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Abhijit Mukherjee *Editor*

Groundwater of South Asia

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Groundwater of South Asia

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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

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

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सत्यमेव जयते

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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.

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

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.

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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.

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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),

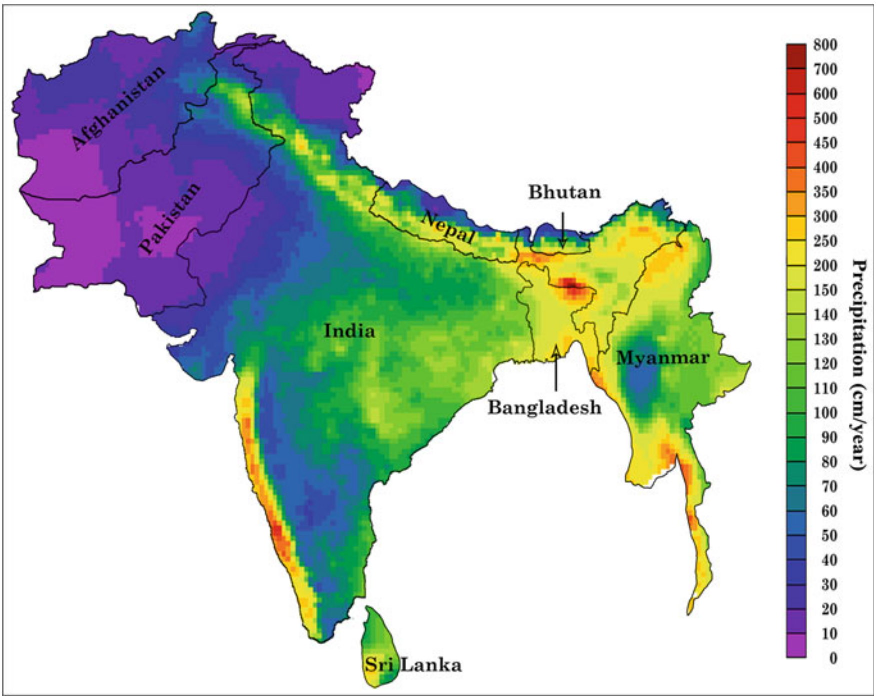

Fig. 1.1 Map of South Asia showing the range of mean annual precipitation distributions (1961–2011). *Source* APHRODITE database. The figure is not to scale, and the country boundaries are for illustrative purpose only

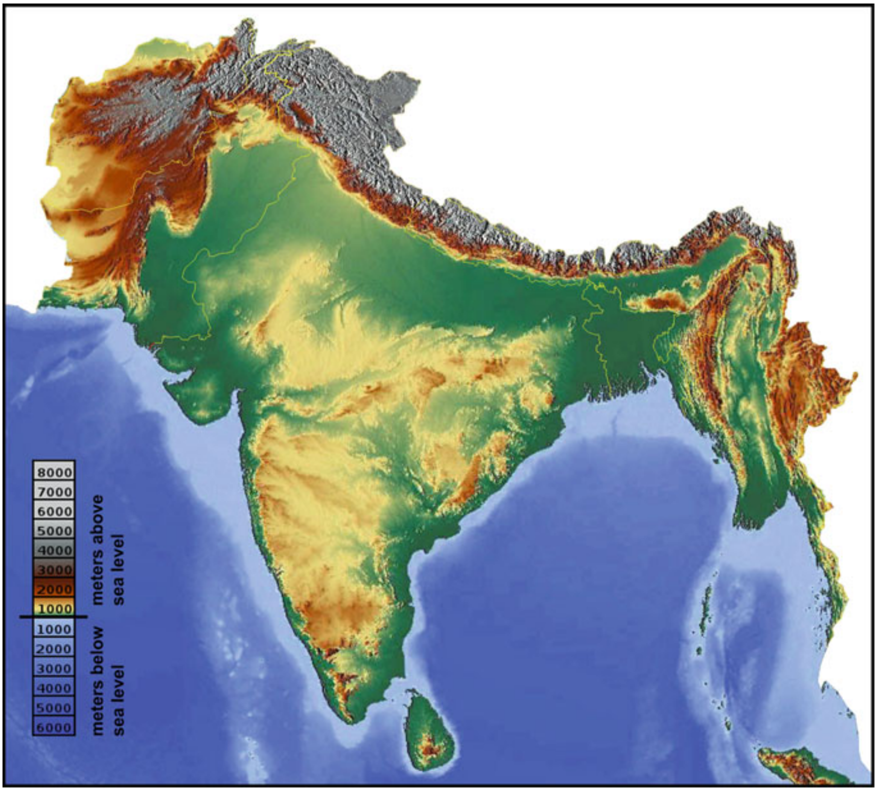

Fig. 1.2 Topographic and geomorphic map of South Asia, demonstrating the major topographic features visible in the area. The figure is not to scale, and the country boundaries are for illustrative purpose only

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 $\sim$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