extensive. The deposit of low-yielding fine sand and silt is nearly equal to sand of high permeability (Ahmad 1995). The hydraulic conductivity is generally high (>91.4 m/day) in vicinity of the active floodplains and gradually decreases toward the central Chaj Doab area (<45.7 m/day) (PPSGDP 2000). The low values of the hydraulic conductivity can be attributed to the presence of piedmont deposits in the subsurface.

Major recharge sources are precipitation, seepage from rivers/canal network, return flows of tubewell pumpage, and subsurface inflows (Sarwar 1999; Ashraf and Ahmad 2008, 2015), while discharge sources include tubewell withdrawals, evapotranspiration, and outflows to the drains and rivers (PPSGDP 2000). Recharge from the rivers was much higher in the pre-irrigation period when the groundwater was at greater depth in the doabs, but with the rise of water table in the irrigated areas the same has reduced considerably (NESPAK 1993). In summers, when the water levels are high in the rivers, spreading of water occurs on the floodplains resulting in considerable percolation of water. However, during the winter months, when the water level in the river falls, recharging from groundwater takes place into the rivers. WASID (1963) carried out extensive tests to determine water losses in the canals of northern zone of Pakistan. The direct methods such as ponding and inflow–outflow and indirect methods such as steady state and canal closure were used to measure the canal water losses. According to its results, the losses vary from 0.683 to 8.207 m^3/s/million m^2 of wetted perimeter in Chaj Doab.

The water table is usually measured in June and October months to perceive pre- and post-monsoon effect on the Indus aquifer. The mean water table depth ranged between 2.9 and 4.09 m during pre-monsoon (2003–05), while it varied between 2.6 and 3.91 m in the post-monsoon period. The minimum watertable depth (WTD) was 1.5 and 1.37 m during pre- and post-monsoon (2003–05 period), respectively. The WTD less than 1.5 m stretches over 11.2% area during pre-monsoon, while 1.5–3.0-m WTD prevailed over 21.7% of the Chaj canal command area during 2005 (Fig. 35.3a). In the post-monsoon season, the former WTD was dominated over 12.2% area, while the later range covers about 23.9% of the command areas, the rest being dominated by greater than 3.0-m WTD (Fig. 35.3b). Overall, the water table depth indicated a net decrease during pre- and

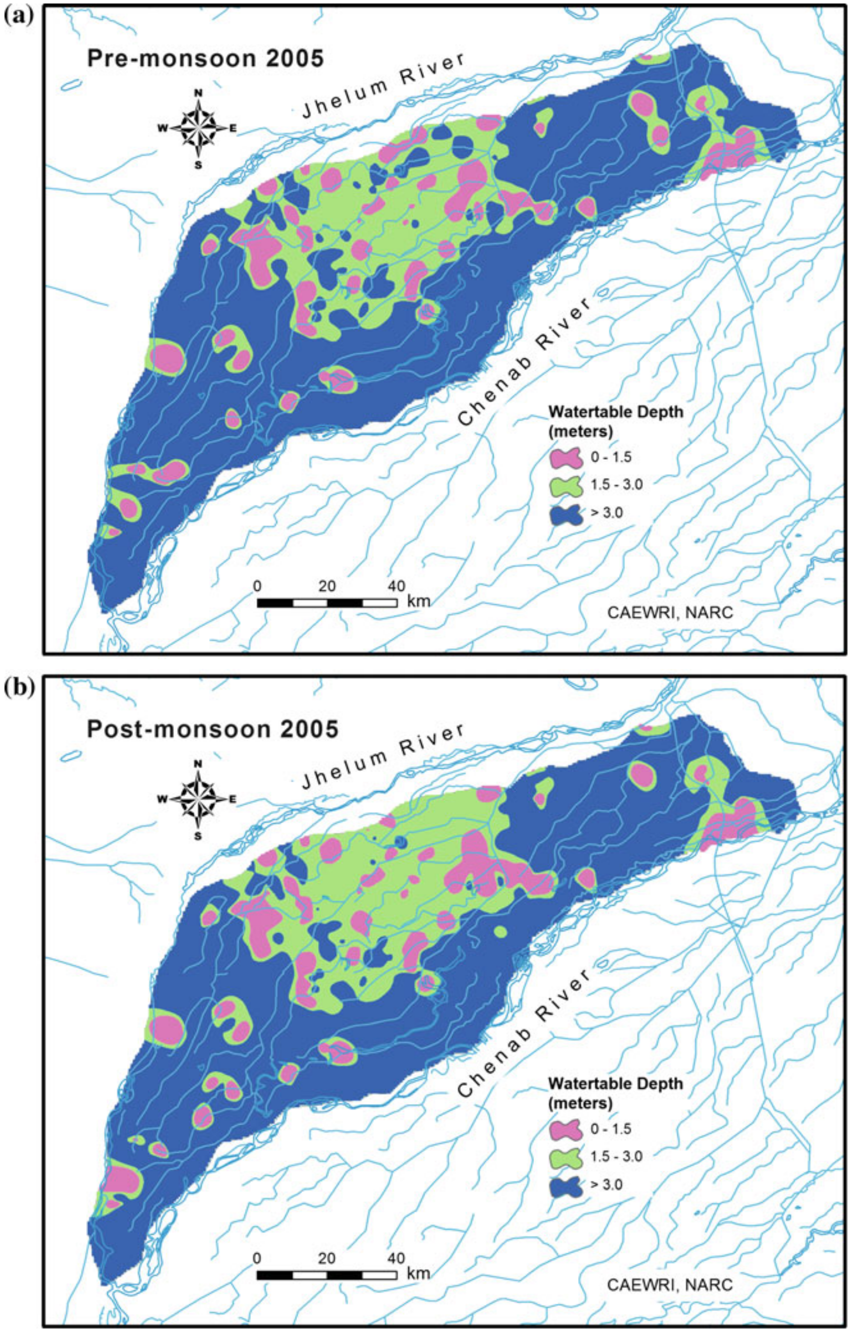


Fig. 35.3 **a** Watertable depth in Chaj Doab during June 2005. **b** Watertable depth in Chaj Doab during October 2005. **c** Change in watertable depth (Oct–June) in Chaj Doab

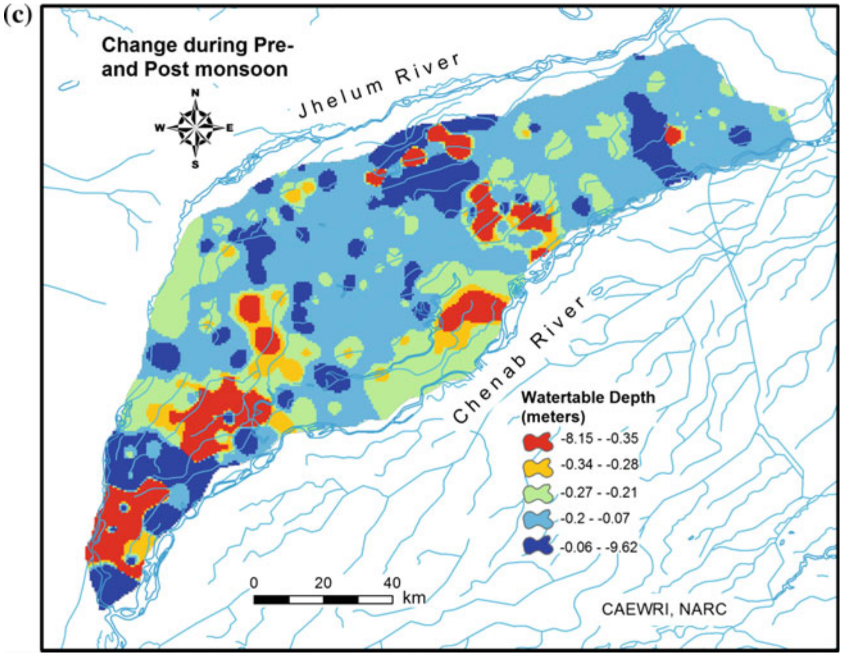


Fig. 35.3 (continued)

post-monsoon period (Fig. 35.3c). According to Tariq (2000), the groundwater exploitation is higher than the recharge at number of places.

35.3 Materials and Methods

35.3.1 Base Data Preparation

In the present study, baseline data like climate, hydrology, irrigation, hydrogeology, and remote sensing images of Landsat ETM plus (2001) were acquired from various sources like Pakistan Meteorological Department (PMD), Water and Power Development Authority (WAPDA), Punjab Irrigation Department, Soil Survey of Pakistan. The spatial data layers were developed for base map preparation using a common coordinate system for data integration and overlay analysis in GIS. The remote sensing data were analyzed to observe the status of land use/land cover (LULC) and physical features, e.g., irrigation and drainage network, water bodies, waterlogged and salinity areas. The extent of waterlogged areas could be assessed rapidly and accurately using remote-sensed data (Choubey 1996). The water bodies like river and canals and the moist areas distinct in blue shades in false color composite (FCC) of 5, 4, 3 (RGB) of Landsat-7 image bands helped in demarcating

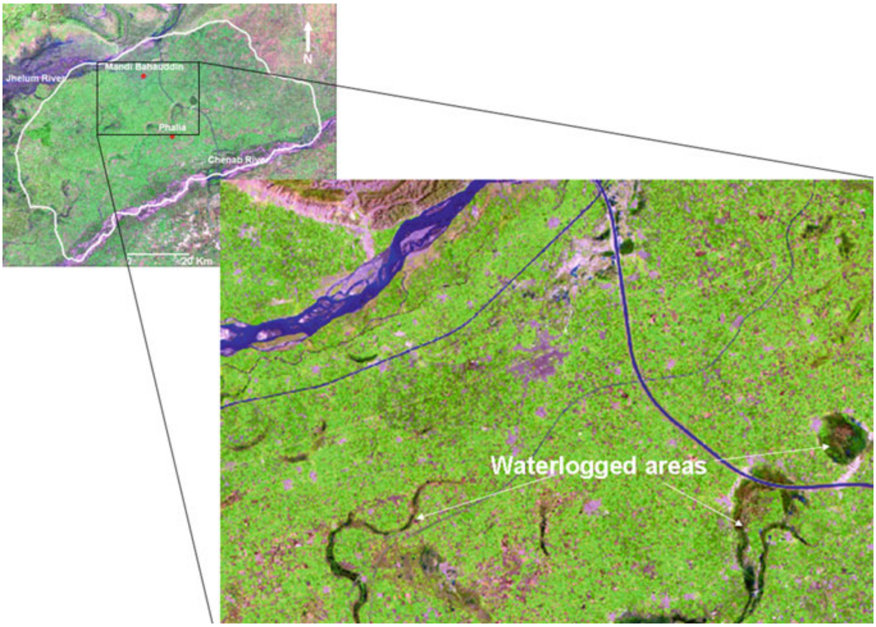


Fig. 35.4 Waterlogged areas in Landsat-7 image of the study area

river flow paths and major canal network, e.g., main canals, link canal, and branches in the irrigated plain. The swamps and waterlogged areas are visible in shades of dark color (Fig. 35.4). Image classification was performed using supervised method to develop and analyze LULC classes, i.e., forest cover, cropland, rangeland, open soil, wastelands, and water bodies. The land cover map helped in defining potential recharge and discharge zones for conceptualizing the groundwater flow model.

35.3.2 Numerical Model Selection

The use of the model with simplifying assumptions is justified because it allows meaningful predictions in a complex hydrogeological system. For this study, the selected model has the capability of simulating the following conditions:

- Confined or unconfined conditions,
- Steady-state or transient conditions,
- Three-dimensional behavior of the aquifer (horizontal and vertical flow),
- Variably saturated conditions,
- Spatial and temporal variations in boundary conditions and hydrologic properties,

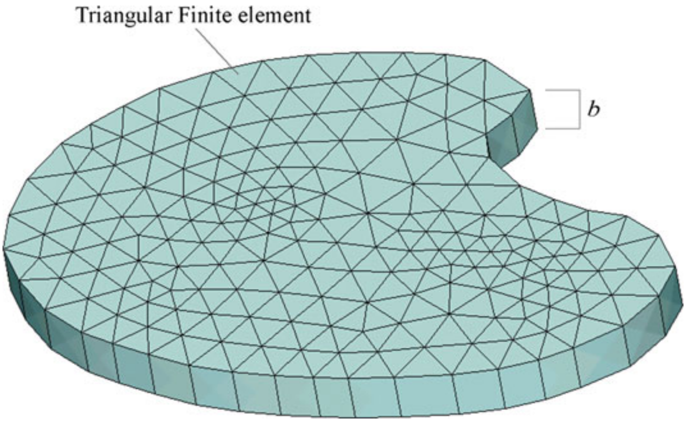


Fig. 35.5 Finite element mesh with triangular elements where *b* is the aquifer thickness

- Variable grid size and time steps,
- Irregular geometry of the site.

Initially, Zeinkiewicz (1971) worked on finite element method to solve civil engineering (structural) problems. Latter, the method was applied by Segerlin (1976) and others in groundwater hydrology. Codes are now available that use finite elements to simulate groundwater flow and mass transport (Voss 1984; Yeh and Huff 1983). In Finite element model (FEM), heads or concentrations are computed at each node of the domain discretized into regular elements (Fig. 35.5). Feflow can tackle a wide range of problems, e.g., related to heterogeneous or anisotropic medium; Irregular boundary conditions, and has the property to retain values of physical parameters like hydraulic conductivity and storativity separately for each element of domain (Thangarajan 2004).

35.3.3 Model Conceptualization and Development

The physical features defining the model boundaries were Jhelum and Chenab rivers, i.e., about 32 and 94 km in length, respectively, in the northwest and southeastern sides, and upper Jhelum canal (UJC) (about 64 km) and lower Jhelum canal (LJC) with its branch (about 42 km) in the northeast and western sides, respectively. A three-layered superelement mesh was drawn consisting of 5343 elements and 3928 nodes in Feflow 5.1. The thicknesses of layers 1, 2, and 3 were kept 8, 32, and 67 m representing different levels of groundwater pumpage (Ashraf and Ahmad 2015). Akima’s bivariate interpolation method was used to develop the model layers from point data. The model domain, about 3417 km^2 in area, has elevation ranging from 200 to 238 m above mean sea level.

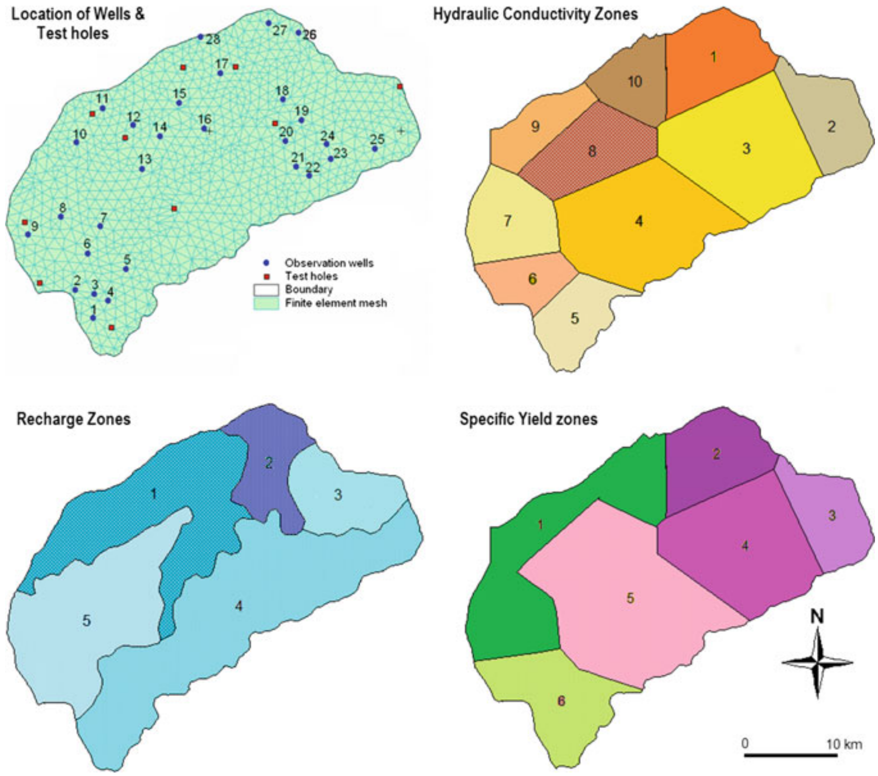


Fig. 35.6 Location of the observation wells and parameter zoning adopted for model calibration

The conceptual model for the study area consists of a set of hydraulic conductivity and recharge zones. These zones (marked as parameters) were used in inverse model PEST (Doherty 1995) to find a set of hydraulic conductivity and recharge values that minimize the model calibration error. Based on the landform, hydrologic and hydrogeological characteristics of the area, 10 hydraulic conductivity zones, and 5 recharge zones were developed in order to calibrate the steady-state model (Fig. 35.6). The hydraulic conductivity zones were delineated using Thiessen polygon method in GIS. The recharge zones were defined on the basis of following criteria:

(i) WAPDA has subdivided the SCARP II-A scheme into units for abstraction of groundwater from the deep tube wells. These units form the command areas of the main tributaries of the upper Jhelum canal and follow the hydrological setup of the area.
(ii) The geomorphological characteristics of the area in which each landform comprises of soil type of different physical characteristics. The texture of various types of soil affects the recharge behavior of the groundwater.
(iii) The land capability of the area based on the suitability for general agriculture use.

Table 35.1 Groundwater recharge estimated from various sources in the study area

Zone	Area (km^2)	STW 25% of withdrawals (MCM)	PTW 20% of withdrawals (MCM)	Canals 80% of seepage loss (MCM)	Rainfall 17.9% (MCM)	W/C & fields 25% (MCM)	Total recharge (MCM)	Recharge (m/day)
1	800.1	49.2	38.5	54.1	74.6	95.7	312.1	2.50×10^{-4}
2	282.8	17.4	13.6	19.1	26.4	33.8	110.3	8.84×10^{-5}
3	302.5	22.4	14.6	20.4	28.2	36.2	121.8	9.77×10^{-5}
4	1237.3	91.7	59.6	83.6	115.3	148.1	498.3	3.99×10^{-4}
5	794.6	113.8	38.6	53.7	74.1	95.1	375.2	3.00×10^{-4}
Total	3417.2	294.5	165.0	230.9	318.5	408.9	1417.8	1.14×10^{-3}

MCM million cubic meter, *STW* shallow tube wells, *PTW* deep tube wells, *W/C* watercourse

A recharge of 80% of the seepage losses was considered from the irrigation channels, while 25% of the delivery at watercourse head had been used as initial recharge from the watercourses. Total recharge estimated from various sources in the five zones is shown in Table 35.1. In the first phase of groundwater flow modeling, steady-state simulation was performed, which was fully implicit with constant time steps. The hydraulic conductivity and recharge values were adjusted during calibration runs until the calculated head values became close to the observed heads. During transient calibration, six zones of specific yields were configured on the basis of field data, pumping test data, and hydrogeological setup (Fig. 35.6). The sensitivity of the model was evaluated in response to changes in the hydraulic conductivity, recharge, and specific yield values.

35.4 Results and Discussion

35.4.1 Spatial Data Analysis

The digital interpretation of RS data indicated major LULC classes of cropland (over 70%), bare soil (10%) and waterlogged areas (about 4%) in the study area. Total of 585 polygons of waterlogged class were generated during image classification, and the major waterlogged areas (>0.02 km^2) with aggregate coverage of about 71 km^2 were selected for overlay analysis in GIS. About 25% of waterlogged areas appears to exist in the young channel levee remnant and meander floodplain, whereas 17% in the scalloped interfluves (Table 35.2). The waterlogging may be created here due to the presence of perched water condition and poor drainage

Table 35.2 Analysis of waterlogged area with associated factors

S. No.	Landform	Total cover (km^2)	Waterlogged polygons			
			Number	%	Area (km^2)	Largest (km^2)
1	Young piedmont plain	111.4	11	3.0	2.2	0.5
2	Piedmont basin	454.8	39	10.8	3.6	0.4
3	Scalloped interfluves	932.9	61	16.9	11.2	2.7
4	Old channel levee remnant	355.5	26	7.2	6.3	1.7
5	Cover flood plain	42.5	7	1.9	0.9	0.3
6	Meander flood plain	709.8	45	12.5	9.8	2.2
7	Young channel levee remnant	327.2	47	13.0	6.3	1.0
8	Active floodplain	311.0	100	27.7	21.6	3.8
9	Braided riverbed	172.1	25	6.9	9.1	3.5
	Total	3417.2	361	–	71.0	–

system. Although active floodplain contains higher percentage of polygons, these may be of temporary nature resulted from river inundation. About 11% of the polygons exist in the piedmont basin which receives water from the adjoining land during the rainy season. Maximum of 154 polygons of wastelands were found in the 500- to 600-mm rainfall zone, whereas 127 appeared in the <500 mm zone. During high rainfall period like monsoon, waterlogging is developed locally in depressions and low-lying areas.

35.4.2 Simulation of Groundwater Flows

In the initial run of calibration for steady-state simulation, the model shows an overall higher trend in the simulated heads. The final calibration results showed a reasonable agreement between the simulated and the observed heads with a mean difference of 0.06 m and variance of 1.46 m between the hydraulic heads. The simulated hydraulic conductivity of each layer appears to have mean values of 69.3 for layer 1, 72.2 for layer 2, and 74 m/day for layer 3 (Table 35.3). At low values of hydraulic conductivity, the groundwater flow becomes disrupted and localized to specific areas. A cross section of head distribution has been constructed along AA′ over an 80 km spread, which shows an overall groundwater flow toward southwest direction, following a similar trend as that of the topographic relief (Fig. 35.7). Mass balance analysis of the inflow entering the system, i.e., from link canals with the addition of areal recharge from all sources like canal seepage/irrigation losses, precipitation, and recycle water of the tube wells over active interior nodes, proved to be in perfect balance with the outflow components moving toward boundaries of the groundwater flow model.

Velocity vectors were drawn over the equipotential surface map to examine the distribution of flow fields and areas of high velocity vectors (Fig. 35.8). In layer 1, high velocity (>0.12 m/day) was observed in northwestern part near Rasul Barrage.

Table 35.3 Simulated hydraulic conductivity values (m/day) in different zones of the three-layered model

Zones	Layer 1	Layer 2	Layer 3
1	15.55	10.02	8.64
2	2.07	2.06	0.69
3	116.64	120.96	125.28
4	90.72	99.36	108.00
5	158.28	153.01	167.62
6	136.51	146.02	147.74
7	6.05	4.32	5.18
8	31.10	69.29	59.44
9	28.51	22.46	28.60
10	108.00	94.18	89.16
Mean	69.34	72.17	74.04

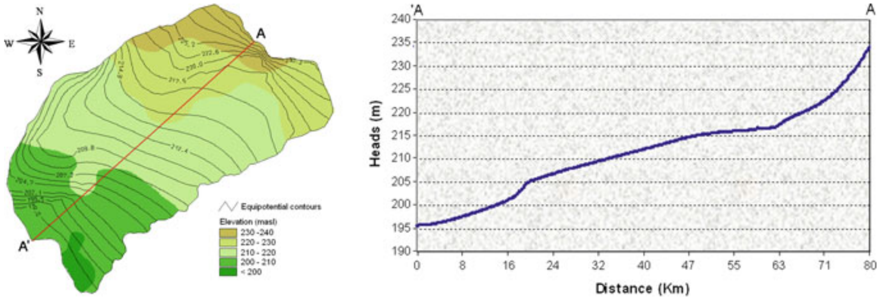


Fig. 35.7 Profile section of heads along AA′ in steady-state condition

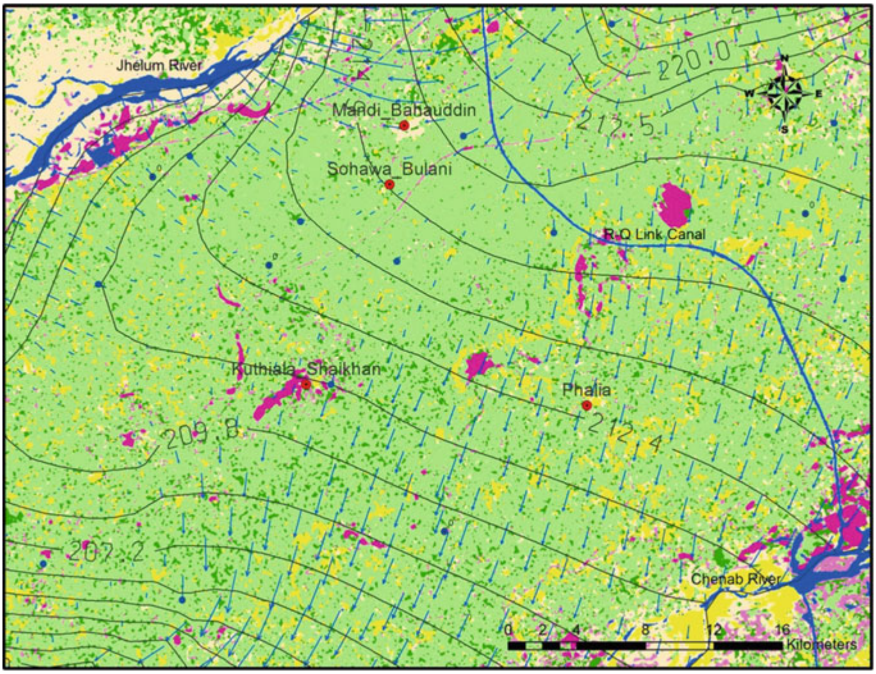


Fig. 35.8 Velocity vectors indicating groundwater flow pattern in irrigated land use containing patches of waterlogged areas in pink

The velocity range 0.04–0.08 m/day was dominant in most of the central and southeastern part of the model area. The patches of low velocity zone (<0.02 m/day) appeared to exist in the northern, northeastern, and western parts extending down to deeper layers. In layer 2, velocity zone 0.02–0.04 m/day was dominated in most of the central part, while the zone 0.04–0.08 m/day had reduced into a narrow belt in the center and appeared in the southern part of the area. In layer 3, velocity

Table 35.4 Specific yield (S_y) values in different zones of the three-layered model

Zones	Layer 1	Layer 2	Layer 3
1	0.150	0.080	0.100
2	0.120	0.130	0.170
3	0.065	0.082	0.076
4	0.070	0.040	0.080
5	0.110	0.100	0.180
6	0.140	0.220	0.270
Mean	0.109	0.109	0.146

Table 35.5 Water budget (m^3/day) in different stress periods (1985–2005)

Year	Inflows	Areal flux	Outflows	Imbalance
1985	1.31×10^5	4.76×10^5	-5.07×10^5	9.95×10^4
1987	1.27×10^5	4.37×10^5	-5.37×10^5	2.69×10^4
1990	1.29×10^5	4.24×10^5	-5.43×10^5	9.57×10^3
1992	1.30×10^5	3.98×10^5	-5.39×10^5	-1.02×10^4
1994	1.32×10^5	3.76×10^5	-5.32×10^5	-2.40×10^4
1995	1.33×10^5	3.76×10^5	-5.29×10^5	-2.02×10^4
1998	1.29×10^5	5.75×10^5	-5.64×10^5	1.40×10^5
2001	1.31×10^5	3.08×10^5	-5.39×10^5	-1.01×10^5
2003	1.42×10^5	2.17×10^5	-4.85×10^5	-1.26×10^5
2004	1.44×10^5	2.55×10^5	-4.79×10^5	-8.07×10^4
2005	1.45×10^5	2.73×10^5	-4.77×10^5	-5.88×10^4

less than 0.02 m/day was dominated in most of the northeastern part, 0.02–0.04 m/day in the center, and 0.04–0.08 m/day in the southern part of the model domain.

Transient-state calibration was performed to monitor the effect of specific yield on equipotential surface and to test the reliability of parameters determined by the pre-development steady-state calibration (Guvanasan et al. 1998). The simulated heads exhibited a reasonable agreement with the observed heads during this calibration with a mean difference of −0.002 m and variance of 1.84 m. The specific yield exhibited mean values of 109, 109, and 146 for layers 1, 2, and 3, respectively (Table 35.4).

The water table exhibited an average decline of about 0.96 m during calibrated period of 1985–2005. According to Qureshi (2011), an extensive groundwater use in Indus basin leads to an annual decline of 1.5 m in the water table which is draining the aquifer faster than the natural recharge process (Laghari et al. 2012). Total subsurface inflows and outflows in the groundwater flow model from 1985 to 2005 were found to be 1.47×10^6 m^3/day and (−) 5.73×10^6 m^3/day. Maximum imbalance of 1.4×10^5 m^3/day in water budget was observed in 1998 (Table 35.5). During the Rabi season of 1997–98 record, weekly rain occurred from

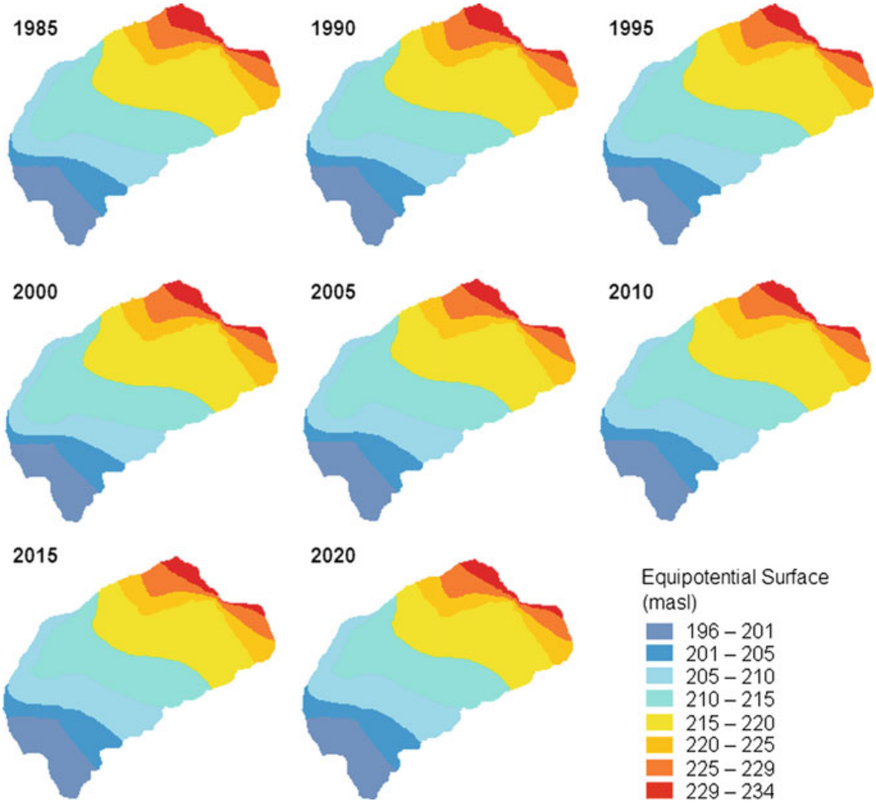


Fig. 35.9 Fluctuations in groundwater levels during 1985–2020

February 12 to 18 in Muzaffarabad and Jhelum. Again, exceptionally high rainfall occurred in the week from February 26 to March 4 in Muzaffarabad and Jhelum (Siddiqi 1999), the effect of which might be resulted in gradual rise of water table during 1998.

Minimum imbalance of (−) 1.26×10^5 m^3/day was found during the year 2003 which may be the result of persistent drought that occurred in the preceding years.

Historical climate data (1971–2004) were used to determine the cyclicity of rainfall trending. Variable trends of cyclicity were observed in the data; i.e., 1972–1984 and 1993–1998 years indicated uptrending, while 1984–1989 and 1998–2004 years had shown visible downtrending. These trends represent behavior of the climate, which were used to foresee the future rainfall conditions. Based on these analogies, years 2006 and 2014 were categorized as wet periods and years 2009 and 2017 as dry periods. Impact of these wet and dry conditions shows a net decline of about 0.81 m in water table during 2020. The trend of decline in groundwater levels was dominant in the central part of model domain (Fig. 35.9). In fact, a major breakthrough of groundwater depletion was occurred in the year 1999 (Fig. 35.10),

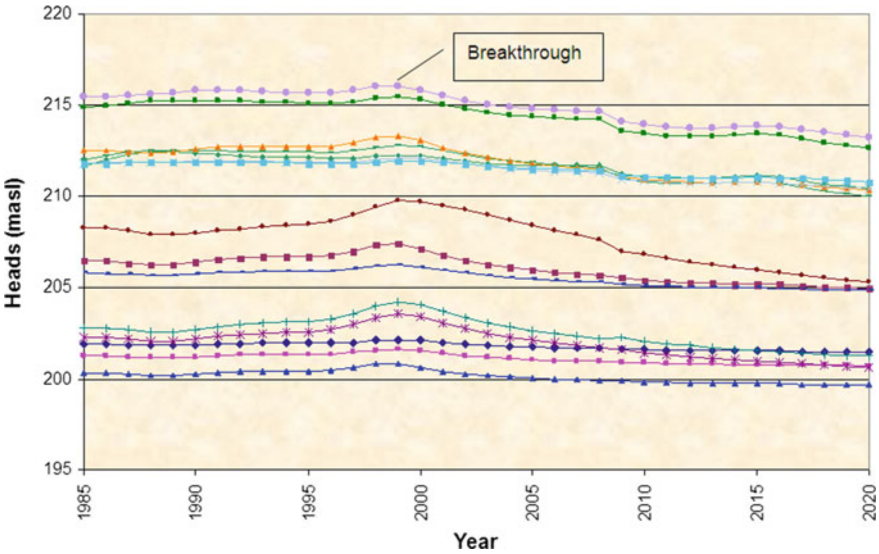


Fig. 35.10 Groundwater behavior in selected observation wells during 1985–2020

Table 35.6 Changes in coverage of various ranges of watertable depth (WTD) during 2005–2020

WTD (m)	2005		2020		Change	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
<1.5	226.9	7.0	73.8	2.3	−153.1	−4.7
1.5–3	1299.4	39.8	1104.8	33.9	−194.6	−6.0
3–4.5	1199.8	36.8	1151	35.3	−48.8	−1.5
4.5–6	477.2	14.6	788	24.1	310.8	9.5
>6	59.7	1.8	145.4	4.5	85.7	2.6
Total	3263	100	3263	100		

when the last drought (1998–2004) hit this region that resulted in the reduction of precipitation and river flows (Ashraf et al. 2011). With the increasing surface water deficit after 1998–99, the farmers started groundwater exploitation at a large scale (DLR-GWM 2002). The coverage of <1.5 m watertable depth appears to decrease from 7 to 2% and of 1.5–3.0 m watertable depth from 39.8 to 33.9% during the 2005–2020 period. On the other hand, the extent of >4.5 m watertable depth exhibits an increase from 2000 onward (Table 35.6).

35.5 Conclusion

The magnitude and timing of surface and subsurface water flows/resources are vulnerable to direct and indirect impacts of climate change in the Indus basin. The groundwater levels examined through numerical groundwater flow modeling had shown an average decline of 0.96 m during the calibrated period and further reduction up to predictive period 2020. The declining trend in the groundwater levels appeared to prevail from year 1999 onward—the time when this region was hit by a severe drought during 1998–2004 period. Some of the major factors causing reduction in the groundwater levels may include decrease in surface water for groundwater recharge, variability and change in rainfall pattern, and overexploitation of groundwater. Although waterlogging is predicted to shrink due to decline in groundwater levels in future, the problem may persist owing to subsurface lithological variations, i.e., in sand and clay, creating perched aquifer conditions. The vulnerability of the groundwater system to climate change can be addressed through adopting proper integrated water management techniques on long-term basis.

Acknowledgements We are thankful to the institutional support of Climate, Energy and Water Research Institute, National Agricultural Research Centre via projects (HIAWARE, ALP PARC) and Department of Earth Sciences, Quaid-i-Azam University, Islamabad, for execution of this work. The data support by Water and Power Development Authority (WAPDA), National Engineering Services Pakistan (NESPAK), Pakistan Meteorological Department (PMD), Pakistan Institute of Development Economics (PIDE), and Punjab Irrigation Department are also gratefully acknowledged.

References

Ahmad N (1995) Ground water resources of Pakistan, revised edn. Book published by Shahzad Nazir, Gulberg, Lahore

Ashraf A, Ahmad Z (2008) Regional groundwater flow modeling of Upper Chaj Doab of Indus Basin, Pakistan using finite element model (Feflow) and geoinformatics. Geophys J Int 173:17–24

Ashraf A, Ahmad Z (2015) Evaluating aquifer response to variable groundwater pumpage scenarios in Indus Basin through finite element modeling. Proc Pak Acad Sci 52(2):125–134

Ashraf A, Naz R, Mustafa N (2011) Evaluating drought impact on vegetation cover of Rarkan Rod-Kohi Area, Balochistan using Remote Sensing Technique. Proc Pak Acad Sci 48(3):143–150

Choubey VK (1996) Assessment of waterlogged area in IGNP Stage-I by remotely sensed and field data. Hydrol J XIX(2):81–93

DLR (Directorate of Land Reclamation) Report (2002) Groundwater monitoring: prospects, strategy and data. Irrigation and Power Department, Lahore, Pakistan

Doherty J (1995) PEST ver. 2.04. Water mark Computing, Corinda, Australia

Guvanasan V, Wade SC, Barcelo MD (1998) Application of MODFLOW-SURF to simulate Regional groundwater flow in Hernanado County, Florida

Ibrahim M, Aziz GN, Ali SF (1972) Tubewell performance and hydrologic monitoring studies in Phalia, Sohawa and Busal schemes of SCARP-II A (July 1970–June 1971), WASID Pub. No. 122, Central Monitoring Organization, Water and Soils Investigation Division Lahore

Immerzeel WW, Pellicciotti F, Bierkens MFP (2013) Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. Nat Geosci 6:742–745

IPCC (2013) Fifth assessment report of intergovernmental panel on climate change: working group 1. Summary for Policy Makers—Climate Change 2013: The Physical Science Basis

Kanwar R (2010) Sustainable water systems for agriculture and 21st century challenges. J Crop Improv 24(1):41–59

Kidwai ZD (1962) The geology of Rachna and Chaj Doabs, water and power development authority, water and & soils investigation division. Bull 5

Laghari AN, Vanham D, Rauch W (2012) The Indus basin in the framework of current and future water resource management. Hydrol Earth Syst Sci 16:1063–1083

Miller J, Immerzeel W, Rees G (2012) Climate change impacts on glacier hydrology and river discharge in the Hindu Kush–Himalayas. Mt Res Dev 32(4):461–467

NESPAK (1993) Pakistan, drainage sector environmental assessment. National Drainage Programme, NESPAK, Mot Macdonald Int. Limited.

Panday P, Frey K, Ghimire B (2011) Detection of the timing and duration of snowmelt in the Hindu Kush-Himalaya using QuikSCAT, 2000–2008. Environ Res Lett 8(1):014020–014033

PPSGDP Report (2000) Groundwater Flow and Solute Transport Numerical Models For SCARP II and Shahpur Area of Chaj Doab, Tech. Rep. No. 39, Punjab Private Sector Groundwater Development Project Consultants, Project Management Unit, Irrigation and Power Department, Govt. of Punjab, Lahore

Qureshi AS (2011) Water management in the Indus basin in Pakistan: challenges and opportunities. Mt Res Dev 31(3):252–260

Qureshi AS, Masih I, Turral H (2006) Comparing water productivities of transplanted and direct seeded rice for Pakistani Punjab. J Appl Irrig Sci 41(1):47–60

Sarwar A (1999) Development of a conjunctive use model, an integrated approach of surface and groundwater modeling using a Geographic Information System (GIS). PhD thesis, University of Bonn, Germany

Segerlin LJ (1976) Applied finite element analysis. Wiley, New York

Siddiqi J (1999) Effect of El-Nino on agriculture of Pakistan. Pakistan Agricultural Research Council, Islamabad

Soil Survey Report (1967) Reconnaissance soil survey of Gujrat district. Directorate of Soil Survey of Pakistan, Lahore

Tariq SM (2000) Canal lining in Pakistan. A briefing to the Chief Executive of Pakistan

Thangarajan M (2004) Regional groundwater modeling. Capital Publishing Company, New Delhi, India

Voss CI (1984) A finite element simulation model for saturated-unsaturated, fluid-density-dependant groundwater flow with energy transport or chemically reactive single species solute transport. U.S. Geological Survey, Water Resources Investment Report, 84-4369, p 409

Wadia DN (1966) Geology of India. The English Language Book Society and Macmillan & Co., Ltd., London

WAPDA (2002) Water resources and Hydropower development Vision-2050. Planning and Design, WAPDA, Pakistan

WASID (1963) Analysis of seepage losses from unlied canal in Punjab. The Paper 4. Water and soil investigation division, WAPDA

WASY (2004) Feflow—finite element subsurface flow & transport simulation system. Institute for Water Resources Planning and Systems Research Ltd, GmbH, Berlin, Germany (www.wasy.de)

Yeh GT, Huff DD (1983) FEW: a finite element model of water flow through aquifers, Oak ridge. National Laboratory Environmental Science Division Publications 2240, Oak Ridge, Tennessee, USA

Zeinkiewicz OC (1971) The finite element method in engineering science. Mc Graw-Hill, London

Part VI
Groundwater Sustainability: Management and Governance

Chapter 36
Groundwater Management in India: Status, Challenges and a Framework for Responses

Himanshu Kulkarni, Uma Aslekar and Siddharth Patil

Abstract India's groundwater situation is complex, to say the least. The myopic view of groundwater, as posed through the national- and state-level aggregate picture, needs to be overcome through efforts at assessment of aquifers at the right scale. However, even the aggregated, national picture on groundwater resources reveals that the groundwater crises of depletion and contamination of India's aquifers are now evident across India's diverse groundwater systems. Disaggregation holds the key to accurate understanding of groundwater problems in India, whether in the case of groundwater overexploitation or groundwater contamination, it is important to 'typologize' the groundwater situation in an area. Such typology emerges as a consequence of mapping aquifers, understanding their behaviour through space and time, understanding patterns of use and exploring opportunities for people to come together and manage groundwater resources collectively. The typology of groundwater resources in India is best defined by the hydrogeological factors that determine aquifer storage and transmission, the time factor over which impacts of overuse and/or quality declines occur and the menu of feasible supply- and demand-side interventions. Piloting groundwater management initiatives is called for, the pilots being defined through the characterization of aquifers at proper scales, beginning with appropriate conceptual models. The fugitive nature of the (groundwater) resource and the open-access domain in which it is commonly used pose major challenges in implementation of common pool resource (CPR) principles in the practice of groundwater management. In this light, the development of strategies to respond to groundwater overuse and deteriorating groundwater quality require a process-based approach, rather than big, one-fit-all prescriptions. Such an approach has many advantages over mainly mainstream 'institutional silo' approaches. First, 'processes' are central to addressing groundwater problems. Second, strategy development can happen efficiently only in a 'phased' manner, with each strategy subject to adaptation and refinement as

---

H. Kulkarni (✉) · U. Aslekar · S. Patil
Advanced Center for Water Resources Development and Management
(ACWADAM), Pune, India
e-mail: acwadam@vsnl.net
URL: http://www.acwadam.org

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_36

experience is gained. And finally, processes form the basis to overcome challenges of scale and diversity in dealing with groundwater management and governance in India.

36.1 Introduction

India's groundwater situation is complex (Chap. 1, Fig. 1.4), to say the least. A groundwater situation is a consequence of the type of aquifers, their properties, groundwater movement, groundwater quality and the nature and extent of usage of groundwater, alongside the impacts of a changing and variable climate. Periodic national groundwater assessments provide an indication of how many parts of India are vulnerable to problems of groundwater depletion and contamination. However, an in-depth understanding of the groundwater situation, at the right scale, divulges the nature and the patterns of such vulnerability.

The 'atomistic' nature of groundwater usage in India calls for a decentralized, local-scale understanding of groundwater depletion and contamination. The typology of groundwater that emerges as a consequence of mapping aquifers, understanding their behaviour through space and time, and understanding patterns of use is important in groundwater management and governance (Kulkarni et al. 2015). Hence, even a broad typology of groundwater conditions in the country is the first step in understanding the wider implications of hydrogeology in the planning and management of groundwater resources.

The typology of groundwater resources in India is best defined by a combination of hydrogeological factors determining the accumulation and movement of groundwater, the effects of groundwater usage and a menu of solutions that enable sustainable groundwater management. Piloting groundwater management initiatives is desired, the pilots being defined through the typological characterization of aquifers at an appropriate scale.

The complexity of groundwater resources and the diversity in the way in which groundwater is used in India define the problems surrounding groundwater resources. The complex nature and diverse contextual regime of groundwater problems in India compel the development of a strategic approach to groundwater management. Recognizing aquifers as 'common pool resources' is important in managing groundwater resources, whether it is addressing groundwater depletion or dealing with groundwater contamination. The uncertainty in groundwater resource characteristics including the spatial and temporal variability poses a major challenge apart from the open access in which groundwater resources tend to be used in India. Hence, strategic management of groundwater problems is necessary, depending upon the situation under which groundwater occurs, moves, and is used. Broad-sweeping solutions are seldom successful in this regard. Moreover, adaptation and refinement of strategies of groundwater management are also important as conditions change over time and responses to a problem have to be modified according to such changes. While this paper deals with groundwater in India, much of the arguments are likely to be relevant to other parts of South Asia about which more description is available in Mukherjee (2018).

36.1.1 Paradox of India's Groundwater Dependency and Crises

The 'silent revolution' by millions of farmers across the globe who have drilled their own wells, often independent of their countries' water policies, clearly points to the socio-economic advantages of groundwater irrigation (Llamas and Martinez-Santos 2005). South Asia's contribution to irrigated agriculture has been largely enabled by such a groundwater revolution particularly in the last couple of decades (Shah 2009). This groundwater revolution in India has meant a remarkable, often-unfathomed societal dependence on groundwater resources.

No other country in the world draws as much groundwater from its aquifers as India does. Annual groundwater extraction in India is of the order of 250 km^3, the largest in the world (Shah 2009). Nearly 90% drinking water needs of rural India are met from groundwater (DDWS 2009; The World Bank 2010). Between 60 and 70% of water for irrigation in India is derived from groundwater (The World Bank 2010; Ministry of Agriculture 2013). Nearly 50% of urban water supply is sourced from groundwater resources. Averaged for 71 Indian cities and towns, it is 48% (CSE 2012). A purely demographic expression of this dependency is summarized in Table 36.1.

It is clear that such a high level of dependency on groundwater is bound to attract problems of overuse and contamination that together define the current crises that envelop groundwater resources in India. Groundwater overexploitation was recognized as a serious problem in India across various aquifer systems, since the 1980s (Bhatia 1994; Dhawan 1990, 1995; Moench 1992; Macdonald et al. 1995. The nature of the groundwater crisis is as much a function of the character and status of aquifers, as on the increasing societal dependency on the resource.

Central Ground Water Board (CGWB), India's apex national institution dealing with groundwater under the Ministry of Water Resources, periodically evaluates the

Table 36.1 Size of India's groundwater dependency

No.		Unit	Quantity
A	Number of Indians using groundwater resources every day	Million	1000
B	Number of people using groundwater in Rural India every day	Million	700
C	Number of farmers using groundwater in at least one cropping season each year	Million	420
D	Estimated Urban India Population with some dependency on groundwater resources	Millions	180

Estimated on the basis of various sources, mainly: Census of India (2011), MoA (2013), CSE (2012) Patel and Krishnan (2007)

Table 36.2 Comparative national figures of groundwater assessments—2004, 2009, 2011

Resource information and Assessment Units	2004	2009	2011
Annually replenishable groundwater resources (bcm)	433	431	433
Net yearly groundwater availability (bcm)	399	396	398
Groundwater extraction for irrigation, domestic and industrial uses in one year (bcm)	231	243	245
The Stage of Groundwater Development (SGD) (%)	58	61	62
Total assessed units	5723	5842	6607
Safe	4078	4277	4530
Semi-critical	550	523	697
Critical	226	169	217
Overexploited	839	802	1071
Saline	30	71	92

Source CGWB (2006, 2010 and 2014)

status of groundwater in the country. The assessment is based on estimates of the ratio of groundwater extraction to the replenishable quantity of groundwater available annually at the sub-district level, i.e. for blocks/talukas/mandals (CGWB 2006, 2010, 2014). This methodology was developed initially by the Groundwater Resources Estimation Committee and revised later in 2009 (GEC 1997, 2002). An index called *Stage of Groundwater Development* (SGD) represents the ratio of groundwater draft and the net annual groundwater availability, in this assessment. When the value of the SGD of the assessment unit (block/taluka/mandal) is less than 70%, its status is considered as *safe* from the point of view of groundwater extraction. The assessment unit is categorized as *semi-critical* when the value is between 70 and 90%; it is categorized *critical* when the value is between 90 and 100%; and overexploited if the value is more than 100%. The SGD of an area along with the long-term decline in either pre-monsoon or post-monsoon water levels decides whether a unit is semi-critical, critical or overexploited. In general, one can say that groundwater resources are under various degrees of stress in semi-critical, critical and overexploited assessment units. Table 36.2 is a synopsis of comparison of groundwater resources through three periodic national assessments by Central Ground Water Board (CGWB 2006, 2010, 2014).

The net groundwater availability has remained more or less unchanged between 2004, 2009 and 2011, but the annual draft by domestic, agricultural and industrial sectors has moved from just over 230 to 245 billion cubic metres (6% increase). As a result, the SGD has moved up from 58 to 62%. Of the total assessed units in 2011, 30% are in semi-critical, critical and overexploited categories, compared to 29% in 2004. These blocks, where the resource is under stress, covered about 25% of the geographical area of the country in 2011. While this in itself is an alarming fact, it is important to recognize that such a broad comparison at an aggregate level can be inadequate and misleading. The unique feature of groundwater problems in India is the combination of availability and scarcity: severe overexploitation of the resource in a few states, districts and blocks combined with relatively unutilized resources in others. For example, share of semi-critical, critical and overexploited units in total geographical area is high in Punjab (77%), Rajasthan (73%), Haryana (59%), Tamil Nadu (59%), Gujarat (46%) and Karnataka (45%). These six states together cover about 30% of the total geographical area of the country. In comparison, other states have a relatively low proportion of units where groundwater is under stress. This is also reflective of the considerable variation in terms of geological strata in the country (Kulkarni et al. 2015). Hence, there is a need to develop a typology of groundwater conditions and situations through a local-level, aquifer-based understanding of various regions of the country, before developing policy-level responses to problems.

The ratio of pumping and annual replenishment is only an indicator of the degree of exploitation of groundwater. The complex relationship between exploitation and recharge depends upon the 'aquifers' from which groundwater is tapped by different types of wells (Margat 1992). Understanding aquifers[1] is based firstly on a good understanding of geology—rock types and rock structure. While India's lithodiversity represents a great variety of rock types and structures, making such understanding challenging, it also becomes crucial in developing local- and region-specific solutions to groundwater problems (Kulkarni et al. 2009; Vijay Shankar et al. 2011). Moreover, these local situations also determine the vulnerability of communities to groundwater overuse, droughts, floods, etc., especially on how drinking water in many parts of rural India is endangered.

The periodic groundwater assessment has not always included an indicative status of groundwater quality or groundwater contamination. An assessment of groundwater quality issues was attempted by CGWB (2010) based on various data sets. A variety of quality issues affect groundwater in India. A single water quality parameter has large-scale implications. Moreover, deterioration of groundwater quality can be attributed to many factors, some of which are part of the groundwater exploitation problem, while others are a result of external contamination from point/non-point sources. Rock–water interaction also causes groundwater contamination, such contamination qualifying as *geogenic*. Biological and chemical contamination of groundwater affects lives and livelihoods across both rural and urban societies, resulting in a range of impacts. Bacteriological contamination in groundwater is quite prevalent in many regions of India, resulting from absence or poor sanitation and sanitation practices. Fluoride and arsenic in groundwater are fast emerging as the two most significant contaminants in drinking water sources across the country. While it remains unclear as to the precise relationship between groundwater overuse and chemical contamination of groundwater resources, observations at specific locations reveal that there is a strong link between the two (Indu et al. 2007).

The report by Planning Commission (2007), Government of India states, 'The fallout of groundwater overexploitation has been contamination of groundwater due

---

[1] An aquifer is a geological formation, i.e. rocks or rock material, capable of providing sufficient quantities of water to springs and wells.

to geogenic factors (i.e. because of particular geological formation at deeper levels), resulting in increased levels of fluoride, arsenic and iron. Groundwater in some parts of West Bengal and Gujarat, which is contaminated by arsenic and fluoride now, were safe at the time of independence’. Groundwater overexploitation can trigger a variety of impacts on human life and livelihoods, including serious implications on the well-being and health of both individuals and communities. Table 36.3 provides a gist of some such impacts stemming from groundwater

Table 36.3 Summary of groundwater quality problems and their impacts in India

Quality problems	Number of Districts	Estimated Population affected/ exposed	Cause	Impact
Salinity	137	No estimates available	Inherent(geogenic)/ Man-made (e.g. coastal saline intrusion due to overpumping)	Kidney stones due to poor hydration in such areas (Cost per family Rs. 7500 per year)
Fluoride	203	65 million	Inherent(geogenic), but aggravated also by overexploitation; increased by malnutrition	Fluorosis; DALY = 38.5 per 1000 population; Cost per capita > Rs. 5000 per year
Arsenic	35	5 million in West Bengal; even more but not estimated in Assam, Bihar	Complex geogenic processes not yet well understood; but suspected to be related to excessive use and related water table fluctuations; increased by malnutrition	Arsenicosis; DALY = 5-27 per 1000 population; skin lesions in extreme cases lead to cancer of lung and bladder
Iron	206	No good estimates	Geogenic mainly	Iron overload; Cirrhosis; suspected diarrheal linkages; cardiac linkages
Biological	No good estimates	No good estimates	Related to poor sanitation and hygiene practices; increased by malnutrition	Diarrheal problems; DALY > 22 million years annually; total 4,50,000 deaths annually
Agrochemicals	No good estimates	No good estimates	Related to pesticide/ fertilizer use in agriculture	Multiple impacts; not understood well
Industrial effluents	No good estimates	No good estimates	Due to effluents from industries	Multiple impacts; not understood well

Source Krishnan (2009), Reddy (2008), Shah and Indu (2004), Susheela (2001), WHO (2002), NICED (2004), NSSO (2006) quality problems, developed by Krishnan (2009). It must be noted, however, that this summary is based on 'sketchy' nation-wide data and represents only an indicative set of impacts. The reality could be much grimmer than what is presented in the table.

36.2 Recognizing India's Hydrogeological Diversity

The large-scale exploitation of groundwater and the co-terminal issues of groundwater contamination can be attributed to three clear causes:

1. The growing demand for groundwater in agriculture, industry and urban growth.
2. The mismatch between growing irrigation demand and correct estimates of groundwater availability and contamination.
3. The power-subsidy regime has been the largest externality to influence the unplanned usage of groundwater resources.

Groundwater overuse is a consequence of poorly planned supply, often ignoring projections of demand. The impacts of poor planning and ignorance are further amplified by poor understanding of groundwater resources (aquifers) across large parts of India. A focused understanding of the quantitative- and quality-related aspects of the groundwater resource and its various supply and demand dimensions is required in taking the agenda on groundwater management forward.

Even a broad typology of six aquifer settings in India divulges the possible variability in groundwater conditions present in the country, especially when overlaid on the outlines of different districts (Fig. 36.1). Most of the larger states show multiple aquifer settings, clearly pointing to the need for a more local assessment of groundwater resources. Moreover, more than 70% of India is underlain by formations that include 'consolidated rock' (the non-alluvial settings in the following Table 36.4). The remaining nearly 30% is unconsolidated alluvium—loose rock material formed due to processes of weathering, erosion and deposition and not yet having consolidated into 'rock'. 'Hard rocks' is a generic term applied to igneous and metamorphic rocks wherein aquifers are a consequence of weathering and fracturing patterns rather than classical pore spaces of intergranular nature formed in alluvial deposits—settings 5, 6 and part of 1 in Fig. 36.1. Availability of groundwater in wells tapping hard-rock aquifers is quite variable even in a small area or watershed. Similarly, the groundwater quality in different wells is also likely to vary more significantly across a single hard-rock aquifer. The broad typology presented here can be further sub-classified as more information becomes available. For instance, the category of mountain systems (mostly the Himalayan System) could be further classified using the rock-type categories, but paucity of hydrogeological information limits further classification at the present moment.

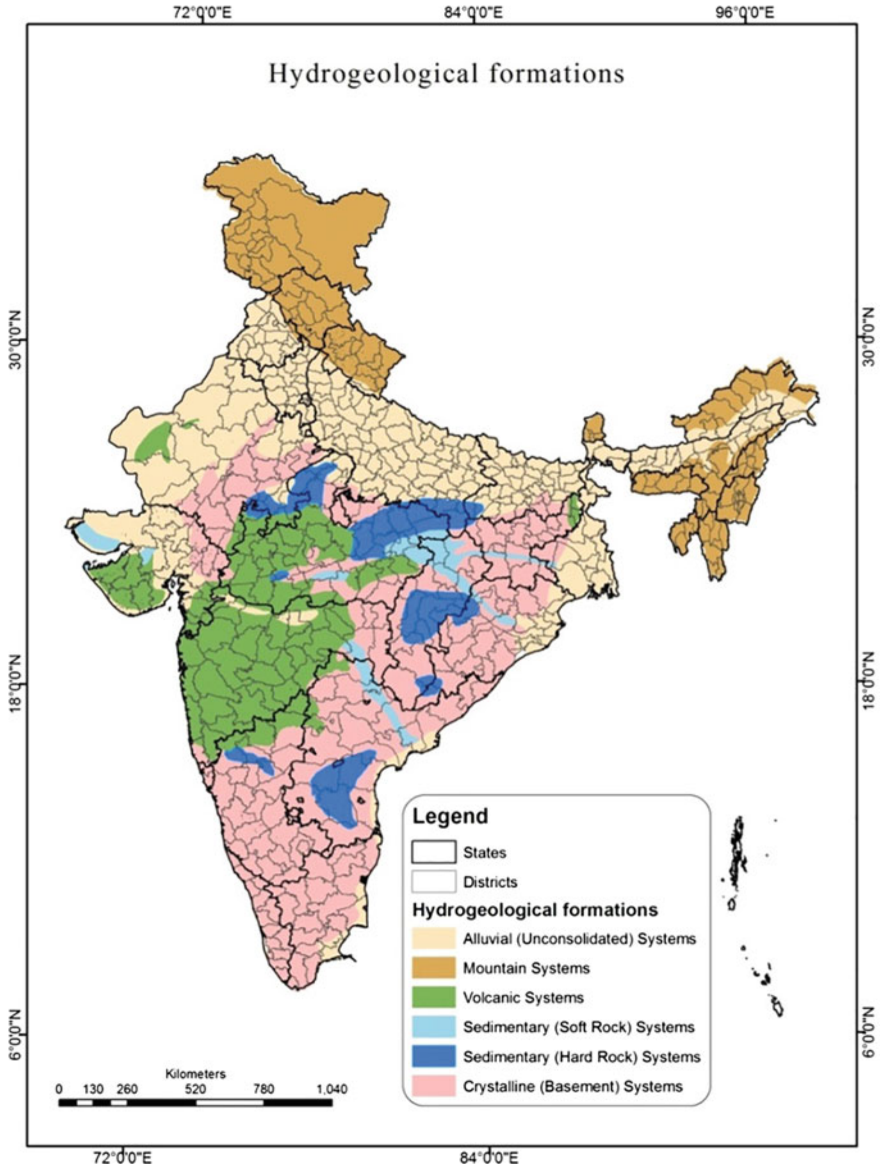


Fig. 36.1 Typology of hydrogeological formations In India (after Kulkarni 2005; Kulkarni et al. 2009)

Annexure to Fig. 36.1

Simplified, Generalized Descriptions of ‘Hydrogeological Settings’

Mountain systems: The Himalayas constitute a structurally complex suite of different types of rocks. The structural elements in the Himalayan geology such as fractures and faults give rise to relatively local, sometimes continuous aquifer systems that have limited stocks of groundwater that often feed perennial springs. The mountainous terrain and complex geology provide a typical setting for such aquifers, which are relatively poorly studied in India.

Alluvial (unconsolidated) systems: Large rivers originating in the mountains such as the Himalaya bring down a lot of sediment along with water and deposit it in vast plains. The *extensive and thick* deposits of gravel, sand, silt and clay within the Indo-Gangetic region of North India have given rise to sets of multiple regional ‘aquifers’. Sometimes, local (perched) aquifers are also found in the region. The large scale of these deposits means large stocks of groundwater, multiple aquifers and complex cycles of recharge. The accumulation, movement and quality of groundwater are basically functions of the nature of the sediments, their thickness and extent.

Sedimentary (soft) systems: Aquifers are formed in sedimentary rocks which largely preserve their sedimentary status. Hence, aquifers are formed in such rocks due to a combination of some intergranular porosity including the size, shape and arrangement of grains as well the structure of the rocks forming including features such as bedding dips, fracturing, faulting and folding patterns. These rocks have not undergone processes like metamorphism leading to further compaction of the rock.

Sedimentary (hard) systems: Harder, more compact sedimentary rocks have become more compact on account of various processes. Aquifers are formed largely due to the structure of the rocks such as bedding, joints, fractures, faults and folds. Intergranular spaces are of secondary nature in these systems. There is relatively lesser likelihood of groundwater stocks in these systems.

Volcanic systems: Large regions of Western and Central India are underlain by rocks formed from the eruption of lava that spread over great areas. These volcanic rocks, mainly in the form of basalts, occur as lava flows or layers of different basalt. Basalt aquifers are a consequence of differential weathering and fracturing patterns in different types of basalt. The degree of weathering and the intensity of fracturing determine the occurrence of water in the basalt aquifers that are quite local in their geometry.

Crystalline (basement) systems: Large regions of India are underlain by ancient igneous and metamorphic rocks. These rocks are formed from the cooling of magma and subsequent metamorphism in some areas (effect of temperature, pressure and burial). Weathering and fracturing of these rocks give rise to aquifers, and the occurrence of groundwater depends upon the ‘layered’ structure and diverse structural features in these rocks.

Groundwater overuse has led to multiple impacts, the most obvious being *fall in water levels* and *reduced well yields*. With users having to pump water from greater depths, *costs* of deepening and drilling have been further compounded by the need to install *high-capacity pump-sets*. In many areas, this has also led to serious declines in groundwater quality with a continuous competition between users, leaving the socio-economically marginalized behind, in such a race.

Some researchers argue that there is no fundamental reason why the temporary overexploitation of groundwater is undesirable. A proper understanding of the groundwater system to ascertain impacts can be a precondition for extracting groundwater for economic benefits as part of a logical water management strategy (Foster 2000; Price 2002). India's groundwater systems are still not as well understood as in some other regions of the world. Moreover, groundwater exploitation in India tends to exhibit a competition on 'who pumps out more and how quickly', either through deeper wells or larger pumps from a system that is often quite poorly understood 'locally' (Kulkarni and Vijay Shankar 2014). The situation of electric supply in rural India only adds to such competition. In other words, groundwater use in India is not subjected to a planned and controllable extraction. Hence, as Foster and Chilton (2003) point out, groundwater resource degradation is 'much more than a localized problem' and that it threatens the sustainability of the resource base on a 'widespread geographical basis'. The inhomogeneous character of the resource itself attributes an inequity of endowment to different users (especially farmers) even in a typical Indian village (Kulkarni and Vijay Shankar 2014). Groundwater overuse further increases such inequity between users; it also creates competition between uses—drinking water and irrigation, for instance. Efficiency of use, equity of natural occurrence and sustainability of groundwater resources have been severely impacted by haphazard groundwater overuse.

Shah (2009) makes two very significant observations with regard to the micro-picture on groundwater resource development in India. Firstly, he states that India's groundwater story has unfolded on the small farms in the nook and corner of the country. Secondly, he states that the socio-economic impacts from the use of groundwater occur through stages of groundwater development, each with a distinct set of features. Both the arguments highlight the need for more localized, micro-analyses of aquifers, nature and patterns of usage, groundwater quality and relevance to social, economic and ecologic factors. The units of groundwater assessment will be sub-units (perhaps villages and town) of the current unit of the national assessment (talukas/blocks/watersheds). Therefore, assessment must include both the temporal and spatial dimensions for the conditions in aquifers and the changes therein.

The typology of groundwater management is related to aquifers, stages of groundwater development (in which socio-ecological situations, such as those defined by Shah 2009, develop) and the menu of responses that are available (or can be developed) as a part of the groundwater management process. To illustrate this point, even a broad comparison of scales of aquifers, time taken to overuse effects to appear and the strategic significance of recharge and drinking water security for each of the types shows how even ideas for systematic recharge and ensuring drinking water security to communities are different across this diverse typology (Table 36.4).

Table 36.4 Summaryof India's Groundwater Typology

Regional groundwater settings	Aquifer scale spatial	Estimated period of impacts from groundwater overextraction to become apparent	Significance, with regard to recharge and drinking water security
Mountain systems in the Himalaya	Highly localized, often multiple aquifers that transcend watershed and village boundaries due to interplay of geology and topography	5 years	Small, sometimes multiple natural recharge zones. Climatic factors, changes in land-use and land-cover and growing competition between sources like springs and bore holes have endangered drinking water security. Major quality issues include bacteriological contamination and prevalence of iron
Alluvial (unconsolidated) systems mainly of the Indo-Gangetic Plains	Thick and extensive aquifers forming regional groundwater systems. A single aquifer lies below multiple villages, towns and even cities indicating a regional context to groundwater occurrence	25–50 years	Large natural recharge zones, often at long distances from where groundwater is extracted. Volumes recharged are large. Extraction of groundwater from multiple depths that goes hand in hand with rising drilling and pumping costs. Groundwater contamination is a more serious problem endangering drinking water security than the problem of exploitation itself

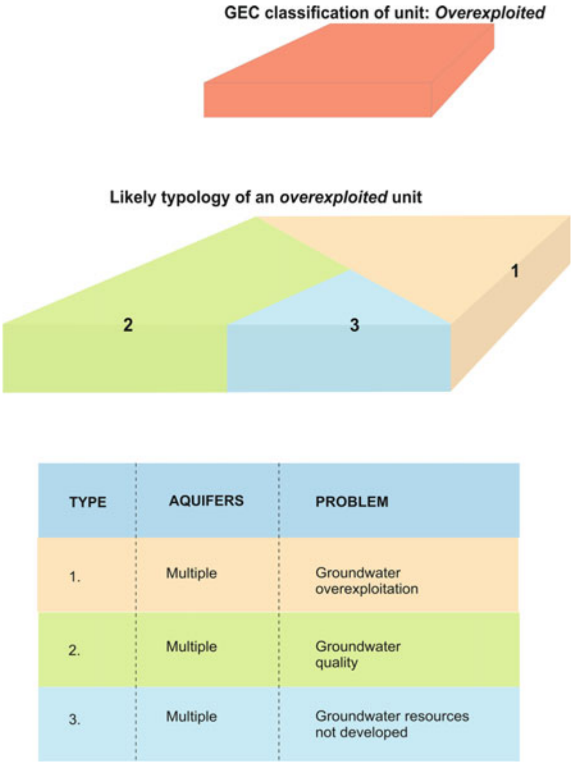
(continued)

Table 36.4 (continued)

Regional groundwater settings	Aquifer scale spatial	Estimated period of impacts from groundwater overextraction to become apparent	Significance, with regard to recharge and drinking water security
Soft sedimentary systems	Scales are variable—from local to regional aquifers—but not of the scale of alluvial systems (above); aquifers are regionally disposed with several villages overlying a single aquifer	15–20 years	Local recharge, although magnitudes of recharge can be large; drinking water impacts on the groundwater quality tend to be more pronounced than on the quantitative side
Sedimentary (hard) systems	Aquifers are generally local, often with coherence between watershed and aquifer boundaries; usually one village-one aquifer	5–10 years	Local recharge systems, at places, outside village and watershed boundaries. Drinking water security is sensitive to both depletion and various types of groundwater contamination
Volcanic systems	Local but layered system of multiple aquifers (vertical); watershed and aquifer boundaries often coherent but village may be underlain by many aquifers	5–15 years	Local recharge systems, at places, outside village and watershed boundaries. Rapid, seasonal and sometimes long-term groundwater depletion endangers drinking water security
Crystalline (basement) systems	Local and regional aquifers with a complex relationship between shallow and deep aquifers. Hence, coherence with village and watershed boundaries is different from place to place	5–25 years	Variable systems of recharge—regional at places, local at others; depletion concurrently affects quantities and quality, making drinking water sources highly vulnerable

36.3 Strategising Responses at Local Scales

Aquifer understanding is crucial in developing a strategy of groundwater management at scales of administrative units. A village panchayat in India might be eager to address a groundwater depletion issue, and therefore, developing a typologized understanding of aquifers across various social and hydrological settings becomes important. The storage and transmission features of aquifers in



TYPE	AQUIFERS	PROBLEM
1.	Multiple	Groundwater overexploitation
2.	Multiple	Groundwater quality
3.	Multiple	Groundwater resources not developed

Fig. 36.2 Conceptualizing the problem typology in the current groundwater assessment unit

different hydrogeological settings are bound to vary, both in space and time. Moreover, similar aquifers are likely to respond differently when the conditions they are exposed to—natural and human-induced—vary significantly due to factors such as rainfall, demand patterns, land use. While hydrogeology forms the basic science behind understanding aquifers, a multidisciplinary approach encompassing sociology, economics and ecology is required to understand the complex issues of groundwater availability, demand on groundwater and supply systems to cater to the demand.

Figure 36.2 illustrates the meaning of typology, with the intention of understanding the 'groundwater situation' in the context of the current *unit* of assessment, say a block or a milliwatershed used at the state and national levels for periodic groundwater assessments (after GEC 2002). An example of an overexploited taluka (as per the periodic assessment) from a district is used to illustrate the point. In this case, the State Government, through the appropriate department, and under certain groundwater legislations, is likely to impose sanctions, such as electricity regulation or even invoke a ban on wells through formal notification to curb further groundwater exploitation in the taluka. However, aquifer-based, local investigations reveal that the taluka can be sub-classified on the basis of three different situations:

a. Area underlain by overexploited aquifers—henceforth called ‘overexploited type’.
b. Areas that are underlain by aquifers showing high groundwater salinity, but with no evidence of overexploitation of groundwater resources—henceforth called ‘groundwater salinity type’.
c. Area underlain by aquifers that show limited or no development of groundwater resources—henceforth called ‘limited groundwater resources development type’.

Differential conditions in a single groundwater typology warrant differentiated solutions, not possible through the current scales of groundwater assessment in India. The aquifers and aquifer conditions for a system of basalt aquifers have been described as a distinct typology of problems and responses by Badarayani et al. (2009). Even in a single hydrogeological setting—the Deccan Volcanic Province or in simpler words by basalt aquifers, three different approaches (illustrated in Figs. 36.3, 36.4 and 36.5) are required to define a typology of responses.

In the first case (Fig. 36.3), there are three basalt aquifers, with aquifers 2 and 3 being heavily exploited due to pumping for irrigation by hundreds of wells. Aquifer 1, at somewhat higher elevations, is not exploited. The figure also shows how, within a single type, there is evidence that the potential recharge locations for the three aquifers are different, necessitating clear strategies for *locating recharge structures*. In the second case (Fig. 36.4), on the other hand, it illustrates the presence of one aquifer (aquifer 2—river alluvium) which is characterized by high *groundwater salinity* compared to the groundwater in basalt aquifers—aquifer 1 and aquifer 3. In the third case (Fig. 36.5), two basalt aquifers—aquifer 1 and aquifer 2—are present with groundwater extraction limited to pumping from tens of wells. Groundwater extraction is limited and, despite low rainfall, shows the presence of active base flow, with perennially flowing streams. Hence, groundwater management design for each case needs to be different with a strategic groundwater

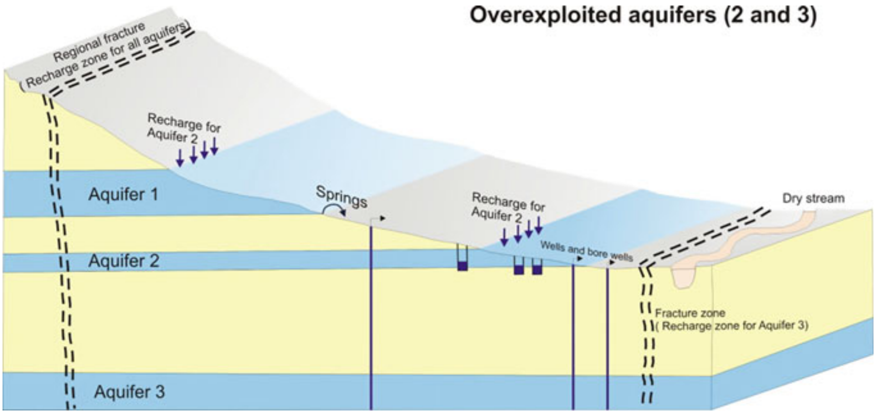


Fig. 36.3 Groundwater overexploited type

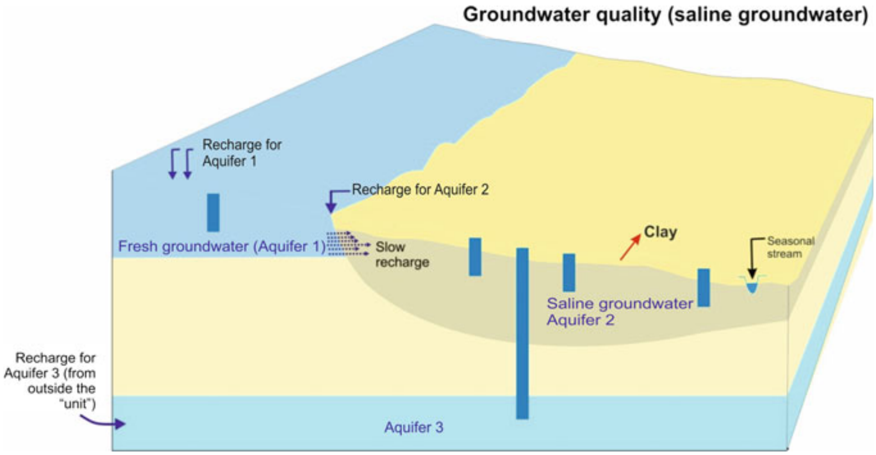


Fig. 36.4 Groundwater salinity type

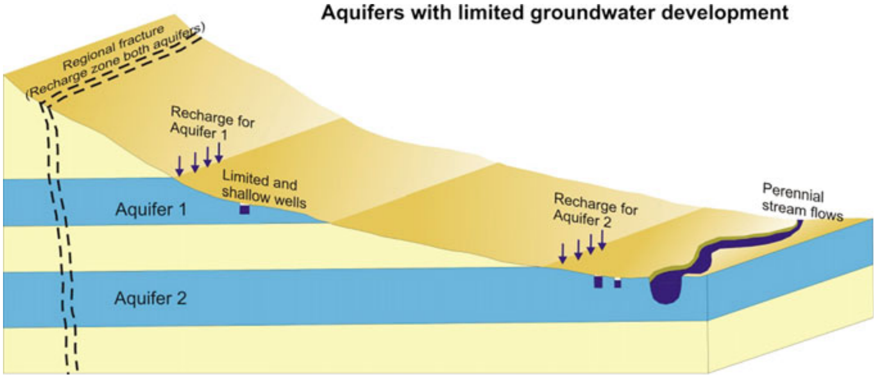


Fig. 36.5 Limited groundwater use type

management framework that considers the precise nature of the groundwater problem (Table 36.5).

Table 36.5 illustrates the potential of using aquifer understanding including the extent and patterns of groundwater usage in a region. Conceptual understanding including details of usage and a variety of interventions as part of offering strategic responses becomes important. Such a framework of typology-based responses also offers a platform to open up a dialogue with communities depending on each aquifer system. The utility of such an approach also lies in providing the community information in a decision-making process that relies on what is necessary and what is democratically acceptable to the community. Piloting such strategies form the next step in the process of groundwater management at local scales. The template provided in Table 36.5 can be further modified depending upon which of

Table 36.5 Strategy of groundwater management based on the 'typology' of situations represented through Figs. 36.3, 36.4 and 36.5

Potential responses in each type	Overexploited type	Groundwater salinity type	Limited groundwater use type
Supply side			
• Water harvesting		✓	✓
• Artificial recharge (spreading)	✓	✓	✓
• Artificial recharge (bore hole injection)	✓		
Demand side *(Legislative/Social)*			
• Distance between wells	✓	✓ aquifer 3	
• Depth regulation for wells	✓in aquifer 1	✓in aquifer 2	
• Pump capacity regulation	✓in aquifer 2 & aquifer 3	✓in aquifer 1 & aquifer 3	
• Water application technology (drips/sprinklers/pipes)	✓	?	
• Comprehensive, community-based management	✓ (only at regional level and with a legal net)	✓	✓
Indirect instruments			
• Electricity rationing	✓		
• Metering and pricing		✓	
• Crop selection	✓	✓	✓
Drinking water security			
• Social fencing		✓	
• Legislation	✓	✓	✓

the above actions are acceptable to the community and how they can be implemented through a formal institutional process involving local government systems. As is obvious, the suite of potential responses is defined by the hydrogeological context and the social and economic factors in a location at a given point in time.

A practical example of defining such pilots is given in Table 36.6, mainly as a starting point to define the piloting process itself. As various stakeholders dialogue and communicate, as a part of the piloting process, these options get refined further. As with any natural resource management pilot, with the right amount of effort, mainly through social skills, even the most challenging of communities can be brought around to view and practise the principles of CPR management in a groundwater management exercise through the development of groundwater management protocols. Protocols are defined here as a set of good practices that lead to improved groundwater management. Implementing the protocols under the types 1 and 2 situations not only requires larger investments in multidisciplinary

Table 36.6 Protocols of groundwater management and appropriateness for the typology

Protocols	Type 1	Type 2	Type 3
Hydrogeology in Watershed Management Program (special reference to recharge area demarcation)	Relevant, but with specific strategy for recharge	Highly relevant, especially with respect to groundwater salinity reduction	Not too relevant as there are few sites left for recharge
Recharge area protection (forest cover and community lands)	Highly relevant, only if groundwater overexploitation is tackled as the single largest issue	Not too relevant as most of the area is under private ownership	Highly relevant, especially in context to the community managed groundwater effort
Improved efficiency of well usage	Relevant to an extent	Not too relevant from a quantitative aspect but needs more investigation with respect to the groundwater quality issues	Highly relevant, especially when dealing with community wells
Pump capacity regulation	Relevant, but very challenging in implementation	Not relevant	Not relevant if collectives are formed
Regulation of distance between wells (especially between drinking water wells and irrigation wells—protection zones)	Relevant but challenging (especially in the absence of formal legislation)	Highly relevant, only after restoration of water quality in the aquifer (may take years)	Not relevant in case of efficient execution of community-based system
Construction of recharge structures for water quality improvement	Not relevant	Highly relevant	Not relevant
Regulation of agricultural water requirement (crop water requirement)	Highly relevant, but challenging	Relevant	Relevant (built into the community based groundwater system)
Sharing of groundwater through community participation	Relevant, but external (formal) support required	Partly relevant from the water quality perspective	Relevant if it is built into the community-based groundwater system)
Awareness building and education of community regarding aquifers as CPR	Relevant	Relevant	Relevant
Government regulation to control further exploitation	Highly relevant	Relevant, but not as stringent as in typology 1	Unnecessary

interventions, longer periods of interventions and formal institutional arrangements that also include groundwater-related legislation. On the other hand, the type 3 situation is lesser challenging on the external institutional front but requires field-level engagement with the community in enabling a systematic and sustainable access to groundwater, possibly even including setting up groundwater management collectives.

36.4 Essentials of a National Groundwater Management Strategy

The responsibility of sustainable, equitable and efficient management of a common pool resource like groundwater falls virtually on the shoulders of the people who access the resource, i.e. on the users themselves. If these users agree to consider groundwater as a community resource, then protocols such as those listed above can be implemented in an effective manner. In such an approach, called 'participatory groundwater management' or PGWM (Kulkarni et al. 2015), the state also needs to play a role of facilitating and coordinating partnerships between organizations and communities. Breaking down internal departmental and disciplinary solos and building partnerships is important in developing a programme on water management in India (Planning Commission 2012). Piloting and scaling up approaches of community-based PGWM would require partnerships between organizations having different disciplinary strengths. Hence, developing collaboration between such organizations is desired through regular dialogue ministerial level down to the level of communities and agencies working with them. Hence, ministerial partnerships between the disciplines of water, rural development, urban and industrial development, drinking water—sanitation and environment—are important as policy decisions in India. The essentials, as mentioned time and again, lie within the broad processes of hydrogeology and socio-economics. Interaction leading to integration is a daunting task, a discussion beyond the scope of this chapter. However, certain *actions* are critical to processes that can help attempt such interaction.

Firstly, breaking down institutional silos and piloting of processes based on the concept of PGWM hold the key in addressing India's groundwater management challenge. A process-driven approach has the capacity to be effective and accommodative, two key elements in beginning to manage groundwater resources. A robust legal framework that facilitates community efforts at management is also required. The response strategies that could emerge through such a framework could be direct, indirect or even adaptive (as some global literature suggests). At the most fundamental level, though, the hydrological aspects of science must be combined with social and economic aspects in order to develop community understanding, decisions and actions on the way groundwater resources are

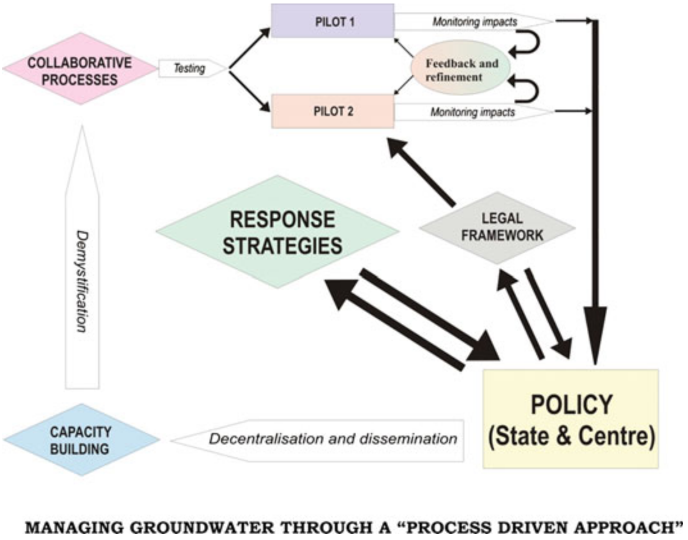


Fig. 36.6 The way forward: broad 'contours' of a process-driven approach

managed at local scales. Figure 36.6 provides a broad process of integration of actions through piloting capacity building, dissemination and demystification to bring practice and policy on groundwater closer than to what they are now. Each component of the process is described in brief below.

1. Capacity building

Unless assessed and considered within the basic framework in which groundwater occurs, i.e. within *aquifers*, the basic understanding (at the right scale) of groundwater will continue to be fuzzy, despite degradation of the resource, legislation to counter degradation and efforts around community management of this fragile resource. The term 'aquifers' figures prolifically in the report by the Planning Commission (2007, 2012), making it relevant in policy. However, in reality, the biggest drawback in converting groundwater policy into good practice is the lack of 'aquifer-based' approaches to groundwater management. Groundwater, within the policy framework, still remains a 'component' of watersheds, river basins, irrigation projects and the environment, and one cannot deny that it is so.

Howsoever, 'aquifers' must become the basis for a national-level comprehensive groundwater management strategy and a starting point for 'capacity building' in the water sector. Basic, but practical capacity building exercises are required and although it would be difficult to lay down the exact *modus operandi* for such capacity building, the content itself will need to be decided, not so much dependent upon the structure of institutions or the hierarchy therein or even the push from funders, but more in terms of understanding the problems (hydrogeological setting, stage of development, extent of water quality and the vulnerability to different stresses) in different types of aquifers. Capacity building modules would need to be customized for different stakeholders, where each stakeholder is a *learner* and there are *no experts*. So, capacity building will need to be more in the ‘workshop’ mode rather than a ‘classroom’ mode, with the onus on ‘aquifers, their mapping and their management’, also keeping the typology of groundwater resources in mind. Such capacity building would be inclusive of both knowledge and skill building of different stakeholders. Knowledge development would, for instance, enable data and information as decision driving instruments, while skill building would drive the process of converting knowledge to decisions and decisions to actions on groundwater management.

Capacity building will also need to consider its primary objective, i.e. *demystification* of a complex subject into understandable concepts. The subject of groundwater, as mentioned earlier, requires intense observation, perseverance and imagination. Hence, a certain degree of demystification is desired in order to get across concepts of aquifers, common pool resources, efficiency, equity and sustainability. Such demystification will pave the way for efficient collaborative processes, leading to pilots on groundwater management, some of which are already happening in different regions of the country.

2. Collaboration

The basic factors that will govern the effectiveness of groundwater management are *a solid hydrogeological base, strategic social engineering and appropriate tools and technologies*. Social surveys, remote sensing, geophysics and GIS are techniques that can prove useful in groundwater management. The need to integrate science, technology, sociology and economics is the fundamental rationale behind such collaborative processes. Protecting rural livelihoods is important in ensuring the country’s food and water security. Ensuring groundwater management is necessary in this regard, but at the same time quite challenging. However, the sustainability of such livelihoods cannot be ensured without proper strategies on natural resource management, groundwater being one of them. Given the diverse nature of the processes that are required as part of such management, it becomes important to involve multiple types of institutions/expertise in developing groundwater management plans for an area. Therefore, rather than specifying institutions, which would be the obvious way forward, if one considers Fig. 36.1 in such planning, the roles required to run the above processes are important. These roles (which also indicate the corresponding process) should broadly include (but not remain restricted to):

- *Aquifer mapping* and *groundwater characterization*
- *Social surveys*

- *Defining the typology of groundwater conditions in the project area/region*
- *Community dialogue and mobilization*
- *Conduct of 'key' meetings like Gram Sabhas, wherein communities lay down some consensus on management of groundwater resources. The PRI framework provides an alternative framework to formal legislative processes, which at the moment are not tuned into the typology approach to looking at groundwater resources*
- *Coordinating roles of formal agencies such as the State Groundwater Boards, Electricity Boards, Soil and Water Conservation Department, Drinking Water and Sanitation Department,* etc.

3. Piloting

A good collaborative process should lead to a concrete strategy of piloting efforts behind community management PGWM in many locations, depending upon the typology of groundwater conditions in a region. The logic for such an approach is quite simple. The complex environment within which groundwater management can occur hinders the development of ideal, textbook models. Groundwater management pilots need not become models for copybook replication, but could function as process templates across similar typologies of groundwater situations, at the same time including enough scope for continuous improvement, especially in the light of the way processes are structured in Fig. 36.6.

Each pilot would have a provision for impact assessment, which could feed back into the improvement of the piloting process itself as well as in improving and scaling up response strategies. These lessons could also lead to the strengthening and evolution of a robust legal framework and refining policy through continuous inputs from developments on the ground.

4. Legal framework

A process-driven approach will also enable a more robust legal framework. Current enactments of groundwater legislations have stagnated primarily because of their command and control approach. The primary focus of a robust legal framework should be to provide the legal cover for a community-based approach to groundwater management. Hence, the priority within the legislative framework will change from a licensing, command-control type to one where there is protection, to efforts of conservation, demand management and drinking water sources.

It is very likely that the successful running of pilots may also require some legal cover. For instance, when a Gram Sabha passes a resolution that all groundwater use in a village will be through a community effort, such a resolution could be strengthened through a state-level legislative norm imposing heavy sanction against free riders who often misuse benefits accrued by conservation efforts by others and thereby erode into the basic sanctity of the principles of managing common pool resources.

5. Policy

Various versions of the National Water Policy (various years) have three basic points pertaining to groundwater resources:

- The need to regulate exploitation of groundwater
- The need to integrate surface and groundwater through conjunctive management
- The need to avoid overexploitation especially in the coastal zone

As a policy statement on groundwater, these very bullets can be expanded through the process outlined above, in order to make the water policy more relevant. Once aquifers are mapped, for instance, it would be clear to policy makers as to *where to do what*. For instance, it would be useful to regulate exploitation of groundwater in areas that are vulnerable to groundwater depletion and contamination. Aquifer mapping through collaborative processes would make such vulnerability mapping possible. Moreover, the coastal zones (or the high mountain zones, for that matter) could be better *typologized* through an aquifer mapping effort, leading to more concrete policy statements in such zones. Similarly, lessons from pilots will feed into policy, enabling both sharpening and expansion of the policy mandate on groundwater. The development of the overall legislative framework ought to evolve on the basis of such lessons and be derived from *guiding legal principles* in the reformed policy environment on groundwater.

At the moment, it will be difficult to make a separation between Central and State Policies on groundwater. Questions such as 'do we need a separate policy on groundwater' are bound to lead to plenty of debate and discussion. In the process-based groundwater management structure (Fig. 36.6), policy will play four major roles:

1. Take *learnings* from the ground and convert them into robust policy statements
2. Help drive more concrete, enabling, protection-based 'legislative' frameworks
3. Provide guidelines (to states and various departments) for scaling up response strategies for different groundwater problems and situations.
4. Develop a skeleton for decentralizing the process of groundwater management and disseminate the learnings that flow to it from pilots and from the broader response domain to improve capacity building efforts (Table 36.7).

Table 36.7 Protocol of actions at different levels will determine the efficiency of a response strategy to combat groundwater overuse (A) and groundwater quality problems (B)

(A) Groundwater overuse scenario					
Protocols/Level	Farm (Well)	Group	Aquifer/ Watershed	Village/ PRIs	Comments
Aquifer mapping and database			✓		Mapping in different settings, on the basis of Table 36.4, at the aquifer level to ensure continuous flow of data; such data will enable decision-making from time to time
Well measurements	✓	✓			These include water levels, groundwater quality, well tests and other such measurements that make enable decisions on 'efficient well use'
Aquifer monitoring		✓	✓	✓	These include pumping tests, groundwater flow analyses and groundwater quality patterns. Monitoring attempts to plot spatial patterns and temporal trends to enable aquifer-level management of groundwater
Decision-making on GW as CPR	✓	✓	✓	✓	For effective management of groundwater resources, decisions ought to be at all levels; decisions at the farm level can impact decisions at the aquifer level; hence, decisions on one scale must feed into decisions at the 'larger' scale
Regulation				✓	PRIs would need to be empowered with more proactive regulatory instruments that are not 'authoritative' but are meant to facilitate principles of groundwater in the CPR[a] framework
(B) Groundwater quality scenario					
Protocols/Scale		Individual	Household	Village/ PRIs	Comments
Water Quality Assessment/ Monitoring			✓	✓	Frequency of measurement ought to be decided based on the parameter, e.g. for pathogenic monitoring, the frequency of monitoring would be greater than that

(continued)

Table 36.7 (continued)

(A) Groundwater overuse scenario

Protocols/Level	Farm (Well)	Group	Aquifer/ Watershed	Village/ PRIs	Comments
					for Fluoride; but for Fluoride one might be interested in spatial and temporal patterns; hence monitoring at many points, say on a seasonal basis may prove more useful
Health Impacts		✓	✓	✓	Health impacts ought to be monitored at all three levels; the aim would have to ensure attribution of health indicators to a particular contaminant at the given location
Water treatment			✓	✓	Water treatment options are required at the household and community levels (especially with regard to public drinking water sources, say in a village or a town)
Improved water management at group level (especially when groundwater quality is impacted by groundwater overuse)			✓	✓	This is critical as most groundwater management strategies (in overexploited areas) may simply regulate the 'demand' or say introduce 'water efficiency technologies'; with such approaches, drinking water security still is at stake—both quantitatively and quality wise. Hence, maintaining a certain quality ought to be part of every groundwater management strategy
Mitigation of health impacts		✓	✓	✓	Interventions on the health of individuals, households and the community are desired as a part of a comprehensive groundwater management strategy

[a] Common Pool Resources: Natural or man-made resources used simultaneously or sequentially by members of a community or a group of communities. These include rangelands, forests, ponds, wetlands and groundwater aquifers

36.5 Conclusion

Groundwater management in India is about bringing three components surrounding groundwater resources together. Firstly, understanding the resource (aquifers) through an increasingly user-oriented approach; secondly, understanding the socio-economic dimensions of the demand for groundwater; and thirdly, efficient, equitable and sustainable supply in meeting the demand through well-understood available resources. A variety of organizations must be empowered to work alongside each other to achieve the objective of sustainable groundwater management. Academia, civil society and government must work together in pursuing this agenda. The sectors of agriculture and industry must become the laboratories to undertake pilots of such collaborative groundwater management and also include incentives and investments of the right nature to facilitate both the management and governance of groundwater in India.

Moreover, there is need to affirm (as a matter of both policy and law) an apex position in stating a national goal of safe and secure drinking water for all. It must gain first charge over all other uses when dealing with locally available water resources. Only when drinking water security is assured for all would other uses be considered. The second unequivocal priority would be what may be called ‘livelihood water’, without which farmers’ livelihoods would be endangered. Protective irrigation for rainfed agriculture is far too critical in a country like India and needs to hold priority over reserving supplies for high-value irrigated cash crops. Here again, it would be important to build in the philosophy of CPR management as part of any livelihood water management strategy. Only after such uses have been taken care of, should water for commercial agriculture and industrial purposes be considered. For industry, the primary emphasis has to be on water recycling and reuse. For agriculture, water-intensive crops would be discouraged in water-scarce regions. Full cost recovery must be made for all commercial uses. And there would need to be a cap to the maximum permissible withdrawal of water for these purposes.

This chapter is a rather quick appraisal of emerging groundwater challenges in India. Having defined the typology of groundwater systems in the country, including the broad challenges on the quantitative and quality front, the report has attempted to provide some framework for fresh thinking on addressing some of the issues. In conclusion, we would like to propose a few points of immediate action to set forth some initial actions for an agenda on *national groundwater governance*. Setting up of a *Groundwater Mission*, on the lines of the Drinking Water Mission to further develop at least some of the action points suggested in this report, could form a first step in this direction. Such a mission could set forth an initial plan based on feedback received from key working groups on groundwater. The working groups (could further be expanded, if deemed necessary) would be as follows:

- Mapping of aquifers and planning and design for PGWM based on such mapping
- Design of recharge systems

- Improved well-water efficiency
- Groundwater power co-management
- Demand management of aquifers, particularly keeping in mind questions of equity and sustainability
- Proactive groundwater legislation to avoid unnecessary competition and conflict around aquifers

References

Badarayani U, Upasani D, Dhawan H, Kulkarni H (2009) Hydrogeological studies for improved groundwater management strategies in the dryland areas underlain by Deccan basalts: an initiative in Purandar taluka of Pune district in Maharashtra. ACWADAM Report ACWA-H-09-1, 108p

Bhatia B (1994) Lush fields and parched throats: political economy of groundwater in Gujarat. Econ Polit Wkly, Dec 19–26

Central Groundwater Board, Ministry of Water Resources (2006) Dynamic groundwater resources of India (as on March 2004). Government of India, Faridabad

Central Groundwater Board, Ministry of Water Resources (2014) Dynamic groundwater resources of India (as on March 2011). Government of India, Faridabad

Central Groundwater Board, Ministry of Water Resources (2010) Groundwater quality in shallow aquifers of India. CGWB, Ministry of Water Resources Publications

Census of India (2011) Chandramouli C, Registrar General

CSE (2012) Excreta Matters - SOE 7 (vol 1). Center for Science and Environment, New Delhi

DDWS (2009) Mid-term appraisal of 11th Plan—rural water supply, mimeo. Department of Drinking Water Supply, Ministry of Water Resources, GoI, New Delhi

Dhawan BD (1990) Studies in minor irrigation with special reference to ground water. Commonwealth Publishers, New Delhi, 209p

Dhawan BD (1995) Groundwater depletion, land degradation and irrigated agriculture in India. Commonwealth Publishers, New Delhi

Foster S (2000) Assessing and controlling the impacts of agriculture on groundwater from barley barons to beef bans. Q J Eng Geol Hydrogeol 33:263–280

Foster SSD, Chilton PJ (2003) Groundwater: the processes and global significance of aquifer degradation. Philos Trans R Soc B Biol Sci 358(1440):1957–1972

Groundwater Resource Estimation Committee (GEC) (1997) Groundwater resource estimation methodology. Report of the Groundwater Estimation Committee, Ministry of Water Resources, Government of India

Groundwater Resource Estimation Committee (GEC) (2002) Groundwater resource estimation methodology. Report of the Groundwater Estimation Committee, Ministry of Water Resources, Government of India

Indu R, Krishnan S, Shah T (2007) Impacts of groundwater contamination with Fluorde and Arsenic: affliction severity, medical cost and wage loss in some villages of India. Int J Rural Manag 3(1):69–94

Krishnan S (2009) The silently accepted menace of disease burden from drinking water quality problems. Paper prepared for the MTA of the 11th plan, CAREWATER, INREM Foundation, Anand

Kulkarni H (2005) Groundwater overdraft: a physical perspective. In: Calow R, Macdonald D (eds) Comman 2005. Community management of groundwater resources in rural India – research report. British Geological Survey Commissioned Report CR/05/36N:1–13

Kulkarni H, Vijay Shankar PS (2014) Groundwater resources in India: an arena for diverse competition. Local Environ 19(9):990–1011

Kulkarni H, Vijay Shankar PS (2009) Groundwater: towards and aquifer management framework. Commentary Econ Polit Wkly XLIV 40:6

Kulkarni H, Vijay Shankar PS, Krishnan S (2009) Reemphasizing drinking water protection. In: Paper prepared for the MTA of the 11th plan

Kulkarni H, Shah M, Vijay Shankar PS (2015) Shaping the contours of groundwater governance in India. J Hydrol: Region Stud 4:172–192

Kulkarni H, Badarayani U, Upasani D, Dhawan H, Gupta R (in press) Understanding the typology of groundwater resources in India: key to building responses through communities. Groundwater Management, Arghyam-ACWADAM Publications

Llamas MR, Martínez-Santos P (2005) Intensive groundwater use: silent revolution and potential source of social conflicts. J Water Resour Plan Manage 131(5):337–341

Macdonald DMJ, Kulkarni H, Lawrence AR, Deolankar SB, Barker JA, Lalwani AB (1995) Sustainable groundwater development of hard-rock aquifers: the possible conflict between irrigation and drinking water supplies from the Deccan basalts of India. British Geological Survey NERC Technical Report WC/95/52, 54 pp

Margat J (1992) The overexploitation of aquifers. In: Simmers I, Villarroya F, Robollo LF (eds) Selected papers on overexploitation. IAH Heise, pp 29–40

Ministry of Agriculture, Government of India (2013) State of Indian Agriculture: 2012–13 (p 221). Department of Agriculture and Co-operation, Ministry of Agriculture, Government of India, New Delhi

Ministry of Water Resources (2002) National water policy. Government of India, New Delhi

Minor Irrigation Census (Government of India) (2001) Report on Census of Minor Irrigation Schemes (1993–94). Minor Irrigation Division. Ministry of Water Resources, New Delhi

Moench M (1992) Drawing down the buffer. Econ Polit Wkly XXVII:A-7–A-14

Moench M, Burke JJ, Kulkarni H (in press) Groundwater and transition. FAO Publications

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore (ISBN 978-981-10-3888-4)

NICED (2004) Estimation of the burden of diarrhoeal diseases in India, as part of WHO India National Commission for Macroeconomics and Health Background Papers

NSSO (2006) Morbidity, healthcare and condition of the aged. Report No. 507 of the National Sample Survey 60th Round (January–June 2004), National Sample Survey Organisation, Ministry of Statistics and Programme Implementation, Government of India, New Delhi

Patel A, Krishnan S (2007) Groundwater in urban India: overview, opportunities and challenges. In: ICFAI (ed) Water supply & sanitation. essentials of urban economic growth

Planning Commission (2012) Report of the steering committee on water resources and sanitation for twelfth five year plan (2012–2017). Government of India, New Delhi

Planning Commission, Government of India (2007) Report of the expert group on groundwater management and ownership. Planning Commission, New Delhi, 61p

Price M (2002) Introducing groundwater, 2nd edn. Taylor & Francis, UK

Reddy DR (2008) Understanding the disease of skeletal Fluorosis and ways to contain it, Telengana Jagruti, Fluorosis Vimukti Vedhika

Shah T (2009) Taming the anarchy: Groundwater Governance in South Asia. Resources for the Future, Washington DC and International Water Management Institute, Colombo, 310p

Shah T, Indu R (2004) Fluorosis in Gujarat: a disaster ahead. In: IWMI-Tata program annual partner's meet, Anand

Susheela AK (2001) A treatise on Fluorosis. Fluorosis Research and Rural Development Foundation, Delhi

The World Bank (2010) Deep wells and prudence: towards pragmatic action for addressing groundwater overexploitation in India (p 97). The World Bank, Washington DC

Vijay Shankar PS, Kulkarni H, Krishnan S (2011) India's groundwater challenge and the way forward. Special Article, Econ Polit Weekly XLVI(2):37–45

WHO (2002) An overview: gaps in health research on Arsenic Poisioning. In: 27th session of WHO South-East Asia Advisory Committee on Health Research 15–18 April 2002, Dhaka, Bangladesh

Chapter 37
Potential Application of Advanced Computational Techniques in Prediction of Groundwater Resource of India

Pragnaditya Malakar, Abhijit Mukherjee and Sudeshna Sarkar

Abstract It is a challenging task now and it will be even more challenging in the future to provide an adequate amount of water to the people in this planet. A proper understanding of present day and future water resources is a serious issue, where worldwide increase in the population further promotes water scarcity problem. Groundwater is the major source of freshwater in most parts of South Asia. Some parts are becoming extensively vulnerable as the consumption groundwater in those areas is prominently faster than restored naturally. Application of artificial intelligence (AI) and data mining techniques can be a big help to determine the influence and interdependence of controlling parameters to delineate future groundwater trends and resources. Use of data mining and AI with available spatio-temporal data (satellite and field-based measurements) of governing factors with the help of high-performance computing, and scalable algorithms would help to explore such complex influences and interferences on the groundwater resource dynamics. The outcome would be to predict future trends of available groundwater in changing socio-economic scenarios.

Keywords Groundwater resources · Prediction · Artificial intelligence
South Asia

P. Malakar · A. Mukherjee (✉)
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee
Applied Policy Advisory to Hydrogeosciences Group, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

S. Sarkar
Department of Computer Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_37

37.1 Introduction

Water resources management is more important than ever with rapid growth in population and diverse purpose of water use. Water resources quantification is a serious issue in the country like India and rest of the countries in South Asia (almost doubled in last 35 years, from ~0.92 billion in 1981 to 1.766 billion in 2016 (**source: World Bank Metadata**; http://databank.worldbank.org/data/reports.aspx?source=2&country=SAS), where it is a challenging task to provide an adequate amount of water to every citizen in the future. Increasing population further facilitates water scarcity problem. In South Asia, groundwater is the primary source of naturally occurring water on earth's surface. Some regions are becoming extensively dependent as the consumption of groundwater in those areas are noticeably faster than it is restored naturally thus causing water tables to decline rapidly. The dynamicity of groundwater is extremely versatile owing to the several influencing factors. Predicting groundwater means mainly predicting the two aspects of groundwater: groundwater quality and groundwater quantity and sometimes predicting the factors that may affect both of them. Some conventional methods are available which are used for the purpose of prediction, but more advanced techniques, i.e., machine learning, artificial intelligence (AI), have many advantages that other methods do not offer. Artificial intelligence, a machine learning tool frequently used by computer scientists and data analysts, seems to increase gradually among hydrologists. Large-scale complex linear or nonlinear hydrological problems, pattern recognition are done with the help of these new techniques as it has a unique feature to generalizing the data into a theoretical and practical understanding. The most interesting character of AI is that it maps the inputs and output relationship without getting involved in the details of the complex nature of the hydrologic and physical processes. From a mathematical point of view, suppose that there is a dependent variable named Y and X_1, X_2,…, X_p are p different predictors. We assume that there exists a nonlinear or linear relationship exists between X and Y, which can be presented as,

$$Y = f(X) + \varepsilon$$

Here, f is some fixed but unknown function of X_1,…, X_p, and ε is a random error term, which is independent of X. More related information regarding groundwater of South Asia is available in Mukherjee et al. (2018).

37.2 Advanced Methods Used in Hydrology

Machine learning and artificial intelligence methods are the recent approaches in the field of groundwater hydrology. Here, we will discuss in short about the various methods, techniques, and algorithm that are successfully used in the prediction of future groundwater resources and their advantages relative to other conventional approaches, with studies from India and other South Asian countries. Machine learning uses the advanced algorithms to learn basic and inside characteristics from data without being involved into the complexities of the actual physical processes. The iterative nature of machine learning is an important feature which allows new data adaptation easy. The success or failure of these advanced techniques such as artificial intelligence techniques are solely dependent upon appropriate variable selection and the availability of sufficient data. If sufficient data are available, then artificial neural networks (ANNs) approaches, adaptive neural-based fuzzy inference system (ANFIS) techniques, support vector machine (SVM), genetic programming (GP) (Wang et al. 2009) are the best suitable and frequently used techniques for hydrological problems.

37.2.1 Artificial Neural Networks (ANNs)

ANN is a mathematical complex structure; following biological neural system, consists of different layers of densely populated nonlinear processing unit or neuron. These neurons, in different layers are interconnected via weights. Moreover, there are three different layers in a standard neural network structure; the data are put forward in the system through the input layer, the data are being processed in the hidden layer(s) and results are generated in the output layer (Fig. 37.1a). When a set of data are introduced in the system, information is extracted from the data by the system through a learning process.

The neural network is classified on the basis of certain properties;

(A) The number of layers;
(B) The flow direction of information and processing.

(a) Feed-forward neural network (b) recurrent neural network;

Suppose, a feed-forward neural network has i input nodes, k output nodes, and j hidden nodes, then the feed-forward neural network can be expressed as

$$y_k = S_1\left(\sum_{j=1}^{J} w_j S_2\left(\sum_{i=1}^{I} w_i x_i\right)\right)$$

Here, y_k is the output vector, x_i is the input vector, w_i and w_j are the weights of the nodes in the input layer, the hidden layer and the output layer, respectively. The activation functions are S_1, S_2 (Luk et al. 2000). Most useful and promising results are given by logistic sigmoidal activation function from a hydrological perspective (Luk et al. 2000).

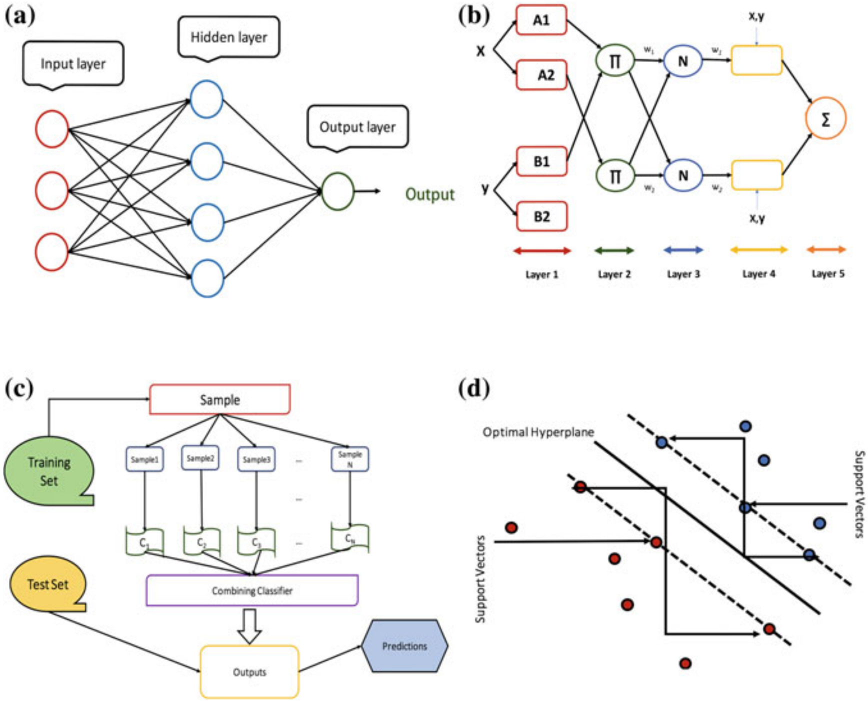


Fig. 37.1 Conceptual diagram of **a** ANN, **b** ANFIS, **c** SVM, and **d** the basic of the SVM

$$s(x) = \frac{1}{1 + \mathrm{e}^{-x}}.$$

The weights between the interconnected units are assigned using the iterative nature of the network so that the desired responses are analogous to the system responses.

37.2.2 Adaptive Neural-Based Fuzzy Inference System (ANFIS)

Neuro-fuzzy techniques are nothing but artificial neural network (ANN) in association with fuzzy interference system (FIS). This hybrid model generates a learning rule by combining the least squares method and the back-propagation gradient descent for the identification of a set of parameters (Wang et al. 2009). The structure of an FIS has three essential aspects: (a) Selection of fuzzy rules, (b) The membership functions (MF) (used in the fuzzy rules), (c) An inference procedure, a reasoning mechanism from the membership function to the output.

After selection and modification of the parameters, the multilayered feed-forward structure is called an adaptive network. The adaptive network's structure consists of a static function in the interconnected node, which turns the input to a single node output function (Nayak et al. 2004). This accomplishment of developing a method combining fuzzy rules with appropriate membership function of the neural network is called an "Adaptive Neuro-Fuzzy Inference System" (ANFIS).

ANFIS mainly has five layers: (1) rule base, (2) database, (3) fuzzification interface, (4) defuzzification interface, and (5) decision-making unit (Jovanovic et al. 2004). The conceptual figure (Fig. 37.1b) is an ANFIS architecture; it has five layers: The first and fourth layer has adaptive nodes, but the output layer has fixed modes.

37.2.3 Support Vector Machine

The support vector machine is a classification and regression approach based on Vapnik's statistical learning theory (Cortes and Vapnik 1995). Unlike ANN, where the structure of the network is decided before training of the model, in SVM, the structure is not determined a priori. By a training process, model selects the input vectors supporting the model structure. Given by a set of N samples of $(x_k; y_k)$, $k = 1(1)N$

$$x \, \varepsilon R^{\mathrm{m}}, \; y \, \varepsilon R,$$

Here, input vector is x of m components and y is a corresponding output vector. An SVM estimator (f) on regression can be written as:

$$f(x) = w \cdot \phi(x) + b$$

where a nonlinear transfer function is ϕ, the weight vector is w, and the bias is b. These coefficients are determined by minimizing risk functions (Vapnik 1995, 1998).

To cope with the complex nonlinear regression of the input space, this transfer function ϕ transforms the input vectors into a high-dimensional feature space in which theoretically it turns into a simple linear regression. The basic idea of SVM is to find the optimal hyperplane for linearly separable data, if not then transform the original data to map into a feature space by the Kernel function. SVM is based on the theoretical model of learning, and an excellent tool for pattern recognition. Unlike some of the machine learning algorithm, it is not affected by local minima and has a unique feature to design and implement the modular component. In a classification problem, support vectors are the data points which are most difficult to classify as it lies closer to the decision surface (Fig. 37.1d). Support vectors are the elements of the training set that controls the position of the hyperplane. Finding the optimal hyperplane is very problematic. A common issue that arrives is the dual optimization problem. A few algorithms are suggested to find the solution. This issue can be avoided by using Lagrange multiplier.

37.3 Groundwater Prediction in India and Rest of South Asia

In the context of South Asia (Chap. 1, Fig. 1.1), machine learning tools have been used in many fields related to groundwater resource management from groundwater-level forecasting; rainfall-runoff assessments to the issue of qualitative modeling including arsenic and other contaminants. In hydrological perspective, few studies are available but not directly related to the groundwater resource management, though they contribute one way or another to groundwater. Dhanya and Kumar developed a fuzzy relationship between the Summer Monsoon Rainfall and different atmospheric indices. Equatorial Indian Ocean Oscillation zonal wind index (EQWIN), El Nino and Southern Oscillation (ENSO) are taken as influencing factors (Dhanya and Kumar 2009b). Again a different study (Dhanya and Kumar 2009a) shows the association rules for drought and floods using rainfall events and climate indices in India. Again in a developing country like India, groundwater resource management is the most critical task which should be dealt immediately. To predict the future groundwater resources, one must have a proper understanding of the present groundwater scenario first. The advantage of machine learning methods and artificial intelligence methods is its ability to allow many parameters to be associated with the model. In India and other South Asian countries, the diversity of all the factors that control groundwater is immense, so to develop a useful prediction model, the important parameters like groundwater level, subsurface lithology, groundwater abstraction or withdrawal, precipitation, temperature, soil moisture, stream parameters. Evapotranspiration, aquifer parameters like storage coefficient (S) and transmissivity (T), canal data needed to be evaluated individually or preferably in the conjugate.

Sustainable use of groundwater resources in a country of 1.3 billion people needs to have a proper management and planning for the present and the future. This enormous task requires models that are capable of explaining the highly scholastic nature of hydrologic processes. Scientists have devolved many black box methods over the past decades to comprehend the complex phenomena in hydrologic processes, among them machine learning and artificial intelligence models are proved to be most promising (Nourani et al. 2014).

Several studies are done in India which deals with the prediction of groundwater resources and management of groundwater resources. Understanding annual to seasonal groundwater storage changes in the Indian subcontinent for the present and the future is extremely important owing to the increasing uses of groundwater in different parts of India. Nonetheless, there is hardly any study that has tried to predict the future trends of groundwater storage on a country scale, though there are studies on groundwater-level prediction either in local or a regional basis and relating it to influencing factors such as land use pattern, climate change, and abstraction patterns. In the context of increasing population, per capita availability of groundwater resources are rapidly depleting in India, estimation of future trends in groundwater level (GWL) and storage (GWS) is a crucial task in this densely populated region. This work will help managers and policy makers to plan for future extreme conditions, e.g., flood and drought.

In this chapter, our aim is to present artificial intelligence and machine learning tools to simulate the prediction by using the existing hydrogeological and climate data. To predict groundwater level, the standard variables taken as input are past groundwater level and rainfall. Lohani and Krishan developed an ANN model with back-propagation (BP) algorithm and with one hidden layer. Monthly groundwater level data (2006–2013) and rainfall data (2006–2010) for four districts in Punjab, India were taken as input. They concluded that observed and predicted values fit well and the results can be used for sustainable management and planning of groundwater resources (Lohani et al. 2015).

A comparative study was performed to predict groundwater level with the Sequential Minimal Optimization Algorithm based Support Vector Regression (SVR) and wavelet packet-SVR (WP-SVR) in the shallow unconfined coastal aquifer in southwestern Karnataka, India. Past groundwater level, tide level, rainfall, and temperature data from 1996 to 2006 were taken as input, and they concluded that WP-SVR carries out better result than classic SVR (Sujay Raghavendra and Deka 2015).

In a similar study, groundwater level was forecasted with wavelet-support vector regression (WA-SVR) using monthly data from 2001 to 2010 of precipitation, past water table records and temperature in Vishakhapatnam, India, and then compared with ANN, SVR, and with autoregressive integrated moving average (ARIMA). The results of the comparative study shows that WA-SVR gives best results (Suryanarayana et al. 2014). A related study shows a comparison of predicting groundwater level based on Bayesian neural networks (BNN) and optimized by scaled conjugate gradient (SCG) (i.e., BNN-SCG); artificial neural networks (ANN) optimized by scaled conjugate gradient (SCG) (i.e., ANN-SCG), and adaptive neuro-fuzzy inference system (ANFIS) in Dindigul, Southern India (Maiti et al. 2014). Particle swarm optimization function is added to SVM in a different study in Rentachintala region, Andhra Pradesh, India, to evaluate future prediction of groundwater level. Results show that hybrid methods serve better than individual methods (Sudheer et al. 2011). Another hybrid model ANN-GA (Genetic Algorithm) was used to predict water table in a semi-arid region in Mahanadi basin, Orissa, India. Three different algorithms namely Bayesian regularization (BR), Levenberg–Marquardt (LM), back-propagation (GDX) were used for developing the ANN model where past water level and rainfall (1993–2002) were the input variable (Dash et al. 2010). Identical work was done in Kathajodi River basin of Orissa, India, to predict water level 1 week ahead with groundwater levels, the water level in the drain, weekly rainfall, pan evaporation, pumping rate, and river stage as input (Mohanty et al. 2010).

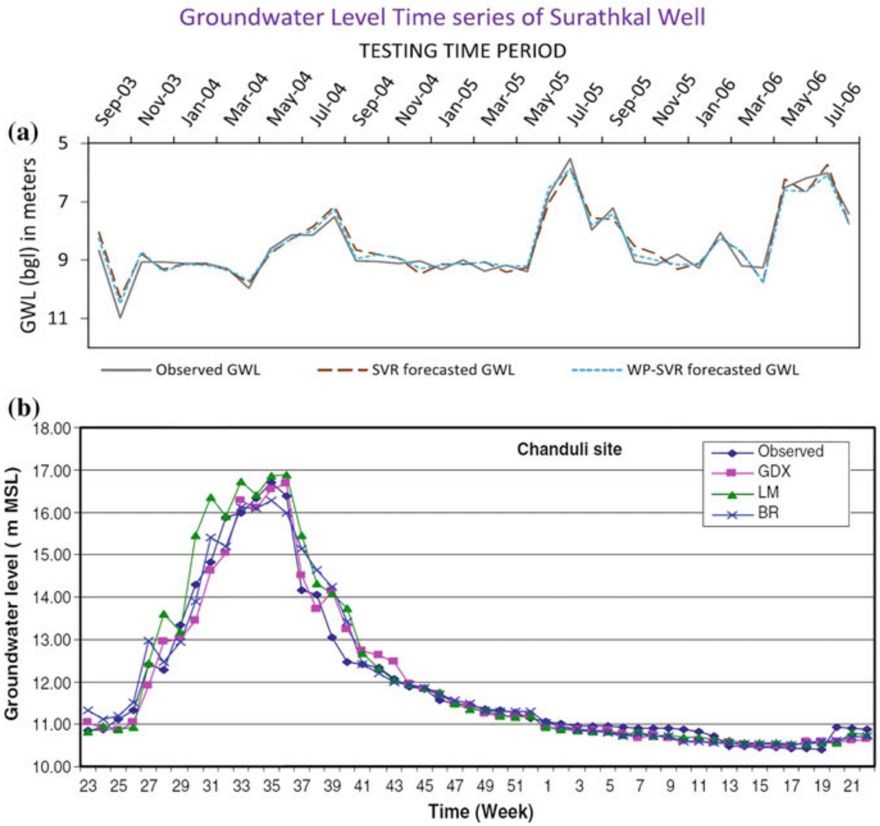


Fig. 37.2 **a** Comparison between predicted and observed groundwater level employing WP-SVR and SVR models at the testing stage in a well located at Surathkal (*source* Raghavendra and Deka 2015). **b** Comparison between the groundwater levels predicted and the observed groundwater levels, one week ahead by GDX, LM, and BR algorithms (*source* Mohanty et al. 2010)

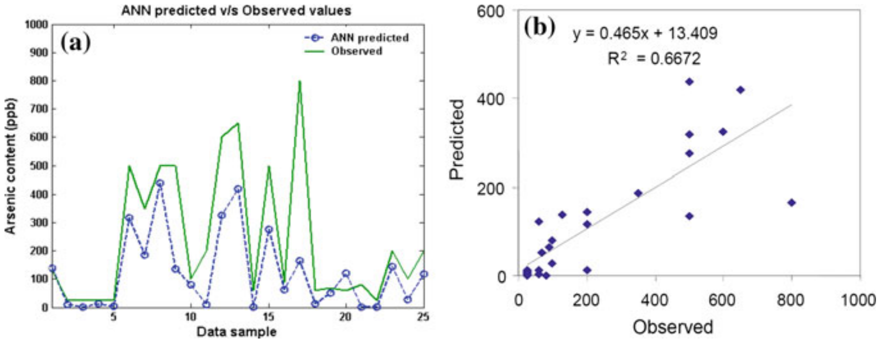


Fig. 37.3 **a** Arsenic content at new locations predicted by ANN (Purkait et al. 2008), **b** Relationship between predicted and observed as (Purkait et al. 2008)

In Kurmapalli watershed, Nalgonda district, Andhra Pradesh, India, a study forecasted groundwater level with feed-forward ANN under different stress condition, i.e., abstraction and groundwater recharge (Banerjee et al. 2009). Another research made a similar prediction with varied conditions (Coppola et al. 2003). A separate study used weekly water level data from 1998 to 2007 from six monitoring wells with the help of ANN to predict one to ten-week lead prediction in Chandpur District, Bangladesh (Husna et al. 2016) (Figs. 37.2 and 37.3).

Numerical modeling of the fate and transport of pollutants are very standard practice in hydrology. Singh and Dutta developed a hybrid model which linked the flow transfer modeling with genetic algorithm (GA). It took the potential unknown pollutant sources as input and used it with genetic algorithm (GA) in the complex aquifer study area with the different scenario (Singh et al. 2006).

In Malda district, eastern India, a different approach has been made to look into the qualitative estimate of groundwater. In the study as mentioned earlier ANN, multiple linear regression, and active set SVM were used to predict arsenic contamination with the information about the geochemical parameters which are related with arsenic (Purkait et al. 2008).

Here, observed values for concentration of arsenic, pH (acidic-alkalinity ratio), depth of tube well water, specific conductivity, dissolved oxygen (DO), total dissolved solids (TDS), salinity, redox potential (Eh) were taken as inputs to the ANN (Purkait et al. 2008). The conclusion was ANN performs better than MLR and SVM in this case unlike the prediction of groundwater level. Another study was conducted in Kavaratti, an island in Lakshadweep, located on west coast of India to estimate and predict the relationship between safe pumping rate and groundwater salinity (Banerjee et al. 2011). In work done by Singh and Gupta, trihalomethanes (THMs) formation due to chlorination was forecasted using ANN, SVM, and gene expression programming, where dissolved organic carbon normalized chlorine dose, temperature, water pH, contact time, and bromide concentration were used as the input variables. The result shows SVM is better than the other two methods (Singh et al. 2012).

Apart from groundwater level and quality, many works had been done to predict rainfall in India and around the world. Due to variation in temporal rainfall in India, It is necessary to incorporate that if a predictive model to be developed. A visual cultural analysis has been achieved with a growing hierarchical self-organizing map (GHSOM) with Indian rainfall data of 142 years (Chattopadhyay et al. 2016). The outcomes that used for generating SVM prediction model for the whole dataset and individual clusters. The models are accurate when individual clusters are considered than overall data.

In Godavari River basin, India, rainfall data at 14 gauging station from 1969 to 1983 was used to build an ANN model and multiple linear regression models to forecast hourly flood runoff and daily river stage, also the prediction of rainfall sufficiency (Thirumalaiah et al. 1998). An alternative study predicted runoff and sediment yield in Kankaimai watershed of Ilam district in eastern Nepal. They used daily rainfall, daily temperature, and daily runoff for rainfall–runoff modelling and used daily runoff and daily suspended sediment yield for sediment yield modelling. They provided a comparative study using ANN, SVM, and simple regression using these variables and concluded that SVM performs superior to other methods (Sharma et al. 2015).

The study presented next, is some of our own work, is to show how a prediction could be performed on a country scale for groundwater resources with advanced techniques. It offers a nonlinear time series model for predicting groundwater level (GWL) using the artificial neural network (ANN). For the development of suitable ANN structure, past records of groundwater level (GWL) from all over India from 2005 to 2013 was taken as an input variable. Other than that a different ANN model is developed using precipitation (*P*) as input as well.

In both the cases, the output variable is groundwater level (GWL). The objective of developing any ANN is to establish a unique relationship between input and output variables. An ANN structure with a feed-forward back-propagation network is used. In a feed-forward back-propagation network, the signals from the input layer to output layer passed in the forward direction only (Luk et al. 2000). The total dataset of 36 months is available, out of that 36 months dataset 24 months of the dataset were used for training the network, and 12 months of the dataset used for testing (Mohanty et al. 2013).

The objective of developing any ANN is to establish a unique relationship between input and output variable.

$$y^m = f(x^n)$$

where X is a n dimensional input variable x_i, $i = 1(n)$, and Y is the m dimensional output variable y_j, $j = 1(m)$. In the documented study, x_i is the past records of groundwater level (GWL) for the first model, past groundwater level (GWL) and precipitation for the second model, and y_i is the values of the predicted groundwater level. The complete dataset is divided into input dataset, target dataset. Water level data for last three years (2011–2013) are predicted based on data from first six years

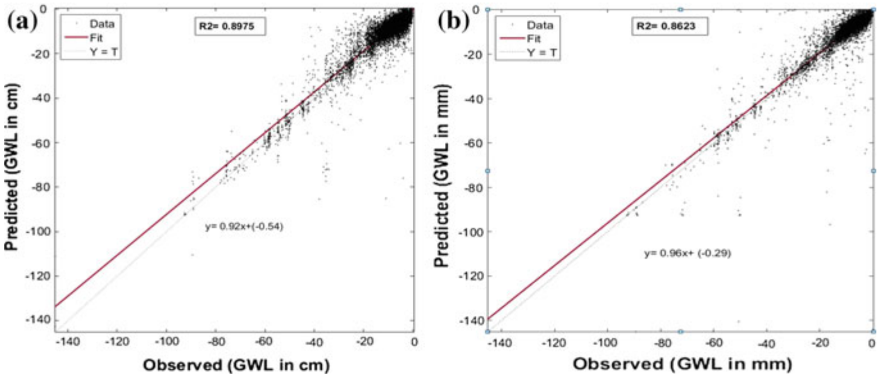


Fig. 37.4 Comparison between predicted and observed groundwater levels for **a** past groundwater level used as input variable; **b** past groundwater levels and precipitation used as input variables

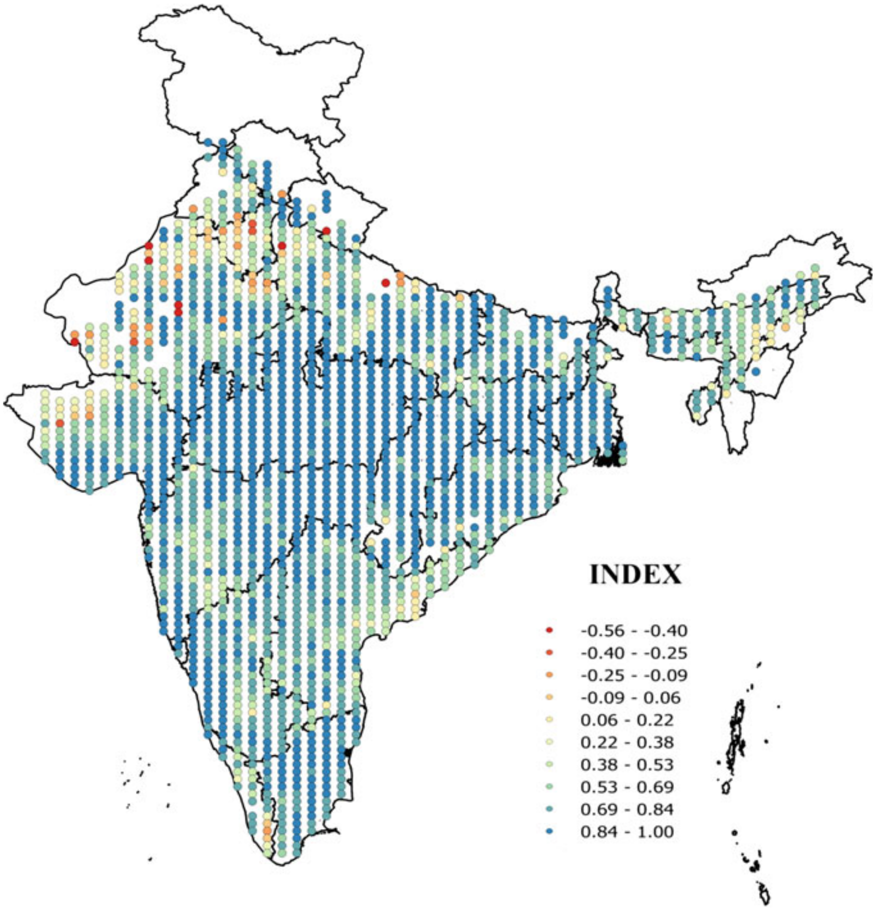


Fig. 37.5 Average R^2 values all over India

(2005–2013). The performance of the developed models is quantified based on the coefficient of determination, R^2. R^2 values for first model (past GWL as input) is 0.8975, and for the second model (past GWL and precipitation as input) is 0.8623 (Fig. 37.4). These results are conclusive that both the models are performing great even at a country scale.

Figure 37.5 shows the spatial change of average R^2 values in India; the differences may be attributed to the effects mostly anthropogenic that disturb the hydrologic cycle. Our aim should be to build tools which can be successfully used for prediction purposes for hydrological resources at a large scale. The subsurface lithologic data is critical; in that sense, it gives the subsurface geologic information which may be included in an artificial intelligence model to get a better picture of the future.

References

Banerjee P, Prasad RK, Singh VS (2009) Forecasting of groundwater level in hard rock region using artificial neural network. Environ Geol 58(6):1239–1246. https://doi.org/10.1007/s00254-008-1619-z

Banerjee P, Singh VS, Chatttopadhyay K, Chandra PC, Singh B (2011) Artificial neural network model as a potential alternative for groundwater salinity forecasting. J Hydrol 398(3–4):212–220. https://doi.org/10.1016/j.jhydrol.2010.12.016

Chattopadhyay M, Chattopadhyay S (2016) Elucidating the role of topological pattern discovery and support vector machine in generating predictive models for Indian summer monsoon rainfall. Theoret Appl Climatol 126(1–2):93–104. https://doi.org/10.1007/s00704-015-1544-5

Coppola E, Szidarovszky F, Poulton M, Charles E (2003) Artificial neural network approach for predicting transient water levels in a multilayered groundwater system under variable state, pumping, and climate conditions. J Hydrol Eng 8(6):348–360. https://doi.org/10.1061/(ASCE)1084-0699(2003)8:6(348)

Cortes C, Vapnik V (1995) Support-vector networks. Mach Learn 20(3):273–297. https://doi.org/10.1023/A:1022627411411

Dash NB, Panda SN, Remesan R, Sahoo N (2010) Hybrid neural modeling for groundwater level prediction. Neural Comput Appl 19(8):1251–1263. https://doi.org/10.1007/s00521-010-0360-1

Dhanya CT, Kumar DN (2009a) Data mining for evolution of association rules for droughts and floods in India using climate inputs. J Geophys Res Atmos 114(2):1–15. https://doi.org/10.1029/2008JD010485

Dhanya CT, Kumar DN (2009b) Data mining for evolving fuzzy association rules for predicting monsoon rainfall of India. J Intell Syst 15(1):25–51. https://doi.org/10.1515/JISYS.2009.18.3.193

Husna NEA, Bari SH, Hussain MM, Rahman MTU, Rahman M (2016) Ground water level prediction using artificial neural network. Int J Hydrol Sci Technol 6. https://doi.org/10.1504/IJHST.2016.079356

Jovanovic BB, Reljin IS, Reljin BD (2004) Modified ANFIS architecture—improving efficiency of ANFIS technique. In: 2004 7th seminar on neural network applications in electrical engineering, 2004. NEUREL 2004, pp 215–220. https://doi.org/10.1109/NEUREL.2004.1416577

Lohani AK, Krishan G (2015) Groundwater level simulation using artificial neural network in Southeast, Punjab, India. J Geol Geophys 4(3). https://doi.org/10.4172/jgg.1000206

Luk KC, Ball JE, Sharma A (2000) A study of optimal model lag and spatial inputs to artificial neural network for rainfall forecasting. J Hydrol 227:56–65

Maiti S, Tiwari RK (2014) A comparative study of artificial neural networks, Bayesian neural networks and adaptive neuro-fuzzy inference system in groundwater level prediction. Environ Earth Sci 71(7):3147–3160. https://doi.org/10.1007/s12665-013-2702-7

Mohanty S, Jha MK, Kumar A, Panda DK (2013) Comparative evaluation of numerical model and artificial neural network for simulating groundwater flow in Kathajodi-Surua Inter-basin of Odisha, India. J Hydrol 495:38–51. https://doi.org/10.1016/j.jhydrol.2013.04.041

Mohanty S, Jha MK, Kumar A, Sudheer KP (2010) Artificial neural network modeling for groundwater level forecasting in a river island of eastern India. Water Resour Manag 24(9):1845–1865. https://doi.org/10.1007/s11269-009-9527-x

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Sujay Raghavendra N, Deka PC (2015) Selection of optimal parameters : GRID search forecasting monthly groundwater level fluctuations in coastal aquifers using hybrid wavelet packet—support vector regression forecasting monthly groundwater level fluctuations in coastal aquifers using hybrid. Cogent Eng 26(1). https://doi.org/10.1080/23311916.2014.999414

Nayak PC, Sudheer KP, Rangan DM, Ramasastri KS (2004) A neuro-fuzzy computing technique for modeling hydrological time series. J Hydrol 291(1–2):52–66. https://doi.org/10.1016/j.jhydrol.2003.12.010

Nourani V, Hosseini Baghanam A, Adamowski J, Kisi O (2014) Applications of hybrid wavelet-Artificial Intelligence models in hydrology: a review. J Hydrol 514:358–377. https://doi.org/10.1016/j.jhydrol.2014.03.057

Purkait B, Kadam SS, Das SK (2008) Application of artificial neural network model to study arsenic contamination in groundwater of Malda district, Eastern India. J Environ Inform 12 (2):140–149. https://doi.org/10.3808/jei.200800132

Sharma N, Harinarayan Z, Dheeraj T (2015) Runoff and sediment yield modeling using ANN and support vector machines: a case study from Nepal watershed. Model Earth Syst Environ 1 (3):1–8. https://doi.org/10.1007/s40808-015-0027-0

Singh KP, Gupta S (2012) Artificial intelligence based modeling for predicting the disinfection by-products in water. Chemometr Intell Lab Syst 114:122–131. https://doi.org/10.1016/j.chemolab.2012.03.014

Singh R, Datta B (2006) Identification of groundwater pollution sources using GA-based linked simulation optimization model. J Hydrol Eng 11(2):101–109. Retrieved from http://ascelibrary.org/doi/abs/10.1061/(ASCE)1084-0699(2006)11:2(101)

Sudheer C, Shrivastava NA, Panigrahi BK, Mathur S (2011) Groundwater level forecasting using SVM-QPSO. In: Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics), 7076 LNCS(Part 1), pp 731–741. https://doi.org/10.1007/978-3-642-27172-4_86

Suryanarayana C, Sudheer C, Mahammood V, Panigrahi BK (2014) An integrated wavelet-support vector machine for groundwater level prediction in Visakhapatnam, India. Neurocomputing 145:324–335. https://doi.org/10.1016/j.neucom.2014.05.026

Thirumalaiah K, Deo MC (1998) River stage forecasting using artificial neural networks. J Hydrol Eng 3(1):26–32

Vapnik VN (1998) Statistical learning theory. Wiley, New York, pp 252–257

Wang WC, Chau KW, Cheng CT, Qiu L (2009) A comparison of performance of several artificial intelligence methods for forecasting monthly discharge time series. J Hydrol 374(3–4):294–306. https://doi.org/10.1016/j.jhydrol.2009.06.019

World Bank Metadata. http://databank.worldbank.org/data/reports.aspx?source=2&country=SAS

Chapter 38
Private Investments in Groundwater Irrigation and Smallholder Agriculture in West Bengal: Opportunities and Constraints

Aditi Mukherji, Partha Sarathi Banerjee and Durba Biswas

Abstract Private investments in groundwater have emerged as the main pathway through which smallholder farmers in India access irrigation. This paper discusses the role of groundwater in agrarian growth in West Bengal, India. It finds that agricultural growth in the state has stagnated since mid-1990s, after an initial period of growth in the 1980s and early 1990s. We hypothesize that this stagnation was a direct result of slowdown in growth in groundwater irrigation. The reason for this slowdown was, in turn, government policies related to groundwater and electricity. The paper then goes on to discuss the Groundwater Act of 2005 as well as electrification policies of the government of West Bengal and locates these policies within the broader backdrop of groundwater resource endowments in the state. By juxtaposing groundwater policies and resource realities, the paper questions the relevance of current regulations and suggests some policy alternatives—alternatives that are likely to propel the state and its smallholder farmers on a path of higher agricultural growth.

Note: This work was done when all the authors were associated with International Water Management Institute, Colombo and New Delhi.

A. Mukherji (✉)
International Centre for Integrated Mountain Development (ICIMOD),
GPO Box 3226, Kathmandu, Nepal
e-mail: aditi.mukherji@icimod.org

P. S. Banerjee
Independent Consultant, 3D Purbali, 507 Purbalok Main Road,
Kolkata 700999, India
e-mail: psb3210@yahoo.co.in

D. Biswas
Centre for Environment and Development, ATREE, Bengaluru, India
e-mail: durba.biswas@atree.org

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_38

38.1 Introduction

India is the largest user of agricultural groundwater in the world. It is estimated that there are over 20 million groundwater wells (GOI 2011) of which more than 95% are privately owned by smallholder farmers. These bestow a range of livelihoods and productivity benefits to millions of smallholder farmers in India (Deb Roy and Shah 2003). There are two distinct and regionally different pathways of groundwater growth story of India.

The first is that of groundwater overuse and its negative consequences in much of northern, western, and southern parts of India and is symptomatic of states like Punjab, Haryana, Andhra Pradesh, Karnataka, Tamil Nadu, Gujarat, Maharashtra, and Madhya Pradesh. All these states receive low to medium rainfall (200–1000 mm a year). Most of these states, except Punjab, Haryana, Rajasthan, and parts of north Gujarat, have hard rock aquifers with complex recharge processes. In alluvial aquifers too, recharge is limited because of low effective rainfall. Almost 70–80% of groundwater extraction mechanisms (GWEMs) are electricity operated, and farmers get free, or highly subsidized electricity. In these states, rural poverty is low and much below the all India average. Most importantly, groundwater and electricity are major political issues and farmers lobbies are strong. This story of groundwater of over-exploitation is fairly well documented (Janakarajan and Moench 2006; Moench 2007; Sarkar 2011).

The second story of groundwater underdevelopment in eastern India (West Bengal, Bihar, parts of Orissa, and Assam) is not as well known or documented as the over-exploitation story. In much of eastern India, groundwater development is much lower than potential recharge, both rainfall and natural recharge are high, most pumps run on expensive diesel or whenever farmers get electricity, they pay full cost of that electricity (Shah 2007; Mukherji 2007a). These are also the places where rural poverty rates are much higher than national average, and crop productivity is low. Here abundant groundwater resources juxtapose with high costs of groundwater extraction, restrictive access policies, low agricultural growth rates, and high rural poverty.

In this paper, we explore the causes and effect of this policy paradox by looking at the state of West Bengal. We discuss the nature of its smallholder groundwater economy, and the role it plays in agrarian growth in the state. We also look at the constraints that farmers face in accessing groundwater and possible solutions.

38.2 Data and Methods

Our findings are based on three sources of data and fieldwork was conducted from 2007 to 2010:

1. Primary questionnaire survey data among 896 respondents in 59 villages spread across 10 districts in West Bengal. The survey instrument consisted of six modules.
2. Interviews with key stakeholders, including
    a. District officials of State Water Investigation Directorate (SWID) who are responsible for implementing Groundwater Act of 2005,
    b. District level staff of West Bengal State Electricity Distribution Company Ltd. (WBSEDCL) who are in charge of giving electricity connections to farmers and implemented metering of agricultural tube wells.
3. Groundwater level data for 508 wells spread across all districts of West Bengal. The period of this data is 1990–2009. We also use rainfall data from 1990 to 2005 to run our models.

38.3 Role of Groundwater in Agrarian Growth Story of West Bengal

West Bengal has 30.4 billion cubic meters (BCM) of annual renewable recharge of which only 43% has been used so far. It also receives high rainfall (1500–2000 mm annually) and the underlying alluvial aquifers and high rainfall leads to high effective recharge (http://cgwb.gov.in/gw_profiles/st_westbengal.html, downloaded on March 15, 2011). According to the fourth Minor Irrigation Census (GOI 2011), West Bengal has 519,000 GWEMs—including dug wells, shallow tube wells, and deep tube wells. Of these approximately half a million GWEMs, approximately 1/5th (~ 110,000) are electricity operated, the rest run on diesel, kerosene, or a combination of two. Farmers who do not own GWEMs irrigate by buying irrigation services from other GWEM owners through informal water markets. Approximately, 3.1 million out of 6.1 million farming households in West Bengal buy groundwater irrigation services from other farmers (NSSO 1999). These informal water markets are influenced by diesel prices and electricity tariffs—and whether or not, electricity is metered or not (Mukherji 2007b). Overall, groundwater irrigates 1.8 million ha out of 2.9 million ha of net irrigated land in West Bengal and provides irrigation to over 4 million households.

Groundwater irrigation is important in West Bengal because majority of agricultural households irrigate using GWEMs, and as we will show in the subsequent paragraphs, groundwater also played an important role in agrarian transformation in the state.

There are three distinct phases of agrarian story of West Bengal. The first from 1900 to 1980 is about stagnation of agriculture and “hunger in a fertile land” (Boyce 1987: 1), the second phase from 1981 to early 1990s is about rapid growth in foodgrain production that was “highest among 17 major states of the Indian union" (Saha and Swaminathan 1994: A2), and the third phase from mid 1990s is about significant slowing down of agricultural growth (Sarkar 2006: 342).

Boyce (1987) captured the century-long agrarian stagnation in otherwise water abundant and fertile Bengal. He and other scholars explained this paradox of hunger amidst plenty in terms of regressive agrarian structure and high rural inequality that prevented adoption of technological improvements for boosting agricultural productivity. In particular, he noted the potential of groundwater irrigation in breaking this agrarian impasse and postulated that private investment in groundwater irrigation due to existing rural inequalities and lack of investment capabilities.

However, just around the same time as the publication of Joyce's book, there were reports of unprecedented growth in agricultural sector. From 1981 to 1991, agriculture in the state grew at 6.5% per annum (Saha and Swaminathan 1994). While this is the official growth figure, there were concerns from many quarters about the reliability of data and choice of base year for growth calculation (Boyce 1987; Rogaly et al. 1999; Gazdar and Sengupta 1999). This remarkable growth after a century-long stagnation was explained in terms of two arguments. One group argued that this was a direct result of West Bengal's Left Front governments' land reforms coupled with local self-governance (*panchayat*) reforms in the late 1970s which somewhat loosened the regressive agrarian structure and incentivized the newly tenured small and marginal farmers to invest in yield-enhancing Green Revolution technologies (Lieten 1992; Dasgupta 1995; Sen and Sengupta 1995; Ghatak 1995; Banerjee et al. 2002; Saha and Swaminathan 1994; Mishra and Rawal 2002; GoWB 1995–1996, 2004). Another group explained this growth in terms of "market and technology" (Harriss 1993; Palmer-Jones 1992, 1995) by pointing out that 1980s also coincided with proliferation of cheap pumps and affordable drilling technologies, and this enabled small and marginal farmers to invest in groundwater wells. For instance, Harriss (1993) observed rapid increase in groundwater use in his study villages in Bankura and Bardhaman and concluded that much of this growth was due increased cultivation of irrigated *boro* paddy (grown in summer)—which was possible only because of investments in wells and tube wells. Palmer-Jones (1995), also noted that in both Bangladesh and West Bengal "…better than expected performance has more to do with ecological factors and technical and institutional innovations (in the form of privately owned shallow tube wells and the development of water markets) than with policies specifically designed and implemented to deal with the obstacles posed by the agrarian structure." Given that availability of cheap pumps and drilling technology coincided with land and *panchayat* reforms means that effect of each on agrarian growth cannot really be separated. Let us suffice it to say that even though land and *panchayat* reforms may have enabled small and marginal farmers to invest in yield-enhancing technologies, it was the availability of ample groundwater resources and affordable means of extracting that resources, which led to the unprecedented growth in agriculture in West Bengal.

Expansion in area under boro paddy in the 1980s and early 1990s was the main contributor to high agricultural growth in West Bengal. Expansion in area under boro paddy was, in turn, facilitated by private investments in GWEMs. That groundwater depths are shallow, and rainfall and recharge are adequate, meant that farmers could irrigate adequately with the help of shallow tube wells and this was affordable for a large majority of farmers. As already mentioned earlier, those who could not invest in GWEMs could buy irrigation services from their neighbors. Boro paddy is the preferred crop of farmers in both West Bengal and Bangladesh because its yields are much higher than traditional varieties of paddy grown in kharif season (aman and aus paddy). In addition, being entirely irrigated crop grown in the dry season, boro paddy is not susceptible to monsoon floods.

While 1980s to early 1990s saw a rapid growth in agriculture in the state, since mid-1990s, West Bengal's agricultural growth again stagnated at 1–2% per annum. Overall, production of boro paddy also started showing a declining trend since mid-1990s. Even more importantly, there was an absolute decline in the number of GWEMs—from 6.48 lakhs in 2001 to 5.19 lakhs in 2006 (GOI 2001, 2011). This overall decline in number of GWEMs is not due to over-exploitation of groundwater resources since in more than 80% of villages, groundwater is available at less than 10 m (Mukherji et al. 2013). In this paper, we hypothesize that the slowdown in agricultural growth since early 2000s is a result of contraction of groundwater economy in the state. That the groundwater economy contracted is, in turn, due to two policies: restrictive clause of the Groundwater Act which made it difficult for farmers to get electricity connection and high cost of electricity connection itself. We will discuss these in detail in sections below.

38.4 Groundwater and Electricity Policies in West Bengal

38.4.1 Groundwater Act of 2005

West Bengal has been a pioneer in legislating a Groundwater Act way back in 2005 and unlike most states, also ensured that its provisions got implemented on the ground. The only other state known to have a working groundwater Act (as opposed to groundwater Acts which are not implemented) is Andhra Pradesh (APWALTA 1999). One of the clauses of this Act specified that all new GWEMs constructed after 2005 needed a prior permit from the State Water Investigation Directorate (SWID), while those which were already constructed before 2005 needed to be registered. The purpose of this registration process was twofold—to create an inventory of all GWEMs in the state and to exercise government control over further expansion of groundwater use. The state electricity utility—the West Bengal State Electricity Board (WBSEB) and its later incarnation—the West Bengal State Electricity Distribution Corporation Limited (WBSEDCL) made it mandatory for farmers to furnish SWID registration certificate before giving electricity connection to GWEMs. The officials of SWID were entrusted with the responsibility to implement the Act, and district level hydrogeologists were in charge of accepting or rejecting any applications for permits or registration of

Table 38.1 Progress in implementation of GW Act of 2005 from 2007 till September 2010

Districts	Permits for new tube wells		Registration for tube wells constructed before 2005		Level of groundwater development
	Applications received	% of permits rejected	Applications received	% of registration rejected	
Bankura	2038	48.6	4215	26.9	28.7
Bardhaman	890	73.6	5911	73.5	43.1
Birbhum	2406	70.6	6448	47.4	23.9
Coochbehar	0		0		16.8
Dakshin Dinajpur	1856	81.5	153	90.8	45.7
Darjeeling	63	98.4	0		5.0
Hooghly	1361	43.6	2812	47.1	40.9
Howrah	136	25	15	46.7	21.6
Jalpaiguri	264	96.6	39	71.8	4.8
Malda	1038	92	2541	88.6	54.2
Murshidabad	1953	79.7	9657	76.9	83.6
Nadia	263	27	1943	2	84.6
North 24 Parganas	439	41.5	367	40.3	70.9
Paschim Medinipur	6036	76.7	6708	40.9	35.2
Purba Medinipur	1116	53.7	2487	34	38.3
Purulia	35	62.9	7	42.9	14.5
South 24 Parganas	125	56	110	80.9	NA
Uttar Dinajpur	2878	27.1	4	50	45.4
West Bengal	22,897	64.1	43,417	54.3	41.3

Source SWID, November 2010

GWEMs. Guidelines for approval were at best indicative, and final discretion was vested with the hydrogeologists, who were mandated to do site verification but were not required to state the reason for rejection of application. This led to some amount of arbitrariness and discretionary behavior with the result that permits (for new GWEMs), and registration (for existing GWEMs) applications were being rejected even in blocks and districts with very less groundwater development (Table 38.1).

Usually, such provisions which require registration of GWEMs have been known to fail due to issues of non-compliance and lack of adequate human resources for enforcement. This has been well documented in Spain (Llamas 2003) and in Andhra Pradesh in India (Ramamohan 2009). The same happened in West Bengal. Table 38.1 shows that less than 10% of the total GWEM owners in the state actually applied to register their existing GWEMs, and as many as 54.3% of applications for registering existing GWEMs were rejected. In essence, very small number of farmers were actually aware of the requirement to register their GWEMs

Table 38.2 Pump owners' awareness of GW Act of 2005 and its provisions

	Number of respondents who answered "Yes"	Total eligible respondents	% of total
Number of respondents who had heard of GW Act of 2005	121	434	28
Number of respondents who knew that they have to apply for registration of existing GWEMs	73	395	18
Of the people who knew about registration provision, how many applied for it?	58	73	79
Of the people who knew about need of permits for new GWEMs, how many applied for it?	11	39	28

Source Survey data from 59 villages, 2010

or get a permit for new GWEMs (Table 38.2). Indeed, the only reason farmers applied for SWID certificate was to get electricity connection from WBSEDCL.

When denied a permit, farmers could still irrigate using diesel pumps because water tables are shallow in much of the state (Fig. 38.3). Yet, as I show in the next section, increasing cost of diesel and stagnant price of paddy meant that irrigating with diesel pumps was becoming a loss-making option and hence, not getting electricity connection, often meant keeping land fallow.

38.4.2 Electrification Procedures for Groundwater Wells and Tube Wells

Even procurement of a SWID certificate offered no guarantee to the farmers that they would indeed get an electricity connection for their GWEM. Since 2003 onwards, WBSEDCL has virtually stopped giving new electricity connections for GWEMs (Fig. 38.1).

There were several reasons for slowdown of electricity connections to farmers—reasons related to both demand and supply side. On the demand side, there was a weak demand for new connections from the farmers. Since 2000, farmers had to pay the full capital cost of pump electrification (including cost of wires, poles, and transformers), this could range from anything between USD 1000 and USD 4000 per GWEM. However, since 2007, there was an increase in demand for electrification of GWEMs (personal communication, CMD, WBSEDCL)—the reason being the introduction of metered tariff, which made it difficult for erstwhile water buyers to buy water on favorable terms and conditions (Mukherji et al. 2009; Meenakshi et al. 2011). Before 2007, farmers without GWEMs could buy water at competitive rates because of prevalence of high flat rate tariff which incentivizes GWEM owners to sell water proactively (Mukherji 2007a, b). However, the

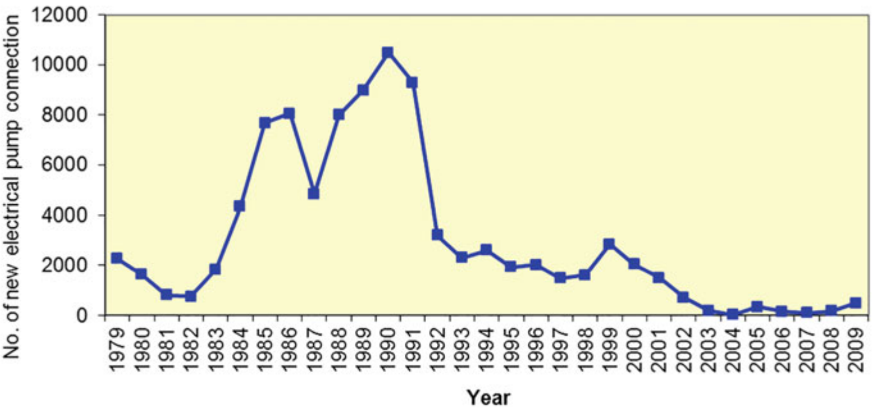


Fig. 38.1 Number of new electrical pump connections given to farmers in West Bengal, 1979–2009. *Source* WBSEB (and now WBSEDCL)

electricity utility could not handle this enhanced demand for electrification after 2007 due to the hurdle of SWID certification, as mentioned in the previous section. That WBSEDCL could not meet the increased demand from farmers is a paradox given that according to Central Electricity Authority (CEA 2010), West had electrified only 116,000 GWEMs out of 650,000 GWEMs that can be potentially electrified.

38.5 Impact of Restrictive Groundwater Policies on Cost of Cultivation and Farm Profits

What has been the impact of these policies on farmers? The main impact has been sharp decline in agricultural profitability. As mentioned earlier, given that groundwater is available at shallow depths in much of the state meant that farmers, who did not get electricity connection, could always revert to pumping using diesel pumps. However, that option slowly became unviable after gradual increase of diesel prices after withdrawal of diesel subsidies since mid-1990s (Fig. 38.2). Increase in diesel prices by itself would not have mattered so much if output price of boro paddy had kept pace with rising input costs. However, as Table 38.3 shows, there was a decline in price to cost ratio of boro paddy in real terms from 1999 to 2007 in the state. While prices of all inputs rose over this time, the increase in irrigation cost was the highest (Table 38.4), while output prices remained more or less constant, thereby, reducing farmers' profit margins.

In response to rising diesel costs and squeezed profit margins, farmers without access to electric GWEMs reduced area under boro paddy cultivation, and shifted to less water intensive, but also less profitable crops. Out of 59 villages, where we

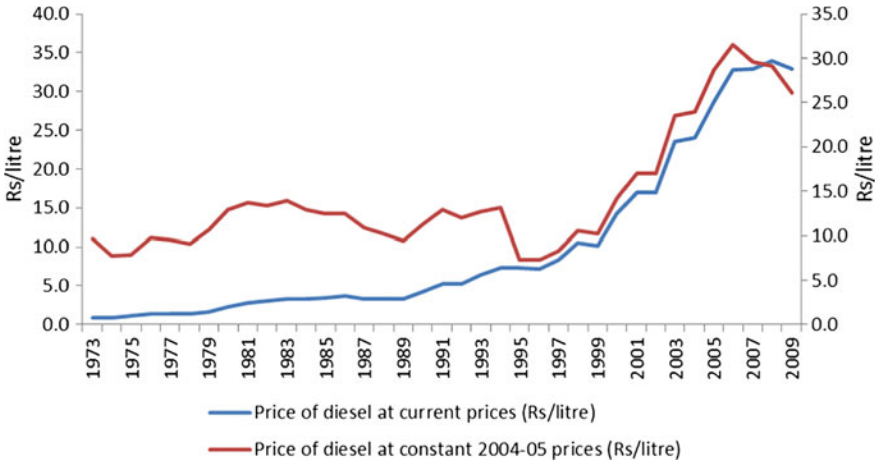


Fig. 38.2 Retail price of diesel in Kolkata in current and constant prices (1973–2009). *Source* Downloaded from indiastat.com on 15th March 2011

collected primary data, 18 of these do not have any electric GWEMs and it is in these villages that boro cultivation has all but stopped. For example, in one village in North 24 Parganas, area under boro paddy declined from 32% of gross cropped area (GCA) to merely 4% of the GCA from 1995 to 2010. Here, we found that only diesel pump owners cultivate boro paddy on small parts of their land for self-consumption, while the rest, keep their land fallow and instead buy rice from the market.

Overall, area under *boro* paddy cultivation in the state declined from 1.6 million ha in mid 2000s to less than 1.2 million ha in early 2010s. This decline has been wrongly attributed to unavailability of surface and groundwater (Ananda Bazar Patrika, March 11, 2011) and was often interpreted to mean that groundwater resources in the state have been over-exploited. The next section examines this claim of groundwater over-extraction in further detail.

38.6 Are Groundwater Levels Declining Over Time?

From the official data (SWID, 2010, last column of Table 38.1), it is evident that overall level of groundwater development in the state is less than 42% of its annual renewable recharge and there no districts which have over-exploited their renewable groundwater resources. Of the 310 blocks in the state, only 38 blocks are in semi-critical stage of groundwater development—which means that in these 38 blocks, groundwater levels are either falling in either pre- or post-monsoon seasons, or that over groundwater development is higher than 75% of renewable recharge. These numbers (42% overall groundwater development and 38 semi-critical blocks)

Table 38.3 Price to cost ratio of boro paddy, 1998–2007

Year	Cost of cultivation of paddy (C2) at 2004–05 constant prices (Rs./100 kilos)	Farm harvest prices of boro paddy 2004–05 constant prices (Rs./100 kilos)	Price to cost ratio
1998	605.4	1513.4	2.5
1999	652.9	1361.8	2.1
2000	632.0	1214.3	1.9
2001	597.9	1030.9	1.7
2002	580.2	1012.6	1.7
2003	616.5	1101.6	1.8
2004	581.1	1096.8	1.9
2005	568.2	1129.0	2.0
2006	597.3	1092.2	1.8
2007	601.1	1236.7	2.1

Source indiastat.org downloaded on March 15, 2011, compiled based on statistics released by Ministry of Agriculture, Government of India; C2 cost of cultivation includes all actual expenses in cash and kind incurred in production by owner + rent paid for leased in land + imputed value of family labor

Table 38.4 Variable input price index of paddy in West Bengal at 1999–2000 constant prices

Year	Human labor	Bullock labor	Machine labor	Seeds	Fertilizer	Manure	Insecticide	Irrigation
1999–00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2003–04	114.0	110.5	139.2	108.2	115.2	112.6	107.0	153.5
2004–05	111.9	114.4	152.2	110.6	120.4	115.9	108.5	133.9
2005–06	122.1	116.1	172.4	112.6	115.2	119.4	116.8	208.2
2006–07	136.4	119.0	187.5	116.6	115.2	123.0	124.3	223.8

Source Ministry of Agriculture, Government of India; downloaded from indiastat.com on March 15, 2011

Table 38.5 Groundwater level trend in 508 observation wells in West Bengal, 1999–2009

	Number of observation wells (% to total)			
	Constant (±20 cm)	Falling (+20 cm and more)	Rising (−20 cm and less)	Total
Pre-monsoon	358 (70.5)	128 (25.2)	22 (4.3)	508 (100)
Post-monsoon	412 (81.1)	85 (16.7)	11 (2.2)	508 (100)

Source SWID, 2010, figures in parentheses show percentage to total of 508 wells

have remained constant since 2000. Table 38.5, using 20 years data of water levels collected from 508 wells from 1990 to 2009, shows that majority of wells (70.5% in pre-monsoon and 81.1%) have a constant trend, while 25.2 and 16.7% of all

Table 38.6 Comparison of trend between pre-monsoon and post-monsoon seasons, 1990–2009

Post-monsoon	Trends	Pre-monsoon			
		Constant	Falling	Rising	Total
	Constant	335 (65.9)	61 (12.0)	16 (3.1)	412 (81.1)
	Falling	*18 (3.5)*	***67 (13.2)***	*0 (0)*	*85 (16.7)*
	Rising	5 (1.0)	0 (0)	6 (1.2)	*11 (2.2)*
	Total	358 (70.5)	128 (25.2)	22 (4.3)	508 (100)

Source SWID, 2010, figures in parentheses show percentage to total of 508 wells

observation wells experienced a declining trend in pre- and post-monsoon, respectively.

In Table 38.6, we cross-tabulate water level trend for each well and in each season, and see that majority of wells have constant water levels across the season. Some 13.2% of all observation wells showed declining water levels in both pre- and post-monsoon seasons, and these are of concern as declines in both seasons may be indicative of long-term secular decline. However, an analysis of water levels in these 67 wells shows that in majority of them (46%), water table is less than 9 m, while in only 15% of the cases, water level is below 12 m—showing that overall, groundwater is available at shallow depths, even in wells which have been experienced groundwater level decline in both pre- and post-monsoon seasons.

We hypothesize that high rainfall and the nature of the alluvial aquifer and its interconnectedness with the Ganges river systems ensure that there is high recharge in the post-monsoon season and whatever decline happens in the pre-monsoon season gets adequately recharged in post-monsoon season (Fig. 38.3).

38.6.1 Groundwater Extraction and Positive Externalities: The Ganges Water Machine Hypothesis

From an analysis of groundwater level data, it is clear that due to high rainfall and alluvial nature of the aquifer, water tables recover during the post-monsoon season and whatever decline is seen in the pre-monsoon season gets reversed after the monsoon rains. In fact, according to Revelle and Lakshminarayana (1975), pumping groundwater in the pre-monsoon season is a good strategy for increasing storage in the post-monsoon season. This is called the Ganges Water Machine hypothesis and was suggested as a mechanism for storing excess water in the monsoon season in aquifers in eastern Gangetic basin where terrain is too flat to construct large water storage structures. Expressed alternatively, this hypothesis says that lowering down water table in the pre-monsoon season leads to higher recharge in the post-monsoon season. This hypothesis has been tested in Bangladesh (Shamsudduha et al. 2011), and it was found that groundwater extraction had increased actual recharge in parts of Bangladesh where groundwater is used intensively for irrigation.

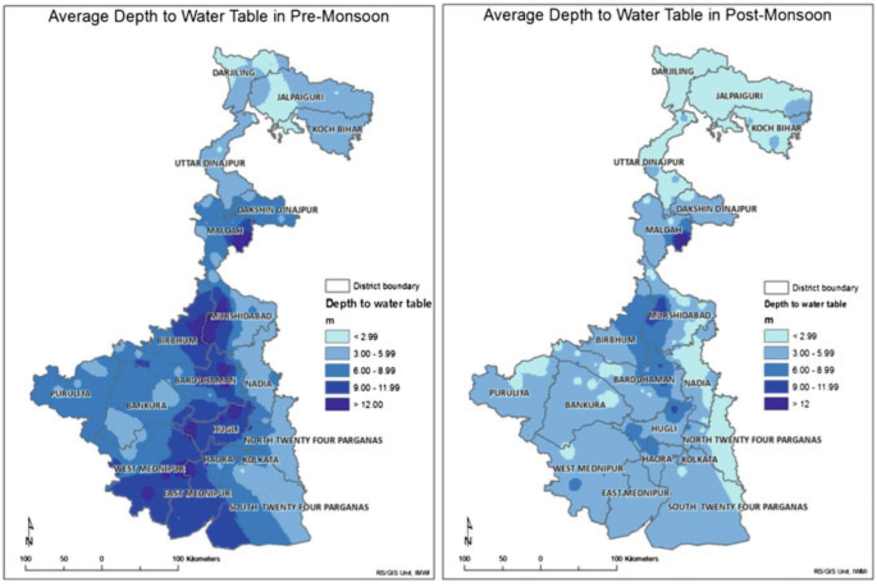


Fig. 38.3 Water tables in the pre- and post-monsoon seasons, 1990–2009. *Source* SWID, 2010

To test the Ganges Water Machine hypothesis, we apply panel data econometric techniques. The panel data is “balanced” wherein each of the 450 wells has data from the year 1990 till 2005 for the variables of pre- and post-monsoon water level and monsoon and non-monsoon rainfall.

The panel data function that we want to estimate is as follows:

$$\begin{aligned}\mathrm{rec}_{it} = {} & \alpha_i + \beta_1 \mathrm{pre\_WD}_{it} + \beta_2 \mathrm{monsoon\_RF}_{it} + \beta_3 \mathrm{nonmon\_RF}_{it} \\ & + \beta_4 \mathrm{LAG\_rec}_{i,t-1} + \varepsilon_{it}\end{aligned}$$

where

Rec	recovery of groundwater, which is calculated as pre-monsoon groundwater level minus post-monsoon groundwater level
pre_WD	pre-monsoon level groundwater levels
monsoon_RF	rainfall levels in the monsoon seasons
nonmon_Rf	rainfall levels in the non-monsoon seasons
LAG_rec	recovery in period $t - 1$

The well level fixed effects regression was estimated[1] using the STATA 11.1 software. The results are given in Table 38.7.

For dealing with possible heteroscedasticity in the model, we have used the robust standard errors. The well-fixed effect shows the within well variations for

---

[1] The fixed effects model was selected based on the Hausman test.

each well after holding time-invariant factors (such as type of aquifer, soils) constant. The model shows that for one meter of additional drawdown (*pre_wd*), the recovery (*RECOVERY*) goes up by 0.83 units. This change is significant and positive at 1% levels. This is our variable of interest as it shows that there is indeed a significant relationship between the pre-monsoon groundwater levels and the post-monsoon recovery. Therefore, far from negative quantity externality, groundwater irrigation in the boro season (pre-monsoon) may have positive externality in terms of reduction in rejected recharge and reduced flood proneness. Similar results were obtained by Roy (1989) in Bangladesh through a modeling exercise and more recently by Shamsudduha et al. 2011 using observational data.

38.7 Conclusions and Policy Recommendations

What can be done to reverse the current situation of agricultural stagnation? In this paper, we have shown that the main reason for this stagnation is policy-induced difficulty in access to groundwater. Therefore, our recommendations veer around making this groundwater access easier for small and marginal farmers.

In 2011, the first author of this paper was invited by the Indian Planning Commission to make a presentation to the Chief Minister of the state of West Bengal. Based on the evidence that has been presented in this paper, and numerous other publications by the author (see Mukherji 2006, 2007a, b; Mukherji et al. 2009), she recommended to the state government of West Bengal to remove the two most important barriers that prevents farmers for accessing groundwater—these being discontinuation of SWID certification and providing one time capital cost subsidy to farmers for electrification of their GWEMs. Both these recommendations were accepted (Mukherji et al. 2012).

The Water Resources Investigation and Development Department (WRIDD) through a memo dated 9th of November 2011 changed a clause of West Bengal Groundwater Resources (Management, Control, and Regulation) Act 2005 that earlier required farmers to get SWID certificate for electricity connection. According to the memo, farmers located in 301 or so “safe” groundwater blocks and owning pumps of less than 5 HP and tube wells with discharge less than 30 m^3/h will no longer need permits SWID before applying for an electricity connection for the GWEMs. This will effectively put all farmers except those located in 37 semi-critical blocks outside the purview of the Act.

Second, the WBSEDCL also changed its policy of GWEM electrification. Earlier, farmers need to pay the full capital cost of GWEM electrification, but as per the revised norms, farmers could get a new electricity connection for their GWEM against a fixed connection charge ranging from Rs. 1000 to Rs. 30,000 per connection, depending on the connected load. However, there was no change in the metered tariff policy and farmers continue to pay an unsubsidized tariff for use of electricity for groundwater pumping. Immediately after these two policy changes, 45,801 and 34,397 new electricity connections for irrigation tube wells were given

Table 38.7 Result of regression equation testing the Ganges Water Machine hypothesis

```
Fixed-effects (within) regression            Number of obs      =     6750
Group variable: well_code                   Number of groups   =      450


R-sq:  within  = 0.6393                    Obs per group: min =       15
       between = 0.5956                                   avg =     15.0
       overall = 0.5744                                   max =       15


                                         F(4,449)          =    937.91
corr(u_i, Xb)  = -0.5960                  Prob > F           =    0.0000


                          (Std. Err. adjusted for 450 clusters in well_code)
------------------------------------------------------------------------------
             |               Robust
   RECOVERY |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
      pre_wd |   .8357348   .0154766    54.00   0.000     .8053193    .8661504
  monsoon_RF |   .0005933   .0000422    14.07   0.000     .0005104    .0006762
NONmonsoon~F |  -.0010074   .0001826    -5.52   0.000    -.0013663   -.0006484
       L1rec |  -.0427493   .0118235    -3.62   0.000    -.0659856    -.019513
       _cons |  -3.243578   .1318401   -24.60   0.000    -3.502678   -2.984477
-------------+----------------------------------------------------------------
     sigma_u |  1.7185471
     sigma_e |  1.0995288
         rho |  .70954905   (fraction of variance due to u_i)
```

in 2011–12 and 2012–13, respectively. The total number of electrically operated GWEMs went up from rapidly from 1.32 lakhs in 2010 to 3.13 lakhs in 2014 (WBSEDCL data—pers comm). While there has been no rigorous impact evaluation of these policy changes yet, it is reasonable to expect that with access to better and assured irrigation, farmers cost of irrigation may have gone down over the years.

Given the large jump in new electrified GWEMs, it is important to ensure that groundwater sustainability is not compromised. Therefore, policies such as pro-rata (metered) tariff must continue (see Meenakshi et al. 2011 for an impact evaluation of metering in West Bengal), and investment in excavating tanks and ponds for recharge should also continue through use of public funds like Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGA). West Bengal is a poor state, with almost 28.5% of this population below poverty line, and 84% of these poor people live in the villages. Agricultural growth in the state is therefore a precondition for poverty alleviation. Making groundwater irrigation accessible and affordable to the small and marginal farmers might as well help unleash another wave of Green Revolution in the state and in the process benefit millions of smallholder farmers.

References

Ananda Bazar Patrika (2011) 11 Mar 2011

Banerjee AV, Gertler PJ, Ghatak M (2002) Empowerment and efficiency: tenancy reform in West Bengal. J Polit Econ 110(2):239–280

Boyce JK (1987) Agrarian impasse in Bengal: agricultural growth in Bangladesh and West Bengal 1949–1980. Oxford University Press, New York

Central Groundwater Board (2011) http://cgwb.gov.in/gw_profiles/st_westbengal.html

Central Electricity Authority (2010) http://www.cea.nic.in/god/dpd/pumpset_energisation.pdf. Downloaded on 15 Feb 2011

Dasgupta B (1995) West Bengal's agriculture since 1977. Paper presented at the workshop on agricultural growth and agrarian structure in contemporary West Bengal and Bangladesh, 9–12 Jan 1995. Centre for Studies in Social Sciences, Calcutta

Deb Roy A, Shah T (2003) Socio-ecology of groundwater irrigation in India. In: Llamas MR, Custodio E (eds) Intensive use of groundwater. Challenges and opportunities. Balkema Publishers, Lisse, The Netherlands, pp 307–336

Gazdar H, Sengupta S (1999) Agricultural growth and recent trends in well being in rural West Bengal. In: Rogaly B, Harriss-White B, Bose S (eds) Sonar Bangla? Agricultural growth and agrarian change in West Bengal and Bangladesh. Sage Publications, New Delhi

Ghatak M (1995) Reforms, incentives and growth in West Bengal agriculture. Paper presented at the Workshop on agricultural growth and agrarian structure in contemporary West Bengal and Bangladesh, 9–12 Jan 1995. Centre for Studies in Social Sciences, Calcutta

GOI (2001) Report of the 3rd minor irrigation census, Ministry of Water Resources Development, Government of India, New Delhi

GOI (2011) Report of the 4th minor irrigation census. Ministry of Water Resources Development, Government of India, New Delhi

GoWB (1995–1996) Economic review, 1995–96. Government of West Bengal, Calcutta

GoWB (2004) West Bengal human development report, 2004. Development and Planning Department, Government of West Bengal, Kolkata

Harriss J (1993) What is happening in rural West Bengal: agrarian reforms, growth and distribution. Econo Polit Wkly 28(24):1237–1247

Janakarajan S, Moench M (2006) Are wells a potential threat to farmers' Well-being? Case of deteriorating groundwater irrigation in Tamil Nadu. Econom Polit Wkly 41(37):3977–3987

Lieten GK (1992) Caste, gender and class in panchayats: case of Barddhaman, West Bengal. Econ Political Wkly 27(29):1567–1574

Llamas R (2003) Lessons learnt from the impact of the neglected role of groundwater in Spain's water policy. Dev Water Sci 50:63–81 (water resources perspectives: evaluation, management and policy)

Meenakshi JV, Banerji A, Mukherji A, Gupta A (2011) Does marginal cost pricing of electricity affect groundwater pumping behavior of farmers? Evidence from a natural experiment in West Bengal, final project report submitted to 3ie

Mishra SK, Rawal V (2002) Agrarian relations in contemporary West Bengal and tasks for the left. In: Ramachandran VK, Swaminathan M (eds) Agrarian studies: essays on agrarian relations in less-developed countries. Tulika, New Delhi

Moench M (2007) When the wells run dry but livelihood continues: adaptive responses to groundwater depletion and strategies for mitigating the associated impacts. In: Giordano M, Villholth KG (eds) The agricultural groundwater revolution: opportunities and threats to development. CABI Publishers, UK, pp 173–192 (comprehensive assessment of water management in agriculture series no. 3)

Mukherji A (2006) Political ecology of groundwater: the contrasting case of water abundant West Bengal and water scarce Gujarat, India. Hydrogeol J 14(3):392–406

Mukherji A (2007a) Political economy of groundwater markets in West Bengal, India: evolution, extent and impacts. Unpublished PhD thesis. University of Cambridge, UK

Mukherji A (2007b) The energy-irrigation nexus and its impact on groundwater markets in eastern Indo-Gangetic basin: evidence from West Bengal, India. Energy Policy 35(12):6413–6430

Mukherji A, Das B, Majumdar N, Nayak NC, Sethi RR, Sharma BR (2009) Metering of agricultural power supply in West Bengal, India: who gains and who loses? Energy Policy 37(12):5530–5539

Mukherji A, Shah T, Banerjee PS (2012) Kickstarting a second green revolution in Bengal. Econo Polit Wkly 47(18):27–30

Mukherji A, Rawat S, Shah T (2013) Major insights from India's minor irrigation censuses: 1986–87 to 2006–07. Econ Polit Wkly 48(26 & 27):115–124

NSSO (1999) 54th Round: cultivation practices in India, January 1998–June 1998. Department of Statistics and Programme Implementation, Government of India, New Delhi

Palmer-Jones RW (1992) Sustaining Serendipity? Groundwater irrigation, growth of agricultural production and poverty in Bangladesh. Econ Polit Wkly 27(39):A128–A140

Palmer-Jones RW (1995) Understandings of recent agricultural growth in Bangladesh and West Bengal. In: Paper presented at the workshop on agricultural growth and agrarian structure in contemporary West Bengal and Bangladesh, 9–12 Jan 1995. Centre for Studies in Social Sciences, Calcutta

Ramamohan RV (2009) Social regulation of groundwater and its relevance in existing regulatory framework in Andhra Pradesh, India. In: Mukherji A, Villholth KG, Sharma BR, Wang J (eds) Groundwater governance in the Indo-Gangetic and Yellow River basins: realities and challenges. CRC Press. Taylor and Francis group, London, UK, 325p (IAH selected papers on hydrogeology 15)

Revelle R, Lakshminarayana V (1975) The Ganges water machine. Science (New Series) 188 (4188):611–616

Rogaly B, Harriss-White B, Bose S (1999) Introduction: agricultural growth and agrarian change in West Bengal and Bangladesh. In: Rogaly B et al (eds) Sonar Bangla? Agricultural growth and agrarian change in West Bengal and Bangladesh. Sage Publications, New Delhi

Roy KC (1989) Optimization of unconfined shallow aquifer water storage for irrigation. PhD thesis, Utah State University

Saha A, Swaminathan M (1994) Agricultural growth in West Bengal in the 1980s: a disaggregation by districts and crops. Econ Polit Wkly 19(13):A2–A1

Sarkar A (2006) Political economy of West Bengal: a puzzle and a hypothesis. Econ Polit Wkly 41(4):341–348

Sarkar A (2011) Socio-economic implications of depleting groundwater resource in Punjab: a comparative analysis of different irrigation systems. Econ Polit Wkly 46(7):59–66

Shah T (2007) Crop per drop of diesel: energy squeeze on India's small holder agriculture. Econ Polit Wkly 42(39):4002–4009

Sen A, Sengupta R (1995) The recent growth in agricultural output in eastern India with special reference to the case of West Bengal. Paper presented at the workshop on agricultural growth and agrarian structure in contemporary West Bengal and Bangladesh, 9–12 Jan 1995. Calcutta Centre for Studies in Social Sciences

Shamsudduha M, Taylor RG, Ahmed KM, Zahid A (2011) The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. Hydrogeol J 19:901–916

Chapter 39

Hydrosocial Implications of Hydropolitical Trajectories: Exploring the Farakka Barrage Project from Indo-Bangladesh Perspectives

Jenia Mukherjee

Abstract The complexity of the South Asian terrain lies in the fact that though politically all eight countries (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka) have their independent territories, yet much of the natural resources are shared by two or more political boundaries. The complexity further aggravates in relation to flow resources like rivers where demarcation is difficult. Numerous water diversion schemes in transboundary South Asian river basins manifest catastrophic implications of reductionist hydroengineering paradigms on ecology and people. There has been a worldwide paradigm shift in water research from both natural and social sciences perspectives and the convergence between the two. While natural sciences have moved from an emphasis on different components of hydrology (surface water, groundwater, saline water, fresh water, etc.) as separate entities towards a composite hydrogeoecological framework that studies hydraulically connected systems, social sciences are perceiving water as an entity that both shapes and is also shaped by social relations, structures and subjectivities. Hydrogeoecological and hydrosocial approaches are extremely significant to explore how political trajectories influence socio-ecological transformations in shared river basins. The paper builds upon the Farakka Barrage, one of the most controversial projects affecting Indo-Bangladesh geopolitics, hydrogeoecological regime and hydrosociality as an inductive-empirical case study to justify the need for application of this transdisciplinary knowledge base within the South Asian context.

J. Mukherjee (✉)
Department of Humanities and Social Sciences, Indian Institute of Technology, Kharagpur, India
e-mail: jenia@hss.iitkgp.ernet.in

J. Mukherjee
Applied Policy Advisory to Hydrosciences (ÃPAH) Group,
Indian Institute of Technology, Kharagpur, India

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_39

39.1 Introduction

The construction of dams and barrages on watercourses has a long history taking us back to the days of the Maribian dam (Yemen) of 600 BC or the Grand Anicut of the second century AD. However, man–nature contradiction (‘metabolic rift’) had intensified with the advancement of capitalism with every country entering into its own struggle of exploiting and pouncing on natural resources to its utmost utilization.[1] Water diversion schemes have had serious consequences, evident from the snowy mountain scheme in Australia (1974), the marshland draining scheme of Southern Iraq (the diversion of the Euphrates River to the Third River Canal), etc. Land, water and soil have been modified with countries getting involved in insane and intense rivalries to claim superiority over others. The socio-environmental outcomes of such politico-economic struggles are being catastrophic. South Asia encounters severe challenges arising out of water diversion schemes for its major rivers: the Ganges, Indus, Kosi, Teesta, etc., (Chap. 1, Fig. 1.3).

The recent scenario of ‘global environmental change’ and ‘anthropocene’ provides the predicament for the convergence of natural (geology and geophysics, etc.) and social sciences (history, political science, sociology, anthropology, etc.) towards comprehensive understanding of riverine systems. The transdisciplinary framework can inform cost-benefit cycles by evaluating technical and social implications of interventions. Power-political equations among stakeholders across countries are strong determinants of water allocation among users. Hydropolitical trajectories impact and influence hydrogeoecological regimes, which, in turn, generate hydrosocial repercussions. These emerging critical transdisciplinary perspectives need to be informed by rigorous and detailed empirical-inductive case studies. The huge, dynamic and diverse South Asian scenario loaded with severe complexities and uncertainties offers an appropriate context towards this direction. The chapter builds upon one of the most controversial projects in South Asia: the Farakka Barrage.[2] More related information regarding groundwater of South Asia is available in Mukherjee (2018).

39.2 Theories and Directions

Two major emerging trends in water research across natural sciences and social sciences offering meaningful framework towards policy/project formulation and execution are:

---

[1] The ‘metabolic rift’ theory is the Marxian ecological perspective that encapsulates theorization of rupture in the metabolic interaction between humanity emanating from capitalist production (Foster 2000).

[2] Though called a barrage, Farakka Barrage is a large dam as per ICOLD, WCD and CWC definitions, with associated large dimensions and impacts (SANDRP 2014).

- A shift in the perception of considering surface water and groundwater as separate entities towards ‘hydraulically connected systems’ where the interaction takes place mainly in two forms: (a) surface water bodies gain water and solutes from groundwater systems and (b) surface water body serves as a source of groundwater recharge and causes changes in groundwater quality (Winter et al. 1998). Though the literature had evolved establishing surface water and groundwater interaction and conjunction since the last 100 years, initiated by Boussinesq’s landmark publication of 1877, yet it is only from the 1990s (Winter 1995; Winter et al. 1998; Lewelling et al. 1998; Larson and Marti 1996) that there had been a spurt in scholarship (especially in the USA), studying not only the stream-(contiguous alluvial) aquifer interaction, but also very many dimensions of interconnections in a wide variety of landscapes: mountainous, riverine, coastal, glacial, dune, karst, etc. (Winter 1995). Different parameters are taken into consideration including climate, surface water type, landscape type and scale of hydrologic systems (Sophocleous 2002). Moreover, a recent connection is being made between biogeochemical processes within sediments and its effects on the chemistry of water interchange (Sophocleous 2002). Within the recent context of environmental changes, the scientific community is pursuing detailed research on the intersections between anthropogenic environmental changes and available management tools that quantify the integrated groundwater and surface water flow processes (Safeeq and Fares 2016). These developments manifest a marked transformation in water research from unilinear perspectives on different components of hydrology (surface water, groundwater, saline water, fresh water, etc.) as separate entities to an understanding of the processes in its entirety through the formulation of the hydrogeoecological framework. The field demands cross-disciplinary collaborations to conceptualize these transformations and develop sophisticated tools to analyse the same.
- A shift in the perception of water with only physical attributes to water as an entity that ‘is both shaped by, and shapes, social relations, structures and subjectivities’ (Linton and Budds 2014: 170). The emerging ‘hydrosocial’ approach within political ecology of water recognizes water as being simultaneously natural and sociopolitical. Moreover, it testifies the dialectical and internal nature of the relation between society and water, bringing out the already intrinsic and embedded interactions between the two (Linton and Budds 2014). There are few studies that have applied this conceptual notion to explore river basin management, discussing and describing the political-material interest of the statecraft and also co-production of science and social order (Bouleau; Swyngedouw XX). Analyses are provided along four dimensions: (a) meaning of water or views, discourses and understandings at stake; (b) internationalization and expression of political strategies and politics in water circulation; (c) relations to larger scales, external actors and moves and (d) water-society dialectic co-production. Recent studies on tropical-estuarine scapes had addressed greater complexities within the ‘hydrosocial’ approach by taking into account mud/sediments (*chars*/riverine islands) as physical–social site of

interactions (Mukherjee and Lafaye de Mischeaux 2016). It is a significant lens to establish and explore the directly proportional relationships between changes in hydrogeoecological regimes influenced by political choices and its social implications for transboundary rivers.

Incorporating these transforming trends in water research, the chapter captures and explores political decisions on water sharing between two South Asian countries (India and Bangladesh) within the politico-historical context of partition and its hydrogeoecological and hydrosocial implications.[3]

39.3 Case Study: The Farakka Barrage Project

39.3.1 Hydropolitical Trajectories

South Asian complexity lies in the fact that though politically all eight countries (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka) have their independent territories, yet much of the natural resources are shared by two or more political boundaries. The complexity further aggravates in relation to flow resources like rivers where demarcation is difficult (Kawser and Samad 2016). India and Bangladesh share 54 rivers, leading to geopolitical contestations, cleavages and negotiations across historical scales since the era of South Asian decolonization. The technical roots of challenges caused by the commissioning of the Farakka Barrage Project in India could be rooted in political decisions and choices made during the post-independent nationalist period following colonial legacy.

The Farakka Barrage Project was formulated to serve the need of preservation and maintenance of the Calcutta Port by improving the regime and navigability of the Bhagirathi-Hooghly River system. Cartographic accounts (especially maps of Matheus Van den Brouche and Major James Rennell) make us aware that the seventeenth and eighteenth centuries were periods of great alterations marked by the decline of volume of water in the Bhagirathi-Hooghly and united mass of waters in the Padma, the right bank distributary of the Ganges flowing through erstwhile East Bengal (Mukherjee 2008–09). From the middle of the nineteenth century, the British became anxious about the future of the Calcutta Port. The plan for the construction of barrage on Ganges near Rajmahal and the creation of a feeder canal to bring the surplus water from the Ganges to the Bhagirathi River had already surfaced in the opinions of Atherton (1853), Vernon Harcourt (1896), Reak (1913), William Willocks (1930), T. M. Oag (1939) and A. Webster (1946) (MEA 1978).

---

[3] It is interesting to note here that the Boundary Commission under the Chairmanship of Cyril Radcliffe also considered the immense importance of the Farakka Barakka and hence deviated from the principle that contiguous Muslim majority areas should form Pakistan. Murshidabad (with a Muslim majority) where Farakka is situated hence remained in India and in exchange a non-Muslim majority district of Khulna went to the former East Pakistan (MEA 1978).

Table 39.1 Sharing of lean season flow at Farakka, India–Bangladesh water sharing agreement 1975 (amount in cusecs)

10 day period	Dependable supplies at Farakka	Amount agreed upon for Hooghly	Remaining flows for Bangladesh
21–30 April 1975	55,000	11,000	44,000
1–10 May 1975	56,500	12,000	44,500
11–20 May 1975	59,250	15,000	44,250
21–31 May 1975	65,500	16,000	49,500

Source Gulati (1985)

In the post-independence period, the question of revival of Calcutta Port seemed to be a vital issue for India. In 1957, under the advice of the internationally renowned river expert Walter Henson, the project was approved. The Farakka Barrage Project started in 1962 and was completed in 1975 at the cost of 1560 million ($ 208 million).

The implementation phase went through a series of memorandum of understandings (MOUs), agreements and treaties between the two countries. A critical review of the treaty regimes sheds light on the history of water sharing of the Ganges River between India and Bangladesh that underwent severe fluctuations from the 'phase of excessively overt friendship to a phase of extreme tension to the current phase of anxiety and apprehension' (Salman 2002: 33). In the 1970s, the Joint Rivers Commission (JRC) was established to work on flood control, irrigation projects, etc., and the Partial Accord (1975) was signed (Table 39.1). The continuous tussle that continued for the next two decades was regarding India's plan of augmenting the flow of the Ganges through diversions from the Brahmaputra River by constructing a link canal and Bangladesh's proposal of building storage reservoirs in the upper reaches of the Ganges in Nepal and India (Salman 2002). MOUs were signed in the 1980s. The 1988 flood devastated Bangladesh when the Ganges flow reached 2.5 million cusecs in the month of August followed by only 9761 cusecs in March 1993 which has been the lowest record since the implementation of the project. The last meeting of the JRC was held in June 1993 in Dhaka. On December 12, 1996, a formal treaty was signed for 30 years. However, it 'turned out to be merely an arithmetical exercise not based on a broader and interdisciplinary ecological perspective on river flows' (Bandyopadhyay and Ghosh 2016: 13). The devastating floods of 1998 proved its clauses to be non-comprehensive.

39.3.2 Hydrogeoecological Regimes

The implementation of the Farakka Barrage Project had disrupted the entire hydrogeoecological regime of the basin, not only affecting Bangladesh but also the Lower Gangetic Basin in West Bengal, India, especially the upstream (Malda) and downstream (Murshidabad) districts.

Bangladesh has suffered in all aspects: agriculture, navigation, irrigation, fisheries and forestry due to the changing hydrogeoecological regime through lack of surface water, reduced groundwater, riverbed aggradations, sediment influx and ingression of salinity in the coastal delta (Illustration 1). Bangladesh's delta receives less sediment and inadequate water flow for navigation and irrigation during the summer months. The summer of 1993 was characterized by almost completely dry river beds. Groundwater also dropped below the level of existing pumping capacity due to lack of recharge from surface water and over extraction by farmers for irrigation against non-availability of adequate surface water (Khalequzzaman 1994). Due to lack of adequate freshwater inflow, coastal rivers experience saltwater intrusion 100 miles farther inland than normal level during summer months, affecting drinking water in these areas (Zaman 1983). Islam and Gnauck (2008) attribute the salinity ingression in the Bangladesh Sundarbans Delta to the construction of the Farakka Barrage in 1975. They find evidence of saline water penetrating the upstream area, with river water salinity increasing significantly in 1976 as compared to the year 1968. Moreover, the reduction in sediment supply to Bangladesh has led to increased coastal erosion. The reduced summer flows allow sediment to be deposited on the riverbeds downstream of the barrage, resulting in decreased water-carrying capacity during the rainy seasons (Alexander 1989). This reduction in carrying capacity due to riverbed aggradations has increased the frequency of severe floods over the last decade (Fig. 39.1).

Though the barrage is considered 'evil' by Bangladesh and emblem of hydraulic modernity by India (D'Souza 2003), yet the later could not escape its catastrophic impact. The most significant knowledge gap in river engineering was relating to the understanding and management of sediments, which are integral parts of water flows. The project had caused huge sedimentation, increasing flood intensity and aggravating tendency of bank failures in the Malda (upstream) and Murshidabad (downstream) districts of West Bengal (Banerjee 1999; Rudra 2003; Mukherjee 2011). It had altered the direction of the river flow which is no longer co-axial to the barrage due to the reduction of the cross-sectional area and gradual meander formation between Rajmahal Hills and Farakka. In Malda, the total eroded land between 1979 and 2004 is 4247 ha. The construction of the barrage has also disturbed the apparent equilibrium through aggradations and degradation of the river bed and channel pattern by erosion and siltation. New or running *chars* (riverine islands or sandy shoals) have emerged with the general rise in riverbed level and formation of deep narrow thalweg on the left side. Several large running chars in Malda have come up since the last few decades such as Gadai *Char*, Dakatia *Char*, Hamidpur *Char* along with the opening up of deep channels which

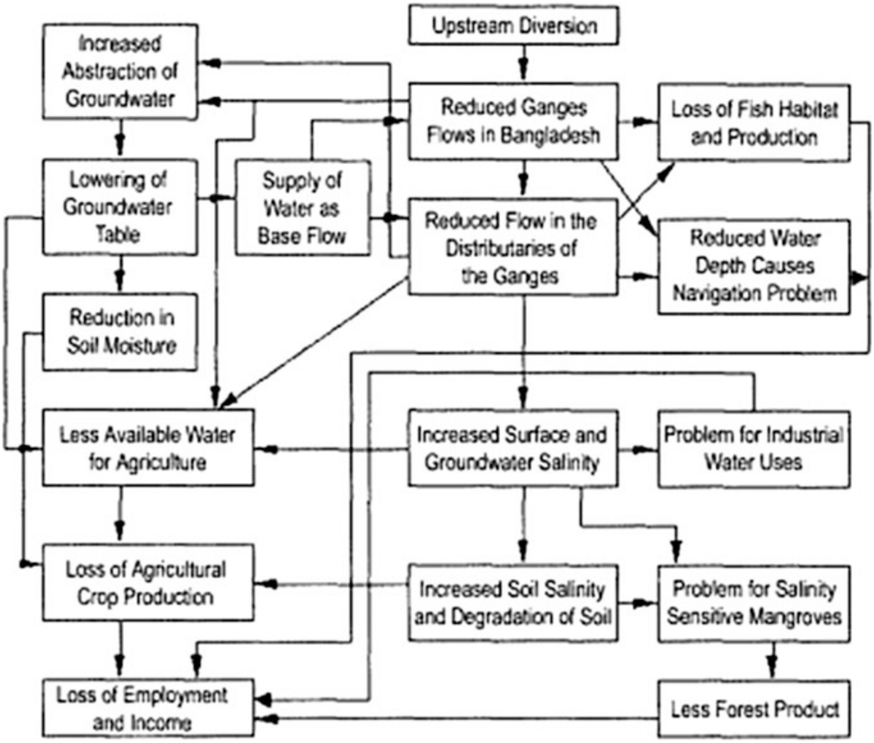


Fig. 39.1 Hydrogeoecological of water diversion on Bangladesh. *Source* Mirza (2004: 7)

has in turn affected the linear path of the river. The appearance, disappearance and reappearance of *chars* in Panchanandapore (Malda) have become a regular phenomenon. In Murshidabad, the same process has been active leading to rise of Nirmal *Char* and Jalangi *Char*.

Even in India, the drying up of the Indian Sundarbans Delta (ISD) and the consequent saline water ingression in the delta region have been attributed to the streamflow depletion due to sedimentation in the Farakka, as also the rise in sea levels (Ghosh et al 2016). Moreover, the recent call (August 21, 2016) by Nitish Kumar, chief minister of the Indian state of Bihar, to remove the Farakka Barrage has added a new dimension to the ongoing debate on the utility of the barrage. Apart from the severe and various challenges in the downstream, the problem with the management of sediments has recently taken an ugly turn with the floods in the Indian states of Uttar Pradesh and Bihar. The Bihar chief minister says that the sediment build-up upstream of the Farakka Barrage has raised the river bed, which is worsening the flood situation (Ghosh 2016).

39.3.3 Hydrosocial Repercussions

This single barrage has crafted severe social implications, affecting lives and livelihoods of millions of people on both sides of the border; till now responses in addressing the challenges had been extremely inadequate. Millions of people suffer from floods and erosion, losing homes, lives and livelihoods. The existence, emergence and submergence of chars have a long association with estuarine-deltaic scapes. However, the project had led to great alteration in the nature and pattern of *char* formation, emergence and submergence, causing vagaries to livelihoods of *choruas* (people who inhabit chars) who are mainly erosion-induced displacees from mainland. The erosion victims in these uncertain patches are affected with the settlement, displacement, resettlement and redisplacement (SDRR) syndrome due to the continuous emergence, submergence, re-emergence and re-submergence of the chars (Mukherjee 2011) (Illustration 2). People have moved between four to 16 times in the last 15 years! The villages in the *chars* are not considered as revenue villages, legitimizing the statist act of non-intervention. The *choruas* in the newly emerged chars are mostly erosion victims (homeless and landless people, land being swallowed by the river) from the mainland. They had lost land, land deeds, ration cards, voters' cards and hence citizenship and identity. The *chars* suffer from the constant risk of submergence leading to justification of the statist cause of no or minimal infrastructural interventions in these muddyscapes (Mukherjee and Lafaye de Micheaux 2016). There are no hospitals; an expecting woman has to be taken minimum 10 km away by boat to the mainland. Child and gender welfare schemes are also not prevalent. Most children suffer from malnutrition; 15–20 children die of malnutrition every year. The *chars* lack basic amenities like water, sanitation, education.

Along with these challenges, there are acute boundary problems at both the interstate and intra-state levels. New *chars* in Murshidabad had emerged towards the neighbouring state of Bangladesh. Akheriganj, which literally means the last settlement, virtually disappeared from the map when the 1989–1900 erosion struck it. It engulfed 2766 houses and left 23,394 persons homeless. They migrated to the newly emerged Nirmal *Char* along the opposite bank of the river. Around 20,000 people live in this *char* stretching up to 50 km. Bangladesh (Rajshahi district) is easily accessible to it compared to Murshidabad (Illustration 3). The international border appears porous and nebulous escalating illegal activities and exchanges. The interstate dimension also remains prominent. In the Malda district, *chars* had developed in close proximity to the adjoining new state of Jharkhand. More than 60 *mouzas* had been unclaimed by the West Bengal government; Jharkhand had issued voters' card to some of the people[4]; many people already had ration cards from the Bengal government, causing them victims of dual citizenship.

---

[4] In India, Pakistan and Bangladesh, mouza implies a type of administrative district within which there may be one or more village settlements.

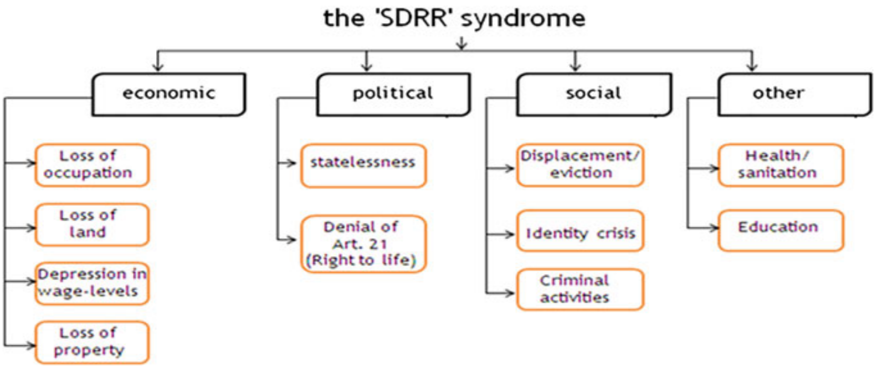


Fig. 39.2 SDRR syndrome. *Source* Mukherjee (2011: 17)

Some remedial measures have been implemented to respond to floods, like the construction of embankments, revetments, spurs. Yet, these had proved to be ineffective owing to the gradual shifting of the Ganges towards the left bank upstream of the barrage. Major portions of embankments and spurs had been washed out. The spurs had created additional problems as tons of boulders used for anti-erosion works along the banks are too often dislodged and deposited into the river causing severe obstructions to flow. 'The construction of embankments does not offer any guarantee against flood yet the engineer- contractor-politician nexus operates in the same fashion every year' (Banerjee 1999: 15–16) (Figs. 39.2 and 39.3).

39.4 Conclusion

Numerous examples from several river basins especially of the complex South Asian context including the Farakka Barrage manifest deleterious implications of nationalistic chauvinism and reductionist hydroengineering paradigms on ecology and people. The major concern for river basin management in South Asia finds reflection in Bandopadhyay and Ghosh's argument, 'The worldwide paradigm shift in river basin management has not affected policymakers in South Asia. Hydro-diplomacy in the Ganges-Brahmaputra-Meghna basin is still based on reductionist engineering, and looks at marginal economic benefits, without showing any concern for the long-run implications for livelihoods and ecosystem' (2009: 50). The new transdisciplinary knowledge base informed by emerging frameworks in water research should find reflection within the South Asian context. The lacunae within the Farakka Barrage Project generate warnings that should be carefully accounted for so that history (of socio-ecological disaster) does not find further scope to repeat itself.

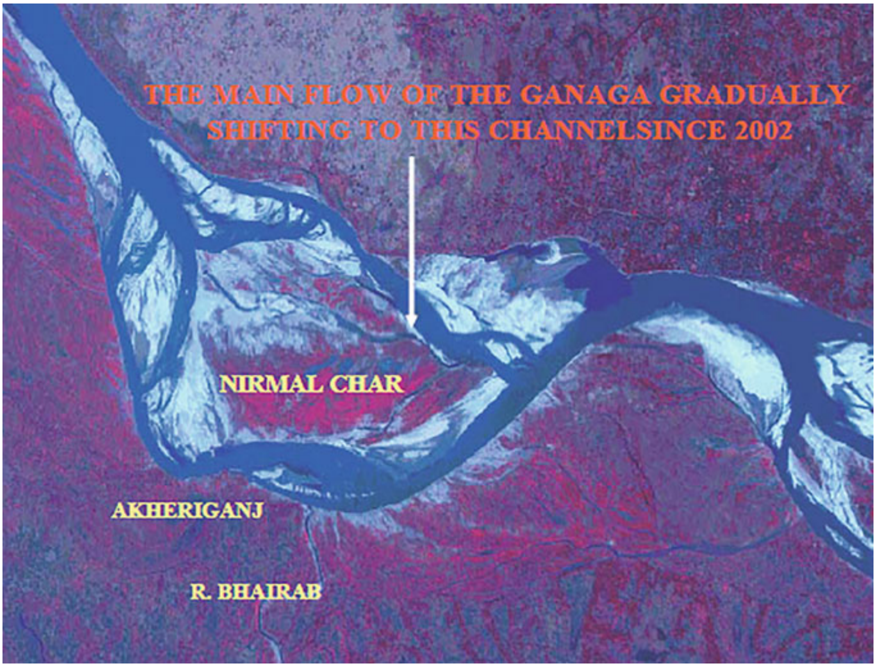


Fig. 39.3 Nirmal *Char* and the shifting course of the Ganges. *Source* Rudra (2003: 31)

References

Alexander D (1989) The case of Bangladesh. University of Massachusetts, Amherst

Bandyopadhyay J, Ghosh N (2016) Hydro-political dynamics and environmental security in the Ganges-Brahmaputra-Meghna Basin. The case of Bangladesh-India trans-boundary water relations. Res J Soc Sci 24:1–25

Banerjee M (1999) A report on the impact of Farakka Barrage on the Human Fabric. SANDRP, Regional and Institutional Profile of Malda District, New Delhi. http://wbplan.gov.in/docs/DHDR/Draft_DHDR_Malda/DHDR_Chapter1.doc. Accessed 23 June 2010

Boussinesq J (1877) Essai sur la théorie des eaux courantes. Imprimerie nationale

D'Souza R (2003) Damming the Mahanadi River: the emergence of Multi-purpose River Valley Development in India (1943–46). Indian Econ Soc Hist Rev 40(1):81–105

Foster JB (2000) Marx's ecology: materialism and nature. Monthly Review Press, New York

Ghosh N (2016) Farakka Barrage, Engineers and Hydropolitics. thethirdpole.net. https://www.thethirdpole.net/2016/09/14/farakka-barrage-engineers-and-hydropolitics/. Accessed 14 Sept 2016

Ghosh N, Danda AA, Bandyopadhyay J, Hazra S (2016) Planned retreat and ecosystem regeneration as adaptation to climate change. Policy, Research, and Innovation Division, Issue Brief No 1. WWF India, New Delhi

Gulati C (1985) Indo-Bangladesh relations. An unpublished PhD Thesis. Jamia Millia Islamia, New Delhi

Islam SN, Gnauck A (2008) Mangrove wetland ecosystems in Ganges Brahmaputra Delta in Bangladesh. Front Earth Sci China 2(4):439–448

Larson A, Marti P (1996) Relationship between ground water and surface water in the Quilceda Creek watershed. Department of Ecology (No. 96-333), Washington State

Lewelling BR, Tihansky AB, Kindinger JL (1998) Assessment of the hydraulic connection between ground water and the Peace River, West-Central Florida. U.S. Geological Survey Water-Resources Investigations Report, 97–4211, Tallahassee, Florida. U.S. Geological Survey

Linton J, Budds J (2014) The hydrosocial cycle: defining and mobilizing a relational-dialectical approach to water. Geoforum 57:170–180

Kawser MA, Samad MA (2016) Political history of Farakka barrage and its effects on environment in Bangladesh. Bandung: J Glob South 3(16)

Khalequzzaman MD (1994) Recent floods in Bangladesh—possible causes and solutions. Nat Hazard 9:65–80

Mirza MQ (2004) The Ganges water diversion: environmental effects and implications. KluwerAcademic Publishers, Netherlands

Mukherjee R (2008–09) The changing face of Bengal: a study in riverine economy, with an introduction by Arun Bandopadhyay. University of Calcutta, Calcutta

Mukherjee J (2011) No voice, no choice: riverine changes and human vulnerability in the “Chars” of Malda and Murshidabad. Occasional Paper, 28

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Mukherjee J, Lafaye de Micheaux F (2016) Intervened River, Transformed Muddyscapes: exploring clashing perceptions across state-society interface in the ‘Chars’ of Lower Gangetic Bengal, India. Muddy footsteps and Hydrosocial Futures: Understanding Relationality with, through and about Water. Durham

Rudra K (2003) The Encroaching Ganga and social conflicts: the case of West Bengal, India. Unpublished paper, 1–38. http://gangapedia.iitk.ac.in/sites/default/files/Rudra.pdf. Accessed 20 June 2010

Safeeq M, Fares A (2016) Groundwater and surface water interactions in relation to natural and anthropogenic environmental changes. In: Fares A (ed) Emerging issues in groundwater resources. Springer, Berlin, pp 289–326

Salman MU (2002) Conflict and co-operation on South Asia’s International Rivers: a legal perspective. Kluwer Law International, Netherlands

SANDRP (2014) Lessons from Farakka as we plan more barrages on Ganga. https://sandrp.wordpress.com/2014/11/25/lessons-from-farakka-as-we-plan-more-barrages-on-ganga/. Accessed 15 Jan 2017

Sophocleous M (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeol J 10(1):52–67

The Farakka Barrage (1978) Ministry of External affairs, New Delhi

Winter TC (1995) Recent advances in understanding the interaction of groundwater and surface water. Rev Geophys 33(S2):985–994

Winter TC, Harvey JW, Franke OL, Alley WM (1998) Ground water and surface water—a single resource. U.S. Geological Survey Circular, Denver

Zaman M (1983) (ed) River basin development. Tycooly International Publishing, Dublin

Chapter 40
Need for a Legal Framework for Groundwater Security in India

Abhijit Mukherjee

Abstract India consists of only ~2% of the world's total land area but supports a large part (~19%) of the global population, thus being inherently stressed for natural resources for its citizens, e.g. safe and sustainable water. Securing water for nourishment, household purposes and food production relates to 'water problems', which can be classified as issues related to water quantity in terms of availability of sufficient quantity of the water (excessive water, e.g. flood and lack of water like drought), and issues of water quality, meaning that the available water should be of safe quality for human consumption purposes. In India, where water resource availability is extremely heterogeneous and is largely dependent on stability of the monsoonal rainfall, aggravating the water scarcity with predicted population growth is going to be a pivotal public health, socio-economic and political issue in near future. Groundwater is the largest resource of freshwater in this planet and India, whose availability is largely dependent on the geological and climatic set-up for an area. Groundwater use and food production are also strongly linked because irrigated agriculture is the primary consumer of global freshwater resources. Globally, being the largest consumer of groundwater resources and being the highest groundwater-irrigated country, by area, India is particularly vulnerable to water and food scarcity. Almost 85% of its groundwater consumption is linked to agricultural practices, which possibly has not much changed since the age of first human settlements in these ancient lands, millennia ago. Groundwater availability problems are likely to be exacerbated in the future by climate change. Thus, these water scarcity problems will most likely translate to food scarcity. In the present situation,

---

A. Mukherjee
Department of Geology and Geophysics, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee
School of Environmental Science and Engineering, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India

A. Mukherjee (✉)
Applied Policy Advisory to Hydrogeosciences Group, Indian Institute
of Technology (IIT)—Kharagpur, Kharagpur 721302, West Bengal, India
e-mail: abhijit@gg.iitkgp.ernet.in

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_40

the lack of a holistic approach to understand the different facets of water cycle translates to the fact that water as an essential commodity is inevitably getting exceedingly scarce in India. Thus, there is a requirement to develop plans for assuring availability of suitable water for drinking and food production as a social security and democratic right for every citizen of India. This strongly entails a clear road map for groundwater security, under a legal framework, such that it focuses on water resources sustainability and the role of resource efficiency and environmental management in reducing risks, i.e. for more efficient and judicial use of water and proper preservation for future generations.

40.1 Introduction

As India (Chap. 1, Fig. 1.1) aspires to become a 'developed' country from a 'developing' country in the impending decades, it is imperative that all citizens of the country should be provided with the basic social securities. India consists of only ~2% of the world's total land area but supports a large part (~19%) of the global population (FAO 2013). And, in a country like India, where a large part of the total population is still below the poverty line and is deprived of being fed twice a day, assuring the minimum security of proper nourishment should be the first priority of any administration. However, even after sixty-seven years of the country's independence, this has remained as a long-sought dream. In this backdrop, the National Food Security Bill 2013 (Right to Food Act) was proclaimed. However, the inherent feeling is that this bill wouldn't be sufficiently able to secure the basic survival needs of Indian citizens. The reason being that even if in future, the administration is able to secure food for everybody, a more fundamental need for survival of life, i.e. *drinking water,* still remains unsecured. In this context, it is delightful to find that the present government has discretely focused on better water management and forwarded the proposition of supplying potable, pathogen-free drinking water for everybody. The budget declaration has also referred to setting up of enhanced irrigation schemes as 'Pradhan Mantri Gram Sinchayee Yojana' with motto of 'har khet ko paani', thereby reducing the farmers' dependence on unpredictable rainfall for cultivation. Even, the Ministry of Water Resource is being restructured and reorganized to better serve the citizens of our great republic. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

While all of these above-quoted plans are very good-willed, there is a need for in-depth understanding of water security, as it will help us to go into a series of issues, based on evidence and cutting through many of the myths and alarmism around water scarcity. On the contrary, an unplanned, adventurous effort can severely further undermine the already dwindling water resource. Securing water for nourishment, household purposes and food production relates to 'water problems', which can be classified as issues related to water quantity in terms of availability of sufficient quantity of the water (excessive water, e.g. flood and lack of water like drought), and issues of water quality, meaning that the available water should be of safe quality for human consumption purposes. In India, where water resource availability is extremely heterogeneous and is largely dependent on stability of the monsoonal rainfall, aggravating the water scarcity with predicted population growth is going to be a pivotal public health, socio-economic and political issue in near future (Mukherjee et al. 2015). Groundwater is the largest resource of freshwater in this planet; however, its availability is largely dependent on the geological and climatic set-up for an area. Impending predicted climate change scenarios would further complicate the groundwater availability. It has been estimated in recent studies (Verma and Phansalkar 2007) that at the beginning of every hydrological year, 4000 billion m^3 of water enters the Indian hydrological system. Almost 2000 billion m^3 is lost in unaccounted processes, including evaporation, supply line leakages, flowing to very deep aquifers or escape by outflow to the sea. The remaining ~50% of water has an extremely skewed distribution with more than 60% being distributed in the great North Indian alluvial plains of the Indus–Ganges–Brahmaputra river systems, which accounts for only ~35% of Indian continental land area. Hence, the rest 65% of the land mass that includes most of southern and western parts of India gets only 40% of India's total annual water resource. Of these, the four monsoon months (June to September) account for 60–80% of the flow through either of the North or South Indian rivers, making it even more skewed distribution in a temporal scale. Consequently, these facts also indicate that the North Indian states are mostly in water-sufficient condition (Kumar et al. 2005). However, indiscriminate use of rivers and other surface water bodies in these states for disposal of sewage and industrial waste have rendered them non-potable (Mukherjee et al. 2011). Moreover, naturally occurring, elevated concentrations of non-point source pollutants such as arsenic, fluoride in groundwater (exceeding the World Health Organization's guideline value for drinking water) have put millions of people at risk (Bhattacharya et al. 2011). Arsenic pollution in the groundwater of Ganges Basin in West Bengal (and adjoining areas of Bangladesh) and its subsequent discovery in Bihar and Uttar Pradesh (Ramanathan et al. 2006) have been attributed as the greatest mass poisoning in human history. Recent discoveries also suggest existence of arsenic-polluted groundwater in wide areas of Brahmaputra Basin in the north-eastern states (Mukherjee et al. 2011). Hence, finding alternate, suitable and sustainable drinking water sources and/or methods have become priority in these areas.

Water use and food production are also strongly linked because irrigated agriculture is the primary consumer of global freshwater resources and accounts for ~90% of fresh groundwater consumption in the last century. India is particularly vulnerable to water and food scarcity (Scanlon et al. 2010) because of its large population (~1.2 billion) with projected increase by another 570 million in the next 50 years, temporal variability in precipitation (up to 80% of precipitation occurs from the southwest monsoon), and globally being the highest groundwater-irrigated country by area (585 km^3 of groundwater withdrawal per year) (FAO 2013). Groundwater-fed irrigated area has expanded from 30% of total irrigated area in 1960 to >60% of total irrigated area in recent years (558,080 km^2, i.e. about 19% of total area of India) and is likely to increase even further, as surface water supply decrease after many of the glaciers have melted. Groundwater availability problems are likely to be exacerbated in the future by climate change, with annual temperature estimated to increase by 3.3 °C by the end of the twenty-first century, and irrigation water demand to increase by 10% per °C. Winter precipitation is projected to decrease and summer precipitation to become more intense with fewer rainy days, further intensifying the hydrological cycle and potentially reducing groundwater recharge. Gross per capita water availability in India is estimated to decline from ~ 1800 m^3/a in 2001 to ~ 1100 m^3/a in 2050 (Gupta and Deshpande 2004). These water scarcity problems will most likely translate to food scarcity. Current groundwater production rates are over-drafting groundwater resources, particularly in North-western India (Rodell et al. 2009) and parts of Gangetic basin (Bhanja et al. 2013, 2016), where groundwater levels are alarmingly declining. The number of mechanized tube wells used for irrigation increased from 1 million in 1960 to ~ 19 million in 2000 (Deb Roy and Shah 2003). Further, unplanned irrigational groundwater extraction has also potentially gravely deteriorated groundwater quality, including spreading of pollutants like arsenic into previously unpolluted aquifers (Mukherjee et al. 2011).

The water security should focus on water resources and the role of resource efficiency and environmental management in reducing risks, i.e. for more efficient and judicial use of water. There are transboundary issues that are clearly important for national security, but more significantly makes a clear link between household access to water and sanitation and national security. Water-related diarrhoea is the biggest killer of life, killing more people than AIDS, TB and malaria. Although the UN Millennium Development Goal for water has recently been met, there are still billions of people without sanitation and safe water, who are mostly the poorest of our country. The previous administrations had implemented several initiatives like the ‘Rajiv Gandhi National Drinking Water Mission’ and ‘War for Water’ by Department of Science and Technology (DST). Several public sector organizations like the Department of Drinking Water of Government of India, Ministry Water Resources, along with central and state water investigation and public health agencies have also been constituted since 1951, in order to provide nationally integrated water and sanitation programmes. A country-scale aquifer mapping program has also been initiated in recent times. However, in spite of their untiring effort, the National Capital Region (NCR) of Delhi is suffering from acute water crisis in the recent summer months; parts of eastern India is going through almost alternate years of drought and flood, or the unresolved decade long legal battle for water sharing of the Cauvery river watershed. Much of these efforts are becoming ineffective because of lack of flow of knowledge between the various stakeholders that includes the scientists, who are evaluating the (surface and groundwater) resources, planners and decision makers at various levels (from national to block levels) and the end-user consumers. There is a great lack of unification for a holistic approach for water resource management and conservation.

A classic example is the Ganges (Ganga) River system (including Yamuna river), India’s primary river basin. In recent times, there have been a lot of positive initiatives (e.g. *Namami Ganga project*) by the administration and various other organizations to rejuvenate the river. The Ganges River, the fifth largest river in the world, together with its tributaries like Yamuna River, has been the lifeline of the Indian civilization in North India for at least last three thousand years. Ancient cities like Varanasi grew up in the banks of this river. Presently, the river system supports more than half-billion people, much higher than any other river in the world. In contemporary times, hundreds of cities and towns, in eleven states, have flourished in the banks of these rivers that provide them water for sustenance. However, in turn, sewage and industrial effluent discharge from these urban centres have largely destroyed the sanctity of these rivers. The river waters, which were used for ages as the primary source of drinking and domestic water, are now polluted to stupendous level, such that, according to recent estimates, about three thousand million litres of sewage are daily discharged to Ganga River alone. Analysed pathogens and inorganic chemical pollutant concentrations in the river water classifies it to be several times above maximum human consumption level. The organic chemical pollutant concentrations in these river waters, which are regarded to be much more poisonous than their inorganic counterparts because of their resistance to remediation by standard techniques, are yet to be analysed in details. It may be noted that many of the North American rivers are generally not used for drinking water purpose because of their organic pollutant contents that were introduced by industrial discharge at earlier days. These pollutants are extremely difficult to remediate by present-day treatment techniques and act as severe carcinogens. It is a fair assumption that the Ganges and Yamuna river waters are also largely polluted by these deadly poisons, so far being largely undetected. In spite of spending huge amount of money, several past administrative initiatives, e.g. National Ganga River Basin Authority (NGRBA), Ganga River Plan, Yamuna River Plan, have severely failed to restore the Ganges and Yamuna. One of the primary reason for this utter failure is that India's rivers face major issues not only due to untreated effluent input, but also due to reduction in water flow (from source and lateral inflow from groundwater) and less water carrying capacity (e.g. siltation). Problem lies in the fact that, while construction of dams and barrages have reduced the surficial river flow, reduction of groundwater discharge to the river beds due to irrigational abstraction has severely dwindled the river water resource. Further, embankment in various sections of these rivers, mostly in vicinity of the large cities (e.g. in Yamuna near NCR), has further reduced the groundwater inflow to the rivers, thus disturbing the natural flow regime. Hence, the planners should have a holistic approach of monitoring the water flow from source to sink, e.g. from Gangotri to the Bay of Bengal for the Ganges, through systematic monitoring by coupling the understanding of surface and subsurface hydrology, and through climatic feedback models, to precisely understand extreme scenarios, e.g. how to control the water quality during low flow in drought to compensate the excess effluents entering the Ganges?

In the present situation, the lack of this holistic approach of understanding of the different facets of the water cycle translates to the fact that water is an essentiality that is inevitably getting exceedingly scarce commodity in India. Thus, there is a requirement to develop plans for assuring availability of suitable water for drinking and food production as a social security and democratic right for every citizen of

India. The fact is that government should take up growth of water resource initiatives seriously, where water security should not only be focusing on the supply chain and securing water as a commercial input, or managing the social licence to operate, but also on the source preservation/conservation.

Many of the above-noted facts are already widely known and also appreciated (in various scales) by many stakeholders, including the present administration. However, the onus lies in implementing a successful preservation and utilization of water resource strategy, such that every citizen of India gets his or her fair share of the resource. This needs a very detailed planning the policy and governance strategies (Fig. 40.1). In 2010, the previous government planned to attain drinking water security in fifteen critical groundwater over-exploited blocks in states like Andhra Pradesh, Gujarat, Punjab, Rajasthan, Tamil Nadu and Uttar Pradesh, within subsequent three years. But the plan remained largely unaccomplished. Recent

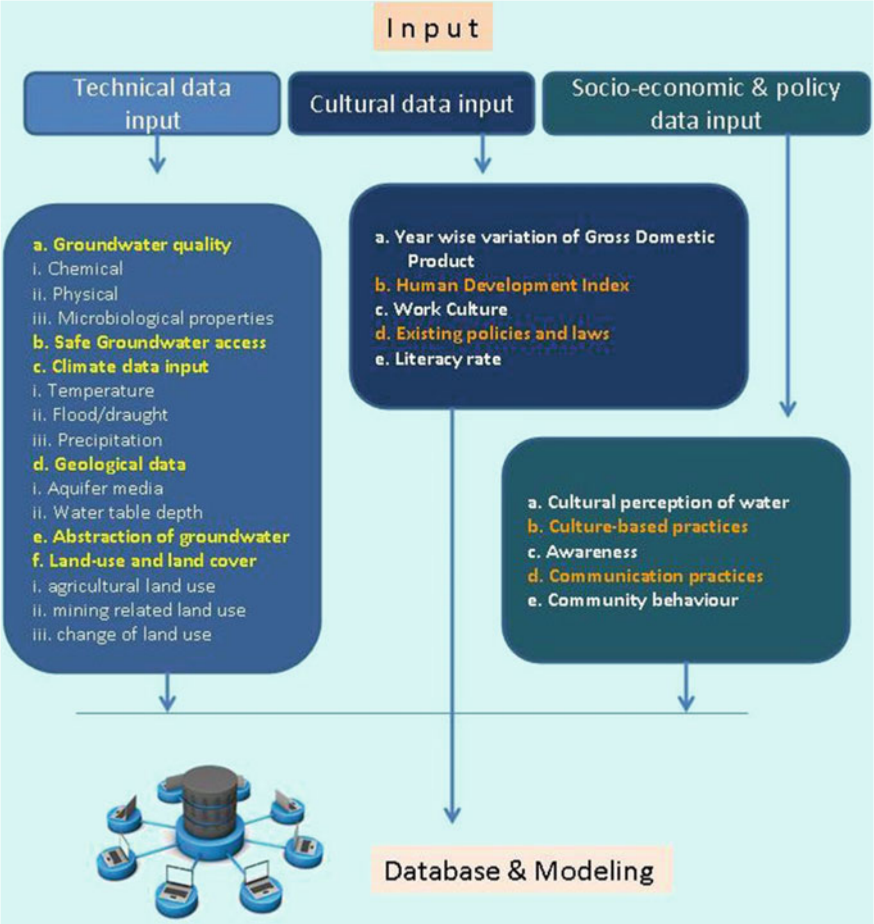


Fig. 40.1 Schematic diagram of the expected input parameters required for informed data analytics and decision-based groundwater management

media reporting suggests that the present government plans to fast track this project, subsequently covering 1065 critical, water-stressed blocks. This can only be done by an intricate integration of knowledge from various related disciplines and plans, and their effective execution within an acceptable legal framework (Fig. 40.2).

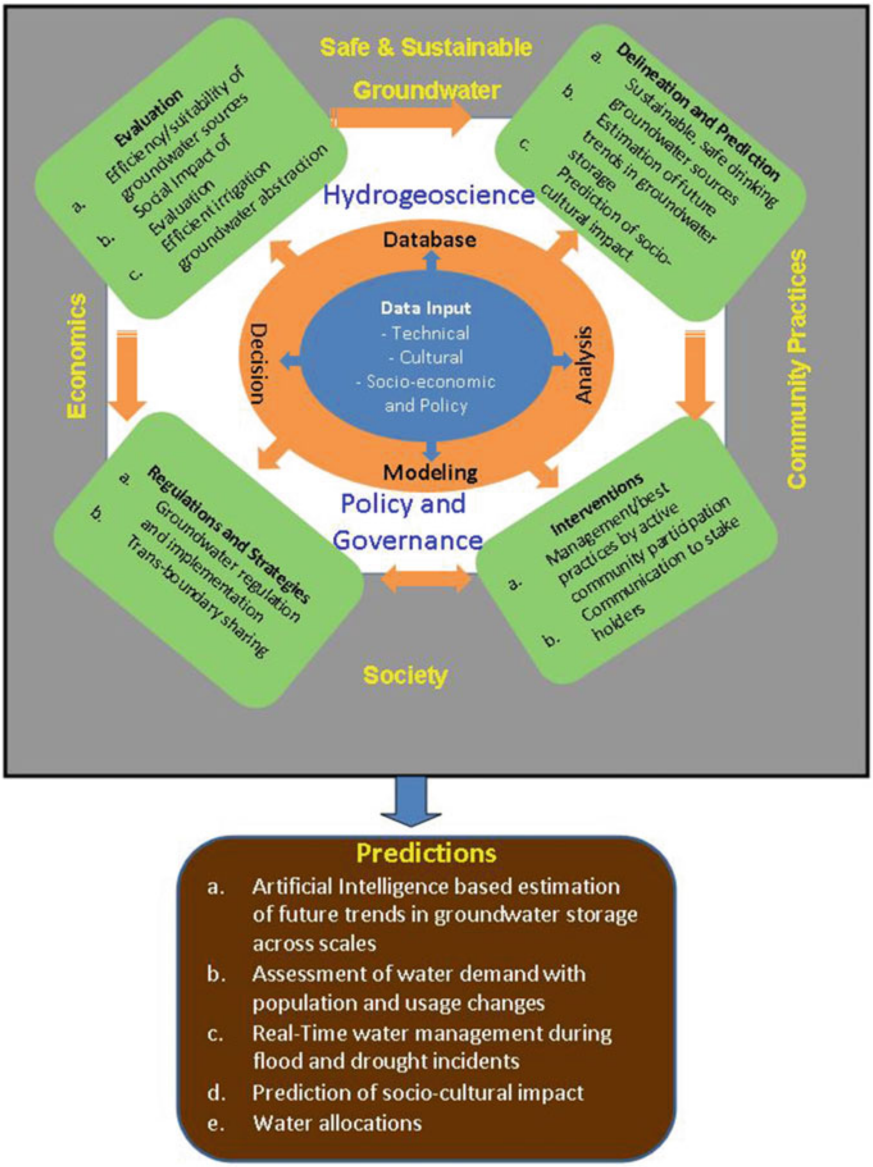


Fig. 40.2 Conceptual model for integration of technical and societal knowledge in developing Socio-Economy based groundwater interventions and predictability for future safe and sustainable groundwater sources

Unplanned implementation might provide initial, short-term benefits but would further aggravate the situation and decline the water resource in the long run (e.g. the spreading of arsenic in previously unpolluted aquifers of Gangetic plain due to uncontrolled groundwater abstraction for irrigation and drinking purposes). Hence, if there is a real goodwill to build India to a developed country in the forthcoming years, it is necessary that the most essential requirement for the sustenance of the citizens of this nation, i.e. drinking water, be secured, with equal share to every inhabitant, in form of a National 'Groundwater Security' Bill or 'Right to Clean Groundwater Act'.

References

Bhanja S, Mukherjee A, Rodell M (2013) Abstraction-triggered long term groundwater storage depletion in parts of the Ganges basin of the Indian Subcontinent. Geol Soc Am Program Abstr 45(7):490

Bhanja SN, Mukherjee A, Saha D, Velicogna I, Famiglietti JS (2016) Validation of GRACE based groundwater storage anomaly using in-situ groundwater level measurement in India. J Hydrol 543:729–738

Bhattacharya P, Mukherjee A, Mukherjee AB (2011) Arsenic contaminated groundwater of India. In: Nriagu J (ed) Encyclopedia of environmental health. Elsevier B.V, Netherlands, pp 150–164

Deb Roy A, Shah T (2003) Socio-ecology of groundwater irrigation in India. In: Llamas R, Custodio E (eds) Intensive use of groundwater: challenges and opportunities. Swets and Zetlinger Publishing Co., The Netherlands, pp 307–336

Food and Agriculture Organization (FAO) of the United Nations (2013) FAO Statistical Yearbook 2013: World Food and Agriculture, 289 p

Gupta SK, Deshpande RD (2004) Water for India in 2050: first-order assessment of available options. Curr Sci 86:1216–1224

Kumar R, Singh RD, Sharma KD (2005) Water resources of India. Curr Sci 89:794–811

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Mukherjee A, Bhattacharya P, Fryar AE (2011) Arsenic and other toxic elements in natural water systems. Appl Geochem 26(4):415–420

Mukherjee A, Saha D, Harvey CF, Taylor RG, Ahmed KM (2015) Groundwater systems of the Indian Sub-Continent. J Hydrol-Reg Stud 4A:1–14

Ramanathan A, Bhattacharya P, Tripathi P (2006) Arsenic in groundwater of the aquifers of the central Gangetic plain of Uttar Pradesh, India. Geol Soc Am Program Abstr 38(7):241

Rodell M, Velicogna I, Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India. Nature 460:999–1002

Scanlon BR, Mukherjee A, Gates JB, Reedy RC, Sinha AN (2010) Groundwater recharge in natural dune systems and agricultural ecosystems in the Thar Desert region, Rajasthan, India. Hydrogeol J 18(4):959–972

Verma S, Phansalkar SJ (2007) India's water future 2050: potential deviations from 'buisness-as-usual'. Int J Rural Manag 3(1):149–179

Chapter 41
Groundwater Resources in the Dry Zone of Myanmar: A Review of Current Knowledge

Paul Pavelic, Robyn Johnston, Matthew McCartney, Guillaume Lacombe and Sonali Senaratna Sellamuttu

Abstract Groundwater resources are vital for the well-being and livelihoods of most of the ten million people living in the Dry Zone of central Myanmar. Despite this importance, there is remarkably little known or documented on the nature, extent and use of these resources. This contribution has attempted to address this gap by reviewing the literature, gathering data and stakeholder consultations. The study reveals that utilizable groundwater is present across most of the Dry Zone, most notably in the unconsolidated sedimentary aquifers that are present across large portions of the region. However, rates of replenishment appear to be relatively modest, and use is limited by high levels of salinity and arsenic that are naturally present in some areas. The scope to access groundwater is generally good, and development has steadily increased to provide water supply for domestic, agriculture and industry. In broad terms, is would appear that prospects to expand groundwater use for irrigation and other purposes are good in almost all districts. In more hydrogeologically complex settings in particular, a lack of information creates more risk that may add to drilling costs. More detailed assessments and databases are required to support effective resource management.

41.1 Introduction

The Dry Zone of Myanmar falls within the rain shadow of two extensive mountain ranges and is the driest part of the country. The mean annual rainfall varies from around 500 to 1,000 mm as compared to over 2,000 mm for the national average. The Dry Zone covers an area of 75,000 km^2 or around 13% of the entire country. This includes 54 townships within 3 regions. The total population is about 10.1 million or around 20% of the country (Fig. 41.1).

P. Pavelic (✉) · M. McCartney · G. Lacombe · S. S. Sellamuttu
International Water Management Institute (IWMI), Vientiane, Lao PDR
e-mail: P.Pavelic@cgiar.org

R. Johnston
International Water Management Institute (IWMI), Yangon, Myanmar

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_41

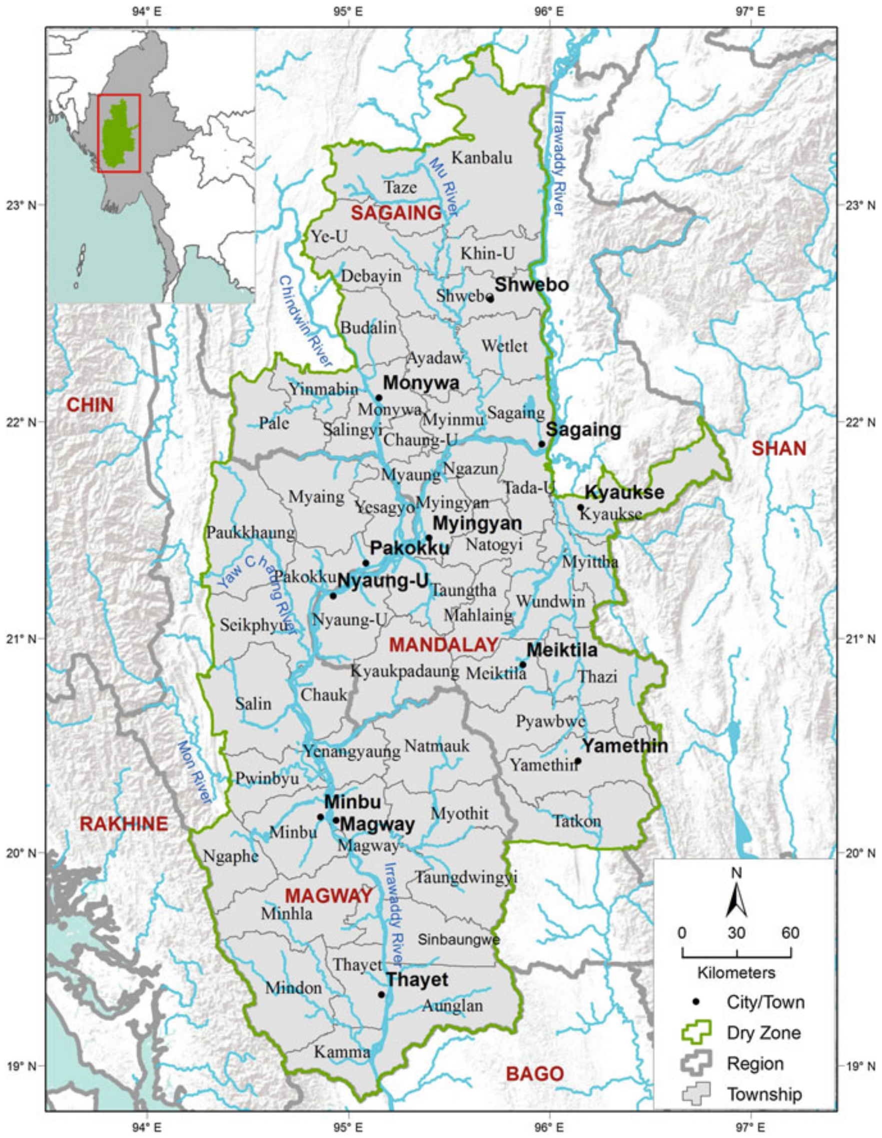


Fig. 41.1 Dry Zone of Myanmar showing regions and townships

The economy of the Dry Zone is largely agrarian-based with high levels of food insecurity and malnutrition. Approximately 43% of households live below the poverty line (JICA 2010; WFP 2011). Levels of poverty and food insecurity, as well as economic growth, are strongly connected to the prevailing water scarcity and climate variability (ADB 2012). The extent to which groundwater can mitigate climate variability and climate-related shocks, more so than surface water in many cases, makes it a highly valued water resource. This is particularly so in the lands situated far from major rivers where groundwater offers year-round supplies.

The natural treatment offered by aquifers and protection from potentially contaminating land use activities implies that deep groundwater is generally free of water-borne pathogens and thus a relatively attractive source of domestic supplies from a human health perspective. The comparatively low cost for establishing shallow well supplies equipped with hand or motorized pumps has helped to promote high rates of groundwater adoption across the Dry Zone.

Despite the recognized importance of groundwater in the Dry Zone, very few technical studies have been conducted. This contribution seeks to summarize the current state of knowledge on the groundwater resources, along with the key issues concerning groundwater availability, quality and access. This, in turn, can help identify priority areas for improved groundwater management. These objectives were addressed by desktop literature review, supplemented by consultations and information gained from the relevant government agencies in Yangon and at regional offices.

41.2 Structural Geology and Hydrogeology

The Dry Zone lies almost entirely within the Central Lowland region of Myanmar. Major faults, oriented from north to south, are present along its boundaries, including the longest Sagaing Fault. The Dry Zone is distinguished from Shan Highland which lies to the east and the Western Fold Belt and Rakhine Coastal Belt regions which lie to the west (Stokes 1988). The Central Lowlands of Myanmar were formed by uplifting of Shan Plateau and the Western Mountains over the late Cretaceous and early Tertiary periods. The gradually subsiding of the central trough led to progressively infilling by an extensive sequence of sediments that may be greater than 20 km thick (Thein 1973). Late Tertiary period tectonic activity led to the emergence of the Pegu Yoma hills. In physical terms, the Central Lowlands may nowadays be considered to resemble a large basin divided into two and consisting of the larger Irrawaddy Valley and the smaller Sittang Valley. Partitioning of this basin is by the complex folded range of the Pegu Yoma. This range is structurally associated with a series of extinct volcanoes featuring small crater lakes and eroded cones and includes Mount Popa, the highest volcano (elevation 1,518 m) which is currently dormant.

The general hierarchy of major aquifers in the Dry Zone is comprised of our major groups: the Eocene, Pegu, Irrawaddy and Alluvial (Table 41.1). Outcrops of Eocene sandstone, shale and clay strata are found predominantly along the margins of the Western Mountains (extending over 7% of the Dry Zone). Many Eocene sub-groups are low in permeability or aquicludes. However, some conglomerate units and sandstone may have groundwater development potential but have yet to be investigated.

Table 41.1 Characteristics of the major aquifers in the Dry Zone

Aquifer groups	Area (%)	Lithology	Occurrence	Quality
Eocene	7	Sandstones, shales and clays	Along foothills of the Western Ranges	Unknown
Pegu	24	Marine sandstone, shales and siltstones	Western and central parts of the Dry Zone	Mostly brackish or saline
Irrawaddy	38	Sands, sandstones, with gravels, grits and sandstones	Common throughout most of the Dry Zone	Usually fresh with high iron content
Alluvial	31	Sands, silts and gravels	Near major river courses and tributaries	Usually fresh

Source Adapted from MOAI (2003)

Pegu strata outcrop over large tracts of the Dry Zone (24%). This unit has been well-characterized due to its favourable oil-bearing properties (Chibber 1934). The Pegu group is composed of stratified sandstones and blue or grey clays and shales. Sandstones layers are often calcareous and often highly cemented. Limited knowledge about the Pegu group suggests that its groundwater potential may be generally low. In some areas featuring a high degree of folding and faulting, exceptions are found where wells can provide for low-level supplies. Some units including the Kyaukkok formation (and others) are comprised of thick, fine-textured sandstones that may constitute reasonable aquifers. Pegu group wells in the Minbu area (Magwe region) may reach depths of up to 165 m and attain yields of up to 540 $m^3\ d^{-1}$.

The Irrawaddy group strata outcrop commonly over the Dry Zone (38%), the highest of all groups. Irrawaddy strata are comprised of massive, loosely cemented sand and sandstone layers. A distinct colour change from yellow-brown to blue-grey is a clear distinguishing indictor between this group and the alluvial group that is overlying. The clastically derived, poorly cemented Irrawaddy deposits have abundant high permeability zones. Irrawaddy aquifers emerge as poorly consolidated sand and gravel layers within the alluvial sequence. These aquifers are generally semi-confined to confined. Irrawaddy aquifers are found at depths of up to 350 m in the Magwe region. In the Sagaing region, the maximum depths are around 120 m. For the case of the Minbu area, for example, wells reach depths of up to 144 m and 'airlift' well yields vary from 360 to 1,600 $m^3\ d^{-1}$ (Drury 1986).

Alluvial group strata lie unconformably on the Irrawaddy and Pegu groups. It outcrops across 31% of the Dry Zone. At some elevated locations remote from present river courses are found alluvial gravels grade laterally into red clayey sands reflecting old laterite soils. Along ancient river courses, older alluvium occurs. Younger alluvium is abundant within the valleys of major rivers such as the

Irrawaddy, Chindwin and Mu. The Alluvial strata are usually good aquifers except in cases where deposits are very fine textured.

41.3 Groundwater Recharge Estimation

Estimates of recharge, based on geologically dependent rainfall infiltration factors and calculated at the district level, vary from 29 to 93 mm y^{-1} and average around 50 mm y^{-1} (Fig. 41.2). In aggregated terms, this translates to an annually replenishable volume of 4,800 Mm^3 y^{-1} over the Dry Zone (MOAI 2003). Most districts have recharge rates of around 30 mm y^{-1}. These values are no dissimilar to the fluxes found in semi-arid regions (Scanlon et al. 2006). Rates of annual replenishment relative to utilization vary from 5% in Monywa district up to 55% at Sagaing district. The district-average value is 23% (Pavelic et al. 2015). Groundwater is used most intensively around the central west of Mandalay and the south of Sagaing where recharge is above average.

41.4 Groundwater Quality

The quality of groundwater of the four major aquifer groups varies according to depositional environment and mineral content. The quality of the groundwater for the alluvial and Irrawaddy aquifers is generally acceptable for domestic and irrigation purposes. For these two aquifer groups, groundwater may be generalized as low to moderate salinity, with electrical conductivity values typically ranging from 1,000 to 2,000 µS cm^{-1} (UNESCAP 1995). Groundwaters drawn from the Pegu

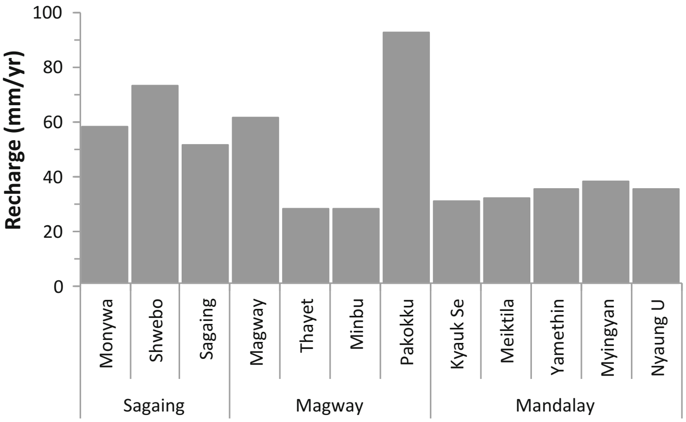


Fig. 41.2 Groundwater recharge estimates at the district level for the year 2000–01

and Eocene aquifers are sometimes acceptable for domestic purposes; however, spatial variations can be a serious constraint to use. For some areas underlain by Eocene marine shales and sandstones as well as for some Pegu group aquifers, enhanced salinity from marine salts trapped within geological formations may constrain use. Deep oil exploration wells in these areas have detected salinities exceeding that of seawater (Drury 1986). Large-scale irrigation projects can induce salinity by enhancing seepage which in turn causes water tables to rise and brings salts to the surface, thereby reducing crop yields and impacting on soil structure.

Generalizations about water quality for a particular formation or area are difficult to make since the controlling mechanisms are complex (Drury 1986). A high degree of variability may be associated with depth and hydrogeological formation type. The salinity of the Monywa irrigation scheme water which draws from both the alluvium and Irrawaddy aquifers varies from 400 to 2,000 mg l^{-1} TDS. This contrasts with more stable quality pumped from Irrawaddy aquifers in the 99 ponds irrigation scheme of 260–510 mg l^{-1} TDS. Poor water quality was a limiting factor for the Monywa irrigation project as it caused at least eight new tube wells to be unusable and added to the establishment cost during the commissioning phase of the project (World Bank 1994).

Microbial pathogen contamination is common for the shallow phreatic aquifers due to pollution from surface water or from latrines, septic tanks or animal enclosures situated within close proximity to wells. A large proportion of shallow aquifers (<10 m deep) has poor quality and can only be used for washing, whereas deeper tube wells (>30 m) are of better quality and generally acceptable for drinking purposes. There is anecdotal evidence of industrial pollution of soils and groundwater due to copper mines located nearby the town of Monywa.

Water quality issues due to iron, manganese and arsenic is associated with minerals found in the host rock at trace levels. Iron is prevalent in most rocks types and has been detected in the groundwaters at Monywa and Yinmarbin at concentrations of up to 4 mg l^{-1}. High levels of iron are not a major concern for human or animal health but may create aesthetic concerns due to staining by precipitates. Manganese is often co-associated with iron and creates similar impacts.

High levels of arsenic have been detected in Myanmar during broad-scale surveys conducted by the Water Resources Utilization Department (WRUD) and the Department of Development Affairs with the support of various international organizations. This has in turn initiated furtherwork to understand the distribution of arsenic better and to identify measures to mitigate arsenic (Jakariya and Deeble 2008). Data from the WRUD indicate that about 80% of around 30,000 samples from Sagaing, Mandalay and Magwe regions contain arsenic concentrations less than the WHO drinking water guideline value of 10 μg l^{-1}. Less than 2% of samples exceed the earlier World Health Organization's (WHO) guideline of 50 μg l^{-1}. Based on this data combined with population data, it is estimated that the number of people subjected to arsenic concentrations is greater than 10 μg l^{-1} number around 81,000 people in Mandalay and 28,000 in Sagaing.

41.5 Groundwater Use

Groundwater is a vitally important source of supply for domestic, agricultural and industrial use across the Dry Zone. The total groundwater withdrawal across the three regions was estimated to be 763 $Mm^3\ y^{-1}$ in 2000–01. More recent estimates are not available. Agriculture and industry account for around 63 and 18% of total use, respectively, while domestic supplies exceed 35% (MOAI 2003). Naing (2005) reports that groundwater irrigation may account for up to 90% of the total volume of groundwater pumped.

Alluvial aquifers are drawn upon for domestic supplies via shallow dug wells. On the alluvial flats in Magwe district, shallow tube wells normally penetrate unconfined or semi-confined sand and gravel aquifers at depths of 40 m or less. Tube wells along the river terraces and flood plains can exceed depths of 52 m in Pakokku district and 70 m in Monywa district. Well depths can reach 90 m in the alluvial aquifer of the Chindwin River valley. Yields may vary between 270 and 4,700 $m^3\ d^{-1}$ (Drury 1986).

Springs are a common feature across the Dry Zone. They vary greatly in their size (large to small), temperature (hot to cold) and salinity (fresh to saline) according to structural controls. Hot water springs, for example, are found at Kyaukpadaung and the Mount Popa complex. Hot saline springs are present at Halin (Drury 1986). The groundwater level can be found at depths ranging from greater than 300 m right to above the ground surface (artesian). Artesian groundwater is used productively in areas such as Yinmabin Township, Ayadaw and Shwebo.

Since around the mid-1980s solid progress in developing safe rural water supplies has taken place. At that time, tube well supplies accounted for only 20% of village domestic supplies in the Dry Zone (Drury 1986). More recent information suggests that 37% of households use a tube well and pump; 32% of households rely on other protected sources such as protected wells, and 4% of households have access to piped water. Around 26% is drawn from unprotected sources such as unprotected wells, open water ponds or streams (WFP 2011). Production for the rural water supply has increased twofold between the early 1960s and 1990. Figures for the year 1990 indicate the presence of 11,000 tube wells pumping an estimated 530,000 $m^3\ d^{-1}$ (Minyt 1991). Up to the year 2000, WRUD had installed more than 13,000 tube wells benefitting a population of around 6.4 million. In comparison, only 0.3 million people had benefited from various surface water supplies.

41.5.1 Irrigation

Groundwater is being increasingly seen as an alternative to surface water. Conventional irrigation from surface water can create problems for pump lift schemes due to large water level fluctuations in major rivers. Groundwater irrigation is of clear benefit for Dry Zone farmers who are situated remote from rivers and dams by helping them to overcome poor productivity and high vulnerability under rainfed conditions. Although small-scale use of groundwater for irrigation in Myanmar is known to have been in place since the 1940s, wide-scale operations started only as recently as the 1980s (UNESCAP 1995). Before the 1980s, groundwater use was constrained to development within the private sector in restricted areas where water tables were shallow and thus could be utilized from dug wells or shallow tube wells using cheap pump sets or by manual effort. While shallow well numbers have grown in recent decades, to better exploit the potential for groundwater irrigation, the installation of deep tube wells has also been necessary. Smallholder farmers across the Dry Zone are known to gain access to groundwater through a range of modalities as described by Pavelic et al. (2015).

A tradition of utilizing groundwater for irrigation emerged only after the World Bank had carried out investigations across the Dry Zone and implemented pilot trials at Monywa district, Sagaing region. These activities took place from the late 1970s to the early 1980s. That project's success reportedly led to further development at the site and triggered development in other areas (Niaz 1985). Since the 1980s the rate of development has increased as a result of large government-driven projects along with smaller farmer-driven investments. The emergence of groundwater irrigation has had an important role in irrigation expansion and assisted in crop diversification and socio-economic development. The increase in groundwater use for irrigation for the Dry Zone over the period from 1988 to 2002 was 2.9% per annum on average, compared with 1.2% for sources other than groundwater. Around 60% of the 33,000 tube wells used for irrigation are found in the three Dry Zone regions (MOAI 2003). From community survey results, it is known that in more recent years the number of wells has steadily continued to increase for all purposes (Pavelic et al. 2015).

41.6 Resource Management

With the clear necessity to develop groundwater resources in the Dry Zone to address many of the sustainable development goals comes greater onus to ensure that management of the groundwater resources is improved commensurately. Rampant groundwater development could result in the typical overexploitation indicators of reduced groundwater availability, deteriorated water quality and potentially also land subsidence. Groundwater's connectivity to surface water makes it equally important to protect groundwater stocks to maintain base flow to rivers and wetlands and to protect groundwater-dependent ecosystems and associated livelihoods. The recharge estimates presented above do not indicate a vast abundance of replenishable groundwater, even under the most hopeful case whereby all of this water may be suitable for consumptive uses. Rather, it suggests a resource of moderate scale that necessitates careful planning to ensure long-term sustainability. Groundwater is not unaffected by the effects of climatic stresses, as illustrated from the case of the 2009 drought that has resulted in water tables falling by up to one metre below normal and caused major losses in perennial crops. This highlights the importance of data and tools to support decision-making that can lead to improved groundwater management.

A basic inventory of tube wells has been conducted by WRUD, but a groundwater monitoring network has not yet be established for the Dry Zone. Instead, limited monitoring has taken place in areas of high groundwater demand. Monitoring of the Ywatha-Aungban aquifer, for example, has enabled the difference in artesian discharge rates to be compared to the total discharge of four types of wells: WRUD artesian wells, WRUD test wells, farmers wells and domestic wells ten years apart (in the years 1999 and 2009). For WRUD wells, the same wells were monitored on both occasions which showed steady reductions of 7–20% relative to the initial rate. For farm and domestic wells, the numbers of wells monitored increased by around twofold to fourfold and therefore, it is not possible to directly compare. However, this does suggest higher flows at wells in 2009, perhaps due to better targeting of wells in high productivity zones. Caution is needed to interpret these results correctly because the installation of artesian wells will invariably cause flow rates to decline due to the steady release of pressure from the aquifer. This is not in itself a firm indicator of unsustainable development. Analysis of sustainable well yields through groundwater flow modelling would help to reveal trends over the longer-term and determine suitable management responses. There are also unsubstantiated accounts of large volumes of artesian groundwater being wasted due to the poor distribution system.

41.7 Conclusions and Recommendations

Groundwater is generally found right throughout the Dry Zone; however, adequate volumes of good quality water are not available everywhere. Areas underlain by sedimentary rock aquifers of the Pegu group have limited resource potential. Opportunities at the local scale for accessing groundwater vary greatly according to the hydrogeological conditions. The Irrawaddy and alluvial groups represent the most productive aquifers. As a result of steadily increasing groundwater use, isolated signs of overexploitation have been observed in recent years. In general terms however, there remains major unrealized potential for increasing groundwater use. Whilst significant opportunities exist, high levels of geogenically derived salinity and arsenic are potential issues of concern. Groundwater development must be constrained within the limits of the resource if it is to be properly managed.

This summary of the groundwater resources of the Dry Zone was reliant upon minimal data taken from previous studies, data from government agencies and a limited number of field investigations. This was adequate to demonstrate that groundwater creates benefits for most of the Dry Zone population. Although there is further potential for groundwater development, reliable and comprehensive data about the location of suitable aquifers to develop are as yet unavailable.

More detailed assessments are required to prioritize the townships and villages where groundwater development is most appropriate. The lack of information may result in poor outcomes due to the high risk of drilling and constructing costly wells that do perform adequately or yield water of unacceptable quality. This is made more challenging due to complex hydrogeology in some areas. This translates to high variability in groundwater potential over relatively short distances. Therefore, enhancing the knowledge of the hydrogeological conditions within the Dry Zone is of paramount importance for planning effectively at the local and regional levels.

Reliable hydrogeological and hydrochemical maps that assist practitioners are not yet available. The best available information known is the earlier work performed by Drury (1986), completed to a draft final stage. It covers the hydrogeology of the entire Dry Zone at approximately district scale. Three decades later, this work has recently been updated by the same author and is expected to provide useful guidance for broad-scale planning purposes (Drury 2017). The monitoring that has been carried out in the Dry Zone has been of limited. To facilitate long-term management, a regional groundwater monitoring network is needed. A groundwater information management system is also needed that can contribute towards effective planning and groundwater management. The way forward must also address the key data gaps so as to more clearly reveal the characteristics of the resource. This would include assessments of groundwater recharge, groundwater pumping, sustainable yield and groundwater quality. Additional work on arsenic would help define the location and depths of high arsenic so that preventative or mitigation measures can be undertaken. Better understanding of the technical and socio-economic factors that control groundwater development would help support policies that rely on groundwater to help alleviate poverty and improve rural livelihoods.

Acknowledgements The work reported here was financially supported by the Livelihoods and Food Security Trust Fund as part of an IWMI-led study on "*Sustainable Management of Water to Improve Food Security and Livelihoods in the Dry Zone of Myanmar*" undertaken in 2013. This project also contributed to the CGIAR Research Program on Water, Land and Ecosystems.

References

ADB (Asian Development Bank) (2012) Myanmar in transition: opportunities and challenges. Asian Development Bank, Mandaluyong City, Philippines

Chibber HL (1934) The geology of Burma. McMillan, London, 538 pp (incl. 37 figs., 23 plates & 3 folding maps)

Drury LW (1986) An assessment of the hydrogeology and geology in the Dry Zone, central Burma. Australian Development Assistance Bureau and Ministry of Agriculture and Forests, Union of Burma, Yangon, 235 pp (Unpublished Draft Report)

Drury LW (2017) Hydrogeology of the Dry Zone. Aqua Rock Konsultants, Central Myanmar, 250 pp

Jakariya M, Deeble S (2008) Evaluation of arsenic mitigation in four countries of the greater Mekong Region. UNICEF—Aus AID Final Report with Two Parts, Dec 2008 (81 p + Appendices)

JICA (Japan International Cooperation Agency) (2010) The development study on sustainable agricultural and rural development for poverty reduction programme in the central dry zone of the Union of Myanmar. Report No. RDJR10-502

MOAI (Ministry of Agriculture and Irrigation) (2003) Agricultural water resources study in Myanmar (Water Scarcity Variations in Myanmar). Agricultural Sector Review Project by Myanmar Academy of Agriculture, Forestry and Livestock and Fisheries, Irrigation Department and Water Resources Utilization Department, Yangon, Myanmar, Dec 2003

Myint O (1991) Environmental issues in land and water development in Myanmar (Water). Paper presented at the 'Regional expert consultation on environmental issues in land and water development', FAO/RAPA Publication 1992/8, Bangkok, Thailand, 10–13 September 1991

Naing MM (2005) Paddy field irrigation systems in Myanmar. In: Proceedings of the regional workshop on the future of large rice-based irrigation systems in Southeast Asia, co-sponsored by Evaluation Study of Paddy Irrigation Under Monsoon Regime (ESPIM) Project funded by the Government of Japan, Ho Chi Minh City, Vietnam, pp 120–130, 26–28 Oct 2005

Niaz SM (1985) International funding of groundwater development schemes. Q J Eng Geol London 18:3–12

Pavelic P, Sellamuttu SS, Johnston R, McCartney M, Sotoukee T, Balasubramanya S, Suhardiman D, Lacombe G, Douangsavanh S, Joffre O, Latt K, Zan AK, Thein K, Myint A, Cho C, Htut YT (2015) Integrated assessment of groundwater use for improving livelihoods in the Dry Zone of Myanmar. International Water Management Institute (IWMI), Colombo, Sri Lanka (IWMI Research Report 164), 47 pp. https://doi.org/10.5337/2015.216

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol Process 20:3335–3370. https://doi.org/10.1002/hyp.6335

Stokes RB (1988) A review of the geology of Myanmar (Burma) (Unpublished report)

Thein Maung (1973) A preliminary synthesis of the geological evolution of Burma with reference to the tectonic development of southeast Asia. Bull Geol Soc Malaysia 6:87–116

UNESCAP (United Nations Economic and Social Commission for Asia and the Pacific) (1995) Assessment of water resources and water demand by user sectors in Myanmar. Economic and Social Commission for Asia and the Pacific, United Nations Publication STIESCAP/1573, New York

World Bank (1994) Burma Groundwater Irrigation Project I—Project Completion Report, Report No. 12891, Agriculture and Natural Resources Operations Division, Country Department I, East Asia and Pacific Regional Office

WFP (World Food Program) (2011) Food security assessment in the Dry Zone Myanmar. Report prepared by Claudia Ah Poe, Food Security Analysis Services (ODXF), 29 pp

Chapter 42
Groundwater Challenges, Governance, and Management in Nepal

Shobha Kumari Yadav

Abstract Managing groundwater resources sustainably is of paramount importance to society and environment. In Nepal, groundwater plays an important role in the lives and livelihoods of the majority of the population. But in the recent decade mismanagement of water resources, urbanization and industrialization together with climate change threaten the harvesting and conservation of groundwater aquifers which are subject to increasing stress both in terms of quantity and quality. In every water sub-sector, the dependence on groundwater is increasing with each passing year. Groundwater serves as an attractive, reliable, and easily accessible source of water. Given its numerous benefits, groundwater management should be more strategic and proactive while dealing with the potential impacts of water scarcity arising due to climate change. However, water management policies in Nepal give little attention to groundwater management and governance. To tackle such problems effectively, there is a need to explore the relationship between groundwater, climate, and people through collaborative efforts, all the while keeping the question of vulnerability in mind. For this, policy reorientation is necessary so that it addresses the potential vulnerabilities of groundwater to the warming climate, the rapidly changing economy, and the diverse social contexts. This requires institutional arrangements to progress alongside engineering. Therefore, progress in groundwater management and governance calls for engaging a broad range of societal actors, through inclusive governance structures that recognize the dispersion of decision making across various levels and entities.

S. K. Yadav (✉)
West Virginia University, Morgantown, USA
e-mail: Shobhas.yadav@gmail.com; sky0003@mix.wvu.edu

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_42

42.1 Introduction

Countries across the world are hit by all sorts of water-induced calamities, every year, due to reasons such as climate change, the El Nino phenomenon, failed monsoons, and unseasonal rainfall, among others. Intensification of droughts and floods is one of the predictable impacts of climate variability and climate instability.

In the winter of 2015 and the spring of 2016, many parts of South Asia faced droughts. Such persistent droughts and soaring temperatures in India caused crops to fail which affected over 330 million people and forced large-scale migration.

The situation in Nepal has been no different. Widespread drought in western Nepal is particularly serious. Today, local springs and water bodies have dried and water levels have lowered in rivers and lakes.

Climate change is already having an impact on the intensity of weather-related hazards, leading to more frequent and more intense extreme events, and will only further exacerbate natural hazards in the coming decades (IPCC 2013). This situation has gotten even worse due to El Nino, a climate pattern responsible for putting extra heat into the atmosphere. The World Bank, in its report 'High and Dry: Climate Change, Water and the Economy,' depicts that water scarcity due to climate change together with effects of growing populations, rising incomes, and rapid urbanization will result in exponential increase in water demand throughout the globe (World Bank 2016). It will undermine economic development of developing countries and will stimulate migration and conflict around the globe.

While climate change is responsible for the rising levels of water scarcity, it is not the only reason. The situation is exacerbated by prolonged mismanagement of water resources, urbanization, and industrialization. Moreover, poor selection of crops, inefficient methods of irrigation, and imbalanced use of surface water result in water scarcity and drought.

Groundwater serves as an important and economical natural source of water for millions of people in South Asia. It plays a fundamental role in increasing production and stabilizing food supplies (Moench et al. 2003a, b). In South Asia, for example, use of groundwater in agriculture has profoundly helped to reduce risks by increasing household production. This has led to reduced poverty (Moench 2003). This is also true in other parts of the world, where access to groundwater has helped improve the livelihoods of individuals and communities. However, on the other hand, unsustainable extraction of groundwater has also been responsible for unprecedented degradation of groundwater systems.

In Nepal, groundwater provides a reliable source of water for a majority of population. Around 50% of water demand for domestic, agriculture, and commercial uses is met by groundwater, thus increasing stress both in terms of quantity and quality. At the same time, poor management threatens the harvesting and conservation of groundwater aquifers. Besides, climate change impacts are also evident in Nepal in the form of increased temperature and erratic precipitation. Climate models have predicted an increase in precipitation all over Nepal in the upcoming years (Shrestha and Aryal 2011). Nevertheless, such precipitation has the tendency to be erratic. This causes the availability of water at any time of the year to be an unpredictable factor. In addition, impact of climate variability in the form of droughts has profound impact on the groundwater resource as climate-related impact can lead to increased groundwater pumping.

Groundwater serves as a buffer against runoff and climate variability as it is more resilient to the effects of climate change than surface water. Thus, it is able to modulate such variability. In addition, since large amounts of groundwater are available in storage and thus immune to short-term variability, its value for both agriculture and urban or domestic supply plays a significant role in the buffering capabilities (Calow et al. 1997). Moreover, because it is locally available and in good quality, harvesting groundwater reduces treatment costs and makes it cheap compared to other water sources.

Given its numerous benefits, groundwater management should be more strategic and proactive while dealing with the potential impacts of water scarcity arising due to climate change. However, water management policies in Nepal give little attention to groundwater management and governance. The nature of groundwater use is also highly fragmented, and the nature of each aquifer is also diverse within themselves.

To tackle such problems effectively, there is a need to explore the relationship between groundwater, climate, and people through collaborative efforts, all the while keeping the question of vulnerability in mind. For this, policy reorientation is necessary so that it addresses the potential vulnerabilities of groundwater to the warming climate (Shah 2013), the rapidly changing economy, and the diverse social contexts.

At the same time, new groundwater legislation and regulations have been promulgated in many parts of the world to increase awareness regarding groundwater issues among policy-makers for sustainable management of the groundwater resource. The key issues addressed by such efforts include the depletion of stored groundwater and the pollution of groundwater.

This chapter builds around these concerns and focuses on several questions: How has increasing water demand affected the quality and quantity of groundwater available in Nepal? What are the achievements and/or challenges related to groundwater use and management in the country? How has groundwater governance emerged as a key gap in the management of groundwater? And what can be a way forward?

42.2 Availability of Surface Water

Nepal is one of the richest countries in water resources. Both surface water and groundwater are important sources for domestic, agricultural, and commercial use. There are around 6,000 rivers and rivulets consisting of total length of 45,000 km with drainage density 0.3 km/km^2 (Shankar 1976). The rivers of Nepal can be chiefly classified into three categories based on their origin: snow-fed, rain-fed

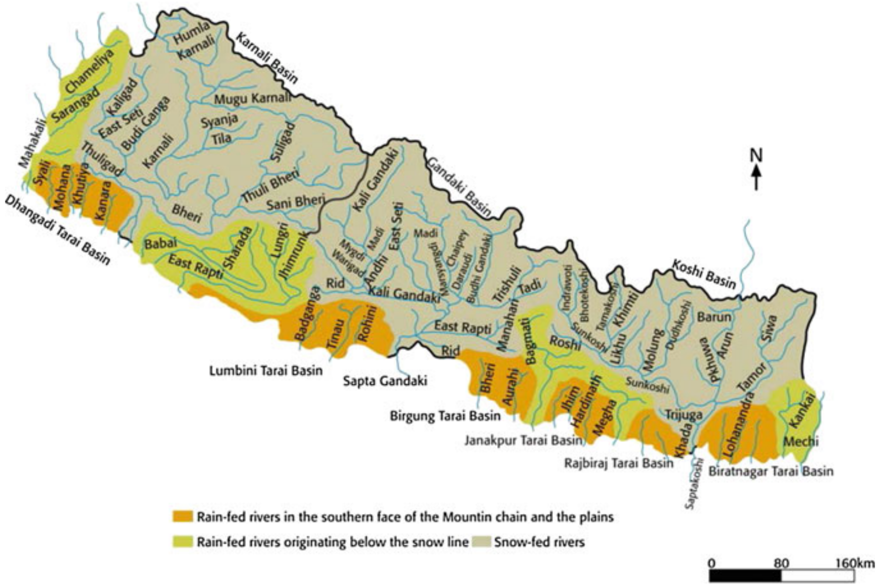


Fig. 42.1 River basins of Nepal (*Source* Based on Government of Nepal Survey Department Publication as in Gyawali 2003)

originating below the snow line, and rain-fed originating in the southern face of the mountain chain and the plains (Fig. 42.1). There are four major river systems that fall under first categories: Mahakali, Karnali, Gandak, and Kosi. They are the main tributaries of the Ganga River and originate in Tibet and Nepal's Himalayas (Dixit 2006). These rivers are perennial and contain sufficient amount of discharge and release water to maintain dependable supplies for the downstream region (Jansson et al. 2003). The second category rivers are rain-fed river that originates in mid-hills (Mahabharat range) of Nepal below the snow line. These are the Babai, the West Rapti, the Bagmati, the Kamala, the Kankai, and the Mechi. The flow of these rivers fluctuates according to season and is fed by rainfall as well groundwater. The third category includes small rivers which originate in Siwalik region of Nepal. These rivers are dependent on monsoon and little or no flow in dry season.

Nepal receives about 80% of the total rainfall from June to September with an annual rainfall of 1,857.6 mm (Practical Action 2009). Owing to orographic effects of the mountain due to high spatial variability of topography, the amount of rainfall also varies from east to west and from south to north (Shrestha et al. 2000; Kansakar et al. 2004). Rainfall is higher in eastern Nepal compared to the western regions. The southern slope of the Annapurna receives more than 5,000 mm of rainfall, whereas Mustang in the north of the Annapurna range receives less than 150 mm. In addition, the amount of rainfall also differs between mountain tops and valley bottoms due to convectional activity (Barros et al. 2000; Lang and Barros 2002; Barros and Lang 2003).

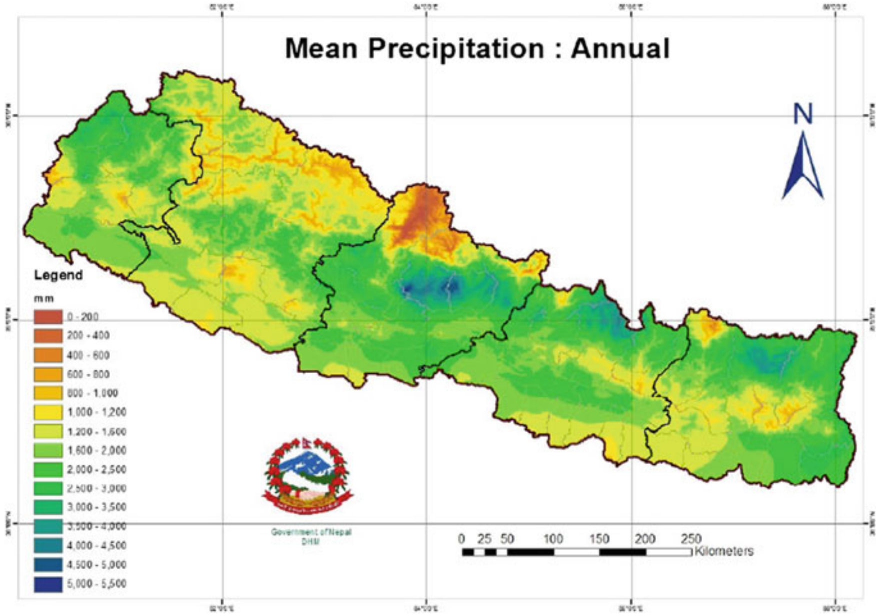


Fig. 42.2 Mean annual precipitation variation over Nepal (*Source* DHM 2015)

The hydrology of Nepal follows monsoon pattern and generally reflects regional rainfall patterns. The rivers are subject to high flow from July to September and start to recede from October to November and reach the lowest levels between December and April (Bricker et al. 2014). Therefore, there is marked temporal variability of flow throughout the year (Fig. 42.2).

Glacier melt constitutes important part of dry season river flow in Nepal. Snowfall in the Himalayan region feeds glaciers and contributes significantly to the flow of snow-fed rivers, thereby influencing hydrological behavior (Dixit and Moench 2006). The snow accumulated during the winter months acts as a reserve and release water as it melts. It provides support for livelihoods and environmental services. In Nepal, about 23% of total area above 5,000 m lies above permanent snow line (MoPE 2004) and about 10% of the total precipitation falls as snow (UNEP 2001). However, today such snow deposits and glaciers in the high Himalayan region are threatened by the changing climate. It is predicted that any increase in the temperature will accelerate the melting of the snow. Studies (Chaulagain 2015; IPCC 2007; Shrestha et al. 2015) indicate that mountain glaciers and snow covers are declining at an alarming rate. Between 1977 and 2010, glaciers receded by an average of 38 km^2 per year, and between 1977 and 2010, about 24% of the total glacier area and 29% (129 km^3) of the estimated ice reserves have decreased (Bajracharya et al. 2014).

42.3 Availability of Groundwater Resource

The Tarai region of Nepal consists of vast resource of groundwater. This region lies in south of the country and accounts for 17% of the total landmass. The Tarai is called food basket of the country because half of the total agricultural comes from this region. Groundwater is the main source of a reliable and sustainable water supply. About half of the populations depend entirely on groundwater for their domestic as well as agricultural water supply (Kansakar 2001) and around 90% of the population withdraw water from tube wells (Guillot et al. 2015). Nepal's Tarai and some of the mid-hill valleys, such as Kathmandu, Dang, and the inner valleys of the hills and mountains have good potential for groundwater harvesting. Much of the Tarai's physiographic region and some parts of Chure range contain shallow or deep aquifers, many of which are suitable for exploitation as sources of irrigation and drinking water (Kansakar 2004). The annual shallow groundwater resource of Tarai, which can be utilized, is estimated to be 12 billion m^3 out of which only 8.8 billion m^3 groundwater is extracted annually (McNellis et al. 1993; Kansakar 2001). GDC (1994) estimated the total annual recharge in the Nepal's Tarai is 14,300 million m^3. The present situation of groundwater balance in Tarai is given in Table 42.1.

In the Tarai, 82% of the total irrigated area (889,000 ha) has access to surface irrigation and the remaining 18% to groundwater irrigation. Shallow and deep aquifers are also present in the young alluvial sediments throughout the Tarai region (Jacobson 1996). The shallow aquifers are unconfined and well developed in most areas, although it is thin or absent in Kapilvastu and Nawalparasi (Upadhyay 1993). The deep aquifers of the Tarai region (whose depth are unknown) are artesian (Basnyat 2001). There are more than 800,000 shallow tube wells (STW), among which 70,000 are developed by government and 30,000 are private. An estimated 20,000 treadle pumps, which draw water from such shallow wells, are also installed. Approximately, 1,000 deep tube wells (DTW) are being in use for irrigation as well as drinking water supply (Rana 2011).

Groundwater is vital for maintaining the life-support systems in the hills and the mountains. A majority of the population in the hills and mountains meet their domestic water demands from spring sources. Springs are the natural discharges of

Table 42.1 Annual groundwater recharge and balance in the Tarai

Available annual groundwater recharge	
Dynamic groundwater reserve	**8,800 MCM**[a]
Abstraction for irrigation/industrial purpose	756 MCM
Abstraction for drinking purposes	297 MCM
Annual balance = 7,747 MCM	

[a] *Source* Ground Water Development Board http://www.gwrdb.gov.np/hydrogeological_studies.php

8800 MCM–Total groundwater reserve in the Tarai region of Nepal

7747 MCM–Avaliable surplus groundwater reserve after abstraction groundwater and provide water supply for domestic and agricultural uses at a relatively low cost. According to Kansakar (2002), the annual groundwater recharge in Nepal's mid-hills is 1,723 million m^3. The rain-fed rivers derive their flow from groundwater.

Springs are the only source of drinking and irrigation in the upland areas. Springs are short-lived and provide water for a certain period after the monsoon. The aquifer starts saturating with the onset of monsoon, and in the first week of July, water source starts to appear in the upper part of hills. Such type of water source is termed as July spring or *AsareMul*. Slowly the water table is filled, and water begins to rise to the surface giving rise to a number of springs. This type of spring is called August spring or *SauneMul*. Thus, as the monsoon peaks, water in the streams and river start to rise. Permanent springs are crucial for drinking water, whereas seasonal springs are essential for farming in the hilly areas. These springs arranged along the hillslopes constitute the water tower in the mid-hills (Fig. 42.1). The flow variability of these springs depends upon the time and amount of rainfall. The mean discharge peak in the post-monsoon months (September–November) and start to diminish during spring, from March to May (Fig. 42.3).

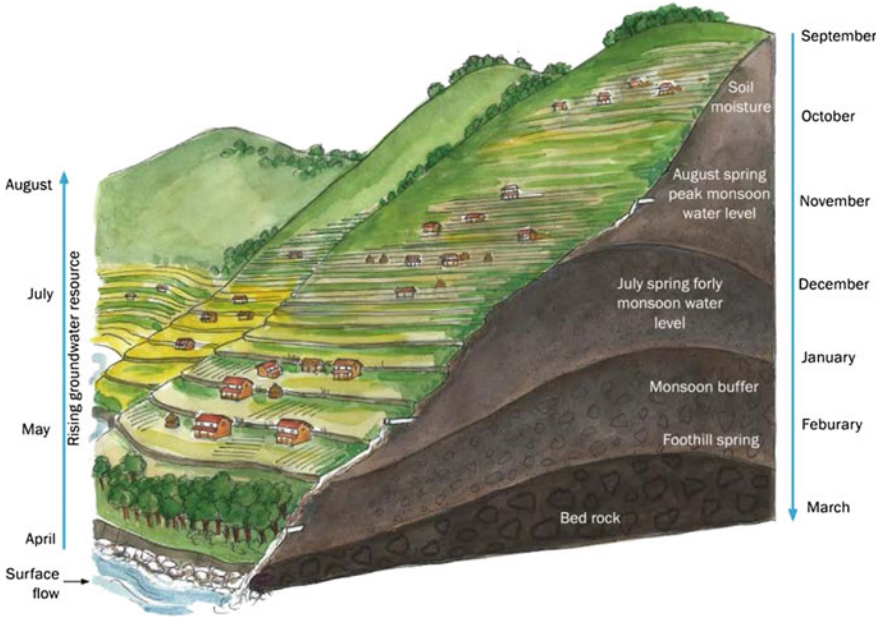


Fig. 42.3 Water tower in mid-hills of Nepal (Adapted from ICIMOD 2015, *Source* ISET-Nepal)

The study, conducted in the mid-hills of Nepal, reveals that even a small area around a hill water tower can be densely populated with more than a hundred spring sources. Such sources can be seasonal as well as permanent in nature (ICIMOD 2015).

Groundwater meets nearly half of the total water demand in Kathmandu Valley (Aryal 2011). This water is extracted from both shallow as well as deep aquifers (Jha et al. 1997; Khatiwada et al. 2002). But due to the rapid increase in urbanization, increase in built-up areas and formation of impervious surface, change in land use pattern and overexploitation, groundwater supply is facing acute shortage, making it rare resource. The study conducted by Sada et al. (2013) depicts the water demand was 195 million litres per day (mld) in 2016, but only 104.5 mld was available during wet season and only 58 mld during dry season (Sada et al. 2013). By 2021, the water demand is predicted to increase to 540.3 mld (Udmale et al. 2016).

A variety of groundwater sources comprising of dug wells, tube wells, stone spouts, and deep tube wells are being used in the valley (Shrestha 2017). However, recent studies show that many of such stone waterspouts, wells, and springs are drying up (ISET-Nepal 2013). Kathmandu Upatyaka Khanepani Limited (KUKL) is responsible for municipal water supply. KUKL uses groundwater since 1980 to meet the demand of the valley mounting population. But in the course of time, municipal water supply became insufficient and private sector began extracting groundwater by them to meet their own water requirements. Gradually, as water scarcity increased, households followed in the footsteps of the industries and started extracting groundwater in an unregulated manner. This led to rapid depletion in groundwater levels, especially in deep aquifers. These aquifers consist of black clay which is impermeable (JICA 1990).

Groundwater basin in the valley has huge potential for shallow and deep aquifers. Both shallow and deep aquifers have a potential of 7,260 and 56,813 million m^3, respectively. The shallow aquifer is denser toward the northern part of the groundwater basin, whereas the central and southern parts of the valley consist of deep aquifers. The annual recharge of groundwater is estimated at 9.6 million m^3 per year. But the extraction of groundwater is rising significantly with passing days. Because of increase in urbanization, anthropogenic activities, land use changes, vegetation covers, and distribution of hotels and factories, the extraction rate is increasing rapidly (Pandey et al. 2010). However, the exact amount of groundwater extraction is not clearly known yet due to lack of control and monitoring mechanism (Fig. 42.4).

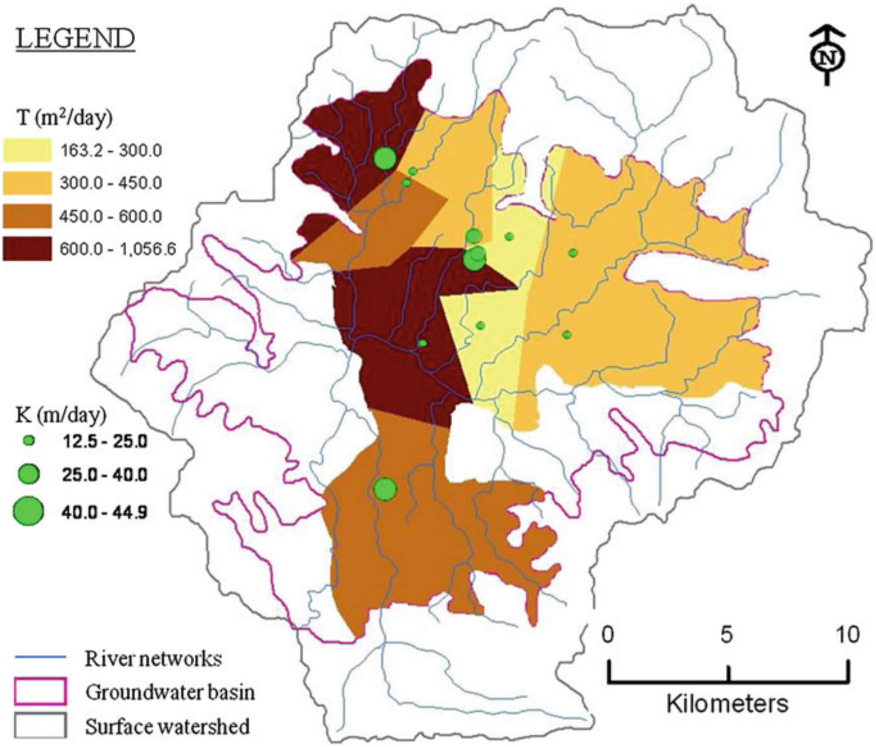


Fig. 42.4 Groundwater potential of Kathmandu Valley (*Source* Pandey and Kazama 2010)

42.4 Groundwater Development and Management

The groundwater investigation started in the 1960s with the inception of borewell technology from India. Significant amount of financial resources was allocated to increase the groundwater development and increase water supply. Bureau of Mines, then, started groundwater resource assessment to study groundwater potential of Kathmandu Valley. In 1976, the Groundwater Resources Development Board (GWRDB) was established with the aim to explore the groundwater potential of the Tarai region of Nepal. GWRDB has been actively engaged in the investigation and development of groundwater resources for irrigation in Tarai as well as in mid-hills of Nepal. In Tarai, groundwater marked its development in the 1980s (Kansakar 2006) with widespread expansion of STW irrigation program as government provided attractive subsidy on STW irrigation programs. Development of the rural power supply network and the easy availability of affordable electric pumps made STW irrigation more accessible and economical to small farmers. Private investment in shallow irrigation tube wells, on the other hand, has also increased extensively in shallow irrigation. In addition, development of domestic self-water supply through hand-pump increased noticeably and almost the entire population of Tarai depends on groundwater supply for their domestic and agricultural needs. Further, the opening up of the market and access to cheap electric pumps has resulted in increasing stress on the available resources. Groundwater exploitation has been unregulated, rampant, and mismanaged.

The development of groundwater resources in Kathmandu valley dates back to the medieval period. But, the modern technology of piped drinking water supply was only introduced in 1891 (Kansakar 2011). This piped water supply system was based on surface water source to cater to the needs of Kathmandu population. But, by the 1980s, demand increases due to rapid population growth and surface water sources were unable to meet the increasing water demands. Thus, the extraction of water from alternative sources, like stone waterspouts (Dhunge Dhara), wells, and springs, began. The Nepal Water Supply Corporation (NWSC) then, now the Kathmandu Upatyaka Khanepani Limited (KUKL) is the government agency responsible for municipal water supply in the Kathmandu Valley. KUKL began the extraction of groundwater since 1980 to meet the need of water supply in the valley. Subsequently, private sector began to extract groundwater to meet their own water requirements as the municipal water supply systems were unable to meet the escalating water demand and gradually, it became common at individual households level.

42.5 Groundwater Management and Governance Challenges

Though groundwater is playing fundamental role in domestic, industrial as well as agricultural water supply of Nepal, its proper management and utilization is still a challenge. Intensive groundwater development, without appropriate resource management regimens, has resulted in resource degradation which has given rise to the following challenges.

42.5.1 Groundwater Depletion

The unplanned, unscientific, and over-extraction of groundwater in many parts of the country has caused water table to drop down significantly. Additionally, due to advent of tube wells, treadle pumps together with rapid growth of agricultural and municipal water demand have resulted in increased extraction rate in all parts of the country.

In densely populated region, Kathmandu, the water table has shrunk from 9 m to as 68 m in Kathmandu valley in the late 1990s (Metcalf and Eddy 2000). The study conducted in 2010 depicts the rise in groundwater use from 0.04 to 12.2 million m/year from the period 1970s to 1980s (Pandey et al. 2010;

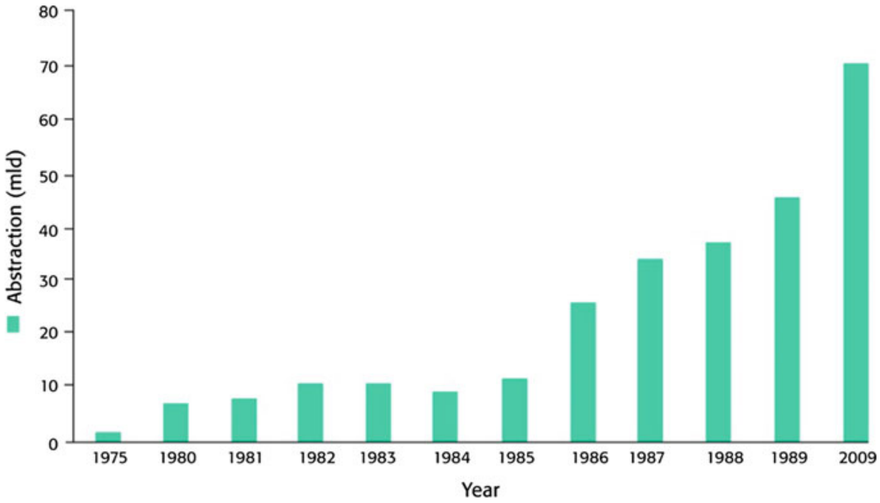


Fig. 42.5 Trend of groundwater abstraction in Kathmandu Valley (*Source* Dahal 2010)

GoN 2004) (Fig. 42.5). Factors such as rise in population, improved lifestyles, and increase in economic activities significantly increase the pressure on groundwater over the years. In addition, urbanization, decrease in green area, increased number of hotels and brick factories together with degradation of recharge areas are making groundwater resource vulnerable.

Consequently, municipal authorities and individuals pumped large quantities of groundwater through unregulated shallow and deep water well to meet domestic and other water needs. The exponential growth of population from 0.41 million in 1994 to 2.5 million in 2011, the demand for water has increased at an alarming rate (Pathak et al. 2013). This has resulted in indiscriminate extraction of groundwater which is done without any regard to the recharging capacity of the aquifers. Sharp increase in the number of private tube wells and expanding water market in the valley have aggravated the situation. A recent study on the water market in the valley has shown that, on average, 25.5 mld of water was sold during dry seasons and 8.5 mld during other seasons in 2009 (Shrestha and Shukla 2010). Spring water sources in the surrounding hills and tube wells in the peri-urban areas are the main sources of water for such water sellers. The haphazard and unscientific increase in private tube wells in the valley is largely unchecked due lack of adequate institutional responsibility that impedes effective monitoring of groundwater resources and its impact.

Bhabar zone, which extends from the foothill of the Siwalik to the Indo-Gangetic Plain in south, is the main recharge zone for groundwater in the Tarai. It consists of sedimentary rock along with boulders, cobbles and pebbles. Because of which, it is highly pervious and immensely contributes to groundwater recharge (Pathak 2016). The Tarai faces substantial consequences due to increase in population from 48.4% of Nepal's population in the 2001 to 50.2% in 2011 (Central Bureau of Statistics 2012) along with clearing of forest for agriculture and human settlement, urbanization, and increase in socioeconomic activities. As a result of which, this regions is under immense threat making groundwater a scare resource.

42.5.2 Groundwater Pollution

Access to quality water also results in water scarcity. Water scarcity is due to the difficulty in obtaining freshwater sources together with depletion and degradation of the available water sources. The contributing factors to water scarcity are increased pollution besides climate change and over-use. In Nepal, arsenic (As) is one of the major water pollutants that has serious health management issues. A majority of the population (around 90%) in the southern lowlands of Nepal Tarai region are exposed to high level of As through the drinking water they extract from tube wells.

A study conducted by National Arsenic Steering Committee (NASC), from the year 2003 to 2008, in 20 Tarai districts reveals that about 34,976 households were exposed to arsenic levels that were above the Nepal Interim Standard, i.e., 50 ppb (parts per billion) and about 111,178 above the WHO Standard (NASC-NRCS 2011). The maximum level of As allowed in drinking water is 0.01 mg/L according to the World Health Organization (2011) and at 0.05 mg/L by the Government of Nepal (GoN/MPP 2006). However, no recent assessment of the status of As in Tarai has been carried out so far.

Many studies in Kathmandu Valley have also reported elevated levels of As, iron, and coliform in its groundwater (Khatiwada et al. 2002; JICA/ENPHO 2005; Maharjan et al. 2006; Chapagain et al. 2009, 2010; Shrestha et al. 2010; Pant 2011). All these studies imply that there is an elevated level of As in the groundwater of Kathmandu Valley. It has also raised serious questions about arsenic negative impacts on health as majority of water supply is met through groundwater. Therefore, there is a need of in-depth studies for arsenic contamination in groundwater resources of the valley. Besides, the contamination of shallow and deep aquifers from E.-coli, nitrates, ammonia, iron and heavy metals has been also reported in Kathmandu valley (Pandey et al. 2012). The occurrence of pollutants in the deep aquifers is due to sedimentary composition whereas contamination of shallow aquifers occurs from improper design and installation of well and inadequate management of abandoned wells (Chapagain et al. 2010). In addition, inappropriate management of domestic and industrial waste management highly contributes to groundwater pollution.

42.5.3 Recharge Potential

In Kathmandu, the annual average rainfall accounts for 1755 mm of rainfall (Pandey et al. 2010). But a significant amount of rainwater flows as surface runoff and there is lack of mechanism to harvet rainfall to recharge groundwater. Artificial recharge of shallow and deep aquifers from rainfall offers a viable approach for increasing groundwater recharge and thus reduce depletion. The northern district of Kathmandu valley is regarded as the potential recharge areas for groundwater. However, with the rapid increase in population, urbanization, reduction in vegetation cover and increase in impervious areas, the infiltration rate has been drastically decreased. Moreover, the information regarding aquifer characteristics is limited and the complexity of groundwater systems in the valley has not received considerable attention. Thus, the challenge today is to devise technical and institutional mechanisms that can improve the recharge potential of groundwater. Recently, a number of initiatives have been devised to increase the municipal supply system. So far, none of them have been effective. Regardless of the long-term plans, most residents of urban Kathmandu experience significant shortages and disruptions in the supply of water provided by the municipal system.

Conservation and protection of water source areas have also not received proper attention by law and regulation. Specific provision for protecting recharge areas is not mentioned in any law or regulation. The Environment Protection Act, 1997 has made some indirect provision toward the protection of water resources, but they are inadequate for effective enforcement. Also, such provisions do not encompass the protection of watershed areas or groundwater recharge areas.

42.5.4 Climate Change Vulnerability

Nepal is one of the most vulnerable countries to climate change, water-induced disasters and hydro-meteorological extreme events such as droughts, storms, floods, inundation, landslides, debris flow, soil erosion and avalanche. According to the ‘Intended Nationally Determined Contribution’ report submitted by the Ministry of Population and Environment, Nepal to the United Nations Framework Convention on Climate Change Secretariat, Nepal is in 145th on the Human Development Index. Nepal’s mountainous landscape and treacherous topography make the country highly vulnerable to climate change. The temperature is projected to increase by 10.5–2.0 °C by the 2030s and 3.0–6.3 °C by the 2090s (NCVST 2009). Similarly, annual rainfall is projected to change by −14 to +40% by the 2030s and −52 to +135% by the 2090s throughout the country. As a result, glaciers, which fed many rivers and streams, are melting at an alarming rate. The acceleration of glacier increased the runoff during summer but decreased the flow of rivers in the dry season.

Climate change affects the water resources through changes in components of the hydrological cycle such as precipitation, evapotranspiration, and soil moisture (Milly and others 2005). The change rainfall characteristics have direct implication on groundwater resulting in high or low groundwater levels. Any changes in surface water have considerable impact on the recharge process. However, the impact of climate change on groundwater has not been sufficiently studied in Nepal. A study conducted by Bricker et al. (2014) suggests that the springs in the mid-hills of Nepal are highly vulnerable to any changes in the climate and would not be resilient to a long-term reduction in precipitation. The study conducted by ICIMOD reveal that 15–30% of springs have dried up in the last decade in midhill watersheds of Nepal (ICIMOD 2015).

The relationship between climate variability and its potential impact on groundwater is very complex to understand in comparison to surface water (Holman 2006). The temporal variability of groundwater-residence times, which varies from days to thousands of years, makes it difficult to discern the exact impact due to climate variability and change (Chen et al. 2004). Furthermore, anthropogenic activities together with increased frequency of extreme events make the distinction of various stressors troublesome (Hanson et al. 2004). For instance, El Nino events are projected to double in frequency as temperature rises having significant impacts on extreme weather events worldwide (Cai et al. 2014). As a result, more occurrences of destructive and damaging weather extreme will occur from one year to the next with profound socioeconomic impacts.

42.5.5 The Changing Landscape

The changing landscape also poses serious problems for the distribution of groundwater in Nepal. For example, the recent 2015 Gorkha Earthquake, which hit central Nepal, raised various issues regarding the distribution of groundwater sources. The land deformation results in three different issues: Firstly, dried stone spouts in many places experience high flow after the earthquake. Secondly, new source of spring water was depicted, and thirdly some rivulets dried out (ICIMOD 2015). Most of the sources dried out after a few months and the flow of old sources was decreased. But no systematic study has been done so far to improve the understanding of linkages between groundwater and the changing landscape. Therefore, it is important to perform an in-depth investigation regarding the geological aspect of spring hydrology.

The changing political landscape within the country is one of the major challenges water resource management is facing. The transformation of country into a federal structure is of paramount important to water resource development and management. The declaration of federalism in Nepal is not based on the scientific study; therefore, the use and management of water resources has not given due consideration. The institutional mechanism to govern the management of water resources at all levels of government has received limited attention. Federalism will increase the conflict between states regarding the sustainable and equitable sharing of water resource for agriculture, domestic, hydropower, and industrial use.

Additionally, transboundary groundwater management and developement is a prominent issue in the Indo-Gangetic Plains which comprises of large floodplains of the Indus and Ganges-Brahmaputra river systems. The basin straddles through northern and eastern India, much of Bangladesh and parts of southern Nepal and

Pakistan. Indo-Gangetic basin is the most populous and complex river basin in the world (Sharma et al. 2008). It is the major source of freshwater for more than 747 million people in Nepal, India, Pakistan, and Bangladesh and accounts for roughly a quarter of the global extraction of groundwater (Fendorf and Benner 2016).

Groundwater plays a crucial role in the socioeconomic development of the people in the Indo-Gangetic basin. But change in the political geography of the region drastically affect the groundwater reserve. This can mainly be attributed to a rising demand for water which is exacerbated by expanding populations, rapid economic development, and improvement of living standard (Kataoka and Shivakoti 2013). As a result, the Indo-Gangetic basin is facing consequences. The over-extraction due to unplanned and poor governance has resulted in quality degradation which threatened lives and livelihoods of local populations, thereby making them more vulnerable. Apart from this, in many places even as groundwater tables are getting alarmingly low, untreated solid waste is dumped on common land and wetlands and in rivers making even these sources unsuitable for use. A recent study depicts that 60% of groundwater in the Indo-Gangetic basin has excessive amounts of arsenic and salinity which makes it unfit for consumption and agriculture production (MacDonald et al. 2016). Further, the study shows that about 23% of the water was very salty and about 37% is contaminated with arsenic at beyond the human consumptions.

The transboundary nature of the water resources together with lack of proper monitoring techniques, institutional arrangements, research collaborations, poor coordination between riparian states makes sustainable management and governance of water resource a serious issues in the region. The most of difficulty arises due to lack of political willingness for cooperation between the institutions involved of the riparian states. Hence, the major challenge lies in setting up a cooperative framework between the riparian states to work more effectively and efficiently. At present, national institutions dealing with groundwater resources are not sufficiently equipped to undertake initiatives for sustainable management of transboundary groundwater in the region.

42.5.6 Regulatory Framework and Legislation

There is a serious lack of appropriate institutional frameworks for effective integrated water resources management in the country. The most important challenge Nepal is facing in regard to water management is the inadequate governance. Several national- and local-level institutional measures that bring environmental considerations into the mainstream of Water Resources Strategy have been developed to improve governance in water resources sector. But the present legal provisions available for protecting and controlling the water resources are not sufficient. Not only this but also they are contradictory to one another. The Water Resources Act of 1992 provides a legal framework for the various uses of water with an emphasis on the state's lead roles in the management of water sector.

There is a lack of provisions to involve the grassroot-level stakeholders in the decision-making processes. Water resource planning strategies had been concentrated primarily on sub-sector level, and most of the investment decisions are made on a project basis. Subsequently, the Water Resources Regulation was enacted in 1993 for the integrated management of water resources. However, despite such efforts, evidence suggests that the results were far from what was expected at the outset. The water resources have been utilized by multiple users–farmers, domestic water-related agencies without any special attention to the water availability.

Groundwater management is limited to the use of groundwater but does not include the problem of depletion. Moreover, the macroeconomic contribution of groundwater is most apparent in agriculture and urban water supply. Various institutional measures adopted in Nepal do reflect a vision for addressing these key characteristics but efforts to ensure that they are in place have largely been lacking. Instead, the focus has been to add more institutional measures such as structuring and restructuring the state's different functionaries, defining and redefining their roles, promulgating legislation one after another, etc., without paying much-needed attention to the aforementioned key characteristics at the local level. Thus, there is an urgent need to create new organizations and redefine the functions and structures of some of the existing organizations. Only actions such as these can help ensure that the objectives enumerated in the strategy document are achieved.

About 80% of country's population depends on subsistence agriculture for their survival (World Bank 2009); however, only 24% of arable land has access to year-round irrigation. Crop production is continuously lowering in the country, and starting from the early 1990s, the country has continuously depended on food imports to meet its domestic demand. In Tarai, groundwater extraction, mainly through shallow tube wells owned by individual farmers, has become an important source of irrigation since the early 1980s. It has also led to the emergence of a water market. Recently, the development of treadle pumps has somewhat made irrigation less strenuous. The treadle pump is suitable for small holders' farming in areas of the Tarai region which have shallow groundwater table (Upadhyay 2004). The performance of installed wells (which was numbered to be around 0.6 million in 2001) was limited to an average output of 30 m^3/h per well (Shah and Desai 2002). The treadle pump technology has potential to elevate poverty in a developing country like Nepal. It is found that the treadle pump on average has the capacity to raise household income by US$100 annually (Shah et al. 2000).

At present, groundwater contribution to irrigated areas exceeds the contribution made by surface water supplies. In the future, there is a huge need to develop groundwater irrigation as it is more productive than surface supplied irrigation, since it allows individual farmers to irrigate 'on demand,' which few surface systems can offer. Furthermore, regulations to prevent pollution of surface and shallow groundwater have not been enforced and a single agency has not been assigned to deal with this problem. While the development of deep tube wells is not regulated, due to huge operation costs associated with them, they have not flourished except in a few areas.

42.5.7 Way Forward

Nepal still holds huge potential for groundwater use and development. The scientific use and sustainable management can reduce depletion and degradation of groundwater resources and thus improve social, economic, and environmental benefits. To maximize the use of groundwater and to manage it in a sustainable manner, the following measures need to be taken into consideration:

42.5.8 Source Protection

Nepal is marked by diversified hydrogeologic settings and variations in the availability of groundwater resources from one part of the country to other. For conservation and management of groundwater, it is necessary to develop a detailed knowledge database for type of regimes in different hydrogeological and socioeconomic conditions. To achieve this, it is essential to carry out detailed studies for each hydrogeologic setting. The conservation and protection of water resources and source protection is not outlined in the Water Resources Act of 1992. Therefore, it is also essential to build policies and laws that will encourage the conservation and protection of groundwater resources.

42.5.9 Groundwater Quality Consideration

In-depth studies of groundwater quality are in few numbers, and some of them are not up-to-date. Therefore, it is essential to investigate the current status and trend of groundwater quality and quantity in different hydrological settings according to seasons. The study should help in building a real-time monitoring database of groundwater use. Further, the study should be able to provide protection mechanism and remedial measures in areas where the resource is threatened. The study needs to make available to community at watershed and village level. This will help them and local institutions to make timely and informed decisions regarding the conservation and management water resources. In addition, reforms are needed in the methods used to assess groundwater resources, mapping of aquifers as well as monitoring the quality. Furthermore, the legal and institutional frameworks for groundwater governance must also be revised.

42.5.10 Groundwater Artificial Recharge Development

Artificial groundwater recharge holds great potential for the increase of groundwater reserve. This can be achieved by management of both surface and groundwater sources simultaneously (Khan et al. 2014). This can be facilitated by augmenting the natural infiltration of rainfall water into ground. These can be done using recharge trenches, ponds, and permeable pathways that help to infiltrate the rainfall water through the soil strata at shallower depths. For the deep percolation, recharge wells, recharge through agriculture lands, ponds can be used (Dixit and Upadhya 2005). Previous studies depict that dug wells, shallow tube wells, and recharge pits are suitable for recharging shallow aquifers, whereas pond restoration and channeling rainwater into ponds also support the recharging of deep groundwater aquifers (Shrestha 2001). Artificial recharge of shallow and deep aquifers offers a viable and sustainable approach for increasing groundwater reserve and reducing groundwater resource exploitation depletion.

The annual average rainfall in the Kathmandu Valley is 1900 mm of which about 80% of falls on a building and thus can be collected easily (UN-Habitat 2006) and can be used for the promotion of artificial groundwater recharge. A study by UN-Habitat reveals that if just 10% of the Kathmandu Valley area was to be used for rainwater harvesting, 128 million m^3/year of area could be recharged. To implement such a plan, there is a need to investigate suitable recharge techniques and appropriate locations. But attention should be given to local topographical, geological, and soil conditions; the quantity and quality of water available for recharge; together with the technological-economic viability and social acceptability of such interventions. So, it is essential to devise more defined groundwater management strategies which incorporate both the supply and demand sides of groundwater resources to maintain a sustainable balance between recharge and withdrawal of groundwater (Kulkarni et al. 2005).

42.5.11 Climate Adaptation Strategies

Agricultural dependency on groundwater in Nepal is increasing rapidly over the past few decades. This includes increase in investment in groundwater extraction structures such as well, electric pump irrigation, and domestic use. However, there are serious constraints on groundwater supplies posed by geological formations as a result of over-extraction. This has led people to adopt coping strategies and migrating and/or diversifying into non-agricultural activities. Disasters such as droughts hasten the degree and intensity by which such options are adopted but do not alter the underlying trajectories. Climate changes intensified droughts in dry region of the world. Groundwater plays an important role in reducing risk and helps in adaption by increasing household income and enables farmers to transit out of poverty (Moench 2002, 2003). Therefore, an assessment of groundwater for alternative source of water is crucial for sustainable groundwater development in the context of climate change. For this community-based organizations can play important role for sustainable and equitable management of groundwater resources (Kulkarni 2003). Groundwater sustainable management goals cannot be met without active participation of communities (Mudrakartha et al. 2003). Hence, responses need to be closely tailored to local conditions and capable of adapting to the changing conditions (COMMAN 2005). There is a need to make policy change that enables local community and stakeholders to participate in a meaningful way to adequately manage groundwater resource. Locally grounded processes, capacity building, research, experimentation, monitoring, and evaluation should be inherent parts of the overall response strategy. Groundwater provides reliable water supplies that help to increase investment in agriculture and reduces the risk of crop loss and production substantially.

Groundwater also acts as a critical buffer against runoff and climate variability as it modulates variability. When it is managed effectively, it can reduce the impact of low river flow or erratic precipitation on water supply systems. Because large amounts of groundwater are available in storage and this is relatively unaffected by short-term variability, its value for both agriculture and urban or domestic supply lies in its buffering capabilities (Calow et al. 1997).

The impact of groundwater problems on poverty may depend, however, as much on the presence or absence of alternative livelihoods within the wider economy as on the direct impact on agriculture. In their classic book, written in the mid-1980s, ‘To the Hands of the Poor, Water and Trees,’ Chambers, Saxena and Shah (Chambers et al. 1987) argue that access to basic productive resources is central to rural poverty alleviation. This has also been suggested in other researches that were carried out in India and Nepal (Shah 1993; Gyawali and Dixit 1999). Groundwater resource management needs to be addressed in a holistic approach involving sustainable suitable management strategies as depicted in Fig. 42.6. It focuses on integrated management of groundwater resource management with supply-side and demand-side measures.

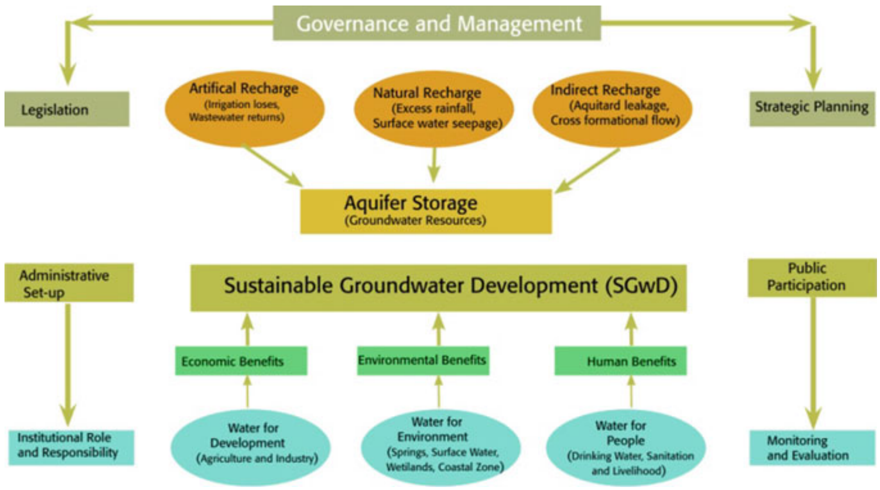


Fig. 42.6 Conceptual approach to achieve sustainable groundwater development balancing recharge inputs to aquifer storage plus change in storage against discharge outputs (Adapted from Hiscock et al. 2002)

42.6 Groundwater and Ecosystem Services

Groundwater plays critical role in maintaining the ecosystem by delivering multiple services that are of great values for human and society (Stuurman and Griffioen 2003; Hassan et al. 2005; Landers and Nahlik 2013; Gou et al. 2015). These services range from purification of water, freshwater supply, biodegradation of human contamination, nutrients recycling, protection against floods and droughts, and cultural services (Figs. 42.5 and 42.7).

Ecosystem services are interlinked, and other ecosystem services depend on groundwater quality and quantity. For instance, rainwater recharge groundwater through infiltration and percolation and groundwater contribute to human development. But the rate of recharge depends upon the local climate and the type of land cover of an area. Precipitation and evapotranspiration are mainly determined by the climate and land cover of an area, whereas the underlying type of soil controls the amount of water infiltrated into the ground (Taylor et al. 2013). The importance of ecosystem services provided by groundwater has not received considerable attention (Tuinstra and van Wensem 2014). Policy-makers more focus on the direct benefits that groundwater and tend to neglect other services it provides (Howe et al. 2014). In additional socioeconomic and cultural aspects also largely determine the success of groundwater policies (Burke and Moench 2000). Currently, the challenge is to improve the understanding and awareness of the linkages between groundwater and ecosystems services and incorporate into decision making. So, there is need to explore the linkages between groundwater policies and ecosystem services at local level.

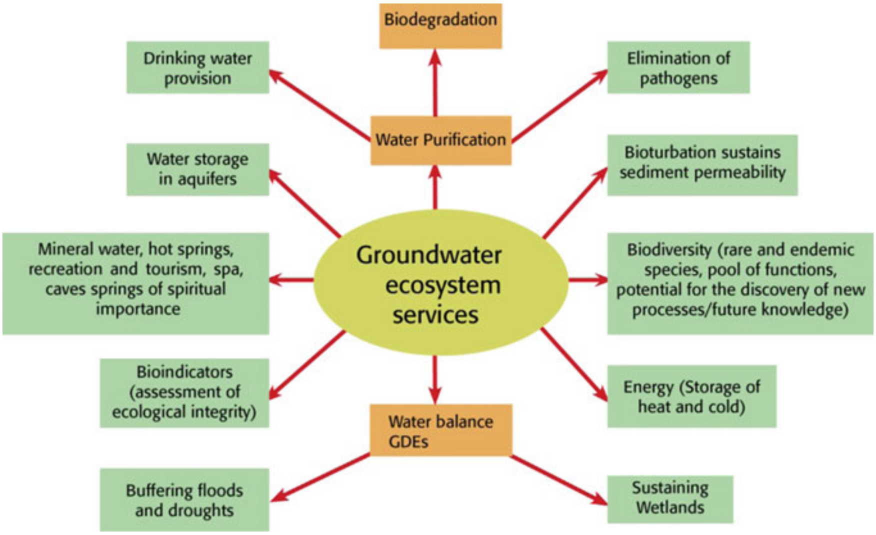


Fig. 42.7 Ecosystem services provided by groundwater (*Source* Adapted from Griebler and Avramov 2014)

42.6.1 Regulatory Framework Reform

In Nepal, the deteriorating level of groundwater level along with poor quality, inadequate quantity, improper monitoring, and lack of good governance is a result of inadequate institutional mechanisms. So there is a need to strengthen the current institutional mechanism to overcome the aforementioned hindrances. This requires that regulatory mechanisms be transparent and people-friendly. Continuous monitoring of groundwater regime is also required. Micro-level studies need to be taken up in such areas on a regular basis to assess the impacts of the regulatory measures on the groundwater regime. Real-time dissemination of information on the groundwater situation in the affected areas is to also be provided to the stakeholders.

It is also important to consider both natural and social factors while devising strategies for effective groundwater resource management. For this, we need to build capacity of local organization to support watershed conservation, improve crop and irrigation techniques, and recharge enhancement. This enables society to participate effectively and contribute to sustainable management of groundwater resource.

42.7 Conclusion

Groundwater management requires sustainable management of resource and takes important steps toward ensuring supply for current and future generations. It provides a dependable water supply and has potential to act buffer against dry seasons under climate change. Therefore, it must be addressed at primary level through the improvement in political, economic, institutional, and social processes. Managing the resource, while meeting the agricultural and domestic and basic needs of the growing population of Nepal, therefore, requires fundamental changes in the way water resources are managed and governed.

It has not been fully recognized in water management plans and policies due to lack of monitoring systems, understanding underlying processes and uncertainties about the future under climate change. To achieve this, institutional arrangements with more scientific studies are required. It requires involvement of broad range of stakeholders and inclusive governance structures at various levels and entities. Additional, technologies such as artificial recharge, aquifer storage, and strengthening the local capacities can promote sustainable groundwater management and mitigate water scarcity. Groundwater can only serve this purpose effectively if it is integrated in water resource management strategy.

Acknowledgement The author is grateful to Ms. Sneha Pandey and Mr. Kanchan Mani Dixit for their help in editing of the manuscript.

References

Aryal RS (2011) Ground water reality. New Spotlight 4(19)

Bajracharya SR, Maharjan SB, Shrestha F, Bajracharya OR, Baidya S (2014) Glacier status in Nepal and decadal change from 1980 to 2010 based on landsat data. ICIMOD, Kathmandu

Barros AP, Lang TJ (2003) Monitoring the monsoon in the Himalayas: observations in central Nepal, 2001. Mon Weather Rev 131:1408–1427

Barros AP, Joshi M, Putkonen J, Burbank DW (2000) A study of the 1999 monsoon rainfall in a mountainous region in central Nepal using TRMM products and rain gauge observations. Geophys Res Lett 27:3683–3686

Basnyat K (2001) Sustainable manageable models essential. The Rising Nepal (Daily), Kathmandu

Bricker SH, Yadav SK, Macdonald AM, Satyal Y, Dixit A, Bell R (2014) Groundwater resilience Nepal: preliminary findings from a case study in the Middle Hills. British geological survey open report, OR/14/069, 67 pp

Burke J, Moench M (2000) Groundwater and Society: resources, tensions and opportunities. United Nations Publication. United Nations Department of Economic and Social Affairs, New York

Cai W, Borlace S, Lengaigne M, Rensch PV, Collins M, Vecchi G, Timmermann A, Santoso A, McPhaden MJ, Wu L, England MH, Wang G, Guilyardi E, Jin FF (2014) Nature Clim Change. http://dx.doi.org/10.1038/NCLIMATE2100

Calow RC, Robins NS, Macdonald AM, Macdonald DMJ, Gibbs BR, Orpen WRG, Mtembezeka P, Andrews AJ, Appiah SO (1997) Groundwater management in drought-prone areas of Africa. Water Resour Develop 13(2), 241–261

Central Bureau of Statistics (2012) National population and housing census (village development committee/municipality). Central Bureau of Statistics, Government of Nepal, Kathmandu, Nepal

Chambers R, Saxena NC, Shah T (1987) To the hands of the poor: water and trees. Water and trees. New Delhi, Oxford and IBH publishing company

Chapagain SK, Shrestha S, Nakamura T, Pandey VP, Kazama F (2009) Arsenic occurrence in groundwater of Kathmandu Valley, Nepal. Desalin Water Treat 4:248–254

Chapagain SK, Pandey VP, Shrestha S, Nakamura T, Kazama F (2010) Assessment of deep groundwater quality in Kathmandu Valley using multivariate statistical techniques. Water Air Soil Pollut 210:277–288

Chaulagain NP (2015) Socio-economic dimension of snow and glacier melt in the Nepal Himalayas. Dynamics of Climate Change and Water Resources of Northwestern Himalaya. Society of Earth Scientists Series. https://doi.org/10.1007/978-3-319-13743-8_15

Chen Z, Grasby SE, Osadetz KG (2004) Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba, Canada. J Hydrol 290(1–2):43–62

COMMAN (2005) Managing groundwater resources in rural India: the community and beyond. British geological survey commissioned report, CR/05/35N

Dahal RK (2010) Engineering geology of Nepal. Published in personal home page. http://www.ranjan.net.np; http://www.ranjan.net.np/ranjan/index.php/resources/engineering-geologyof-nepal

Dhakal HP (2010) Groundwater depletion in Kathmandu valley need for management. Water Environment Partnership in Asia (WEPA)-Nepal Dialogue Kathmandu

DHM (2015) Study of climate and climatic variation over Nepal. Government of Nepal Ministry of Science, Technology and Environment Department of Hydrology and Meteorology

Dixit A, Moench M (2006) Hydrologic variability and uncertainty: implications for local management in Nepal. In: Dixit A (ed) WaterNepal. J Water Resour Dev 12(1/2)

Dixit A, Upadhya M (2005) Initiatives for augmenting groundwater resources by artificial recharge, augmenting groundwater in Kathmandu Valley: challenges and possibilities. Nepal Water Conservation Foundation, Kathmandu

Fendorf S, Benner SG (2016) Indo-gangetic groundwater threat. News & Views. Nature Geoscience

GDC (1994) Reassessment of groundwater development strategy for irrigation in the Terai, 6 volumes

GoN/MPP (2006) National drinking water quality standards. In: Nepal Gazette (B.S. 2063/03/12), Kathmandu, Ministry of Physical Planning, Government of Nepal

Gou S, Gonzales S, Gretchen GR (2015) Mapping potential groundwater-dependent ecosystems for sustainable management. Groundwater 53(1):99–110. https://doi.org/10.1111/gwat.12169

Government of Nepal (GoN) (2004) Optminizing water use in Kathmandu Valley (ADB-TA) project. Final report. Ministry of Physical Planning and Works, Nepal

Griebler C, Avramov M (2015) Groundwater ecosystem services: a review. Freshw Sci 34(1). https://doi.org/10.1086/679903

Guillot S, Garçon M, Weinman B, Gajurel A, Tisserand D, France-Lanord C, et al (2015) Origin of arsenic in Late Pleistocene to Holocene sediments in the Nawalparasi district (Terai, Nepal). Environ Earth Sci. https://doi.org/10.1007/s12665-015-4277-y

Gyawali D (2003) Rivers, technology and society: learning the lessons of water management in Nepal. Himal Books and Panos South Asia with Nepal Water Conservation Foundation

Gyawali D, Dixit A (1999) Fractured institutions and physical interdependence: challenges to local water management in the Tinau River Basin, Nepal. Rethinking the Mosaic: investigations into local water management. Moench M, Caspari E, Dixit A (eds) Kathmandu, Nepal Water Conservation Foundation, Institute for Social and Environmental Transition, pp 57–123

Hanson RT, Newhouse MW, Dettinger MD (2004) A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States. J Hydrol 287(1–4):252–269

Hassan R, Scholes R, Ash N (2005) Ecosystems and human well-being: current state and trends Island Press, Washington, DC

Hiscock, KM, Rivett, MO, Davison RM (2002) Sustainable groundwater development. In Hiscock KM, Rivett MO, Davison RM (eds) Sustainable groundwater development. Geological Society of London, Special Publication, vol 193, pp 1–14

Holman IP (2006) Climate change impacts on ground-water recharge—Uncertainty, shortcomings, and the way forward? Hydrogeol J 14(5):637–647

Howe C, Suich H, Vira B, Mace GM (2014) Creating win–wins from trade-offs? Ecosystem services for human well-being: a meta-analysis of ecosystem service trade-offs and synergies in the real world. Glob Environ Change 28:263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005

ICIMOD (2015a) Reviving the drying springs: reinforcing social development and economic growth in the Midhills of Nepal. Issue Brief. International Centre for Integrated Mountain Development, Kathmandu, Nepal

ICIMOD (2015b) How big earthquakes rattle spring dynamics. By Santosh Nepal on 27 May 2015. International Center for Integrated Mountain Development http://www.icimod.org/?q=18472 . Accessed on 2 June 2016

International Center for Integrated Mountain Development (ICIMOD) (2007) Kathmandu Valley Environmental Outlook, Kathmandu, Nepal

IPCC (2007) Climate change 2007: synthesis report. In: Team CW, Pachauri RK, Reisinger A (eds) Geneva, Switzerland

IPCC (2013) Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the intergovernmental panel on climate change. In: Stocker TF, Qin, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM (eds) Cambridge University Press, Cambridge, 1535 pp. https://doi.org/10.1017/cbo9781107415324

ISET-Nepal (2013) Stone spouts status, their use and significance in Lalitpur Sub-Metropolitan City. Institute for Social and Environmental Transition-Nepal. Chandol, Kathmandu

Jacobson G (1996) Urban groundwater database. AGSO Report, Australia. http://www.clw.csiro.au/UGD/DB/Kathmandu/Kathmandu.htm

Jansson P, Hock R, Schneider T (2003) The concept of glacier storage: a review. J Hydrol 282(1):116–129

Japan International Cooperation Agency (JICA) and Environment and Public health Organization (ENPHO) (2005) Arsenic vulnerability in groundwater resources in Kathmandu valley. Final report

Jha MG, Khadka MS, Shrestha MP, Regmi S, Bauld J, Jacobson G (1997) The assessment of groundwater pollution in the Kathmandu Valley, Nepal: report on Joint Nepal-Australia Project 1995–96. Australian Geological Survey Organisation, Canberra, pp 1–64

JICA (1990) Groundwater management project in Kathmandu Valley. Final report, Executive summary. JICA, Kathmandu, p 2

Kansakar DR (2001) Ground water resources in the hills and mountain regions of Nepal. DoI, Kathmandu

Kansakar DR (2002) Groundwater in the Mountains and Hills of Nepal: resource potential and development. JalsrotBikasSanstha, Nepal

Kansakar DR (2004) Geologic and geomorphologic characteristics of arsenic contaminated groundwater areas in Tarai, Nepal. In: Kansakar DR (ed) Proceeding of the seminar on arsenic study in groundwater of Tarai & summary project report, arsenic testing and finalization of groundwater legislation project. DOI/GWRDP/WB/BNWPP, pp 31–47

Kansakar DR (2006) Understanding groundwater for proper utilization and management in Nepal. International Water Management Institute

Kansakar DR (2011) Regulating common pool groundwater under fugitive surface water law: limitations in laws and regulations in Nepal: a final report. JalsrotVikasSanstha/Global Water Partnership, Nepal

Kansakar SR, Hannah DM, Gerrard J (2004) Spatial pattern in the precipitation regime of Nepal. Int J Climatol 24:1645–1659. https://doi.org/10.1002/joc.1098

Kataoka Y, Shivakoti BR (2013) Groundwater governance regional diagnosis: Asia and the Pacific region. Groundwater governance: a global framework for action. Global Environment Facility, Food and Agriculture, UNESCO's International Hydrological Programme, the International Association of Hydrologists and the World Bank

Khadka MS (1993) Groundwater quality situation in alluvial aquifers of the Kathmandu Valley. J Aust Geol Geophys 14:207–211

Khan MR, Voss CI, Yu W, Michael HA (2014) Water resources management in the Ganges 1154 Basin: a comparison of three strategies for conjunctive use of groundwater and surface 1155 water. Water Resour Manage. https://doi.org/10.1007/s11269-014-0537-y

Khanal K (2016) Water sources run dry in Nepal after 2015 earthquake, forcing people to leave their ancestral villages or hike to faraway wells. Global Press J. https://globalpressjournal.com/asia/nepal/water-sourcesrun-dry-nepal-2015-earthquake-forcing-people-leave-ancestral-villages-hikefaraway-wells/. Accessed on 10 June 2016

Khatiwada NR, Takizawa S, Tran TVN, Inoue M (2002) Groundwater contamination assessment for sustainable water supply in Kathmandu Valley, Nepal. Water Sci Technol 46(9):147–154

Kulkarni H, Sharma S, Badarayani U, Mudrakartha S, Palanisami K, Rathore MS, Madhusoodhanan MP, Srinath J (2003) Community management of groundwater resources in rural India: reconnaissance case studies. Advanced Center for Water Resources Development and Management

Kulkarni H, Badarayani U, Phadnis V, Robb R (2005) Detailed case study of Kolwan valley, Mulshi Taluka, Pune district, Maharashtra. AGRAR Project, Final case study report. www.bgs.ac.uk/hydrogeology/agrar

Landers DH, Nahlik AM (2013) Final ecosystem goods and services classification system (FEGS-CS). EPA United States Environmental Protection Agency. Report number EPA/600/R-13/ORD-004914

Lang TJ, Barros AP (2002) An investigation of the onsets of the 1999 and 2000 monsoons in central Nepal. Mon Weather Rev 130:1299–1316

MacDonald AM, Bonsor HC, Ahmed KM, Burgess WG, Basharat M, Calow RC, Dixit A, Foster SSD, Gopal K, Lapworth DG, Lark RM, Moench M, Mukherjee A, Rao MS, Shamsudduha M, Smith L Smith, Taylor RG, Tucker J, Steenbergen FV and Yadav SK (2016) Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. Nature Geoscience https://doi.org/10.1038/ngeo2791

Maharjan M, Shrestha BR, Shrestha KB, Shrestha R, Raut-Khadka R, Shrestha SD, Kafle B, Ishihara H (2006) Arsenic contamination in groundwater resources in Kathmandu Valley. Paper presented at the 4th international symposium on Southeast Asian water environment, Bangkok

McNellis J, Tuladhar RM, Shrestha R, Amatya SC, Shrestha I, Kansakar DR (1993) Ground Water in the Terai, Nepal. UNDP/HMGN. Shallow ground water investigations in Terai. Technical report no. 3

Metcalf and Eddy (2000) Urban water supply reforms in the Kathmandu valley (ADB-TA). Report no.: 2998-NEP

Moench M (2002) Groundwater and poverty: exploring the connections. In: Llamas R, Custodio E (eds) Intensive use of groundwater challenges and opportunities. Balkemam, Abingdon, 478 pp

Moench M (2003) Groundwater and poverty: exploring the connections. In: Llamas MR, Custodio E (eds) Intensive use of groundwater: challenges and opportunities. Swets and Zeitlinger, The Netherlands

Moench M, Caspari E et al (eds) (1999) Rethinking the mosaic: investigations into local water management, Kathmandu. Nepal Water Conservation Foundation and the Institute for Social and Environmental Transition

Moench M, Burke J, Moench Y (2003a) Rethinking the approach to groundwater and food security. Food and Agriculture Organization of the United Nations (FAO), Rome. Water reports, vol 24, 52 pp

Moench M, Dixit A, Janakarajan S, Rathore MS, Mudrakartha S (2003b) The fluid mosaic: water governance in the context of variability, uncertainty and change. A synthesis paper, NWCF (Nepal) and ISET (USA) publ., 66

MoPE (2004) Initial National Communication to the conference of parties of the United Nations framework convention on climate change. Ministry of Population and Environment of Nepal, Kathmandu, p 153

Mudrakartha S, Madhusoodhanan MP, Srinath J (2003) Community management of groundwater: a study of Bhanavas, Samrapur and Nana Kothasana Villages of Satlasana Taluka, Mahesana District, Gujarat. Vikram Sarabhai Centre for Development Interaction

NASC-NRCS (2011) The state of arsenic in Nepal - 2011. Nepal arsenic steering Committee/ Nepal Red Cross Society. Kathmandu, Nepal

NCVST (2009) Vulnerability through the eyes of vulnerable: climate change induced uncertainties and Nepal's development predicaments, Institute for social and environmental transition-Nepal (ISET-N, Kathmandu) and Institute for social and environmental transition (ISET, Boulder, Colorado) for Nepal climate vulnerability study team (NCVST) Kathmandu

Pandey VP, Kazama F (2011) Hydrogeologic characteristics of groundwater aquifers in Kathmandu Valley, Nepal. Environ Earth Sci 62(8):1723–1732. https://doi.org/10.1007/s12665-010-0667-3

Pandey VP, Chapagain SK, Kazama F (2010) Evaluation of groundwater environment of Kathmandu Valley. Environ Earth Sci 60:1329–1342

Pandey VP, Shrestha S, Kazama F (2012) Groundwater in Kathmandu Valley: development dynamics, consequences and prospects for sustainable use. European Water 37:3–14

Pandey VP, Shrestha S, Kazama F (2013) A GIS-based methodology to delineate potential areas for groundwater development: a case study from Kathmandu Valley, Nepal. Appl Water Sci 3:453–465

Pant BR (2011) Ground water quality in the Kathmandu Valley of Nepal. Environ Monit Assess 178(1–4):477–485. https://doi.org/10.1007/s10661-010-1706-y

Pathaka DR, Yatabeb R, Bhandary NP (2013) Statistical analysis of factors affecting groundwater quality in shallow aquifer of Kathmandu, Nepal. Int J Water Res 1(1):12–20

Practical Action (2009) Temporal and spatial variability of climate change over Nepal (1976-2005)

Rana K (2011) Uses of ground water in Nepal. Second small towns water supply and sanitation sector project department of water supply and sewerage, Nepal. http://www.iges.or.jp/en/naturalresource/groundwater/PDF/activity20110602/S14_Mr.Krishna_Rana_Nepal.pdf. Accessed on 19 June 2016

Sada R, Shrestha A, Karki K, Shukla A (2013) Groundwater extraction: implications on local water security of peri-urban area of Kathmandu Valley. Nepal J Sci Technol 14(1):121–128

Shah T (1993) Groundwater markets and irrigation development: political economy and practical policy. Oxford University Press, Bombay

Shah M (2013) Water: towards a paradigm shift in the twelfth plan. Econ Polit Wkly XLVIII: 40–52 (Special Article)

Shah T, Desai R (2002) Decentralized water harvesting and groundwater recharge: can these save Saurashtra and Kutch from desiccation? Paper presented at 1st IWMI–Tata Annual Water Policy Work

Shah T, Alam M, Dinesh KM, Rashmi KN, Singh M (2000) Pedaling out of poverty: social impact of a manual irrigation technology in South Asia. Working paper. International Water Management Institute (IWMI) research report, no. 45, Colombo, Sri Lanka. URI: http://hdl.handle.net/10535/3757

Shankar K (1976) Water resources development with references to surface water hydrology in Nepal. Paper presented to the symposium on water and energy resources 22–24 November, at the Centre for Economic Development and Administration, Kathmandu

Sharma BR, Amarasinghe UA, Sikka A (2008) Indo-Gangetic River basins: summary situation analysis. International Water Management Institute, New Delhi, India. http://cpwfbfp.pbworks.com/f/IGB_situation_analysis.PDF

Shrestha KB (2001) Concepts and methods of geostatistics in agricultural sciences and forestry with an application in groundwater data. PhD thesis, Technical University of Vienna, Austria

Shrestha S (2017) The contested common pool resource: groundwater use in urban Kathmandu, Nepal. Geogr J Nepal 10:153–166. Central Department of Geography, Tribhuvan University, Kathmandu, Nepal

Shrestha AB, Aryal R (2011) Climate change in Nepal and its impact on Himalayan glaciers. Reg Environ Change 11(S1):65–77

Shrestha D, Shukla A (2010) Private water Tanker Operators in Kathmandu: analysis of water services and regulatory provisions. A paper present in regional conference on water & governance, organized in Bhutan, SaciWATERs

Shrestha AB, Wake CP, Mayewski PA, Dibb JE (2000) Precipitation fluctuations in the Nepal, Himalaya and its vicinity and relationship with some large scale climatological parameters. Int J Climatol 20:317–327

Shrestha SM, Dhakal P, Khadka M, Shrestha S (2010) Status of arsenic in groundwater of Kathmandu Valley, Nepal. In: Proceedings of the first national youth conference on environment (3–4 June 2010), Kathmandu. Himalayan Alliance for Climate Change, Kathmandu, Nepal

Shrestha SM, Rijal K, Pokhrel MR (2013) Arsenic contamination in the deep and shallow groundwater of Kathmandu Valley, Nepal. Sci World 11(11)

Shrestha SM, Rijal K, Pokhre, MR (2014) Spatial distribution and seasonal variation of arsenic in groundwater of the Kathmandu Valley, Nepal. J Inst Sci Technol 19(2):7–13. Institute of Science and Technology, Tribhuwan University

Shrestha AB, Agrawal NK, Alfthan B, Bajracharya SR, Maréchal J van Oort B (eds) (2015) The Himalayan Climate and Water Atlas: impact of climate change on water resources in five of Asia’s major river basins. ICIMOD, GRID-Arendal and CICERO

Sigdel M, Ikeda M (2012) Summer Monsoon Rainfall over Nepal Relatedwith large-scale atmospheric circulations. J Earth Sci Clim Change 3:112. https://doi.org/10.4172/2157-7617.1000112

Stuurman RJ, Griffioen J (2003). System based groundwater management. Three cases with groundwater management problems. Commissioned by TCB Soil Protection Technical Committee

Taylor RG et al (2013) Groundwater and climate change. Nat Clim Change 3:322–329

Tuinstra J. Wensem VJ (2014) Ecosystem services in sustainable groundwater management. Sci Total Environ 798–803. https://doi.org/10.1016/j.scitotenv.2014.03.098

Udmale P, Ishidaira H, Thapa BR, Shakya NM (2016) The status of domestic water demand: supply deficit in the Kathmandu Valley, Nepal. Water 8(5):196. https://doi.org/10.3390/w8050196

UNEP (2001) Nepal: state of the environment. United Nations Environment Programme and International Centre for Integrated Mountain Development, Kathmandu, Nepal, p 211

UN-Habitat (2006) Rainwater harvesting and utilisation, Blue drop series, Books 1 to 3. United Nations Human Development Programme, Water and Sanitation Infrastructure Branch, Nairobi

Upadhyay SK (1993) Use of groundwater resources to alleviate poverty in Nepal: policy issues. In: Kahnert F, Levine G (eds) Groundwater irrigation and the rural poor: options for development in the Gangetic Basin. World Bank, Washington DC

Upadhyay B (2004) Tradle pumps transform rural life in Nepal Tarai. Appropr Technol 31(4)

World Bank (2009) Shared views on development and climate change. Retrieved August 23, 2010, from http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/SOUTHASIAEXT/0,contentMDK:22038355,pagePK:146736,piPK:146830,heSitePK:223547,00.html. Accessed on 18 June 2016

World Bank (2016) High and dry: climate change, water, and the economy. World Bank, Washington, DC. License: Creative Commons Attribution CC BY 3.0 IGO

Young OR (2011) Effectiveness of international environmental regimes: existing knowledge, cutting-edge themes, and research strategies. Proc Natl Acad Sci 108(50):19853–19860. https://doi.org/10.1073/pnas.1111690108

Chapter 43
Challenges and Opportunities of Groundwater Management in Pakistan

Asad Sarwar Qureshi

Abstract Groundwater is playing a critical role in supporting irrigated agriculture which is producing about 90% of the total grain production in Pakistan. However, uncontrolled and unregulated exploitation of this resource has questioned its ability to feed the rising population. This demands an urgent action to bring a balance between recharge and discharge components. The challenge is to work on both supply-side and demand management solutions. Effective implementation of governing laws is needed to manage groundwater abstraction. Adoption of water conservation practices, introduction of micro-irrigation technologies, and using groundwater to grow high-value crops can assist in boosting groundwater economy. There is also a strong need to rationalize cropping patterns keeping in view food demands of the country and the sustainable supply of groundwater. Educational programs should be initiated to create awareness for all groundwater users to maximize economic returns by growing high-value crops and adopting water conservation practices to minimize groundwater extraction.

43.1 Introduction

Pakistan is the third largest consumer of groundwater with about 9% of the total groundwater extraction in the world (Giordano 2009). The cropped land occupied by groundwater irrigation in Pakistan is 4.6% of the world's total groundwater irrigated area (Siebert et al. 2010). Increased use of groundwater in Pakistan helped in the expansion of irrigated area after the 1960s' Green Revolution, which increased irrigation water demand by about three times (Ahmad et al. 2004). In subsequent years, the reduction in surface water supplies and the urge to increase irrigated area kept the water demand on rise. This prompted farmers to increase groundwater exploitation (Leghari 2012). Presently, Pakistan is among those

---

A. S. Qureshi (✉)
Senior Scientist—Irrigation and Water Management, International Center for Biosaline Agriculture (ICBA), Dubai, United Arab Emirates
e-mail: a.qureshi@biosaline.org.ae

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_43

countries where groundwater withdrawals exceed renewals and the groundwater resources are not enough to meet the unimpededly outpacing irrigation water demands (Wada et al. 2010; Qureshi 2015).

The surface water availability in Pakistan is not sufficient to support year-round basin-wide intensive cropping systems. In addition, there is a possibility of additional reduction in surface water supplies because the storage volume of the major reservoirs is decreasing due to sedimentation. This deficit between demand and supply of surface water is usually rendered through groundwater abstraction. During the last three decades, groundwater has played a crucial role in thwarting water shortages and to guarantee food security for the increasing population of Pakistan. However, the nature of occurrence of groundwater coupled with complexity of the aquifer, and historic development approaches have seriously threatened the sustainability of Indus basin aquifer from which most of our groundwater is derived. It is increasingly realized that negligence on this issue could be disastrous for the economy of the country. Therefore, there is a strong need to give special attention to the management of this valuable resource base at all levels from policymakers to actual users of water.

The large-scale groundwater exploitation in Pakistan has helped in combating hunger, reducing poverty, and achieving economic growth. In water short areas of Pakistan, unrestricted access to groundwater has helped farmers in attaining high crop yields and creating opportunities to diversify cropping patterns and to overcome miseries of low rainfall years. However, unregulated and uncontrolled groundwater exploitation has raised serious concerns about the sustainability of irrigated agriculture because it produces more than 90% of the total grains in Pakistan. The dependence of two-thirds of the rural population on groundwater for food security and to earn their livelihood has further compounded the problem. Therefore, it is now broadly realized that Pakistan needs to take serious steps to create an equilibrium between groundwater discharge and recharge. As the scope for increasing water supplies is limited, controlling demand by optimizing water use in agriculture should be given more attention.

This chapter reviews the role of groundwater in increasing the productivity of irrigated agriculture in Pakistan. It also discusses difficulties in managing groundwater in the sociocultural environment of Pakistan and attempts to identify strategic areas for policymakers to intervene to ensure sustainable management of groundwater resources. More related information regarding groundwater of South Asia is available in Mukherjee et al. (2018).

43.2 Water Resources of the Indus Basin

The Indus basin has the largest irrigated area on any one river system. The total area of the Indus basin is 1.17 million km^2 with an annual water availability of 244 billion m^3. Out of this total area, 632,954 km^2 is in Pakistan, 373,887 km^2 is in India, 86,432 km^2 is in China, and 76,542 km^2 is in Afghanistan. The flows originated from the Indus River and its tributaries (Jhelum, Chenab, Ravi, Sutlej, Beas, and Kabul) are the major source of surface water in Pakistan. The rainfall in the catchment areas and the water obtained from the snow and glaciers melt is the major source of inflow for these rivers. The small ephemeral streams outside the Indus basin flow only during the rainy season and are of less importance in terms of overall water availability. The Indus Basin Treaty of 1960 permitted Pakistan full use of Indus, Jhelum, and Chenab rivers, whereas India was authorized to use flows of Ravi, Sutlej, and Beas rivers. Because of this treaty, Pakistan constructed a huge network of link canals, barrages, and dams, which makes the Indus basin largest contiguous irrigation system in the world (Chap. 1, Fig. 1.3). The network of Indus basin comprises of 4 storage dams (Warsak, Chasma, Mangla, and Tarbela), 16 barrages, 12 link canals, and 44 canal commands (23 in Punjab, 14 in Sindh, 5 in Khyber Pukhtunkhwa, and 2 in Baluchistan). Main features of the Indus Basin Irrigation System (IBIS) are shown in Fig. 43.1.

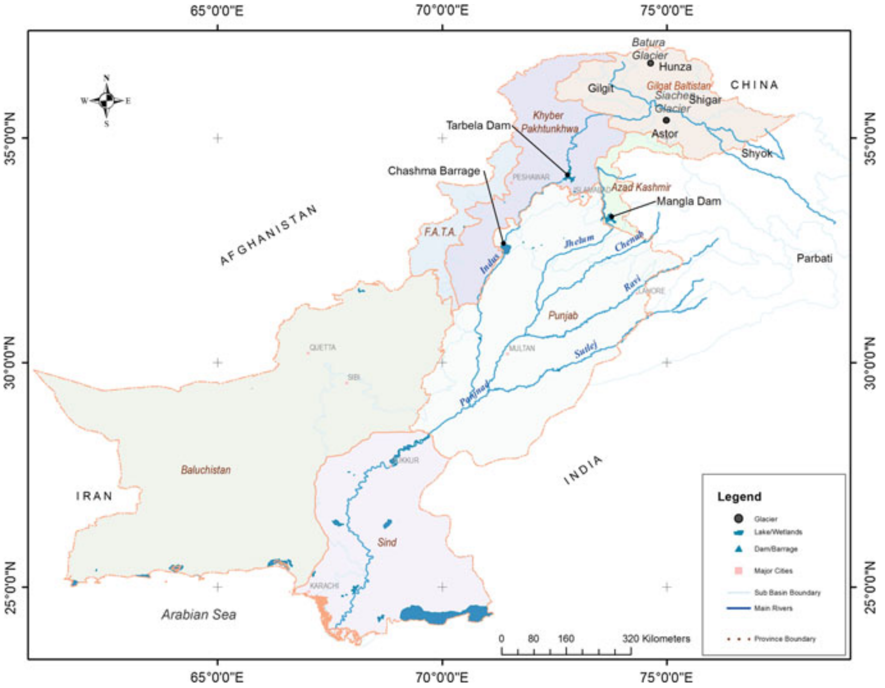


Fig. 43.1 Main features of the Indus Basin Irrigation System (IBIS)

The average annual flow brought in by the Indus River and its tributaries is 190 billion cubic meters (Bm^3), of which 179 Bm^3 comes from the Indus, Chenab, and Jhelum rivers, whereas the rest 11 Bm^3 is contributed by Ravi, Sutlej, and Beas rivers. About 130 Bm^3 is diverted for irrigation, 50 Bm^3 flows to the sea, and 10 Bm^3 is wasted due to soil evaporation and seepage losses from the canal network. Presently, out of 190, 177 Bm^3 is allocated for agriculture, 7.6 Bm^3 for domestic purposes, and the rest 5.7 Bm^3 for industrial purposes (Bakshi and Trivedi 2011).

The total area irrigated by the Indus Basin Irrigation System (IBIS) is 16 million hectares (mha), out of which only 8.6 mha has year-round access to surface water supply while the rest gets water during the summer season only. The water availability in the IBIS may vary between 230 and 120 Bm^3 depending on the year. This makes the storage critical for agriculture in Pakistan particularly during the winter season because 85% of the flow occurs during the summer season.

The water quality of Indus River (Chap. 1, Fig. 1.3) and its tributaries is suitable for irrigation. The river water quality degraded toward the tail reaches of the canal system. It varies from 200 ppm at the head reaches to 400 ppm at the tail reaches. The discharge of drainage effluents into the rivers and canals is considered as the major reason for this degradation of water quality. The BOD values in most river systems range between 2 and 5 mgl^{-1}. The River Ravi is by far the most polluted river (BOD = 77 mgl^{-1}) because it accrues 47% of the total pollution load discharged into the rivers of Pakistan. The DO contents in most of the rivers are higher than the threshold levels of 4 mgl^{-1} (Halcrow 2003).

The groundwater quality in major parts of Sindh, Punjab, Baluchistan, and south Khyber Pakhtunkhwa provinces is not suitable for irrigation and drinking purposes. The quality of groundwater in Punjab and Sindh is closely linked to the river morphology. The salt concentrations in the shallow groundwater of Punjab are often higher than 3000 mgl^{-1} (PHED 1999). However, in some areas of Punjab, salt concentration in the groundwater may go up to 20,000 mgl^{-1} or more. The fresh groundwater occurs in lenses below the rivers. The thicknesses of these lenses are decreasing with distance away from the river. In the Thal Desert, Cholistan region, and the lower reaches of Indus plain in Sindh, groundwater is even more saline. Generally, large parts of the southern Pakistan have groundwater of poor quality. In the coastal areas of Sindh, groundwater is extremely saline due to seawater intrusion.

43.3 Characterization of the Indus Basin Aquifer

The dominant physiographic units are the alluvial plain of the Indo-Gangetic Plain, which consists of sand and silt and minor amounts of gravel and clay. In accordance with their mode of deposition by large constantly shifting rivers, the alluvial deposits are heterogeneous, and individual strata have limited horizontal and vertical continuity. The alluvium of the Punjab plains has been deposited by the present and ancestral tributaries of the Indus River. The Indus plain is underlain with rich alluvial deposits more than 300 m deep. The alluvium of aquifer has medium sand to silty clay texture with predominance of sandy sediments. The lithology of the alluvium shows a series of geologic sections in each doab, with the heterogeneous character of the uppermost 200 m of the alluvium in downstream and sloping directions and the arbitrary spreading of clay zones. The alluvial deposits of the Punjab, in spite of their heterogeneous composition, form a unified highly transmissive aquifer, in which groundwater occurs for the most part under water table conditions. The uppermost 100 m of the compacted aquifer is the most productive zone. Small capacity tubewells (50–100 l per second) can theoretically be installed almost everywhere.

The underlying aquifer in IBIS covers an area of 16 mha, of which 6 mha is covered by good quality groundwater and the remaining 10 mha with poor-quality groundwater (Qureshi et al. 2010). The alluvium beneath about two-thirds of the Punjab is saturated to an average depth of 200 m or more, with water of acceptable quality for irrigation supply. The average concentration of dissolved solids in these supplies is less than 1,000 ppm. The upper limit of concentration is fixed at 1,800–2,000 ppm, which allows to mix groundwater with canal water at a ratio of 1:2. The aquifer is recharged from precipitation and leakage from the rivers, unlined canals, and percolation from the cropped lands.

In any event, assuming an effective porosity of 20% for the saturated sediments, the available volume of groundwater is estimated at 2470 Bm^3. The safe groundwater yield is about 68 Bm^3, whereas the groundwater extraction has already reached to 51 Bm^3. The remaining groundwater potential is in mountainous areas (e.g., Balochistan) where exploitation of groundwater is not economically feasible. This means that groundwater resource in Pakistan is almost exhausted.

This rapid growth of private tubewells for the extraction of groundwater for irrigation proceeded without consideration of its impact on the aquifer, which as has been said is both complex structurally and in terms of quality of water it holds in storage. Obviously uncontrolled and unregulated extraction got concentrated closer to the rivers and away from the center of *doabs* that are underlain with highly salinized water. This led to migration of saltwater to sweet water areas in many places.

Earlier, it was thought that the saltwater and freshwater interface as it moves caused mixing due to molecular diffusion which is a very slow process. But later scientific studies indicated that the mixing was taking place due to dispersion, which is thousands of times faster process depending on aquifer characteristics. As can already be seen unchecked and unplanned growth of private tubewells will exacerbate mixing and cause untold harm to sustainability of the aquifer and long-term use of groundwater.

43.4 Development of Irrigation in the Indus Basin

The major objective of the development of IBIS was to provide water over large areas to facilitate the settlement and agricultural prospects for the disintegrated population (Jurriens and Mollinga 1996). However, even today, the system is gravity run supply-based and has no relevance with the crop water demand during different growing seasons. The system requires minimum operational and management skills, but with an intrinsic disadvantage of inflexibility. The system was designed for an annual cropping intensity of 70%, which has now increased to 150% due to rising demand for food. The consistent poor maintenance of the system has reduced its efficiency to 35–40%, which has further reduced the surface water availability per unit of irrigated land (Tarar 1995). The Indus plain does not have a well-defined drainage system. The differences in topography helps in generating surface runoff during the monsoon and flooding season. Due to poor drainage conditions, flooding of agricultural lands during the monsoon season has become a permanent feature in many parts of the Indus basin.

The groundwater table levels at the time of IBIS development were 20–30 m below the soil surface; therefore, provision of subsurface drainage system was not realized. However, due to continuous seepage from network of canals and consistent percolation losses from irrigated fields, groundwater table started rising resulting in large-scale waterlogging and salinity problems. These issues became worse in saline groundwater areas because pumping was restricted owing to quality concerns. Figure 43.2 shows the groundwater levels before and after the introduction of IBIS in the Punjab Province.

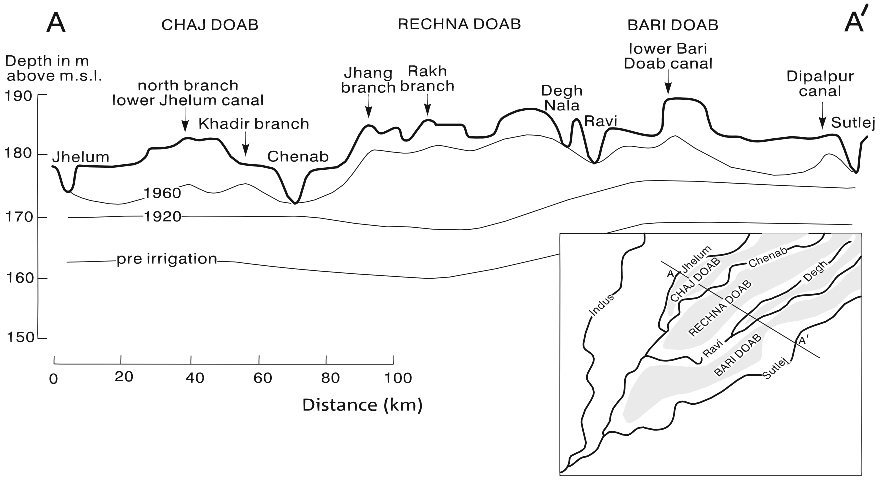


Fig. 43.2 Comparison of groundwater levels before and after (1920 and 1960) the introduction of irrigation system in the Punjab, Pakistan (Wolters and Bhutta 1997)

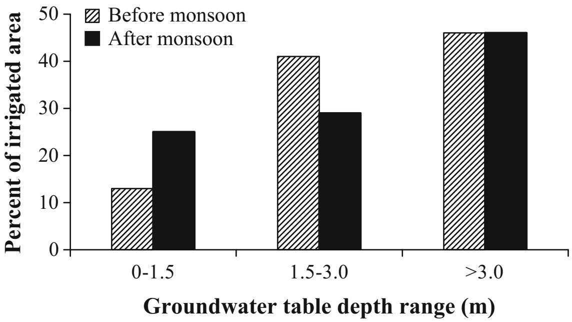


Fig. 43.3 Groundwater table depths in the Indus Basin before and after the monsoon season

The groundwater levels are deepest in the dry month of May and lowest after the rainy season (i.e., September). It is estimated that 30% of the cultivated area (4.7 mha) has a groundwater table within 1.5 m of the soil surface (severely waterlogged) after the summer rainy period (Wolters and Bhutta 1997). Before the rainy season, this area is deceased to 13% (2 mha). Currently, about 25% of the irrigated area in Punjab and 60% in Sindh are severely waterlogged, abandoning about 40,000 ha annually due to salinity problems (WAPDA 2010). Figure 43.3 shows that regardless of the season, 46% of the cultivated area in the Indus basin has groundwater tables deeper than 3 m.

43.5 Contours of Groundwater Development

Like many other dry regions of the world, the major problem of the water sector in Pakistan is also of low supply and high demand. The rainfall in the Indus basin accomplishes only 15% of the total agricultural water demand, and the rest needs to be provided through irrigation (Bhutta and Smedema 2007). As the surface water availability is only partially sufficient to meet evapotranspiration demand of crops, the gap is met through the exploitation of groundwater. The groundwater pumped for irrigation is essentially the water “recharged” from the irrigation network. Due to this interconnectivity, estimating the total available water resources needs much caution (Leghari 2012).

Historically, groundwater abstraction in Pakistan was started using open wells, hand pumps, karezes, and Persian wheels. However, extensive groundwater exploitation started in 1960s when 16,700 large capacity (0.080 m^3s^{-1}) tubewells were installed in the Indus basin under the Salinity Control and Reclamation Projects (SCARPs). These wells were installed to control waterlogging and salinity problems in 2.6 mha of irrigated area and increase water supplies at the farms by using the extracted groundwater for irrigation alone in conjunction with the canal water. Realizing the initial benefits, farmers started installing private wells of smaller capacities (28 ls^{-1}) in the 1980s. Since then, private wells are increasing at the rate of about 9.6% per year (Qureshi 2014) and the population of private wells

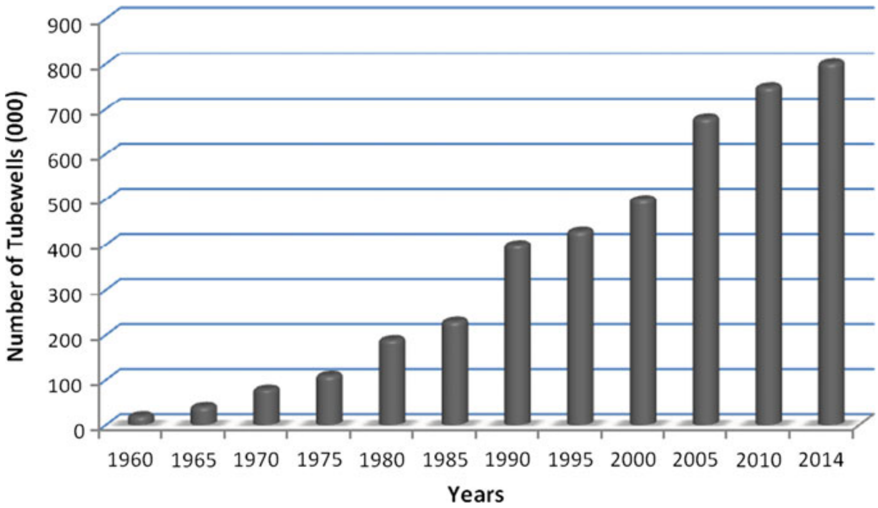


Fig. 43.4 Expansion of private wells in the Punjab Province of Pakistan

has reached to 1.2 million with 800,000 only working in Punjab (Qureshi et al. 2004). Provision of subsidized electricity and easy access to small diesel engines provided the much-needed incentive for this dramatic increase of groundwater wells over the last three decades (Fig 43.4).

Currently, in Pakistan, 52 Bm^3 of groundwater is extracted annually (Qureshi 2014). Of this, 14 Bm^3 is pumped using electric motors and the remaining 38 Bm^3 using small capacity private diesel engines. Due to increasing prices of electricity, farmers are more attracted to diesel pumps. Today, 87% wells are operated by diesel pumps compared to only 13% by electric motors (Qureshi 2014). Diesel pumps are preferred due to their feasibility for small and fragmented land holdings and low installation and operation and maintenance costs compared to electric wells (Shah 2007). Farmers have invested over US$400 million in groundwater wells, which has increased groundwater contribution in Punjab from 8% in 1960 to 60% in 2015. During the last two decades, groundwater has contributed more than 70% of the total increase in irrigation supplies. This has benefited national economy by US $2.0 billion in the form of agricultural production (World Bank 2008). Due to this process, the canal system is only recharging groundwater instead of delivering irrigation water. For example, canal system in Punjab contributes 80% of the groundwater recharge (Bhutta and Smedema 2007).

43.6 Socioeconomic Benefits of Groundwater Development

The groundwater development in Pakistan was accelerated due to the pressure to grow more food for the increasing population and to handle the decreasing surface supplies because of depleting storage capacity of reservoirs and changing rainfall patterns in the wake of climate change. The smallholder farmers could achieve predictable crop yields and diversify their income base, thereby creating more jobs and reducing poverty. Studies have shown that farmers with groundwater access attained 50–100% better crop yields than those who were fully reliant on canal water (Shah et al. 2003; Shah 2007). Farmers having access to groundwater also started growing water thirsty crops such as sugarcane and rice. This has helped increase the production of these crops and improve livelihood of farmers. At present, about 2.5 million farmers in Pakistan are using groundwater to supplement irrigation supplies (Qureshi 2011). However, most of these farmers understand very little about any adverse effects of unsystematic groundwater extraction on groundwater quality and soil salinization.

Groundwater has helped Pakistani farmers in stabilizing crops by creating a buffer during droughts and dry spells (Tsur 1990). During the extraordinary drought of 1998–2002, the surface water supplies were reduced by 26% and the growth of groundwater wells was increased by 59% because this was the only choice for irrigation and drinking water for humans and livestock (Bhutta 2002). Farmers having access to both surface water and groundwater earn five times higher than those limited to surface water only (Latif and Tariq 2009). This demonstrates that access to groundwater guarantees a farmer of increased income due to timely availability of irrigation water.

43.7 Challenges to Groundwater Economy in Pakistan

43.7.1 Depleting Aquifers Due to Overdraft

Despite unique benefits, unchecked groundwater pumping has resulted in dropping groundwater levels in many irrigated areas. Due to declining water tables, smallholder farmers on 5% irrigated area in Punjab and 15% in Baluchistan have lost access to fresh groundwater. In the *business as usual* scenario, this area may increase to 15% in Punjab and 20% in Baluchistan by 2025 (Qureshi et al. 2010). Comparison of changes in groundwater levels from 1993 to 2013 in the Punjab Province is shown in Fig. 43.5. In Sindh Province, changes in groundwater levels are less pronounced due to restricted exploitation pertaining to poor quality (Khan et al. 2008).

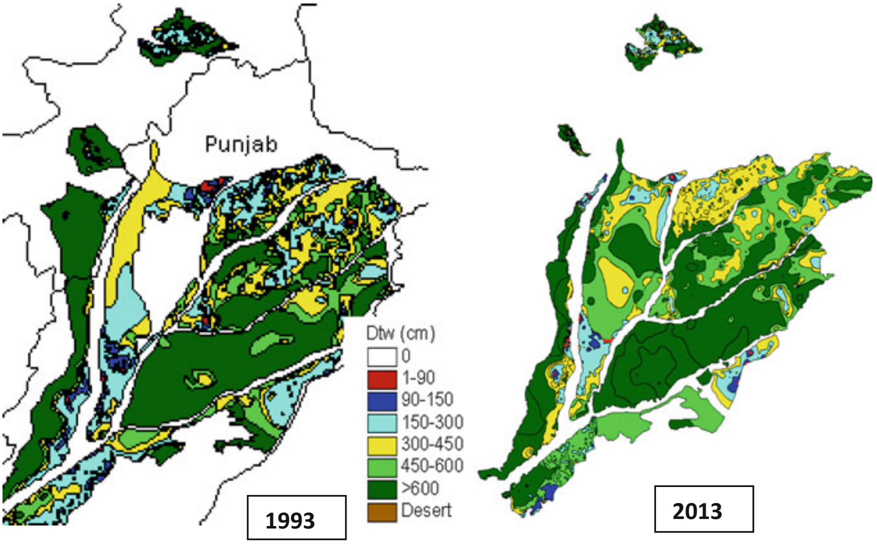


Fig. 43.5 Changes in groundwater levels in the Punjab Province of Pakistan (*Source* Qureshi et al. 2004)

43.7.2 Increased Energy Use and Environmental Concerns

The average annual groundwater extraction in Pakistan is about 52 Bm^3. This amount of groundwater is pumped through 1.0 million diesel wells (38 Bm^3) and 200,000 electric wells (14 Bm^3) (Qureshi 2014). In the Baluchistan Province where water table depths have gone much deeper than the capacity of diesel engines (>20 m), pumping has become costlier and energy intensive. Increased water table depth requires deeper drilling and installation of turbine/submersible pumps, which costs US$10,000 for each well. Due to surge in energy prices, the cost of pumping 1000 m^3 of groundwater has reached to US$4.2 for shallow wells and US$12 for a deep well (Qureshi et al. 2008). To make these costs affordable for smallholder farmers, electricity is heavily subsidized in Baluchistan. However, there are evidences that the subsidized electricity is exacerbating the problems of groundwater overdraft and mainly benefiting large farmers as they own most of the deep wells (Ahmad 2009). Therefore, urgent measures are needed to halt excessive groundwater extraction.

The annual extraction of groundwater for irrigation in Pakistan consumes 6 billion kWh of electricity and 3.5 billion liters of diesel, which releases 4.2 million metric tons (MMT) of CO_2 (Qureshi 2014). This amount is equivalent to 1.4% of total carbon emissions in Pakistan. Out of the total, 1.6 MMT of CO_2 is produced through electric pumps and 2.6 MMT of CO_2 from diesel pumps. This means that the extraction of each cubic meter of groundwater consumes 0.82 kWh of energy and emits 80 g of CO_2. This shows that increasing water use efficiency in agriculture will reduce energy use, stabilize aquifers, and help in controlling carbon emissions.

43.7.3 Deficient Recovery of Energy Costs

Increasing energy prices, poor mechanism of cost recovery and changing energy subsidy policies of the government has been a matter of grave concern for the groundwater irrigation economy. It was generally argued that diminishing energy subsidies may help reducing groundwater extraction because direct management through authorization permits will not be effective in the Pakistan (Shah 2007). Learning from the Indian experience, Pakistan also decided to use energy pricing policies as a surrogate for groundwater management.

The electrification of groundwater pumps started in 1970s when the government decided to facilitate farmers by bearing all capital installation costs for wells and electricity tariffs were subsidized. This initiative increased the number of wells from 37,000 to 84,000 within 5 years. However, this created huge burden for the government to monitor electric meters to collect electricity charges from farmers (Qureshi and Akhtar 2003). In 1990s, government withdrew subsidies due to rising energy costs, which resulted in the replacement of large numbers of electric wells with the diesel wells. Smallholder farmers preferred diesel wells due to low installation and operational costs (Qureshi and Akhtar 2003).

The analysis done by the World Bank (2007) reveals that the changing energy prices in Pakistan forces farmers to shift from electric to diesel form of energy without any significant decline in groundwater overdraft. Currently, the electric wells are about 10% of the total private well population and their contribution is only 20% of the total groundwater extraction in Pakistan. This suggests that changing energy prices would not be a robust tool to manage groundwater overdraft in Pakistan, as has been the case in many parts of India. Therefore, there is a strong need to search for more innovative solutions to match with the sociocultural environment of Pakistan.

43.7.4 Deteriorating Groundwater Quality

The groundwater salinity in Pakistan is closely related to the river morphology. The shallow groundwater in Punjab is of low salinity (<1000 ppm), whereas the deep groundwater has higher salt concentrations (>3000 ppm). The deep groundwater is generally present in the areas located between the major rivers and canals. The groundwater quality in 77% of the irrigated area in the Punjab (4 mha) is suitable for irrigation. In the upper parts of Punjab where areas are subjected to heavier rainfall, groundwater has low mineralization. The groundwater in the dry areas of southern Punjab is not fit for drinking and agricultural purposes due to high salinity. In many parts of Punjab, groundwater also contains high fluoride (7–12 mgl^{-1}) and arsenic concentrations (50 $\mu\mathrm{gl}^{-1}$). In fresh groundwater areas of Punjab, quality of pumped groundwater has also degraded due to disproportionate pumping. According to recent estimates, about 70% of the wells extract saline groundwater, which is aggravating salinity problems in the irrigated areas. (Bhutta and Alam 2012). The distribution of saline groundwater area in four provinces of Pakistan is shown in Fig. 43.6.

The problems of groundwater quality in the lower parts of the Indus plain are more serious. In the Sindh Province, only 28% of the area is underlain by fresh groundwater, whereas the rest 72% is underlain by brackish groundwater. The fresh groundwater is confined to a small strip along the Indus River (Leghari et al. 2012). The coastal areas of Sindh and Makran coastal zone have saline groundwater (>3000 ppm) due to seawater intrusion. The groundwater in the Khyber Pakhtunkhwa Province tends to be fresher. In the saline groundwater, sodium and chloride ions are more common, whereas the presence of sulfate, magnesium, and potassium has also been observed in drinking water (Khan et al. 2013).

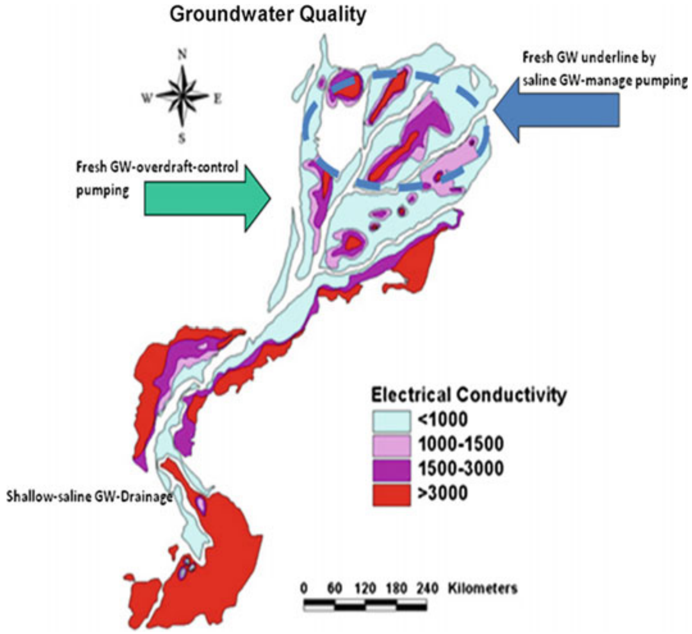


Fig. 43.6 Distribution of saline groundwater along the Indus Basin of Pakistan

The discharge of untreated wastewater into rivers and canals is the main source of pollution. The recent evaluations have shown that most of the groundwater is biologically contaminated (JICA 2010). The analysis of wastewater samples collected from 25 different localities of the Lahore city has shown concentrations of Cu, Mn, Ni, and Cd above the permissible WHO limits (Khan et al. 2013). The water from highly polluted River Ravi is posing a serious health risk for the large population who used it for drinking purposes (Basharat and Rizvi 2011; Ejaz et al. 2011).

43.7.5 Degradation of the Resource Base—Soil Salinization

The large network of canal system deposits salts in the Indus River. The total salts brought in annually are about 33 million tons (Mt). Out of this, 16.4 Mt outflows to the sea, while the rest 16.6 Mt is added to the system. Considering 16 mha of irrigated area in the Indus basin, one ton of salts is added to each hectare of land annually. Currently, about 4.5 mha is affected with soil salinity (WAPDA 2010). The extent of soil salinity is higher in the tail-end areas of the canal system where poor-quality groundwater is used for irrigation. The trends of surface salinity in four provinces of Pakistan are shown in Fig. 43.7. In the Sindh Province, 54% of the total irrigated land is salinized due to poor drainage conditions, lack of leaching opportunities, and existence of shallow saline groundwater (Bhutta and Smedema 2007). The seawater invasion is detrimental for the wetlands in the coastal areas. The mangrove forests over 130,000 ha are under serious threat and need to be protected.

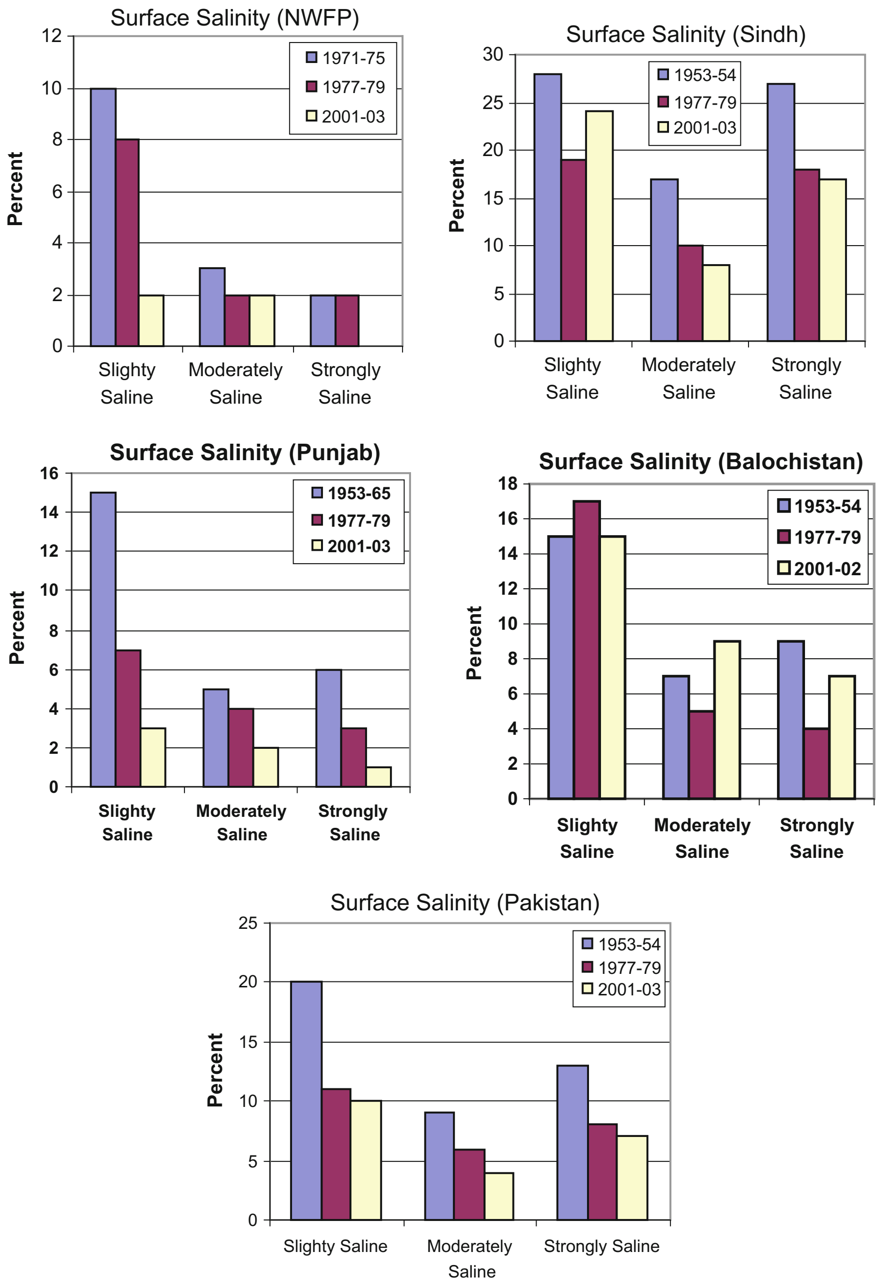


Fig. 43.7 Trends of surface salinity in four Provinces of Pakistan (*Source* WAPDA 2010)

43.8 Opportunities for Improving Groundwater Management

43.8.1 Stabilizing Aquifers

The emergence of groundwater challenges demands that the performance of existing surface water supply systems is enhanced, and groundwater management is given more attention. Generally, recharge to groundwater is taken as by-product of irrigation, whereas it should be considered necessary for sustainable groundwater management. Therefore, increasing recharge to groundwater is necessary to maintain strategic storage and at the same time regulate pumping according to hydro-geological conditions prevailing in different parts of the Indus basin. In many parts of the world, artificial groundwater recharge is used as an effective tool for stabilizing aquifers. The artificial recharge to total groundwater use varies from 12% in England to 30% in Germany (Li 2001). The rainwater harvesting community ponds at the village level in India and check dams in different parts of Pakistan are commonly used as artificial recharge structures (Shah 2007; Qureshi 2015).

For sustainable groundwater management in the Indus basin, aquifer can be divided into three zones. In Punjab, a thin layer of fresh groundwater is present above deep saline groundwater. The thickness of this layer varies from a few meters to over 150 m and is found close to rivers and *the area between two rivers*. In fresh groundwater areas, this layer is about 40 m thick, whereas it is less than 40 m in saline groundwater areas (Leghari 2012). This situation demands careful groundwater extraction to avoid mixing of fresh and brackish interface. The use of skimming well technology has proven successful in extracting groundwater from thin lenses without disturbing the underlying saline groundwater.

In the central Punjab where groundwater is fresh and shallow, overexploitation of groundwater is causing drastic water table drops and deterioration in groundwater quality. In these areas, unregulated groundwater extraction needs to be checked. This can be done by rationalizing crops, enforcing laws, and ensure consistent monitoring. In the lower parts of the basin, drainage of brackish groundwater should be given priority to lower groundwater levels below crop root zone. The establishment of groundwater safety zones may also help in controlling excessive groundwater pumping.

43.8.2 Rethinking Conjunctive Water Management

In 1960s when decision was taken to develop groundwater to lower the water tables and increase water supply at the farm gate, it was realized that for rationalizing use of water from all sources in the spirit of conjunctive use, water would be required to move from groundwater excess areas to groundwater short areas, or where groundwater quality is not suitable. However, due to heavy involvement of private sector in the groundwater development, this could not happen. Currently, surface water is used in conjunction with the groundwater on 70% of the irrigated area in Pakistan. This does not mean that this practice is effective and optimal. Over the last two decades, the groundwater irrigated area has jumped from 2.6 to 3.7 mha. On the other hand, area irrigated with the canal water has reduced from 7.9 to 6.8 mha (Fig. 43.8).

Contrary to common wisdom, groundwater is equally used by head-end and tail-end farmers. Logically, head-end farmers should use less groundwater than tail-end farmers because they have more access to surface water. This unmanaged groundwater use is causing waterlogging problems at the head-end of the canal system and increases soil salinization at the tail-end of the system because farmers continue to use poor-quality groundwater for irrigation (Qureshi et al. 2008). Consequently, crop yields and farm incomes of tail-end farmers are reduced to half compared to head-end farmers (Latif and Tariq 2009) (Fig. 43.8).

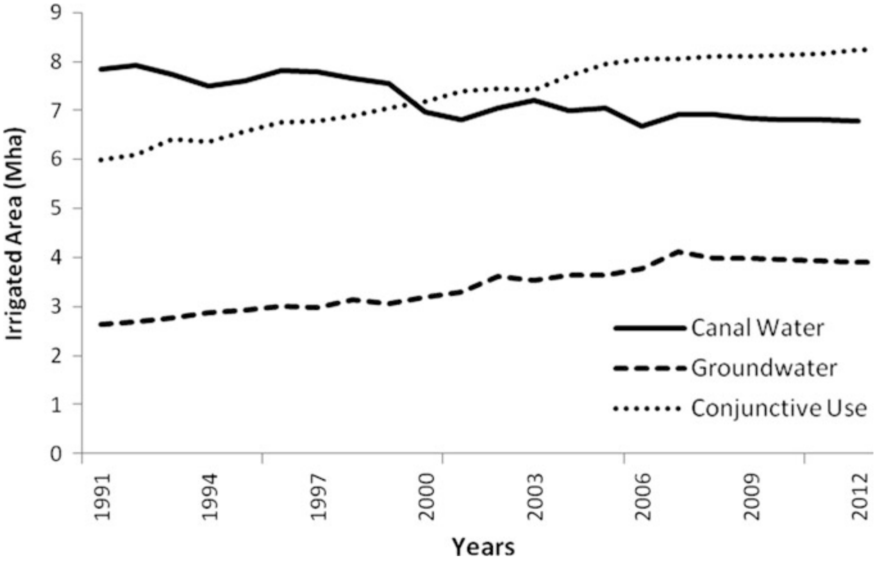


Fig. 43.8 Trends of different modes of irrigation in the Punjab Province of Pakistan

For salinity management in the Indus basin, existing water allocation criteria of providing equal access to canal water (*warabandi system*) needs serious debate. The canal water allocation to head-end farmers should be reduced to increase share of canal water for the tail-end farmers, and they should also be discouraged to use inferior quality groundwater for irrigation. The implementation of these water allocation strategies would require adjustments in policies to provide more access to groundwater to head-end farmers at the cost equivalent to canal water.

43.8.3 Increasing Economic Productivity of Groundwater

In most irrigated areas of world, groundwater is used to grow high-value crops. In China, for example, more than 60% of cotton, vegetable, and oil crops are grown using groundwater (Wang et al. 2009). In Mediterranean countries such as Andalusia and Spain, groundwater use efficiency is high because farmers apply only 3,900 m^3 per ha of groundwater compared to 5,000 m^3 per ha of surface water. Consequently, groundwater users in Spain attain higher economic return of US\$3.24 per m^3 compared to US\$0.95 per m^3 for surface water (Hernandez-Mora et al. 2010). By selecting proper crops, groundwater productivity can be increased. For example, groundwater productivity of peppers and tomatoes can go up to US \$5.52 per m^3 compared to only US\$0.25 per m^3 for crops like corn, sunflower, and cereals (Garrido et al. 2006). In the extreme dry regions such as Jordan River Valley, farmers have earned up to US\$16,000 per ha (Venot and Molle 2008). Similarly, in Morocco, 75% of the horticulture crops are grown with groundwater. This shows that understanding the economics of using groundwater for irrigation is very critical for managing groundwater.

In Pakistan, productivity of groundwater use is far lower than the regional standards. The productivity of groundwater for wheat crop is only 0.5 kgm^{-3} compared to 0.9 Kgm^{-3} in India and 1.6 Kgm^{-3} in California. Groundwater is used to grow high water-demanding crops such as rice and sugarcane. Considering the overall groundwater situation, Pakistan needs to decide whether to grow rice for export or replace it with other high-value crops to match the availability of groundwater. The sunflower, oil, fruit, and vegetable crops can help increase farm incomes and support national economy by reducing their import from other countries and saving huge foreign exchange.

43.8.4 Increasing Groundwater Use Efficiency

Farmers having access to groundwater tend to apply higher amounts of water for each irrigation event. Studies done in Pakistan have shown that irrigation amounts to wheat and cotton can be reduced by 40–50% without conceding yields and increasing soil salinity (Prathapar and Qureshi 1999; Qureshi and Bastiaanssen

2001). Adoption of water saving methods for rice such as direct plantation and alternate wet and dry irrigation technique can save substantial amount of irrigation water (Qureshi et al. 2006).

The sprinkler and drip irrigation techniques are widely used for promoting sustainable groundwater use. These methods improve application efficiency by reducing loss of water through soil evaporation and excessive deep percolation. However, impact of these technologies can only be achieved if farmers do not use the saved water to increase their irrigated area. The drip irrigation technique also saves energy and labor, reduces salinity, and increases crop yield, although these claims need more verification. The viability of micro-irrigation is more appealing where high-value crops are grown under greenhouses because productions are many folds higher and so does the incomes. In Pakistan, micro-irrigations are also getting popularity with the initial support of government. However, their large-scale adoption would require quality goods with access to lucrative international markets. In the absence of such arrangements, their economic feasibility for small farmers will remain a challenge.

Water conservation strategies such as improved land levelling, zero tillage, bed and furrow planting also have the potential to reduce water demand. Studies done in India, Pakistan, and Bangladesh have shown that up to 40% water can be saved by bed planting compared to flood irrigation (Hobbs and Gupta 2003); Mollah et al. 2009). The efficiency of water use for the rice crop can be increased by applying alternate wetting and drying method of irrigation (Bouman et al. 2007). This technique also has the capacity to increase concentration of zinc in the harvested rice (Price et al. 2013). However, fixed rotational irrigation system and lack of working knowledge are considered as the major limitations in the large-scale adoption of AWD in Pakistan.

43.8.5 Promote Use of Alternate Water Resources

Globally, 1500 Bm^3 of wastewater is produced every year and about 20 mha of land is irrigated with wastewater (Jiménez and Asano 2008). The Asian and African farmers intentionally use untreated wastewater because it contains essential nutrients needed by crops. The wastewater use for irrigation is also getting popular in the Arabian countries where 11 Bm^3 of wastewater is generated every year. Out of this, 5.6 Bm^3 is treated and 75% of this water is used for irrigation (Qureshi and Shoaib 2015). In Pakistan, 4.5 Bm^3 of wastewater is produced annually and only a small proportion of this is used to grow vegetables in peri-urban areas around the large cities, whereas the rest is discharged into rivers or thrown in open areas around cities (Qureshi 2011). This is causing huge environmental and health problems. Therefore, there is a strong need to develop a strategy for the profitable use of this resource and its environmentally safe disposal.

Currently, wastewater use for agriculture is limited to grow vegetables and fodder crops (Raschid-Sally and Jayakody 2007). However, by adopting proper management practices and selecting appropriate crops, wastewater can also be used to irrigate wheat, cotton, pearl millet, and many other crops. In deep groundwater areas, soil salinity can be managed through controlled seepage during the monsoon season. However, in shallow groundwater areas, installation of effective drainage systems is necessary for sustainable use of wastewater. The local governments should facilitate treatment of wastewater and devise effective policies for the safe use of this resource for agriculture. However, long-term impacts of wastewater use for agriculture on soil and human health need to be carefully evaluated.

43.8.6 Improving Groundwater Governance

Groundwater management has proven to be much more difficult relative to other natural resources. The direct management of groundwater (i.e., enforcing permit systems and extraction rights) has worked successfully where the State was strong to ensure implementation of governing laws and groundwater users are manageable, such as in Australia and Oman. Groundwater management has failed in countries where governments were relatively weak such as Jordan (Venot and Molle 2008), China (Wang et al. 2009), India (Shah 2007), and Pakistan (Qureshi et al. 2010). In Pakistan, India, and China, where users are numerous and dispersed, administration of groundwater becomes very difficult if not possible. For the similar reasons, even in Europe, monitoring of groundwater extraction by individual farmers has proved difficult to implement (Zoumides and Zachariadis 2009).

In many countries where groundwater is excessively used for agriculture, energy prices are used as a surrogate for groundwater pricing. In China, India, and Iran, electricity prices are subsidized. In China, for example, the electricity charges for agriculture wells are only 25% of the usual electricity rates (COWI 2013). In Iran and Mexico, energy charges for farmers are only 20% of the actual cost of electricity (FAO 2009; Soltani and Saboohi 2008). Generally, a flat rate of electricity is charged in India regardless of groundwater use (Shah 2007). In the Mediterranean region, manipulation of energy prices is possible, although it will not have any impact unless prices are raised significantly (Zoumides and Zachariadis 2009). Studies have shown that a 25% increase in electricity prices would have a marginal reduction (2–3%) in groundwater use in India (Badiani and Jessoe 2010). Pakistan has also miserably failed in controlling groundwater overdraft by regulating energy prices, and groundwater extraction keeps on rising because it was crucial to meet water demand (Qureshi et al. 2010).

Pakistan has presented plethora of laws for regulating groundwater extraction. Starting with the introduction of licensing and permit system in 1980s, the national groundwater management policy was drafted in 1999 under Provincial Irrigation and Drainage Authority (PIDA) Act. These rules suggested delineation of critical areas, licenses for tubewell installation in critical areas, and regular monitoring of all tubewells (Halcrow-ACE 2003). Despite all these efforts, effective implementation of these laws remained a challenge due to poor political will. The governance of groundwater has also become complicated because no single organization is responsible for managing this resource. Moreover, political governments intentionally allow farmers to extract groundwater to ensure rural food security as they could not fulfill their responsibility of maintaining the surface supply systems. Therefore, Pakistan needs to increase the capacity of institutions to effectively implement governing laws and organizational changes for the management of groundwater resources.

43.9 Conclusions

Groundwater is playing an important role in improving sustainability of irrigated agriculture in Pakistan. However, this luxury is now coming to an end because this resource is being over tapped in many areas, which has threatened the capacity of the Indus basin to feed its growing population. The deterioration of groundwater quality is even a more serious problem because large tracts of irrigated areas are becoming saline due to use of poor-quality groundwater for irrigation.

Pakistan should learn from its experience of groundwater development without proper planning and management. There is an urgent need to create balance between groundwater discharge and recharge. Pakistan requires a practical, persistent, and well-determined strategy for managing its groundwater resources with the active engagement of its users and increasing investments in promoting advanced water management techniques. The government needs to play a dynamic role as developer and implementer of the enabling laws and regulations and provider of well-tested decision support systems to facilitate the groundwater management process.

Pakistan needs to develop legal frameworks and tools suited to its needs. The major challenge is to increase supplies and decrease water demands. Water demands can be reduced by adopting water conservation technologies. The government policies should aim at encouraging the use of micro-irrigation technologies and using groundwater to grow high-value crops. Cropping patterns should be rationalized considering country needs and the availability of surface water and groundwater supplies. In addition, awareness raising campaigns about the management of groundwater resources and its impact on environment and crop production should be initiated.

Pakistan also needs to strengthen institutions by building their capacity and organizational changes to enable them to undertake challenging task of groundwater management. Pakistan should revisit its policies for the management of groundwater to make them more susceptible to local socioeconomic and cultural conditions. In addition, coordination and cooperation between organizations and institutes responsible for groundwater management need to be improved.

References

Ahmad S (2009) Water availability and future water requirements. Paper presented at the national seminar on “Water conservation, present situation and future strategy” organized by Ministry of Water and Power, Islamabad, Pakistan, May 2009

Ahmad I, Hussain SAS, Zahid MS (2004) Why the green revolution was short run phenomena in the development process of Pakistan: a lesson for future. J Rural Dev Adm 1–4:89–104

Badiani R, Jessoe KK (2010) Electricity subsidies, elections, groundwater extraction and industrial growth in India. Paper submitted to the pacific development conference 2010, Berkeley, University of California. Available at: http://mitsloan.mit.edu/neudc/papers/paper_194.pdf

Bakshi G, Trivedi S (2011) The Indus equation. Strategic Forsight Group C-306, Montana, Lokhandwala Complex Andheri West, Mumbai 400 053, India

Basharat M, Rizvi SA (2011) Groundwater extraction and wastewater disposal regulation—Is Lahore aquifer at stake with as usual approach. Pak Eng Congr 135–152

Bhutta MN (2002) Sustainable management of groundwater in the Indus basin. Paper presented at second South Asia Water Forum, Pakistan Water Partnership, Islamabad, Pakistan, Dec 14–16

Bhutta MN, Smedema LK (2007) One hundred years of waterlogging and salinity control in the Indus valley, Pakistan: a historical review. Irrig Drain 56:581–590

Bhutta MN, Alam M (2012) Prospective and limits of groundwater use in the Indus Basin of Pakistan. Paper presented in the World Water Day symposium organized by the Pakistan engineering council, Lahore, Pakistan, 22 March 2012

Bouman BAM, Humphreys E, Tuong TP, Barker R (2007) Rice and water. Adv Agron 96:187–237

COWI (2013) Groundwater in China. Part 1—Occurrence and use. COWI, Kongens Lyndby, Denmark

Ejaz N, Hashmi NH, Ghumman AR (2011) Water quality assessment of effluent receiving streams in Pakistan: a case study of Ravi river. Mehran Uni Res J Eng Technol 30(3):383–396

Food and Agriculture Organization of the United Nations (FAO) (2009) Groundwater management in Iran. Draft synthesis report. FAO, Rome, Italy

Garrido A, Martínez-Santos P, Llamas MR (2006) Groundwater irrigation and its implications for water policy in semiarid countries: the Spanish experience. Hydrogeol J 14(3):340–349

Giordano M (2009) Global groundwater? issues and solutions. Annu Rev Environ Resour 1:153–178

Halcrow-ACE (2003) Exploitation and regulation of fresh groundwater—main report. ACEnHalcrow JV Consultants, Gulberg III, Lahore, Pakistan

Hernández-Mora N, Martinez L, Llamas RM, Custodio E (2010) Groundwater in the southern member states of the European Union: an assessment of current knowledge and future prospects. Country report, European Academies Science Advisory Council. Available at: http://www.easac.eu/fileadmin/PDF_s/reports_statements/Spain_Goundwater_country_report

Hobbs PR, Gupta RK (2003) Resource-conserving technologies for wheat in the rice-wheat system. In: Improving productivity and sustainability of rice-wheat systems: issues and impact. American Society of Agronomy Special Publication, vol 65, pp 149–171

Japan International Cooperation Agency (2010) Preparatory study on Lahore water supply, sewerage, and drainage improvement project in Islamic Republic of Pakistan

Jurriens R, Mollinga, PP (1996) Scarcity by design: protective irrigation in India and Pakistan, ICID Journal 45(2):31–53

Jiménez B, Asano T (2008) Water reclamation and reuse around the world. In: Jiménez B, Asano T (eds) Water reuse: an international survey of current practice, issues and needs. IWA Publishing, London, p 648

Khan S, Rana T, Gabriel HF, Ullah M (2008) Hydrogeologic assessment of escalating groundwater exploitation in the Indus Basin, Pakistan. Hydrogeol J 8:1635–1654

Khan A, Javid S, Muhmood A, Mjeed A, Niaz A, Majeed A (2013) Heavy metal status of soil and vegetables grown on peri-urban area of Lahore district. Soil Environ 32(1):49–54

Latif M, Tariq JA (2009) Performance assessment of irrigation management transfer from Government to farmer-managed irrigation system: a case study. Irrig Drain 58:275–286

Leghari AN, Vanham D, Rauch W (2012) The Indus Basin in the framework of current and future water resources management. Hydrol Earth Syst Sci Discuss 8:2263–2288. https://doi.org/10.5194/hessd-8-2263-2011

Li Y (2001) Groundwater recharge. Unpublished. Nanjing Institute of Hydro and Water Resource, China

Mollah MIU, Bhuyia MSU, Kabir MH (2009) Bed planting—a new crop establishment method for wheat in rice-wheat cropping system. J Agric Rural Dev 7(1&2):23–31

PHED (1999) Hydrogeological map of Punjab. Public Health Engineering Department, Lahore

Prathapar SA, Qureshi AS (1999) Modeling the effects of deficit irrigation on soil salinity, depth to water table and transpiration in semi-arid zones with monsoon rains. J Water Resour Dev 15(1–2):141–159. https://doi.org/10.1080/07900629948989

Price AH, Norton GJ, Salt DE, Oliver Ebenhoeh O, Meharg AA, Meharg C, Islam MR, Sarma RN, Dasgupta T, Ismail AM, McNally KL, Zhang H, Dodd IC, Davies WJ (2013) Alternate wetting and drying irrigation for rice in Bangladesh: is it sustainable and has plant breeding something to offer? Food Energy Sec 2:120–129

Qureshi AS (2011) Water management in the Indus Basin in Pakistan: challenges and opportunities. Mount Res Dev 31:252–260. https://doi.org/10.1659/mrd-journal-d-11-00019.12011

Qureshi AS (2014) Reducing carbon emissions through improved irrigation management: a case study from Pakistan. Irrig Drain 63:132–138

Qureshi AS (2015) Improving food security and livelihood resilience through groundwater management in the Indus Basin of Pakistan. Global Adv Res J Agric Sci 4(10):687–710. ISSN: 2315-5094. Available online http://garj.org/garjas/home

Qureshi AS, Akhtar M (2003) Effect of electricity pricing policies on groundwater management in Pakistan. Pak J Water Resour 7(2):1–9

Qureshi AS, Bastiaanssen WGM (2001) Long-term effects of irrigation water conservation on crop production and environment in semi-arid zones. ASCE Irrig Drain Engg 127(6):331–338

Qureshi AS, Shoaib I (2015) Evaluating benefits and risks of using treated municipal wastewater for agricultural production under desert conditions. Paper presented in the DT12 conference, held in Cairo, 16–19 Nov 2015

Qureshi AS, Asghar MN, Ahmad S, Masih I (2004) Sustaining crop production under saline groundwater conditions: a case study from Pakistan. Aust J Agric Sci 54(2):421–431

Qureshi AS, Masih I, Turral H (2006) Comparing water productivities of transplanted and direct seeded rice for Pakistani Punjab. J Appl Irrig Sci 41(1):47–60

Qureshi AS, McCornick PG, Qadir M, Aslam M (2008) Managing salinity and waterlogging in the Indus Basin of Pakistan. Agric Water Manag 95:1–10

Qureshi AS, Gill MA, Sarwar A (2010) Sustainable groundwater management in Pakistan: challenges and opportunities. Irrig Drain 59(2):107–116

Raschid-Sally L, Jayakody P (2007) Understanding the drivers of wastewater agriculture in developing countries—results from a global assessment. In: Comprehensive assessment research report series, IWMI, Colombo, Sri Lanka

Shah T (2007) The groundwater economy of South-Asia: an assessment of size, significance and socio-ecological impacts. In: Giordano M, Villholth KG (eds) The agricultural groundwater revolution: opportunities and threat to development. CABI Publications, pp 7–36

Shah T, Debroy A, Qureshi AS, Wang J (2003) Sustaining Asia's groundwater boom: an overview of issues and evidence. Nat Resour Forum 27:130–141

Siebert S, Burke J, Faures JM, Renken KF, Hoogeveen J, Döll P, Portmann FT (2010) Groundwater use for irrigation: a global inventory. Hydrol Earth Sys Sci 3:3977–4021

Soltani G, Saboohi M (2008) Economic and social impacts of groundwater overdraft: the case of Iran. Paper submitted to 15th ERF annual conference, Cairo, Egypt, Nov 2008, pp 23–25

Tarar RN (1995) Drainage system in Indus plains—An overview. In: Proceedings of national workshop on drainage system performance in Indus plains and future strategies, Vol. II. Tandojam, Pakistan, pp 1–45, 28–29 January

Tsur Y (1990) The stabilization role of groundwater when surface water supplies are uncertain: the implications for groundwater development. Water Resour Res 26(5):811–818

Venot JP, Molle F (2008) Groundwater depletion in the Jordan highlands: can pricing policies regulate irrigation water use? Water Resour Manage 22(12):1925–1941

Wada Y, van Beek LPH, van Kempen CM, Reckman JWTM, Vasak S, Bierkens MFP (2010) Global depletion of groundwater resources. Geophys Res Lett 20:L20402

Wang J, Huang J, Huang Q, Rozelle SC, Walker HF (2009) The evolution of China's groundwater governance: productivity, equity and the environment. Q J Eng Geol Hydrogeol 25(1):141–158

WAPDA (2010) Hydropower potential in Pakistan, Lahore, Pakistan. www.wapda.gov.pk

Wolters W, Bhutta MN (1997) Need for integrated irrigation and drainage management, example of Pakistan. Proceedings of the ILRI symposium, towards integrated irrigation and drainage management, Wageningen, The Netherlands

World Bank (2007) Punjab groundwater policy—mission report. WB-SA-PK-Punjab GW Mission report, June 2007. www.worldbank.org/gwmate

World Bank (2008) World development report 2008. Washington, DC, p 96

Zoumides C, Zachariadis T (2009) Irrigation water pricing in southern Europe and Cyprus: the effects of the EU common agricultural policy and the water framework directive. Cyprus Econ Policy Rev 3(1):99–122

Chapter 44
The New Water: Opportunities and Challenges of the Rise to Prominence of Groundwater in Sri Lanka in the Face of Socioeconomic and Climatic Change

Sanjiv de Silva, Mohamed Aheeyar, Indika Arulingam and Herath Manthrithilake

Abstract Overall high annual precipitation in Sri Lanka belies significant spatial and temporal variation in surface water availability. The 'dry zone' comprising two-third of Sri Lanka's land area receives significantly less rainfall and has high precipitation rates and a five-month dry season. Nevertheless, these regions account for the majority of rice production, the staple crop, thanks largely to the ancient hydraulic civilization based on networks of rainwater harvesting (irrigation) tanks. This manipulation of surface water resources including modern surface irrigation schemes continues to form the backbone of dry zone farming. Groundwater irrigation has remained in the shadows except in the North where surface flows are absent. This scenario is now changing as population growth; poorly maintained infrastructure; commercial agriculture; sectoral competition for water and climate change combine to exert severe pressure on surface water resources. Since the dry zone is also home to a large number of Sri Lanka's poor households, and a close association exists between high poverty clusters and access to irrigation, the implications of water insecurity for a range of poverty indicators are clear. Not surprisingly, these pressures have prompted an increasing recourse to groundwater in several parts of the dry zone, as governments and farmers recognize the imperative to increase agriculture output, promote crop diversification, and improve agrarian incomes. Yet, with limited groundwater potential, limited detailed knowledge of this resource, and under-developed groundwater-oriented institutions, it is far from certain whether future groundwater exploitation can steer away from anarchy.

Keywords Sri Lanka · Groundwater · Water governance · Climate adaptation Resilience

---

S. de Silva (✉) · M. Aheeyar · I. Arulingam · H. Manthrithilake
International Water Management Institute, Head Quarters, Colombo, Sri Lanka
e-mail: s.s.desilva@cgiar.org

© Springer Nature Singapore Pte Ltd. 2018

A. Mukherjee (ed.), *Groundwater of South Asia*, Springer Hydrogeology,
https://doi.org/10.1007/978-981-10-3889-1_44

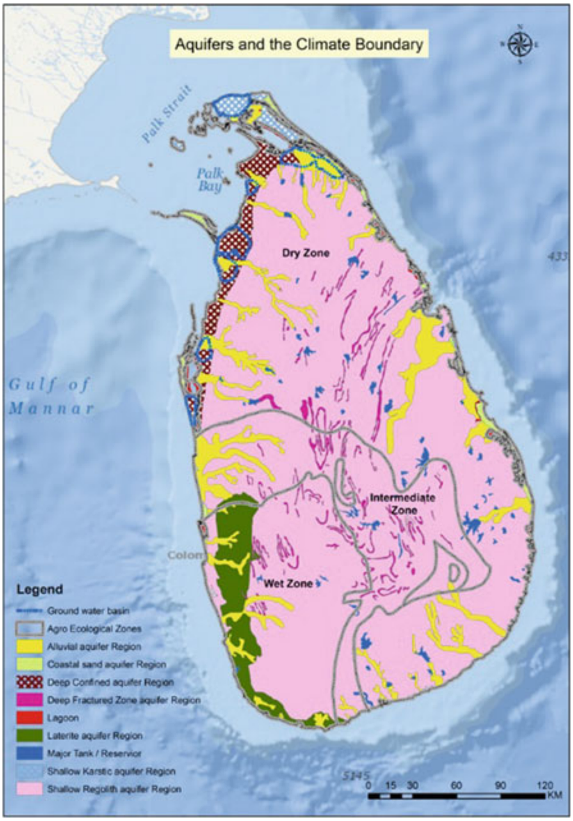


Fig. 44.1 Aquifers in Sri Lanka

44.1 Introduction

44.1.1 Groundwater in the Overall Water Context

An examination of the status and recent emergence to prominence of groundwater in Sri Lanka needs to be framed by the historical context of water use and its management in Sri Lanka (Chap. 1, Fig. 1.1), which has been dominated by an overall high annual precipitation level. At face value, this has created a perception of water security by virtue of ample surface water flowing in Sri Lanka's 103 major rivers which cover 90% of the islands land extent (Irrigation Department[1]). However, that this belies significant spatial and temporal variation is clear from the extensive hydrological civilization based on man-made rainwater storage and water conveyance for irrigation developed by the ancient kingdoms since at least

---

[1] http://www.irrigation.gov.lk/index.php?option=com_content&view=article&id=340&Itemid=245&lang=en. As defined under the Agrarian Services Act, No. 58 of 1979.

300 B.C. (Brohier 1935). This infrastructure, ranging from small village tanks to much larger tanks or reservoirs that supply entire regions, is a direct response to the natural segmentation of the island into three climatic zones based on rainfall (Fig. 44.1), where the ‘dry zone’ comprising roughly two-third of the land area receives on average less than 1,750 mm of rainfall (Punyawardane 2008), of which very little falls during the long dry season between May and September. This contrasts with an annual average evaporation rate of 1,700–1,900 mm (Panabokke et al. 2002) which makes clear that water in the dry zone is far from being abundant. Thus, the majority of the estimated 30,000 tanks (functioning and abandoned) of varying size are also distributed across this dry zone landscape (Mendis 2003). Between 12,000 and 16,000 of these functioning tanks are ‘small’ in scale (less than 80 ha[2]) according to Panabokke (2009) and provide water at village scale, while most dry zone villages possess several such tanks. As noted by Brohier (1935), some of these tanks have been in continuous operation for over 2,000 years. Another important feature is the ‘cascade’ approach to the use of many of these tanks, whereby a series of tanks are connected within a micro-(or meso-) catchment for storing, conveying, and using and reusing water. These cascades further represent a distinct small watershed or meso-catchment ranging from 13 to 26 km^2 in extent (Madduma Bandara 1995). These investments in water storage are intertwined with paddy cultivation as the mainstay of agrarian livelihoods especially in the dry zone, with typically one major rainfed (*maha*) crop and one surface irrigated crop in the dry (*yala*) season, traditionally utilizing water stored in the irrigation tanks.

Annual total freshwater withdrawals in Sri Lanka were estimated at 13 billion m^3 in 2014 according to the World Bank (2014), where irrigation for agriculture accounted for 87%, of which rice accounted for 82%. Employing nearly 30% of the total labor force, the agriculture sector is also an important foreign exchange earner, accounting for about 30% of the total earnings. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

44.1.2 Groundwater Resources

This manipulation of surface water resources through irrigation tanks continues to form the backbone of dry zone farming, while its prevalence in the national consciousness contributes to a hydraulic culture focused almost exclusively on surface water resources. Consequently, although Sri Lanka has six types of aquifer systems across its 65,000 km^2 land area (Fig. 44.1), and a variety of geological and hydrogeological settings, extraction of groundwater for agriculture has traditionally been limited to the northern and eastern provinces which lack perennial surface water resources. In the Jaffna Peninsula that forms the northern part of the island, for

---

[2] As defined under the Agrarian Services Act, No. 58 of 1979.

instance, groundwater use for domestic and agriculture purposes, has occurred for nearly 1,500 years (Panabokke and Perera 2005). Groundwater has however been used for drinking and other domestic purposes throughout the country and is the only source of domestic water in a number of districts, including Jaffna, Vavuniya, Batticaloa, and Mannar (Villholth 2013). In fact, despite this secondary role of groundwater in irrigation, it is estimated that over 55% of Sri Lanka's population relies on groundwater for their daily domestic needs (Herath 2006). The main types of both shallow and deep groundwater aquifers identified (Panabokke 2003) are: (1) Shallow unconfined karstic aquifers; (2) Deep confined sandstone and Miocene limestone aquifers; (3) Shallow quaternary unconfined coastal sand aquifers; (4) Alluvial aquifers of variable depth; (5) Lateritic (cabook) aquifers, and (6) Regolith aquifers of the hard-rock region. Investigations have shown that groundwater in the regolith aquifer occurs in two main forms, namely (i) the shallow regolith aquifer and (ii) the deeper fracture zone aquifer. The deep fracture zone aquifer occurs at random at depths of 30–40 m in the hard-rock metamorphic regions according to the presence of lineaments in the basement rocks. Each of these aquifers has distinct characteristics (Annex). Overall, the groundwater potential of Sri Lanka is lower compared to surface water resources. Total estimated groundwater potential is 7.8 billion m^3 per annum (UNEP 2005), equal to about 15% of the country's surface water resources (Climate Change Secretariat 2010), with rainwater as the main source of the recharge. According to WRI (2003), the amount of groundwater available in the island is 8 km^3, with another 7 km^3 shared between surface and groundwater.

Even among the six aquifers, about 90% of the island's land mass relies on the regolith (fractured crystalline) aquifer for groundwater supply, while the remaining groundwater supply is sourced from confined sedimentary type aquifers located mainly in the north and northwestern provinces of the country (Panabokke 2003). Yields of the regolith aquifer systems are reported to be l–4 L/s (Hapugaskumbura 1997), indicating the overall limitation to groundwater use in a significant portion of the country. Shallow aquifers play an important role in providing domestic supplies from traditional wells of between 6 and 9 m depth, and also in discharging water to rivers and other water bodies during low flow periods, while supporting wetlands and native vegetation (Panabokke and Perera 2005).

44.1.3 Emerging Water Stress, Socioeconomic Change, and the Rise of Groundwater in the Dry Zone

Despite Sri Lanka being categorized as a middle-income country, 6.7% of its population of 20.48 million was estimated to be living below the poverty line in 2012/13 (World Bank 2016a). Figure 44.2, adapted from a mapping of households below the poverty line by Amarasinghe et al. (2005), makes clear that a large number of these poor households remain within the dry zone. The same authors also found a close association between high poverty clusters and areas lying outside of

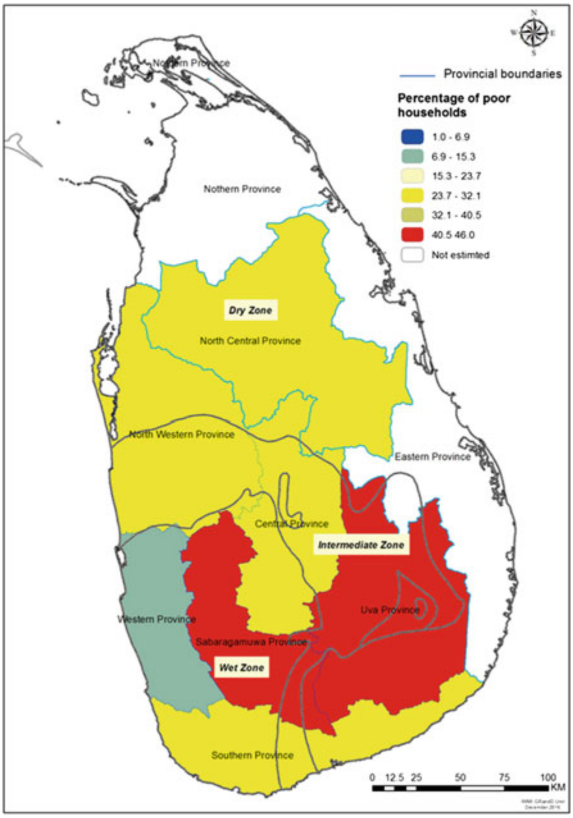


Fig. 44.2 Distribution of poor households in Sri Lanka. *Source* Adapted from Amarasinghe et al. (2005)

modern irrigation schemes, indicating the material influence of access to irrigation to the incidence of poverty. A number of factors can be attributed in explaining this finding, including the gradual loss of efficacy of the village tanks, a number of which are abandoned due to poor maintenance, while others' water-holding capacity has diminished due to siltation (Panabokke 2009). This diminished storage capacity contrasts with growing water demand in agriculture, industry, and urban sectors, and consequently, unless served by a modern irrigation scheme, many dry zone villages can in fact only cultivate rainfed rice, with agriculture in the dry season limited to slash and burn subsistence highland cultivation. This inability to generate economic returns during almost half of the year remains a significant challenge to agrarian communities, especially as Sri Lanka rapidly transitions to a middle-income country driven by a market economy that grew by an average of 6.4% between 2010 and 2015 (World Bank 2016b) concurrently consolidating a monetized market-based society. This, along with population growth, now places increasing pressure on agriculture (and water resources) to satisfy both domestic and export markets as well as to generate economic values that can meet the growing material aspirations of especially the youth.

Intensifying these anthropogenic drivers are the impacts of climate change. Although the predicted impacts of climate change in Sri Lanka vary according to the models used, Ahmed and Suphachalasai (2014) conclude that under a business-as-usual scenario, the impact would be an annual loss of 1.2% of GDP by 2050, which would increase to 6.5% in the long term. Impacts on agriculture predict both increases and decreases in yield, depending on the location of production and time-scale. Of particular relevance is Seo et al.'s (2005) prediction that changes to net income from rice production could decrease by 27–46%. Decreased precipitation in the central highlands is also expected to lead to a change in the catchment for the multipurpose Mahaweli Complex, by far the largest investment in providing dry season irrigation to paddy farmers in the dry zone (North Central Provinces). Consequently, due to the combined impact of reduced precipitation, increased potential evapotranspiration and rainfall seasons that end earlier, irrigation water requirements in this area are expected to increase by up to 23% (De Silva et al. 2007; Eriyagama et al. 2010). Since 71% of agriculture land holdings in Sri Lanka are less than one hectare, where surplus production is not common, smallholder farmers with land that is rainfed or irrigated from minor tanks are considered to be particularly vulnerable to the impacts of climate change (Esham and Garforth 2013). With respect to groundwater resources, Eriyagama et al. (2010) note that this has been the subject of only limited studies, even though most available sites for surface water storage are exploited, and previously under-developed groundwater resources may become increasingly important going into the future. Overall, the impact of climate change on the water sector in Sri Lanka will be felt more strongly by those dependent on the agriculture sector for livelihood and food security, with parts of the dry zone considered as some of the most at-risk areas (Eriyagama et al. 2010). This culmination of pressures has prompted recourse to groundwater in several parts of the dry zone, as both governments and farmers recognize the imperative to increase agriculture output, promote crop diversification, and improve agrarian incomes. These are discussed in the next section.

44.2 Current Trends in Groundwater Use

As already noted, increasing pressures on surface water resources are resulting in a growing demand for groundwater to meet domestic water needs, small-scale irrigation, industrial uses, and the service sector. This has led to groundwater extraction at an accelerated pace over the last few decades for the cultivation of high-value cash crops and other development activities that now exert considerable pressure on the shallow and ephemeral nature of groundwater resources in the country. The Government of Sri Lanka was instrumental in promoting groundwater irrigation through the National Agro-well Program initiated in the late 1980s to increase the income levels of rainfed farmers living in the dry zone through high-value crop cultivation. These emerging trends in groundwater use are discussed below.

44.2.1 Agricultural Use

Groundwater is cheap and an easily accessible source of irrigation for both poor and rich farmers, where pump ownership means access and use is controlled by the users themselves. The adoption of low-cost technologies for accessing groundwater (open/tube wells and pumps) has allowed farmers to grow high-value crops, minimize the risks posed by drought, and enhance income from higher cropping intensities. Income received by the groundwater irrigation in Sri Lanka is consequently 4–5 times higher compared to other South Asian countries due especially to diversification to high-value cash crops. For example, one acre (0.4 ha) of land cultivated with cash crops under agro-wells in Anuradhapura has provided a net income equivalent to the income of 5–15 acre (2–6 ha) of irrigated paddy (Shah 2013). Not surprisingly, extraction of groundwater for cash crop production has been increasing rapidly during the last two decades in the dry zone areas of Sri Lanka (IWMI 2003; Athukorala and Wilson 2012). The highest number of agro-wells is located in the regolith aquifer, which is replenished by the extensive irrigation tank cascade system functioning as recharge structures. Coastal sand aquifer areas in the northwestern and northeastern regions are extensively used for intensive agriculture in an area of around 125,000 ha (Panabokke and Perera 2005). While IWMI (2003) estimated the total number of agro-wells in the dry zone to be around 50,000 in the year 2000, Shah (2013) expects this number to have increased to 200,000–250,000 by 2013. This growth in groundwater used for agriculture also represents the evolution of a number of enabling factors such as the availability and affordability of pumps and machinery for well construction on the supply side, and several facets of the country's economic development that has generated the market and other conditions favorable for diversification of farming from the primary paddy crop to parallel production systems-based around high-value non-paddy crops (NPCs). These are demonstrated and discussed in the case studies presented in Sect. 44.3 that represent the major forms of emerging groundwater use in agriculture.

44.2.2 Industrial Uses

Groundwater is the primary source of water for export promotion zones, industrial estates, and small and large enterprises. For example, only a part of the water requirement of the 98 factories established within the Katunayake Export Processing Zone is supplied from surface water sources and the rest of the water requirement is fulfilled by groundwater obtained from 44 shallow and deep tube wells. These wells supply an estimated 3,000 m^3 per day. The tourist hotels in the Katunayake area and most of the private establishments located along the coastal belt also rely on this aquifer (Wijesekara and Kudahetti 2011), which is a growing industry especially after the cessation of the civil conflict in 2009. This is most likely to continue in the current context due to the cheapness of groundwater and the lack of potable water to meet the growing demand.

In the southwestern lateritic aquifers, high rates of extraction for industrial estates, the tourism industry, urban housing schemes, and bottled water projects exert considerable pressure on the groundwater resource (Panabokke and Perera 2005). Many industries have their own wells which, whether or not registered, are not monitored in terms of water extracted. Multiple industries, especially in the metropolitan area of Colombo and in stretches of the southwestern coast, take advantage of deep groundwater resources from self-managed wells.

44.2.3 Domestic Use

Groundwater is the preferred low-cost source of water for most rural and semi-urban domestic water supply (Table 44.1). The Department of Census and Statistics (2012) estimates that nearly 54% of the population in Sri Lanka was dependent on groundwater for drinking needs in 2011. This reflects the approximately 400 million m^3 households directly withdraw from domestic wells and tube wells. This figure does not reflect the populations covered by groundwater-based pipe-borne state-sponsored and other water supply schemes which account for nearly 30% of drinking water supply schemes in the country according to Panabokke and Perera (2005). The same authors therefore estimate that the total contribution of groundwater to domestic water supply may be as high as 80%. Moreover, this excludes the groundwater used as a supplementary source by households that receive pipe-borne water supplies (Herath 2006).

This dependence on groundwater for rural and semi-urban water supplies has spawned nearly 30,000 tube wells in various parts of the country (Prematilaka 2011) constructed during the last three decades by various organizations such as NWSDB, water resources board (WRB), foreign funded-projects, and private sector organizations. These wells are of various types, including hand pump wells for the rural populations, and several deep wells (Prematilaka 2011). There are also some shallow open dug wells constructed by local organization and individuals for which no reliable records are available. This dependence on groundwater in the domestic

Table 44.1 Available estimated annual groundwater withdrawals for domestic water supply

Users	Function	Total annual withdrawal (m^3)
NWSDB	Pipe-born domestic water supply	1,908[a]
Households	Primary source of domestic water supply	400 million
Households	Supplementary to surface drinking water schemes	Unknown

[a] Prematilaka (2011)

Source Compiled by authors from multiple sources sector is likely to increase in view of recent droughts where some regions such as Humbantota and Monaragala districts (Southern and Uva Provinces, respectively) run out of surface water supplies. This has prompted the NWSDB to look at the potential for supplementing domestic supplies from aquifers during drought periods (K. M. Premathilake,[3] pers. com.).

44.3 Case Studies Representing Emerging GW Use in the Agriculture Sector

44.3.1 Emerging Uses Outside of Surface Systems

44.3.1.1 The Evolution of High-Value Commercial Cropping in Kalpitiya

Kalpitiya is a low-lying sandy peninsula of 160 km^2 situated in the Northwestern Province of Sri Lanka (Fig. 44.3). The area is classified as part of the dry lowland (DL$_3$) agroecological zone with an average annual rainfall of about 900 mm. This rainfall is however limited to 2–3 months, with about 280 days in a year passing without rainfall. Available groundwater consists of a freshwater lens at 1–3 m depth floating over brackish water. The sandy aquifer is recharged by both direct infiltrations from the northeast monsoon and return irrigation flows.

With no surface irrigation or rainfed cultivation, farmers in Kalpitiya are completely dependent on groundwater. Before the 1990s, shallow dug wells were the main source of irrigation water. Each well costs approximately LKR 50,000–75,000 (USD 394–590). Groundwater use was effectively self-regulated as farmers used to irrigate manually with buckets, and any changes occurred in the water level were visible in the open dug wells. Manual irrigation required four to five person-days to irrigate one acre (0.4 ha), which limited the extent cultivated by a farmer from 0.1 to 1 ha. This changed with the introduction of energized water pumps in the mid-1980s and triggered substantial shifts in cultivation patterns and crop intensification. These pumps and hoses to convey the water to fields were adopted rapidly as this reduced the labor demand for irrigation by over 50%. This reduced dependence on labor also enabled an expansion in cultivation area. Further technological innovation occurred after 2005 with the gradual increase in labor cost, whereby, despite the labor savings from pumps, the average cost of irrigation accounted for nearly 35% of the total production cost (Melvani et al. 2006). Farmers therefore developed user-friendly and cost-effective local sprinkler irrigation systems. With the adoption of local sprinkler technology, crop intensification and commercialization of cultivation further expanded as this technology reduced the labor requirement to 0.5 person-days per acre (1.25 person-days per ha). Almost

---

[3] Manager (Groundwater Studies), National Water Supply and Drainage Board.

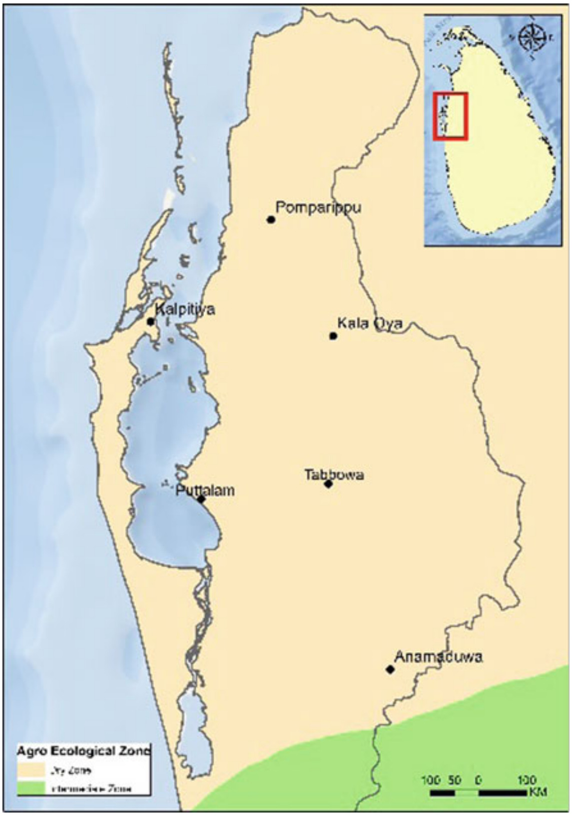


Fig. 44.3 Location of the Kalpitiya peninsula

all the farmers involved in cash crop cultivation have adopted this technology and have also expanded the area cultivated.

To support the sprinkler irrigation systems, farmers needed two to three extra wells per hectare to irrigate the expanded land, and by 2010 there were over 1,500 farmers using more than 4,500 tube wells/agro-wells (Hydrosult Inc. 2010). The construction of additional wells was simplified with the cost-effective and easy-to-construct tube well technology. The construction cost of a 10.5 m deep and 15 cm diameter tube well was only LKR 12,500–15,000 (USD 98–118) at 2012 prices, only about 20% of the cost of an agro-well. Two or three tube wells located about 8 m apart are connected to a single centrifugal pump to irrigate one hectare. These pumping arrangements are similar to the skimming of wells used in Pakistan to draw water from relatively shallow, freshwater lenses overlaying saline water at greater depths, thereby avoiding saltwater intrusion (Sufi et al. 1998; Saeed et al. 2002; Saeed and Ashraf 2005). In Kalpitiya, the group of wells reduces drawdown and enables the pump to maintain adequate water pressure to operate the sprinklers. Shah (2009) described the unregulated proliferation of wells, such as those seen in Kalpitiya, as ‘anarchy.’ An unfortunate side effect of the transition from agro-wells to tube wells is that the water table has become invisible to the users, eroding an important component of the earlier self-regulation.

Despite the general and repeated failure of formal promotion of micro-irrigation across the country, this was not the case in the Kalpitiya Peninsula, where the sprinkler technology has been adopted and spread quickly in this groundwater-based agricultural economy during a short period of 10 years. It continues to expand and be adopted. The adoption of sprinkler irrigation enabled the majority of farmers to cultivate three or more crops each year, resulting in an increase in the net sown area, net irrigated area, cropping intensity, and irrigation intensity. Crop intensification, land expansion, and crop commercialization accomplished through the groundwater-based sprinkler irrigation technology has increased agricultural income substantially, providing a net income per season in the range of LKR 300,000 (USD 2,360) to LKR 1,000,000 (USD 7,875) from a single hectare of cultivation. These impacts are importantly attributed to groundwater and its buffering role in food production and agrarian livelihoods as seen across the world where groundwater protects against droughts helps intensify cropping and allows farmers to diversify to high-value crops (Shah 2014).

Success, however, has often sown the seeds of trouble as over-exploitation and ineffective governance given diffused pump ownership, have led to declining groundwater tables (Shah 2014). The low water-holding capacity of Kalpitiya's sandy soils force farmers to apply more water and/or irrigate more frequently. This also unintentionally pollutes the aquifer with irrigation return flows carrying agricultural pollutants such as fertilizer and pesticide residues (Lawrence and Kuruppuarachchi 1986; Kuruppuarachchi and Fernando 1990, 1999; Matara Arachchi et al. 2014; Melvani et al. 2006). In addition, heavy abstraction from this shallow coastal aquifer may result in saline water intrusion, particularly during dry months.

Attempts to indirectly regulate groundwater use through the introduction of micro-irrigation technologies has produced substantial benefits for individuals by increasing production and income. However, the sustainability of these benefits is at risk as a result of the negative consequences of over-extraction and pollution of the resource, which are occurring due to the absence of effective governance arrangements to regulate the use of the aquifers. In the absence of any formal regulation from government agencies or self-regulation of abstraction, use of this common property resource for individual benefit is causing considerable damage to the groundwater asset base. A concerted effort is required to help communities to assess and monitor the status of groundwater regularly at the village level. Agencies must use relevant knowledge and scientific principles to help estimate the available water for each crop season. Kalpitiya case suggests that the groundwater intervention focus so far has been largely on 'resource development,' and not on 'resource management.' This has witnessed the problems of excessive drawdown in the fragile environment, and the deterioration of groundwater quality.

44.3.1.2 Agro-Well-Driven Cultivation of High-Value OFCs in the North Central Province

In 1989, the government started to provide subsidies to construct agro-wells (typically 20 ft in diameter and between 20 and 30 ft deep) in parts of Sri Lanka's dry zone through the National Agro-well Program to address persisting poverty by stimulating dry season cultivation which historically suffered from the long dry season, especially in areas unserved by surface water irrigation schemes. Households in these areas remained poor, with few employment opportunities outside of paddy cultivation. Through the Agro-well Program a few households in several villages in Anuradhapura District (Fig. 44.4) in the North Central Province (NCP) received a 50% subsidy for digging agro-wells and the purchase of diesel pumps. The program coincided with the groundwater-driven green revolution that made pumping technologies available and affordable. With each agro-well irrigating up to one acre, groundwater was pumped from the shallow regolith aquifer lying under the NCP and much of the dry zone, as these 'test case' farmers moved

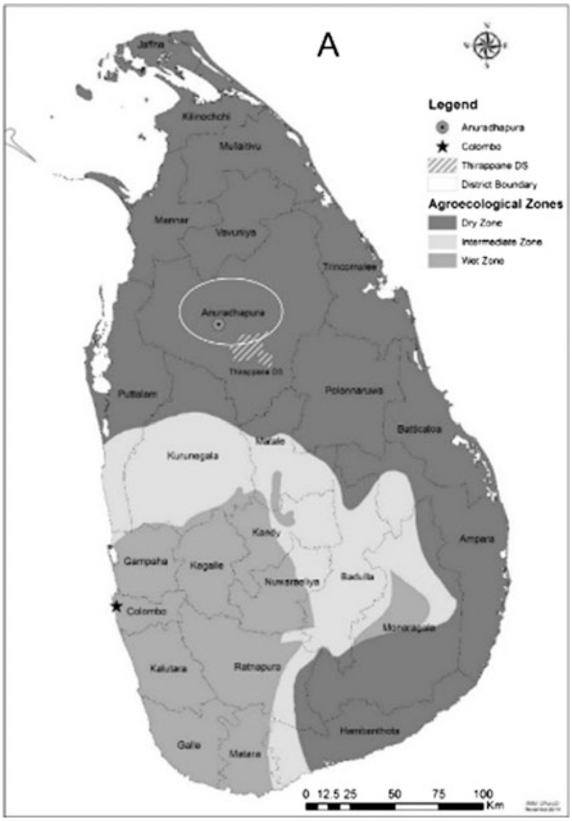


Fig. 44.4 Location of Anuradhapura District

from main subsistence traditional rainfed upland cultivation with low-value crops to cash crops such as soya, chili, and onions (Panabokke 2003) for profit during the dry season.

The success of these test cases saw further investments in this production system with support from donors, NGOs, and provincial ministries, although investments by farmers themselves soon became a major driver in agro-well expansion (Karunaratne and Pathmarajah 2003). Consequently, the number of agro-wells in the dry zone by the year 2000 was estimated to be 50,000, with the highest density in Anuradhapura District (Kikuchi et al. 2003). With this ready source of irrigation, traditional dry season crops such as mustard and finger millet chosen for their drought-tolerant properties have given way to chili and onions today for their profitability. Maize is grown in the wet season giving rise to a mainly two-crop cropping calendar on highland plots. This occurs in parallel to the two paddy crops on lowland plots irrigated by rain and limited quantities of water from small village irrigation tanks. This shift from subsistence to profit-oriented cropping also spurred the expansion of land brought under cultivation. In Puliyankulama village in the Anuradhapura District, for example, this area increased by 470% between the late 1980s to 2012, mainly at the expense of forest land.

Economic Prosperity and Climate-Proofing

This groundwater-driven dry season cultivation system has achieved transformative socioeconomic impacts in the villages where agro-wells have been adopted. The contribution of agro-wells to total household net income per acre (from chili and onions grown in the dry season) is an estimated USD 4,855 or almost 60% of annual agricultural income (Table 44.2), suggesting a more than doubling of households' annual income from agriculture. This is all the more important given that farmers had virtually no earnings from highland cultivation during this season prior to the agro-wells, which translates into significantly higher food security and nutrition during this 'hungry' period. Other dimensions of well-being have also improved as evidenced by increased physical assets such as the high incidence of mechanization (e.g., two-wheel and four-wheel tractors, motorbikes). Not only do the farmers attribute these changes to agro-well production, it can also be inferred from the official employment statistics (Thirappane Divisional Secretary Division 2012) that confirm that only 16% of the population between 18 and 60 years of age

Table 44.2 Net income per acre from lowland paddy and highland cultivation (USD)

Season	Lowland	Highland			Annual net income
	Paddy	Maize	Chili	Big onion	
Wet	1,330	1,699	Not cultivated	Not cultivated	3,029
Dry	237	Not cultivated	2,098	2,757	5,092
Annual net income	1,567	6,554			8,121

Source de Silva et al. (in prep.)

in the study villages that inform this case study are employed outside of farming in public or private employment (de Silva et al. in prep.). In contrast to the virtually full engagement of households in these villages in agriculture, Gamage and Damayanthi (2012) found that in the smallholder agriculture sector overall, as much as 35.2% of farmers who focused mainly on paddy cultivation were ‘unemployed.’

Underwriting these changes is the resilience, this agro-well-driven production system appears to provide the face of seasonal water stress, at current levels of extraction. This was demonstrated during the extended dry conditions experienced in the latter half of 2013 and first half of 2014 when net income from chili and onion rose despite two failed monsoons. During this period, farmers without agro-wells or access to surface irrigation abandoned dry season cropping in many parts of the dry zone, resulting in supply shortages in chili in particular. This allowed those farmers irrigating with agro-wells, such as those in these study village, to sell some part of their chili crop at approximately three times the peak farm gate price they would get during normal dry seasons. Another interesting aspect of this resilience lies in the manner in which farmers manage groundwater during times of stress. Despite the absence of any formal institutions for regulating abstraction, de Silva et al. (in prep.) report how individual farmers voluntarily decided to reduce the cropping area by half during the extended dry conditions referred to above, and the seeming prevalence of this behavior throughout their study villages. Representing a seemingly rare example of sustainable groundwater (self-)management, the same authors highlight the observability of the groundwater on a daily basis, and the knowledge of and respect for the resource thereby developed in farmers over time. Central to this approach is also the high economic returns from high-value NPCs, which provides an ‘economic space’ for farmers to modulate groundwater use in response to different climatic conditions.

Success Has Required an Alignment of Diverse Enabling Conditions

In addition to the access to groundwater, and the resilience such access and the manner in which it has been managed by farmers, this success in alleviating poverty in these communities is derived from a diverse but interrelated set of enabling factors across social, political, institutional, economic, ecological, and physical dimensions. For example, land availability has been critical given the expansion of highland cultivation by conversion of state land (mainly forests). Such large-scale conversion of forests could not have occurred without purposefully lax rule enforcement by line agencies and local government. Interviews by de Silva et al. (in prep.) with law enforcement officers from these agencies confirm that poverty alleviation was consciously prioritized over rule enforcement. The availability of agricultural mechanization has saved on labor and time. The diversification and accessibility of credit sources have facilitated mechanization, following the entry of several private lending institutions and the penetration of service delivery to nearby towns. Similarly, affordable communication technology has linked farmers to diverse service providers including markets, credit suppliers, and state sector service providers.

The concurrent development of agricultural markets has been critical not only in absorbing production, but doing so at prices that have thus far outstripped costs of production and farmers' perceptions of risk. Government investments in a wholesale market in Dambulla is a major asset, accessed with ease due to improvements in the rural road network, combined with mobile communication that enable farmer-buyer negotiations. Market structure is also central to the current profitability of chili and onions. Their markets are characterized by domestic production deficits to the order of almost 50% of demand (Sri Lanka Government 2008). While the deficit is addressed through imports, changes in domestic output produce sharp price fluctuations through the dry season especially with chili where short-term price spikes grant farmers significant profit margins. This is possible also because of the nature of the specific crop, since chili allows for continuous harvesting once the plant reaches maturity. The sustainability of this production over the past 25 years is also indebted to the three to five small irrigation tanks located in different parts of each village. Meant for irrigating lowland paddy, these tanks nevertheless provide a preexisting groundwater recharge mechanism that underwrites the continued supply of groundwater (Panabokke et al. 2001).

Considering Scalability in the Face of Externalities

By successfully overcoming the historical constraints to profitable cultivation in the dry zone of Sri Lanka, and by demonstrating considerable resilience during normal and exacerbated water stress conditions, the agro-well-based cultivation of high-value OFCs demonstrates significant economic potential for transforming rural dry zone livelihoods. Yet although Panabokke et al. (2001) believe the network of small tanks in the dry zone can support agro-well densities higher than what is recommended, the consensus appears to be that agro-wells are by no means a panacea to the woes of the dry zone farmer (e.g., Pathmarajah 2002; Jayakody 2006; de Silva et al. 2007). Firstly, the fact that the regolith aquifer that underlies much of the dry zone offers limited and spatially irregularly located pockets of water (Panabokke and Perera 2005) has caused concern over over-abstraction, especially when the actual groundwater potential of the aquifer across different parts of the dry zone is not known. De Silva et al. (2007) note that the development of agro-wells has occurred randomly without a general assessment of the hydrogeological properties of the aquifer, the possible yield and a rational siting of wells. The same authors also point out that there is nothing to stop a farmer on private land from exploiting this resource at will, given the absence of regulations specifying well densities.

Concern also exists over groundwater quality (e.g., Kendaragama 2000; Perera 2001), and Jayakody (2006) estimates that around 30% of agro-wells have been abandoned due to such impacts. Senaratne and Wickramasinghe (2011) highlight the impacts of highland cultivation on small tanks by way of accelerated siltation due to farming in upland catchment areas, a process that has been significantly accelerated by the recent spread of commercial highland cultivation. They also refer to instances of chemical runoff causing eutrophication of village tanks, and further suggest the potential for an overall imbalance in local water availability, leading to a decline in the moisture content of the local ecosystem in general.

44.3.1.3 Intensification of Groundwater Use in the Jaffna Peninsula

In the northernmost part of Sri Lanka, lies the Jaffna peninsula, a land trisected by three lagoons (Fig. 44.5). The peninsula, the lagoons, and seven inhabited islands further north of it cover an area of 1,012 km^2, making up the Jaffna District (Jaffna District Secretariat 2015). The peninsula is underlain by a Miocene limestone aquifer, about 100–150 m thick, and consists of an extensive network of karst and channels (Panabokke and Perera 2005). Calcic red-yellow latosols overlie this in most areas, forming soils that are finely textured and well drained with high infiltration characteristics (De Alwis and Panabokke 1972). The highly channeled nature of the aquifer also leads to 50% of annual recharge being lost to the sea (Balendran et al. 1968). While seawater intrusion is an issue at the margins, substantial quantities of freshwater are collected in the center (Kodituwakku 2009). As a result, this Miocene limestone aquifer system is considered to be the richest source of groundwater among the aquifer systems in Sri Lanka, and the most extensively used, historically (Panabokke and Perera 2005).

As none of the 103 perennial rivers that radiate from the central hills of Sri Lanka reach the peninsula, rainfall is the only source of recharge. Eighty percentage of this falls during October and December as the northeastern monsoons and contributes to aquifer recharge. This recharged volume diminishes throughout the remainder of the year (Mikunthan et al. 2013). The dry zone climatic conditions of the area together with high evaporation rates, a short rainfall season and the absence

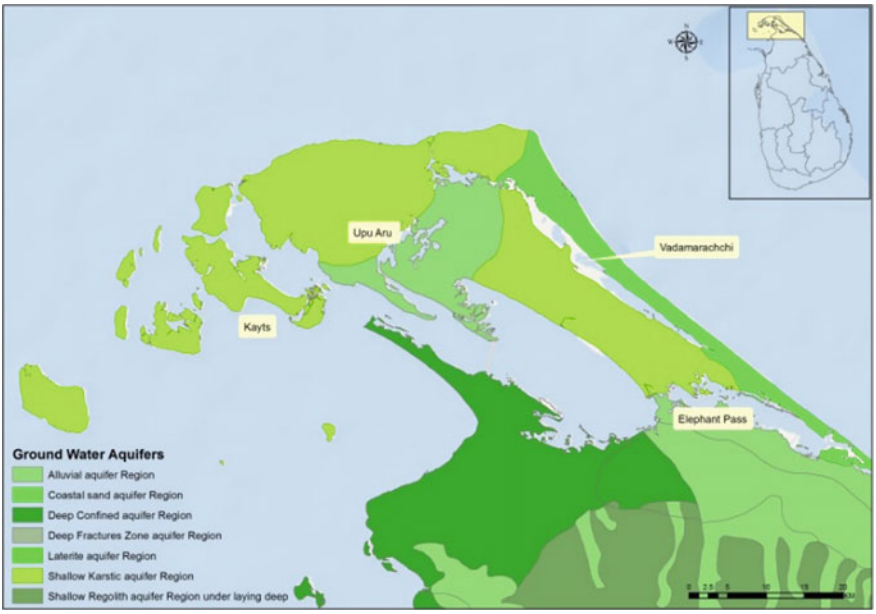


Fig. 44.5 Map of Jaffna District

of fresh surface water bodies of significance, result in groundwater being the only available source of water for human usage.

This dependence on groundwater is framed by Jaffna District being the seventh most densely populated district in the island, with a population of 610,640, in 2013 (Jaffna District Secretariat 2015). Apart from extraction for domestic use, around 80% of the water extracted is used in agriculture that continues to dominate the economy in the district (Panabokke and Perera 2005). Agriculture is the mainstay of economic activity in the area accounting for 44–65% of employment (Jaffna District Secretariat 2015; Thadchayini and Thiruchelvam 2005). Paddy cultivation is mostly rain-fed and occurs at subsistence levels. Incomes come from high-value cash crops, such as red onions, chilies, potatoes, tobacco, vegetables, bananas, and grapes. While these crops are already consumers of large volumes of water, the frequency of cultivation too is extremely intensive. Production is year-round, with no fallowing in between cropping cycles, while pumping can be up to 3 h daily (Mikunthan et al. 2013). An estimated 100,000 dug wells (agro-wells, public wells, and wells for domestic use) operate in the area, of which about 17,000 are agro-wells, with well densities reported to be increasing steadily (Punthakey and Gamage 2006; Jaffna District Secretariat 2015; Sood et al. 2015). Such groundwater development is already considered to be unsustainable, as indicated by Thushyanthy and Silva (2012) who reveal that extraction can be higher than the annual recharge, whereas the safe limit is considered to be 50% of recharge. Apart from the large number of wells and increasing well density, the introduction of electric lift pumps since the 1960s, replacing previous traditional methods, has been a key driver of over-extraction (Sood et al. 2015; Thushyanthy and Silva 2012).

With such intensive use, it is not unexpected that the aquifer already suffers from issues related to salinization and contamination from agriculture and poor urban sewage and solid waste management. As the peninsula is surrounded by the sea, the groundwater exists as a freshwater lens floating above saline water, making it vulnerable to upconing, which results in saltwater intrusion into wells, particularly in areas adjacent to the coast. Sutharsiny et al. (2012) found that 68% of the wells studied in the Chunnakam Aquifer (the largest and most extensively used in the peninsula) had high salinity levels, and 16% had very high salinity. This poses a major threat to the yields of some of the popularly cultivated crops in the area. Nitrate pollution is also prevalent with severe consequences for human health. Mikunthan and De Silva (2008) found nitrate-N levels to be higher than the WHO standards for drinking water in most of the public and farm wells studied. Some studies conclude that up to 80% of wells in the peninsula could be subjected to high levels of nitrate concentrations (Mikunthan et al. 2013). Such contamination in public wells is attributed to the close proximity to soakage pits, the most common form of sewage disposal in households, and in the farm wells attributed to the extensive use of nitrogenous fertilizers. Contamination of the aquifer system also includes point sources of pollution, such as that in Chunnakam, where a power plant is alleged to have leaked 400,000 L of crude oil into the aquifer system (Rink et al. 2016).

Usage of the system can only be expected to expand following the cessation in 2008 of the three-decade-long civil war in the North and East of Sri Lanka. Some of the people displaced have returned to their lands, and many have resumed farming. (Vithanage et al. 2014). The pressure on farming to meet family needs is likely to remain until other opportunities for economic development arise in the area. While any form of further agricultural or industrial development will create further demands on the groundwater system. Concurrent to expanded economic opportunities, the idea of surface water transfers to alleviate pressure on the aquifer has been discussed for many decades. One such scheme is the ‘River for Jaffna Project’ also known as the ‘Arumugam Plan’ (named after the engineer who conceptualized the idea) which envisages converting the Elephant Pass Lagoon (see Fig. 44.6) which lies in the east from a brackish to a freshwater body from which water is to be conveyed to the peninsular. This lagoon receives freshwater from a catchment area beneath the peninsula during monsoonal rains, and closing of the mouth of the lagoon is expected to convert it into a freshwater body. Two more lagoons Vadamarachchi Lagoon in the North and the Upparu Lagoon in the West are also to be similarly cut off from the sea, with the water received by the Elephant Pass

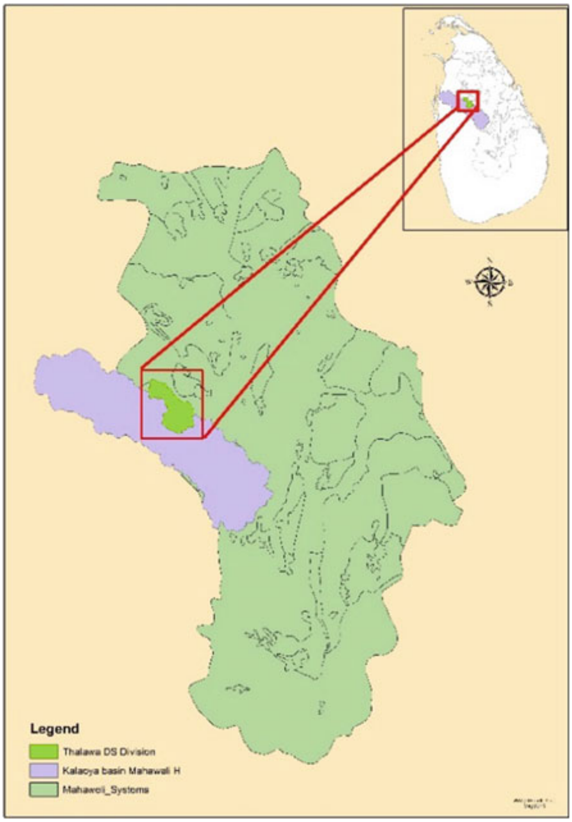


Fig. 44.6 Study area in Mahaweli System H

Lagoon being then transported to these water bodies by a channel. As the Vadamarachchi and Upparu Lagoons account for 10% of the surface area of the peninsula, this concept foresees ambitious results. The benefits expected include improving the quality of water in wells in the peninsula that have become saline as well as facilitating additional pumping without causing saline intrusion and the leaching out salts from the soils adjacent to the lagoons. A cultivation area of 4,400 ha is expected to be supported. (Ministry of Rehabilitation, Resettlement and Refugees 2003; Shanmugarajah 1993). Different components of this scheme have been in implementation at various points in time in the past hundred years, but the infrastructure is now in a state of dilapidation. The increasing urgency of the need to provide the peninsula with good quality water has seen its revival again, by the Irrigation Department, under the Ministry of Irrigation and Water Resources (IWMI 2013a).

This scheme is therefore one that covers the extent of the peninsula, and due to its magnitude, promises to generate benefits that could prove to be a substantial part of the solution. The scale of the problem and the near-complete dependency of the peninsula on groundwater will, not surprisingly, make such a one-stop solution an attractive one to pursue. While in reality, it remains to be seen to what extent these benefits may actually be realized, it is not clear if other implications of changing the ecological conditions of the lagoons have been looked at. Fishing is the second highest source of livelihoods in the district (Jaffna District Secretariat 2015). The ecological services provided by lagoons to fisheries, such as providing a sanctuary to young aquatic organisms is well known, and the Jaffna lagoons are considered to be utilized at substantial levels by the fishermen from the area, for prawn and crab fishing (Sivalingam 2010). The changed salinity levels that this scheme expects to lead to can therefore be expected to impact these fisheries negatively. Thus, the trade-offs that could arise between the expected benefits of such schemes and the impact on the biodiversity of the lagoons and ecosystem services they provide, and the consequent impact on the socioeconomic health of the communities represent important uncertainties to be addressed.

Unlike in the cases of the Kalpitiya Peninsula prior to the 1990s and the North Central Province, and despite well-understood trends such as the salinization of aquifers, instances of collective governance of groundwater use as a common pool resource in the peninsula appear to be missing. In the absence also of any formal groundwater management institutions and paucity of extension services, Arasalingam et al. (2013) find that both irrigation and inorganic fertilizers are used in excessive amounts, with timing of cropping, irrigation, and fertilizer application practices-based mainly on farmers' experience. The uncertainty and lack of permanency created by the war, followed by an absence of suitable formal structures to support farmers no doubt contributes to this.

44.3.2 Conjunctive Use Within Surface Systems

44.3.2.1 Managing Seasonal Water Stress Through Conjunctive Use in Mahaweli System H

While minimizing water losses to seepage in surface irrigation schemes is usually expensive in terms of construction and maintenance costs, such ‘losses’ in fact present opportunities to collect and reuse these ‘losses’ stored as groundwater. Therefore, the prospect of groundwater irrigation is high within surface irrigation command areas due to the recharge of the aquifer from water in irrigation canals, reservoirs, and other distribution systems. These volumes of ‘lost’ water are also substantial given that water use efficiency of the developed water resources in Sri Lanka is very low, largely due to the low level of reuse of groundwater return flows (Amarasinghe 2010). He further pointed out that, conjunctive water use in major irrigation command areas in Sri Lanka is almost non-existent, unlike in other South Asian countries.

The Mahaweli Irrigation Scheme is the largest surface irrigation project ever undertaken in Sri Lanka. The Mahaweli Irrigation Development and Settlement Program are divided into several systems, including A, B, C, D, and H. Rice is the most popular surface irrigated crop cultivated in the scheme as in other surface irrigation schemes in the country. The Mahaweli System H is situated in the Kala-Oya river basin (Fig. 44.6) and covers a total land area of 50,994 hectares, and by 2011, this included 36,119 ha prepared for rice or other lowland crop cultivation. The System H predominantly located in the dry zone has an average annual rainfall 1,018–1,897 mm during the ten year period up to 2003 recorded at the nearest meteorological station Maha Illuppallama that mainly falls during the northeast monsoon, spanning September to February. Water scarcity in the dry season is therefore one of the key challenges for reservoir managers in System H.

The Mahaweli Authority of Sri Lanka (MASL) which manages the Mahaweli system implemented a subsidy program in the 1990s to promote construction of agro-wells (large-diameter dug wells) in System H to minimize water scarcity problems by encouraging use of untapped groundwater resources. However, similar to the previous case studies, rapid expansion of well development has occurred after the year 2000. Although there is often resistance to change from surface irrigation to conjunctive irrigation among line agencies mandated to develop and manage surface water sources, MASL has been an exception. According to the agro-well census conducted by Aheeyar et al. (in prep.) in Mahaweli H during 2014, 4,746 wells have been constructed during the last five years for the purpose of conjunctive use. Groundwater irrigation as a buffer against water scarcity and the unreliability in surface water supplies has clearly become popular in Mahaweli H over the past 15 years. About 70% of farmers using groundwater have invested their own money without subsidies, driven by hopes of minimizing crop failures, increase cropping intensity, and growing high-value crops. Consequently, cultivation of low water consumption and high return NPCs is most popular among 90% of well owners.

The extent under groundwater irrigation ranges from 0.1 ha to over 1 ha. About 55% of the conjunctive irrigation farmers cultivate more than 0.4 ha during the dry season. Over 25% of these farmers own more than one well which indicates the considerable income and the welfare gain from groundwater irrigation to these farmers who have hitherto lived in a traditional surface irrigation scheme. Conjunctive irrigation has therefore positively contributed to the social and economic transition of many households in the area and has allowed previously subsistence farmers to gradually progress to a middle-class status. The average annual household income has increased from LKR 353,000 in surface irrigation to LKR 426,000 and LKR 974,000 in conjunctive irrigation and conjunctive irrigation supported by micro-irrigation technology, respectively. These are increases of 21 and 175%, respectively, compared to surface irrigators. The reallocation of labor time has allowed households to either extend reproductive or leisure activities or alternatively, to use this saved time for productive farm and non-farm economic activities. Enhanced household income has been used to finance to improve the quality of the daily meal, health, and welfare of family members, children's education, improving housing conditions, and improved access to household and farm assets. This economic empowerment and greater control over productive resources have also empowered farmers as decision-making and promoted gender equity. There are changes in inter- and intra-household division of labor with the introduction of non-paddy crops and groundwater irrigation. Assured water supply is made to farmers to perform high input agriculture, which demanded more labor per unit area of cultivation. This has resulted in more opportunities for household and hired labor, especially for women. Enhanced household income allowed farmers to obtain the services of hired labor for agricultural activities that have provided more leisure time for women and children in the farmers' families. Groundwater irrigation also contributes to improve food security and is a viable solution to enhance climate resilience of the farmers. It has therefore been an important means of farmers to improve their livelihood conditions, especially during dry seasons.

The irrigation method adopted by a majority of the groundwater farmers is through surface channels/furrows though this leads to high conveyance losses. Some farmers are in a position to use better agricultural technologies to grow high-value crops that demand less water. Investment made in micro-irrigation (sprinkler) technologies has been spontaneous from their own savings or from credit sources ranging from LKR 10,000 to 240,000 (USD 80–1,890). Farmers are able to repay their creditors the surplus income earned from conjunctive irrigation. The major drivers of the sprinkler technology were water scarcity in dry periods, high labor costs in groundwater irrigation, and labor scarcity.

In spite of this groundwater boom, groundwater levels recuperate to original levels within 8 h after pumping in 95% of the wells during the periods of canal water issues (Fig. 44.7). Only 13% of the wells completely dry up during the driest months of August/September (Aheeyar et al. in prep.). Therefore, there are currently no real water issues reported by the majority of farmers and the depth of wells has not been increased in searching more water or no sign of groundwater depletion. The water scarcity problem in the system is further complicated by serious

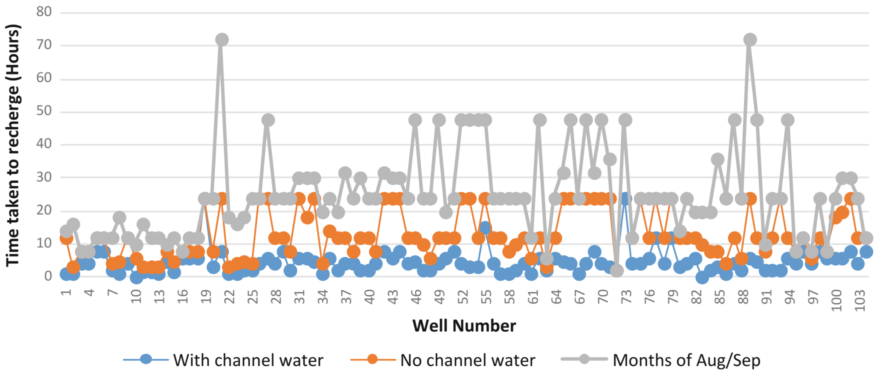


Fig. 44.7 Time taken to recharge well to the original level after pumping. *Source* Aheeyar et al. (in prep.)

groundwater quality issues due to hardness, fluoride, and iron concentration. Only 26% of the groundwater in the basin is completely free from fluoride and 40% of the groundwater is affected by unsafe iron concentration (Bandara n.d.; quoted from Saleth et al. 2007).

According to observations made by Water Resources Board, whenever water flow takes place in the canal network (main canals, branch canals, distributary canals and field canals) of Mahaweli System H, the regolith aquifer within the irrigation scheme get fully charged with the seepage and infiltration water from canals to a specific height according to the lay of the landscape. This water table recedes at a slow rate after irrigation supply through the canals is cut off (Panabokke and Perera 2005). Therefore, there is a limit in the utilization of shallow water table and any over-extraction of water during cessation of water in the canals in the absence of any governance arrangements would lead to negative externalities in the system.

The existing water sector agencies often tend to focus and limit their scope to historical water supply development mandates and find it difficult to grasp or incorporate conjunctive use opportunities. The promotion and implementation of improved conjunctive use and management of groundwater and surface water resources required significant strengthening of the existing institutional arrangements for water resource management, proper coordination among the water management agencies, and gradual institutional reform from the lessons of the experiences of pilot projects. An awareness creation effort from the government water sector agencies would facilitate the social learning and institutional development process and lead to the promotion of attitude changes and the acceptance of implementable regulations.

The performance of conjunctive irrigation farmers indicates that major irrigation schemes like Mahaweli H have aquifer space for storage of recharge water, and stored water is economically accessible at the needed time. Irrigation reservoirs and channel networks are playing a great role in the replenishment of groundwater aquifer through seepage and percolation losses. The stored groundwater can be effectively used to fill the gap in water availability through proper planning of the conjunctive use of available surface and groundwater. Underutilization of groundwater is a potential problem, especially in surface irrigation command areas, where alternative water supply options are considered at greater environmental and economic costs. Therefore, the lost opportunity of implementing conjunctive irrigation needs to be on the agenda of line agencies to improve the livelihoods of poor farmers.

44.4 Discussion: The Governance Challenge of Balancing the Benefits and Risks

44.4.1 Emerging Values of Groundwater Use and Attendant Risks

The case studies presented in Sect. 44.3, together with the existing literature demonstrate clearly the significant positive impacts that emerging models of groundwater development are having on rural poverty alleviation and food security. Of particular significance is that these gains accrue during the dry season—the period when traditionally households face the greatest food security and livelihoods constraints. At the heart of this agrarian livelihoods revolution, be it still in limited geographical areas, are the humble pump and associated technology that have almost silently (Shah 2013) freed smallholder farmers from the collective decision-making processes that characterize surface water irrigation schemes controlled by state rules. Pumps, by shifting control over the water itself and irrigation decisions to individual farmers, have injected a new energy into farmer entrepreneurship, seen not just in their diversification to high-value non-paddy crops, but in their innovation in adapting technology to suit specific production needs and biophysical conditions, as noted in Kalpitiya, and willingness to risk private funds without waiting for the next government handout that characterizes all three case studies. This access to groundwater along with control over how it is used has, subject to concerns discussed below, generated a new resilience to seasonal and climatic water stress. One notable difference between this groundwater economy in Sri Lanka and others in South Asia as noted by Shah (2013) is that groundwater mainly irrigates high-value crops in Sri Lanka, while in other countries it is used primarily for paddy, which makes little economic sense. Groundwater irrigated farming in Sri Lanka generates 4–5 times the income compared to other South Asian countries[4] A preoccupation with paddy has also driven down groundwater levels as is the case in northern Bangladesh (Qureshi et al. 2014), India, and others.

---

[4] The authors recognize that although these benefits are distributed equally among groundwater users, what is relevant for this discussion is the overall upliftment of households' livelihoods.

Contrasting with these important socioeconomic benefits are growing concerns in Sri Lanka over the sustainability of groundwater resources from both quantity and quality standpoints. With respect to the former, over-extraction issues are problematic primarily in the shallow unconfined karstic aquifers, lateritic (cabook) aquifers, and shallow regolith aquifers. Many observers such as Panabokke (2003) have cautioned about the rapid and haphazard development of wells taking place without understanding the nature and behavior of the aquifers. Shah (2013) in fact notes that India began developing low-yielding hard-rock aquifers suitable for intensive groundwater use in the 1970s, and that Sri Lanka is following suit where the relatively thin groundwater layer means this shallow aquifer is limited in its quantity (Senaratne 1996), causing Dharmasena (2001) to recommend that only 25% of its potential groundwater storage be exploited. However, while recognizing these limitations, Panabokke and Perera (2005) believe that this aquifer nevertheless represents a highly renewable groundwater resource due to the abundance of the small irrigation tanks through much of the dry zone providing unmanaged aquifer recharge. A different challenge arises by the fact that in the regolith aquifer there is no continuous body of groundwater with a single water table in the crystalline rocks, but rather separate pockets of groundwater each with a distinct water table (Cooray 1988). This makes clear the importance of ensuring sufficient knowledge exists to ensure effective well location. According to Panabokke and Perera (2005), the coastal sand aquifer is also under stress due to human and agricultural activities. Similarly, Thushyanthy and Silva (2012) reported that the groundwater withdrawal from the shallow limestone (Karstic) aquifer in the Jaffna peninsula is 16% higher than the average annual recharge of the aquifer.

Concern over groundwater quality arises from natural conditions as well as a range of dispersed human activities (Table 44.3) including over-extraction, sand mining, poor waste and wastewater management, and high rates of especially nitrate containing agrochemicals (Wijesekara 2013). The increased cropping intensities and reliance on agrochemicals that characterize groundwater-based agriculture is therefore seen as a major externality. These not only introduce pollutants, but also cause land subsidence and seawater intrusion through excessive groundwater extraction. Poor management of domestic and industrial waste is another significant consideration, with growing impacts on groundwater quality either directly or through surface water and soil pollution. Increasing solid waste generation on the one hand, and vastly insufficient sanitary landfills or incineration options on the other hand, increases the impacts of leaching from both domestic and industrial sources. Industrial zones generate significant volumes of hazardous waste, of which as much as 75% do not reach a sanitary waste site. Consequently, the contribution to groundwater pollution from poor waste management is now considered as important as agricultural sources at least within the Central Environmental Agency (CEA officials, pers. com.).

Table 44.3 An overview of groundwater contamination and their drivers

Region	Province	Aquifer	Contamination	Causes
Jaffna	Northern	Shallow karstic	Enhanced levels of nitrate pollution with high levels of chloride and salinity	Overuse of agrochemicals. High settlement density with poor sewage effluent disposal from pit latrines. Excessive groundwater use, seawater intrusion
Kalpitiya Peninsular	Northwest	Coastal sand	Nitrates, chlorides and potassium, four times the WHO guideline values; seawater intrusion	Intensive cultivation, excessive fertilizer use, and untreated wastewater
Puttalam	Northwest	Coastal sand	Very high levels of manganese and salt. High levels of total dissolved solids in some locations	Over-extraction. Seawater intrusion. Organic pollution through liberal use of organic manure and inorganic fertilizer. Shrimp aquaculture
Chilaw	Northwest	Coastal sand	High concentration of iron and salt	
Northeastern region	Northeast	Coastal sand	Seawater intrusion	Over-abstraction
Anuradhapura, Polonnaruwa	North central	Regolith	Fluoride	Geogenic formation
Colombo and Gamapha Districts	Western	Lateritic	Geogenic contamination related to iron and acidity in the lateritic formation	High extraction for industrial estates, tourism industry, urban housing and bottled water, Industrial pollution

Source Authors' compilation from multiple sources

44.4.2 Heading Toward Anarchy? The Current 'Governance Deficit' in Managing Groundwater and Ways Forward

The trajectory of groundwater development in Sri Lanka, as described in this chapter, aligns with Shah's (2009) portrayal of groundwater governance in South Asia as an anarchy of atomistic pump irrigation, where control over water resources has shifted from the state to individual farmers in the case of groundwater. If not already anarchistic in nature, the groundwater development scenarios that occur with very limited, if any, management oversight suggests groundwater use in Sri

Lanka is at least on the same trajectory as India and other South Asian neighbors. With high returns on investments for farmers further random expansion of abstraction appear very likely. As such, a key defining characteristic is this 'governance deficit' or the gap between rapid developments on the ground driven predominantly by private investment, and inaction in balancing resulting benefits and negative externalities on the part of government, arguably still preoccupied with surface water delivery.

The following discussion around this governance deficit brings to the fore the paralyzing effect of institutional compartmentalization with respect to water resources management that contrasts not only with the classic common pool resource nature of groundwater (Villholth and Giordano 2007), but also of the connectivity between ground and surface water for optimizing water resources overall. Villholth and Rajasooriyar (2010) point out that planning for effective and sustainable groundwater use requires considering surface water systems and describes surface water as a reflection of groundwater. This approach is currently mostly absent in Sri Lanka where groundwater and surface water are still thought of as two separate resources. This is despite the dense network of rivers, many of which are fed by groundwater (Vilholth 2013).

One cause for this dissonance in the manner in which surface and groundwater are conceptualized is a national consciousness honed to think of water in terms of surface flows over at least two millennia. Not only did the past kings of Sri Lanka focus almost exclusively on surface flows, the vast majority of water sector investments by post-colonial governments have followed suit, except in the case of domestic water supply. As aptly noted by Samad (2013), 'we do not see politicians inaugurating a tube well or a public well… we do not see bureaucrats around that.' This emphasis on surface flows is also reflected in the structural composition of water-relevant institutions (Table 44.4), all of which, with the exceptions of the

Table 44.4 Key organisations relevant to groundwater management

Organization	Overall mandate	Links to groundwater
Water Resources Board (WRB)	An advisory body to the Minister on all matters concerning the control and use of water resources in Sri Lanka with emphasis on groundwater	Assumed the primary mandate for groundwater management since 1999. Identification, investigation, and development of groundwater resources in the country. Maintains a database of hydrogeological and other information related to groundwater and its use
National Water Supply and Drainage Board (NWS&DB)	Responsible for the domestic and industrial water supply and sanitation	Installation of groundwater-based public and private water supply schemes for domestic and industrial purposes. Collects geological and spatial data on bores, agro-wells and water supply wells which they construct.

(continued)

Table 44.4 (continued)

Organization	Overall mandate	Links to groundwater
		Maintains a database of hydrogeological information to inform its groundwater use—includes considering cumulative impacts
Irrigation Department (ID)	Development of land and water resources for irrigated agriculture. Preparation of Master plans for development of the different river basins for the optimum utilization of land and water resources. Integrated Water Resources Management and Participatory Management in Major/Medium Irrigation systems. Project formulation and detail designs of Irrigation, Hydropower, Flood control and Reclamation Projects	The activities and the performance of the department on their mandated activities of operation and maintenance of major irrigation schemes, drainage and flood protection schemes and salt water exclusion schemes, which has an impact on quantity and quality of available groundwater resources in the irrigated command areas and beyond
Department of Agrarian Development	The Department is responsible for the management of village irrigation (Minor irrigation) schemes and also mandated to implement Agrarian Development Act (2000)	Minor irrigation cascade recharged the groundwater aquifer in the dry zone where agro-well cultivation is more popular. Agrarian Development Act has provisions to regulate the digging of agro-wells, though it is not enforced
Mahaweli Authority of Sri Lanka (MASL)	Overall mandate over water management and cultivation programmes in the declared Mahaweli Project regions, as well as other basins which have been declared by the government as special areas	MASL's Water Management Secretariat co-ordinates with other operating agencies, creating scope for brining groundwater into agricultural strategies
Extension and Training Division (Department of Agriculture)	Enhancing access to hard and soft technologies for land and water management at farm level and farmer capacities to engage in value chains	Dissemination of new technologies related to the water management including micro-irrigation
Central Environmental Authority (CEA)	Regulates industrial pollution by establishing standards and licensing linked to Initial Environmental Examination (IEE) and Environmental Impact Assessments (EIA). CEA is a national level regulating institution to prevent and control pollution of water resources	IEEs and EIAs required to consider impacts on groundwater contamination. It deals with on-site pollution of groundwater mainly through the issuing of Environmental Pollution Licenses (EPL) that can either be withheld (i.e., not issued) or include conditions for groundwater management (e.g., requiring on-site waste management)

(continued)

Table 44.4 (continued)

Organization	Overall mandate	Links to groundwater
Geological Survey and Mines Bureau	Responsible for geological mapping and implements the Mines and Minerals Law No 4 of 1973 which is mandated to prospect for minerals and explore and appraise the island's mineral resources	Survey activities provide important knowledge on geology-groundwater relationships. However, mining activities including surface sand mining threaten aquifers as well as recharge capacities
Municipal Councils, Urban Councils, Pradeshiya Sabhas, and Divisional Secretariats	Empowered to provide local water supply services for the benefit of persons residing within their areas of jurisdiction and management of solid wastes generated in the respective divisions	Delegated authority from the CEA for issue of licenses to and monitoring some industry types Also provide local water supply and sanitation, small-scale and provincial irrigation and drainage activities
Provincial Councils	Overall developmental planning and plan implementation in each province	Several water-related functions were handed over to the Provincial Council through the implementation of the 13th Amendment to the Constitution of 1987
Board of Investment of Sri Lanka	A central facilitation point for investors, mandated to expand and strengthen the base of the economy. Focuses on encouraging Foreign Direct Investment. Establishes Investment Promotion Zones throughout the country. BOI companies account for nearly 65% of all exports and 86% of industrial exports	Significant direct use of groundwater as well as direct and indirect impacts on groundwater quality through water and soil pollution. Issues Environmental Protection Licenses for BoI approved industries, but needs CEA's concurrence along with any conditions the CEA may impose
Registrar of Pesticides (ROP) (Under the Department of Agriculture)	ROP regulate the importation, storing, and selling of agrochemicals including pesticide formulation, packing, labeling and monitoring pesticides exposures occur during formulation, storage, and use. Enforcement based on registration of pesticides, but does not directly regulate or monitor pesticide at user levels	The post-registration monitoring activities of pesticides are dormant and carried out on an ad hoc basis due to lack of trained manpower, insufficient financial allocation, lack of laboratory facilities or non-availability of laboratory facilities and other field support requirements which could lead to misuse, overuse, and abuse of pesticides causing water and environmental pollution

Source Authors' compilation

Water Resources Board (WRB) and the National Water Supply and Drainage Board (NWS&DB), predominantly utilize surface water, although many enjoy the option of exploiting groundwater. Groundwater has therefore been quite literally ‘out of sight, out of mind.’

In fact, it was not until 1999 that groundwater received a focal agency in the form of the Water Resources Board, following amendment of the Water Resources Board Act No. 29 of 1964 in that year. Originally established as an advisory body to the minister on all matters concerning the control and utilization of water resources in Sri Lanka, the WRB’s focus became groundwater. It consequently conducts policy-oriented research on groundwater and maintains a database of hydrogeological and other information related to groundwater and its use. However, the fact that the WRB recognizes the need to work with at least 18 authorities/organizations either in respect of groundwater or surface water[5] is an illustration of the challenge faced in coordinating a holistic governance response to the rapidly evolving groundwater development on the ground. These agencies represent not only those with some role in groundwater management, but also sectors that may directly or indirectly impact this resource. A number of these agencies are highlighted in Table 44.4 which also serves to emphasize the compartmentalization of water resources management at national planning scale, but nevertheless, the opportunities available for collaboration in developing a coherent and rational groundwater strategy. Such coordination will also have to address the absence of an effective institutional mechanism that promotes conjunctive use of surface and groundwater.

This absence of a coordinating influence has blunted the mandate over groundwater bestowed on the WRB and maintains a status of segmentation and duplication. For example, the National Water Supply and Drainage Board (NWS&DB) also conducts research on groundwater and also maintains a database for the purpose of supporting its mandate of providing drinking water, even though groundwater extraction for this purpose and for agriculture and other needs occur from the same aquifers. Consequently, no single database provides a complete picture of wells constructed in the country. The issue of basic data for the framing of a more coherent approach to groundwater governance illustrates this issue well. The existence of knowledge gaps and the unavailability of 30 years of research results (Panabokke and Perera 2005) for planning purposes has been consistently highlighted as a fundamental constraint (e.g., Ferdinando and Premathilake 2013; Villholth and Rajasooriyar 2010). Much of the existing data is also geographically limited, and some may be outdated given the rapid increase in recent groundwater use (Karunaratne 2013). The piecemeal nature of research and monitoring, and the residence of results in various state, private and non-governmental organizations mirrors the current institutional failure to coordinate a resource governance response.

---

[5] Water Resources Board http://www.wrb.gov.lk/web/.

This failure is also visible in the absence of a policy, guiding principles and rules on for sustainable and socially equitable groundwater management. The subject of groundwater has been a victim of the failure over nearly two decades to formulate a comprehensive national water policy, with past attempts falling foul of strong political interests linked to poor public awareness of the issues. An important aspect of future attempts at policy as well as rule formulation is to ensure flexibility to reflect the differing hydrogeological and groundwater use contexts across the different aquifers—a challenge impossible without sufficient data that is collected and made available systematically. Specific data and regulatory issues identified based on several sources (e.g., Ferdinando and Premathilake 2013; Villholth and Rajasooriyar 2010; Panabokke and Perera 2005) include:

- Concerns over consistent data standards, accuracy and reliability of data and information both between databases and within the same database;
- Insufficient knowledge of groundwater dynamics at operation level (e.g., recharge mechanisms, recharge levels, flows, and transport) as well as the spatial variation of water quantity to address over-extraction causing quality changes and finally well failure.
- Understand the socioeconomic implications of groundwater use and threats.
- Identifying sensitive and vulnerable areas of groundwater pollution due to natural and anthropogenic reasons, including chemical processes in the aquifer systems;
- Effects of climate change on groundwater;
- Integrated region specific groundwater models leading to groundwater vulnerability maps;
- The need for coordinated construction of wells in the same aquifer by different agencies, and sometimes even the same agency;
- Addressing the lowering of the general groundwater table (aquifer drainage) due to sand mining along rivers, and decreasing recharge related to aquifer drainage, and
- Opportunities for artificial recharge.

Of particular note is the need for a system that can generate, organize and convey a continuous stream of real-time data for groundwater management to ensure different stakeholders are aware of conditions and can use the data in planning (IWMI 2013b). This status quo contrasts unfavorably with surface water where understanding already exists to develop and utilize most if not all surface water resources (IWMI 2013b).

In the absence of a coordinated information and awareness system, despite a considerable amount of essential and basic data, Panabokke and Perera (2005) point out quite fundamentally, that Sri Lanka's groundwater resources are seriously misunderstood by decision makers and also by major groundwater users. Given the range of sectors across which data is needed, Panabokke and Perera (2005) also highlight the critical need for a coordination mechanism to ensure any concerted research program is well coordinated, thereby addressing a major gap in the governance framework. It could be further argued that bridging this gap to provide a more coherent picture of the resource base, its use and impacts should in fact represent the beginning of a coordinated process that leads from greater understanding to effective management. As such, improving understanding of the resource, its use and challenges should provide a strong impetus and a point of focus for greater institutional collaboration in filling other gaps in this broader governance landscape.

Attempts at institutional building to address these fundamental issues shaping the current governance of groundwater resources are likely to also contend with issues around capacity, both human and financial. In addition to the manpower and other resources needed for a more comprehensive research and monitoring program, Table 44.3 makes clear that a good number of drivers, especially of groundwater quality, depends on the capabilities and commitment of other sectors. This is well illustrated by the lack of proper wastewater and solid waste management facilities and systems in urban and industrial centers. While agencies such as the Central Environmental Authority now recognize the hitherto under-appreciated threats to groundwater quality posed by waste (CEA officials, pers. com.), the paucity of enabling rules, processes and physical infrastructure for effective waste management represents a major part of this groundwater governance deficit. The absence of sufficient waste disposal capacity such as sanitary landfills and incinerators is a fundamental roadblock and results in growing urban garbage dumps. The garbage dumping site at Meethotamulla on the periphery of Colombo, for instance, has existed for over 20 years, with unknown levels of leaching of pollutants into the soil and local waterways.

The absence of centralized waste management facilities has also placed greater emphasis on-site-based action which however is marked by illegal on-site waste disposal practices that are difficult to trace, and poor rule enforcement. Even where such illegal practices are known, the offending industrial operators are rarely prosecuted due to fear of undermining employment opportunities. In addition to the links this highlights to broader developmental considerations, it also implies that illegal disposal is widespread within industry. A related weakness is the exemption from EPLs enjoyed by industrial operations that employ less than 200 people. These are treated as domestic enterprises despite their significant cumulative capacity to pollute. The EPL regulatory system is further weakened by the fact that for those industrial operations that do require an EPL, this comes into play only after the building and other structures are constructed, often leaving no physical space for a treatment facility on-site. Even where room is available, retrofitting such a facility may be costlier than if it had been integrated in the structural designs from the outset.

The devolution of the granting of EPLs to the Provincial Councils established through the 13th Amendment to the Constitution of Sri Lanka is yet another source of weakness in two ways. The first relates to low staff capacity, whereby putting the pollution in the ground is seen as a solution and not a problem. Such issues are being addressed by the CEA through training. The second issue arises from the Provinces' ability to deviate from rules set by central government, as is currently the case with respect to the Northwestern Province where it Environmental Act does not require the BoI to seek formal approval from the Environmental Authority of that province. While this is currently being remedied by the CEA, it does highlight the additional institutional and political complexities created by the devolution of regulatory powers. It may however be argued that this devolution offers be it untapped opportunities for more localized and context-oriented management regimes to evolve, given the diversity of aquifer types and other ecological and social contexts.

Compounding these practical gaps around groundwater pollution is the absence of an agency that is assessing the risks to groundwater posed by different industries. Although the CEA analyses treated effluents using upstream and downstream samples in rivers, it does not currently consider impacts on groundwater. Similarly, while addressing soil pollution is included as a function of the CEA in National Environmental Act that governs the CEA's mandate and functions, it has not featured in this agency's focal areas around pollution management. This is in addition to poor waste management capacities of provincial and local government authorities.

44.4.3 The Nascent Groundwater Monitoring Network: A First Step Toward Closing the 'Governance Deficit'

Given the central role played by information systems, the WRB's current attempt to establish a groundwater monitoring network represents a potentially major step in addressing the hitherto fundamental issue of data. When complete, this network will consist of 1,300 data loggers covering the entire island including 103 river basins. A real-time groundwater database will support a coherent groundwater management system by supplying data for decision makers, researchers, stakeholders, and the general public. This network will in fact be central to the future plans of WRB regarding management of groundwater (Karunaratne 2013) which include groundwater modeling under various scenarios; hydrogeochemical modeling; optimization modeling; preparation of groundwater vulnerability maps and community participation and awareness programs to actively enroll civil society in minimizing pollution and over-abstraction in the first place. The rationale appears to view such an investment as a lever to generate change in institutional behavior necessary to translate adequate data into effective management responses.

The first phase of this network established over 2014 and 2015 consists of seven pilot Divisional Secretary Divisions (DSDs), selected to focus on a specific management challenge. These include extensive agriculture including areas using agro-wells; areas with a high incidence of kidney disease, and areas with industrial pollution, salinity, and other qualitative issues. The activities in each DSD include geophysical surveys, test bore hole construction, pumping tests, water quality analysis (physical, chemical, heavy metal, bacteriological, and pesticides) and DGPS leveling of monitoring points. While this pilot phase has been made possible under the donor funded Dam Safety and Water Resources Planning Project (DSWRPP), this also instills uncertainty regarding continuity post-project. The current expectation is that expansion of the network to the entire country and its sustenance will be financed by the government, or through further donor funds (IWMI 2013b). If used effectively, a strong case for government support exists by way of potentially significant government savings by avoiding expensive remedial interventions as well as production losses and adverse impacts on human health.

44.5 Conclusions

The case studies presented in this chapter represent different models of growing groundwater use in the agriculture sector, across different regions of Sri Lanka. The case on the Jaffna peninsula shows how context driven traditional dependence on groundwater is intensifying. The other three examples are of relatively recent production systems driven by an increased affordability and availability of technology for tapping groundwater, and the desire by households as well as government to overcome seasonal surface water scarcity as well as climatic uncertainty. That groundwater is rising to prominence even in part of the Mahaweli surface irrigation scheme also suggests the confluence of other anthropocentric drivers such as population pressure and increased water demand from other sectors of human activity. That all applications of groundwater are linked to diversification high-value commercial crops with low water demands relative to paddy is a key element in the transformative economic benefits from groundwater exploitation to previously mostly poor rural households. Indeed, this groundwater high-value crop combination sets Sri Lanka's groundwater use apart from its neighbors in South Asia. Large economic benefits have over time also helped farmers take control of investments in groundwater which, while an important attribute at farmer scale, threatens to continue the haphazard nature that has characterized groundwater use expansion to date. This is especially of concern with respect to the regolith aquifer that underlies the majority of the country, but offers limited groundwater potential. Other aquifers such as the sandy coastal aquifers and that in the Jaffna peninsula offer higher potential, but offer different causes for concern such as the higher irrigation frequency demanded by sandy soils, accelerating aquifer contamination. Concerns over contamination, arise in each example of groundwater use, and thus emerges as a major area of concern, especially in light of the considerable costs of remedial action. That this contamination is linked to drivers other than agriculture also highlights the dispersed components to be addressed in managing this issue.

The benefits from groundwater use are thus clearly significant, as is the vulnerability of aquifers from qualitative and quantitative standpoints that threaten the foundations of these production systems. Balancing these trade-offs and providing a rationalizing influence in these production systems thus emerges as the critical policy and regulatory challenge. The current institutional architecture however is drawn along hard lines of delineation between various service delivery functions (irrigation, domestic supply) and water sources (surface and ground) will need to acquire a conceptual and structural flexibility to adapt to ground realities where these distinctions are already fading. The current institutions in fact reflect a hydrosocial history dominated by surface water resources. However, three developments suggest movement toward meeting the groundwater governance challenge. The first is the recognition of the fundamental need for a more systematic process for generating and sharing information on groundwater resources, their interactions with human society and resulting feedback loops. The second is the emergent attempts to address this knowledge gap in the form of the recently initiated groundwater monitoring network. The third source of optimism emerges from the field level where key agencies such as the MASL as well as the Irrigation Department are already working with farmers to adapt to growing water scarcity and uncertainty (in Mahaweli System H) by combining surface and groundwater flows. It is hoped that such cases can provide the knowledge and attitudinal shifts necessary for such adaptive management at larger scales.

These developments are however only a beginning and subject to uncertainty. The groundwater monitoring initiative, for instance, is financed by time-bound donor funding, and thus its continuation will depend on government commitment or further donor support or a combination of the two. Moreover, while individual agencies demonstrate the imagination for adapting conventional approaches to irrigation, this may not wholly compensate for the absence of an institutional mechanism to ensure overall water resources planning and policy setting spanning all water demands in light of all management options. An important and interesting dimension to this challenge is the heterogeneity in groundwater resource availability given the six aquifer types in the country, linked to varying types and degrees of use, from the traditional groundwater culture on the Jaffna Peninsula, to the emerging groundwater markets. While a systematic data system will contribute to making these geographically specific challenges more explicit, it is suggested that the delegation of powers to provinces through the 13th Amendment to the country's Constitution will be an important factor in resolving the question of what scale might be most appropriate for groundwater management. Here too, the spatial misalignment between aquifer and administrative boundaries may add another layer of complexity.

Annex: Different Types of Aquifers and Their Occurrences in Sri Lanka

	Aquifer type	Occurrence and distribution	Salient features
1.	Shallow unconfined karstic aquifers	Occurs in the channels and cavities of the Miocene limestone formation. Distinctly bedded, well joined and highly karstified. The whole of Jaffna peninsula is underlain by this formation. All the shallow water originates from rainfall infiltration	Generally, 100–150 m in thick with an average of 60 m. Karstification intensifies the subsurface water flow and causing significant water loss (around 50%), especially along the coastal lagoon. Around 80% of the remaining water is used for agriculture and rest for domestic use. The estimated usable groundwater is 10–25 million m^3
2.	Deep confined sandstone and Miocene limestone aquifers	Occur within sedimentary limestone and sandstone formations of the northwestern and northern coastal plains. Sedimentary limestone is highly faulted and separates the aquifer into a number of isolated blocks. Seven distinct groundwater basins have been identified and named as Mullaitivu, Vanathavillu, Kondachchi, Murunkan, Mulankavil, and Paranthan	These are relatively more than 60 m in deep and one of the richest groundwater basins in the country with Artesian conditions. These aquifers expand during rainy season and contracts in the dry season. About 125,000 ha of high-value intensive agriculture, intensive human settlement, and flourishing coastal tourism industry are supported by these aquifers
3.	Coastal sand aquifers	Consist of three different types, i.e., Shallow aquifers on coastal spits and bars (type 1) found in Kalpitiya, Pooneryn, and Mannar island in the northwestern region; Shallow aquifers on raised beaches (type 2) found in Nilaweli-Kuchchaweli, Kalkuda and Pulmoddai in northeastern region and moderately deep aquifers on old red and yellow sands of prior beach plains (type 3) found in Katunayake and Chilaw	These aquifers expand during rainy season and contracts in the dry season. Total extent under type 1 and type 2 aquifers is estimated to be 140,000 ha that supports high-value intensive agriculture, intensive human settlement and flourishing coastal tourism industry are supported. Extent of type 3 aquifer is around 40,000 ha
4.	Alluvial aquifers of variable depth	Occur in coastal and inland floodplains, inland river valleys small rivulets, and old buried riverbeds	Alluvial formation in the larger rivers varies from 10 to 15 m and up to 35 m in thickness and may extend to several hundreds of meters on either side of river beds.

(continued)

(continued)

	Aquifer type	Occurrence and distribution	Salient features
			Groundwater potential is very high in these aquifers and water could be tapped continuously for industrial and agricultural purposes
5.	Lateritic (cabook) aquifers	Occurs in the southwestern low-lying parts of the country. Aquifer is highly fragmented into a number of discreet, low mounds	It has considerable water-holding capacity depending on the depth of the 'Cabook' formation. The storage capacity of the complex mosaic of meso-aquifers is large due to the high porosity of the typical cellular honeycomb structure. Easily accessible to shallow dug wells and tube wells. The water table can recede up to 15 m below the ground during the dry periods for more than 65 days. The aquifer recharge rate is fast due to its structural characteristics and location in the wet zone
6.	Shallow regolith aquifers of the hard-rock region	Groundwater in these formations is found as separate pockets formed in the shallow weathered mantel rock (regolith) or in deeper fracture zones of the unweathered material. Occurs in the north central and northwestern part of the island	Aquifer in the weathered zone generally ranges from 2 to 10 m in thickness, while the fractured zone is located at more than 30–40 m depth. Limited groundwater potential due to low storage capacity and transmissivity of underlying Crystalline basement rock. Nearly nine-tenths of the country is underlain by crystalline hard rock. Agro-wells have been mainly constructed in these aquifers

Source Adopted from Villholth and Rajasooriyar (2010), Panabokke and Perera (2005), Panabokke and Sakthivadivel (2002), Panabokke (2007)

References

Aheeyar M, Manthrithilake H (in prep.) How groundwater is taking over surface irrigation and resulting livelihood improvements in Mahaweli System H, Sri Lanka. International Water Management Institute, Colombo

Ahmed M, Suphachalasai S (2014) Assessing the costs of climate change and adaptation in South Asia. Asian Development Bank, Mandaluyong City, Philippines

Amarasinghe UA (2010) Spatial variation of water supply and demand in Sri Lanka. In: Jinapala K, de Silva S, Aheeyar MMM (eds) Proceedings of the national conference on water, food security and climate change in Sri Lanka, Vol 3: Policies, institutions and data needs for water management. BMICH, Colombo, Sri Lanka, 9–11 June 2009. International Water Management Institute, Colombo, Sri Lanka, 162 pp. https://doi.org/10.3910/2010.203

Amarasinghe UA, Samad M, Anputhas M (2005) Locating the poor: spatially disaggregated poverty maps for Sri Lanka. Research report 96. International Water Management Institute, Colombo, Sri Lanka

Arasalingam S, Pathmarajah S, Mikunthan T, Vithanage M, Manthrithilake H (2013) Impact of agricultural activities on groundwater quality and its suitability for drinking in Valikamam area, Jaffna Peninsula. In: Sri Lanka Water Partnership (Lanka Jalani), International Water Management Institute (IWMI), Unilever-Pureit (eds) Proceedings of the first young water professionals symposium, Colombo, Sri Lanka, 22–23 Nov 2012. Sri Lanka Water Partnership (Lanka Jalani), Colombo, Sri Lanka; International Water Management Institute (IWMI), Colombo, Sri Lanka; Unilever-Pureit, Colombo, Sri Lanka, pp 74–81

Athukorala W, Wilson C (2012) Groundwater overuse and farm-level technical inefficiency: evidence from Sri Lanka. Working/Discussion paper No. 279, School of Economics and Finance, Queensland University of Technology, Brisbane

Balendran VS, Sirimanne CHL, Arumugam S (1968) Groundwater in Jaffna. Water Resources Board, Colombo

Brohier RL (1935) Ancient irrigation work of Ceylon. Mahaweli Center, Mahaweli Authority of Sri Lanka, Colombo

Climate Change Secretariat (2010) Sector vulnerability profile: water. Supplementary document to: the national climate change adaptation strategy for Sri Lanka 2011 to 2016. Ministry of Environment, Colombo, Sri Lanka

Cooray PG (1988) The geology of Sri Lanka (Ceylon) Colombo. National Museum, Sri Lanka

Department of Census and Statistics (2012) Census of population and housing—2011-provisional information based on 5% sampling. Department of Census and Statistics, Colombo. Retrieved from http://www.statistics.gov.lk/PopHouSat/CPH2011/index.php?fileName=CPH_2012_5Per_Rpt&gp=Activities&tpl=3

De Alwis KA, Panabokke CR (1972) Handbook of soils of Sri Lanka (Ceylon). Soil Sci Soc Ceylon 2:1–97

De Silva CS, Weatherhead EK, Knox JW, Rodriguez-Di JA (2007) Predicting the impacts of climate change—a case study of paddy irrigation water requirements in Sri Lanka. Agric Water Manage 93:19–29

De Silva S, Curnow J, Ariyaratne R (in prep.) Groundwater driven agrarian change in Sri Lanka's North Central Province: a microcosm of a national need for groundwater governance. International Water Management Institute, Colombo

Dharmasena PB (2001) Towards efficient utilization of surface and ground water resources in food production under small tank system. In: Gunasena HPM (ed) Proceedings of the workshop on food security and small tank systems in Sri Lanka. National Science Foundation, Colombo, Sri Lanka, pp 103–110

Eriyagama N, Smakhtin V, Chnadrapala L, Fernando K (2010) Impacts of climate change on water resources and agriculture in Sri Lanka: a review of preliminary vulnerability mapping. Research report 135, International Water Management Institute, Colombo

Esham M, Garforth C (2013) Agricultural adaptation to climate change: insights from a farming community in Sri Lanka. Mitig Adapt Strat Glob Change 18(5):535–549

Ferdinando DNJ, Premathilake M (2013) Groundwater development for potable water supply. In: International Water Management Institute (IWMI) (ed) Proceedings of the national seminar on groundwater governance in Sri Lanka, Colombo, Sri Lanka, 15 Aug 2013. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp 35–46

Gamage D, Damayanthi NMK (2012) Major dimensions of contemporary smallholder agriculture sector in Sri Lanka. Research report 146. Hector Kobbekaduwa Agrarian Research and Training Institute, Colombo

Hapugaskumbura K (1997) Groundwater. In: Somasekaram T, Perera MP, de Silva MBG, Godellawatta H (eds) Arjuna's atlas of Sri Lanka. Arjuna Consulting, Dehiwela, Sri Lanka

Herath G (2006) Overview of groundwater management, the agrowell program, and the impact of the 2004 Tsunami in Sri Lanka. Int Rev Environ Strat 6(2):373–386

Hydrosult Inc. (2010) Kalpitiya pilot area—groundwater monitoring programme. Report submitted to the Dam Safety and Water Resources Planning Project. Ministry of Irrigation and Water Resources Management, Colombo

International Water Management Institute (2003) Planning groundwater use for sustainable rural development. International Water Management Institute (Water Policy Briefing, Issue 14), Colombo

International Water Management Institute (IWMI) (2013a) Proceedings of the senior stakeholders' meeting on groundwater in the Jaffna Peninsula, Jaffna, Sri Lanka, 16 May 2013. International Water Management Institute (IWMI), Colombo, Sri Lanka, 34 pp. http://dx.doi.org/10.5337/2015.004

International Water Management Institute (IWMI) (2013b) Proceedings of the national seminar on groundwater governance in Sri Lanka, Colombo, Sri Lanka, 15 Aug 2013. International Water Management Institute (IWMI), Colombo, Sri Lanka, 134 pp

Jayakody AN (2006) Large diameter shallow Agro-wells—a national asset or a burden for the nation? J Agric Sci 2(1)

Jaffna District Secretariat (2015) Statistical information. Available online at: http://www.jaffna.dist.gov.lk/index.php?option=com_content&view=article&id=45&Itemid=57&lang=en

Karunaratne GRR (2013) Overview of efforts of water resources board. In: International Water Management Institute (IWMI) (ed) Proceedings of the national seminar on groundwater governance in Sri Lanka, Colombo, Sri Lanka, 15 Aug 2013. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp 21–34

Karunaratne ADM, Pathmarajah S (2003) Groundwater development through introduction of agrowells and micro-irrigation in Sri Lanka. In: Proceedings of symposium use of groundwater for agriculture in Sri Lanka, 30 Sept 2002. Agricultural Engineering Society of Sri Lanka, University of Peradeniya, Sri Lanka, pp 29–41

Kendaragama KMA (2000) Water quality of Agro-wells in the Dry Zone: a case study in Anuradhapura District. J Soil Sci Soc Sri Lanka 12:33–36

Kikuchi M, Weligamage P, Barker R, Samad M, Kono H, Somaratne HM (2003) Agro-well and pump diffusion in the Dry Zone of Sri Lanka; Past trends, present status and future prospects. IWMI Research report 66. International Water Management Institute, Colombo

Kodituwakku KAW (2009) Groundwater resources in Sri Lanka and its importance towards economic development. Economic Review. Peoples Bank Publication, Colombo, Sri Lanka

Kuruppuarachchi DSP, Fernando WARN (1990) Impact of agriculture on groundwater quality in Kalpitiya peninsula in the north-western dry zone of Sri Lanka. In: Gunawardena ERN (ed) Irrigation and water resources. Proceedings of a symposium, 24–25 Aug 1990, Kandy, Sri Lanka, pp 199–213

Kuruppuarachchi DSP, Fernando WARN (1999) Impact of agriculture on groundwater quality: leaching of fertilizers to groundwater in Kalpitiya Peninsula. J Soil Sci Soc Sri Lanka 11:9–16

Lawrence LR, Kuruppuarachchi DSP (1986) Impact of agriculture on groundwater quality in Kalpitiya, Sri Lanka—Implications for future development. British geological survey report WD/OS/86/20

Madduma Bandara CM (1995) Tank cascade systems in Sri Lanka: some thoughts on their development implications. In: Haq KA, Wijayaratne CM, Samarasekera BMS (eds) Summaries of papers presented at Irrigation Research Management Unit seminar series during 1994, Colombo, Sri Lanka, IIMI, p 14

Matara Arachchi SD, Piyadasa RUK, Wickramasinghe D (2014) Groundwater quality variation in Kalpitiya peninsula-Sri Lanka. In: Proceedings of the 4th SAITM research symposium on engineering advancement-2014, South Asian Institute of Technology and Medicine [SAITM], Malambe, Sri Lanka, 26 Apr, pp 113–115

Melvani K, Chandrasekera K, Mudannayake R (2006) The role of trees in the bioremediation of drinking water—a research experiment in Nawakkaduwa, Kalpitiya. In: Proceedings of the 32nd WEDC international conference on sustainable development of water resources, Water Supply and Environmental Sanitation, 13–17 Nov, Colombo

Mendis DLO (2003) Environment and conflict: a Kuhnian paradigm-based approach to understanding some socio-cultural and economic causes of problems and conflicts in modern irrigation projects in southern Sri Lanka. In: Water for people and nature. Ministry of Irrigation and Water Management, Sri Lanka, pp 95–122

Mendis DLO (2009) A river for Jaffna-The Arumugam Plan. Daily News, 5 May. Available online at http://archives.dailynews.lk/2009/05/05/fea03.asp

Mikunthan T, De Silva CS (2008) Vulnerability assessment for shallow aquifer using chemical quality of groundwater: a case study from Thirunelvely and Kondavil in Jaffna District. Trop Agric Res 20:303–312

Mikunthan T, Vithanage M, Pathmarajah S, Arasalingam S, Ariyaratne R, Manthrithilake H (2013) Hydrogeochemical characterization of Jaffna's aquifer systems in Sri Lanka. International Water Management Institute (IWMI), Colombo, Sri Lanka, 69 pp. https://doi.org/10.5337/2014.001

Ministry of Rehabilitation, Resettlement and Refugees (2003) Program framework for resettlement, rehabilitation, reconstruction and development

Mukherjee A (2018) Groundwater of South Asia. Springer Nature, Singapore. ISBN 978-981-10-3888-4

Panabokke CR (2003) Nature of occurrence and sustainable use of groundwater resources for agriculture in the North Central, North Western and North Eastern regions in Sri Lanka. Trop Agric Res Ext 6:8–13

Panabokke CR (2007) Groundwater conditions in Sri Lanka. A geomorphic perspective. National Science Foundation of Sri Lanka, Colombo

Panabokke CR (2009) Small village tank system of Sri Lanka: their evolution, setting, distribution and essential functions. Hector Kobbekaduwa Agrarian Research and Training Institute, Colombo

Panabokke CR, Perera APGRL (2005) Groundwater resources of Sri Lanka. Water Resources, Board, Colombo

Panabokke CR, Sakthivadivel R (2002) Coastal sand aquifers in Sri Lanka, general characteristics, present utilization and gaps in knowledge. In: Unknown (ed) Critical issues facing groundwater section in Sri Lanka and south India. Kodaikkanal, Tamil Nadu, pp 1–20

Panabokke CR, Tennakoon MUA, De Ariyabandu RS (2001) Small tank systems in Sri Lanka: issues and considerations. In: Gunasena HPM (ed) Proceedings of the workshop on food security and small tank systems in Sri Lanka. National Science Foundation, Colombo, Sri Lanka, pp 1–6

Panabokke CR, Sakthivadivel R, Weerasinghe AD (2002) Evolution, present status and issues concerning small tank systems in Sri Lanka [Small tanks in Sri Lanka: evolution, present status and issues]. International Water Management Institute (IWMI), Colombo, Sri Lanka 73 pp

Pathmarajah S (2002) Use of groundwater for agriculture in Sri Lanka: a synthesis of the past, present and the future. In: Proceedings of symposium "Use of groundwater for agriculture in Sri Lanka," Peradeniya, Sri Lanka, 30 Sept 2002. Agricultural Engineering Society of Sri Lanka, Peradeniya, pp 1–9

Perera MP (2001) The impact of Agro-wells in the vicinity of small tanks on the watershed management, B.A. dissertation, University of Peradeniya, Peradeniya

Prematilaka KM (2011) Groundwater resources and sustainability experience in Sri Lanka. In: Tennakoon MUA et al. (ed) Proceeding of the workshop on challenges in groundwater management in Sri Lanka. Water Resources Board, Sri Lanka

Punthakey JF, Gamage PDN (2006) Coupled flow and salinity transport modelling and assessment of groundwater availability in the Jaffna Peninsula, Sri Lanka. In: 32nd WEDC international conference 2006, Colombo, Sri Lanka

Punyawardane BVR (2008) Rainfall in Sri Lanka and Agro-ecological Zones. Department of Agriculture Press, Peradeniya, Sri Lanka

Qureshi AS, Ahmed Z, Krupnik TJ (2014) Groundwater management in Bangladesh: an analysis of problems and opportunities. Cereal Systems Initiative for South Asia Mechanization and Irrigation (CSISA-MI) Project, Research report No. 2, Dhaka, CIMMYT, Bangladesh

Rink P, Semasinghe C, Manthrithilake H (2016) The potential benefits of rainwater harvesting for households in the Jaffna Peninsula. Sri Lanka J Aquat Sci 21(1)

Saeed MM, Ashraf M (2005) Feasible design and operational guidelines for skimming wells in the Indus basin, Pakistan. Agric Water Manage 74:165–188

Saeed MM, Ashraf M, Asghar MN, Bruen M, Shafique MS (2002) Farmers' skimming well technologies: practices, problems, perceptions and prospects. Working Paper No. 40, International Water Management Institute, Lahore, Pakistan

Saleth RM, Dinar A, Neubert S, Kamaiah B, Manoharan S, Abayawardana S, Ariyaratne R, de Silva S (2007) Institutions, impact synergies and food security: a methodology with results from the Kala Oya Basin, Sri Lanka. International Water Management Institute, Colombo, Sri Lanka, 42 pp (IWMI Research report 124)

Samad M (2013) Wells and welfare: the Sri Lankan case. In: Water Management Institute (IWMI) (ed) Proceedings of the national seminar on groundwater governance in Sri Lanka, Colombo, Sri Lanka, 15 Aug 2013. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp 51–60

Senaratne A (1996) Use of groundwater in the NCP. Consultancy report to IIMI

Senaratne A, Wickramasinghe K (2011) Commons vs. commons: managing scarce water resources in dry zone village tank systems in Sri Lanka. Technical report, The Economy and Environment Program for Southeast Asia

Seo SNN, Mendelsohn R, Munasinghe M (2005) Climate change and agriculture in Sri Lanka: a Ricardian valuation. Environ Dev Econ 10(05):581–596

Shah T (2009) Taming the anarchy: groundwater governance in South Asia. RFF, Washington, DC

Shah T (2013) Groundwater governance in Sri Lanka: lessons from around the world. In: Proceedings of the national seminar on groundwater governance in Sri Lanka. International Water Management Institute, Colombo, 15 Aug 2013

Shah T (2014) Groundwater governance and irrigated agriculture. Global Water Partnership Technical Committee (TEC), Background paper No. 19

Shanmugarajah K (1993) Water resources development: Jaffna Peninsula. Available online at http://www.noolaham.net/project/43/4287/4287.pdf

Sivalingam S (2010) General features and fisheries potential of Palk Bay, Palk Strait and its environs. J Natl Sci Found Sri Lanka 33(4)

Sood A, Manthrithilake H, Siddiqui S, Rajah A, Pathmarajah S (2015) Managing shallow aquifers in the dry zone of Sri Lanka. Environ Monit Assess 187(7):1–16

Sri Lanka Government Ministry of Agricultural Development and Agrarian Services (2008) Let us cultivate and uplift the nation. National Campaign to Motivate Domestic Food Production 2008–2010. Proposed Plan for Presidential Task Force

Sufi AB, Latif M, Skogerboe GY (1998) Simulating skimming well techniques for sustainable exploitation of groundwater. Irrig Drain Syst 12:203–226

Sutharsiny A, Pathmarajah S, Thushyanthy M, Meththinka V (2012) Characterization of irrigation water quality of Chunnakam aquifer in Jaffna Peninsula. Trop Agric Res 23(3)

Thadchayini T, Thiruchelvam S (2005) An economic evaluation of drip irrigation project for banana cultivation in Jaffna district. In: Galagedara LG (ed) Water resources researches in Sri Lanka. Symposium proceedings of the water professionals' day, pp 111–126

Thirappane Divisional Secretary Division (2012) Thirappane Divisional Secretary Division Resource Profile. Sri Lankan Government

Thushyanthy M, De Silva CS (2012) Assessment of groundwater resources in Jaffna limestone aquifer. Trop Agric Res 23(2)

UNEP (2005) Sri Lanka—National Rapid Environmental Assessment-After Tsunami. Retrieved from http://www.unep.org/tsunami/reports/TSUNAMI_SRILANKA_LAYOUT.pdf

Villholth K (2013) Challenges of groundwater management in Sri Lanka. In: International Water Management Institute (IWMI) (ed) Proceedings of the national seminar on groundwater governance in Sri Lanka, Colombo, Sri Lanka, 15 Aug 2013. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp 67–80

Villholth K, Giordano M (2007) Groundwater use in a global perspective: can it be managed? In Giordano M, Villholth K (eds) The agricultural groundwater revolution: opportunities and threats to development. Wallingford, UK, CABI, pp 393–402 (Comprehensive Assessment of Water Management in Agriculture Series 3)

Villholth K, Rajasooriyar L (2010) Groundwater resources and management challenges in Sri Lanka—An overview. Water Resour Manage 24:1489–1513

Vithanage M, Mikunthan T, Pathmarajah S, Arasalingam S, Manthrithilake H (2014) Assessment of nitrate-N contamination in the Chunnakam aquifer system, Jaffna Peninsula, Sri Lanka. SpringerPlus 3(1):1

Wijesekara RS (2013) Management and monitoring strategy of groundwater in Sri Lanka. Water Resources Board. PowerPoint presentation. Available at: http://www.narbo.jp/data/01_events/materials(tp7)/12%20-%20Mr.%20R.S.%20Wijesekara.pdf

Wijesekara RS, Kudahetti C (2011) Water quality study in the shallow aquifer system of the Attanagalu Oya basin. In: Proceeding of the workshop on "Challenges in Groundwater Management in Sri Lanka" Organized by Ministry of Irrigation & Water Resources Management, Water Resources Board and Dam Safety & Water Resources Planning Project, Colombo, 15th Mar

World Bank (2014) World development indicators: fresh water. The Word Bank Group, Washington DC. Available at http://wdi.worldbank.org/table/3.5

World Bank (2016a) Sri Lanka overview. Worldbank.org. Available online at http://www.worldbank.org/en/country/srilanka/overview

World Bank (2016b) Sri Lanka—ending poverty and promoting shared prosperity: a systematic country diagnostic. World Bank Group, Washington, D.C. Available online at http://documents.worldbank.org/curated/en/363391467995349383/Sri-Lanka-Ending-poverty-and-promoting-shared-prosperity-a-systematic-country-diagnostic

World Resources Institute (WRI) (2003) Water resources and freshwater ecosystems. Country profile: Sri Lanka. Earth Trends: The Environmental Information Portal, New York. Available at http://earthtrends.wri.org/text/water-resources/country-profile-167.html