Pradip K. Sikdar *Editor*

Groundwater Development and Management

Issues and Challenges in South Asia

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Preface

Groundwater is the most preferred source of water in different user sectors in South Asia due to its near-universal availability, dependability, and low capital cost. The increasing dependence on groundwater as a reliable source of water has resulted in indiscriminate extraction in various parts of South Asia without taking into account the recharging capacities of aquifers and other environmental factors. The irrigation sector remains the major consumer of groundwater in India, accounting for 92% of its annual withdrawal. The development of groundwater in India is highly uneven and shows considerable variations from place to place. Meeting the growing demand for water is further constrained by the deteriorating groundwater quality. In the past, a major advantage of using groundwater was that it normally required little or no treatment, but this is no longer the case. High arsenic, fluoride, chloride, nitrate, etc. concentrations, primarily as a result of increased agricultural production since the 1960s, affect many groundwater supplies. The same is true for pesticides that are widely used for weed control in agriculture, on roads, and railways, and that are also used to control pests in agriculture and industry. Perhaps the greatest threat to South Asia and India's water resources, and as a consequence also water supply and the environment, may come from the changing climate. However, there is great uncertainty about what the effects on water resources will be from climate change. From a groundwater perspective, it could cause a long-term decline in aquifer storage, increased frequency, and severity of droughts and floods as well as the mobilization of pollutants due to seasonally high water tables and saline intrusion in coastal aquifers.

Management of groundwater resources in South Asia is an extremely complex challenge. The highly uneven distribution of groundwater and its utilization make it impossible to have a single management strategy for the region as a whole. Any strategy for scientific management of groundwater resources should involve a combination of supply-side and demand-side measures depending on the regional setting. The likely adverse impacts of global climate change on the availability and quality of groundwater also demand significant political attention at the international and national levels. Groundwater management also calls for a paradigm shift from development strategy to management strategy against the backdrop of several million operating groundwater abstraction structures in South Asia to ensure food and energy security in the region.

This book is organized in twenty-three chapters, which not only highlight the problems of groundwater management in South Asia, in general, and in India, in particular, but also provides solutions using both traditional and modern techniques. The first two chapters cover the problems and challenges in groundwater management in South Asia and India. The next five chapters deal with the various tools that are used in understanding the geology, structure, 3D configuration of the aquifer systems, and groundwater flow and pollutant transport, such as geophysical techniques, environmental isotopes, geostatistics, remote sensing, geographical information system, and numerical modeling. Chapters 8 and 9 describe the development and management of the coastal aquifer systems and springs in hilly regions for community water supply. Drilling, construction, design, and development of wells are very important for a sustainable supply of groundwater from different geological formations; these are covered in Chap. 10. Chapter 11 deals with pumping tests and a field method to analyze pumping test data to determine the cardinal aquifer parameters, such as hydraulic conductivity, transmissivity, and storage coefficient; and safe spacing between two pumping wells. The next five chapters cover the quality of groundwater with respect to arsenic and fluoride, their impact on the food chain and human health, and the methods of treatment of arsenic and fluoride contaminated groundwater. The likely adverse impacts of global climate change on the availability and quality of groundwater also invite significant political attention at the international and national levels, which are covered in Chap. 17. Aspects related to rainwater harvesting, artificial recharging, and development and management of baseflow for public water supply in semi-arid areas are included in the next two chapters. The subject of groundwater governance has been addressed in Chaps. 20, 21, and 22 encompassing economics, pricing, jurisdiction, legislation, policy and regulations, legal framework, and community participation. The final chapter of this book depicts a road-map to evolve a paradigm to ensure safety and security of groundwater-based water supply.

This book addresses the various technical aspects of groundwater development and management and offers a meaningful and feasible guidance for better managing the stressed groundwater resources in South Asia including India. The book will serve as a guide to those who are concerned with various aspects of groundwater science like researchers, academics, professionals, and students in diverse fields like geology, geophysics, hydrology, environmental science, environmental engineering, environmental management, civil engineering, and irrigation engineering. Others who will benefit from this book are administrators, policy makers, and economists who are also concerned with the formulation and evaluation of plans for the development and management of groundwater resources.

The editor conveys his appreciation to all the authors of this book for their invaluable contributions. Without their contributions and support, this book would not have been possible. The editor is thankful to the Director of the Indian Institute of

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Kolkata, India Pradip K. Sikdar

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About the Editor

Professor Pradip K. Sikdar received his education at the University of Calcutta (Geology/Hydrogeology) and the University of Newcastle-upon-Tyne, UK (Integrated Coastal Zone Management). A teacher by profession and a hydrogeologist by education, he was a Senior Scientist and Executive Secretary at the Centre for Study of Man and Environment, Kolkata, and a Lecturer at the Department of Applied Geology, Indian School of Mines, Dhanbad, before joining the Indian Institute of Social Welfare and Business Management at the Department of Environment Management in 2000. Currently as a Professor at the Department of Environment Management, he is actively engaged in research and teaching of groundwater hydrology and environmental impact assessment. He has over 28 years of experience in project management and implementation, field and research work in groundwater systems including the application of computer models in the scientific evaluation of hydrogeologic systems, and groundwater resources development and protection. He also provides technical and management advice on a wide range of subjects dealing with watershed management: natural resources development; and environmental management issues to industries, consultant groups, and NGOs. He has carried out extensive research on arsenic contamination in groundwater of the Bengal Basin, and his primary interest in arsenic is to explain the spatial distribution of As-pollution in aquifers of the Bengal Basin. His present research also deals with the sustainability of water supply in the fluoride affected and semi-arid regions of West Bengal and the design of groundwater abstraction structures.

Professor Sikdar supervises several students for Master, Doctoral, and Postdoctoral research work. Up until now, five research students have been conferred the Ph.D. degree under his guidance. He is also Visiting Faculty at the Departments of Geology and Environmental Science of the University of Calcutta and at the Department of Geology of the Presidency University, where he teaches Hydrogeology and Water Resource Management. He has delivered several lectures in national and international conferences, seminars, workshops, UGC-sponsored refresher courses, etc. He is serving as a reviewer for many national and international journals. He is a member of several national and international professional institutions and societies, and is also on the Board of Editors of some leading national journals. He was a Member of the CGWB State-Level Technical Evaluation Committee and West Bengal Fact-Finding Commission on Environment. He has published more than 100 research papers in international and national journals, conference proceedings, books, and 35 project reports. He has authored the book "Groundwater of West Bengal: Assessment, Development and Management" (in Bengali) and co-authored the book "A Text Book of Environment". He has also edited two books on "Interlinking of Indian Rivers." He is the recipient of the 22nd Dewang Mehta Business School Award 2014 for the "Best Professor in Water Resources Management" and Groundwater Science Excellence Award in 2015 by the International Association of Hydrogeologists – India Chapter in appreciation of his achievements in the field of groundwater in India.

Chapter 1
Problems and Challenges for Groundwater Management in South Asia

Pradip K. Sikdar

1 Introduction

South Asia represents the southern region of the Asian continent, which comprises Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, India, Pakistan and Sri Lanka. Topographically, it is dominated by the Indian Plate, which rises above sea level as Nepal and northern parts of India situated south of the Himalayas and the Hindu Kush. South Asia is bounded on the south by the Indian Ocean and on land by West Asia, Central Asia, East Asia, and Southeast Asia. South Asia covers about 5.1 million km^2, which is 11.51% of the Asian continent or 3.4% of the world's land surface area. The region is home to about 39.5% of Asia's population and over 24% of the world's population, making it both the most populous and the most densely populated geographical region in the world. The important rivers of South Asia are Ganges, Indus and Brahmaputra. These rivers have contributed to the rise and prosperity of some of the earliest civilizations in history and today are the source of livelihood for millions. The South Asian river basins, most of which have their source in the Himalayas, support rich ecosystems and irrigate millions of hectares of fields, thereby supporting some of the highest population densities in the world.

The climate of this vast region varies considerably from area to area from tropical monsoon in the south to temperate in the north. The variety is influenced by not only the altitude, but also by factors such as proximity to the sea coast and the seasonal impact of the monsoons. Southern parts are mostly hot in summers and receive rain during monsoon periods. The northern belt of Indo-Gangetic plains also is hot in summer, but cooler in winter. The mountainous north is colder and receives snowfall at higher altitudes of Himalayan ranges. As the Himalayas block the north-Asian

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bitter cold winds, the temperatures are considerably moderate in the plains. South Asia is largely divided into four broad climate zones (Olive 2005). They are (i) dry subtropical continental climate between the northern Indian edge and northern Pakistani uplands, (ii) equatorial climate between the far south of India and southwest Sri Lanka, (iii) tropical climate in most of the peninsula with variations such as hot sub-tropical climate in northwest India, cool winter hot tropical climate in Bangladesh and tropical semi-arid climate in the centre, and (iv) alpine climate in the Himalayas.

Maximum relative humidity of over 80% has been recorded in Khasi and Jaintia Hills and Sri Lanka, while the area adjoining Pakistan and western India records lower than 20%. Climate of South Asia is largely characterized by monsoons. Two monsoon systems exist in the region (Tyson 2002). They are (i) summer monsoon when wind blows from southwest to most of parts of the region and accounts for 70%–90% of the annual precipitation, and (ii) winter monsoon when wind blows from northeast. The warmest period of the year (March to mid-June) precedes the monsoon season. In the summer the low pressures are centered over the Indus-Gangetic Plain and high wind from the Indian Ocean blows towards the centre. The monsoon season is relatively cooler because of cloud cover and rain. In early June the jet streams vanish above the Tibetan Plateau, low pressure over the Indus Valley deepens and the Inter-tropical Convergence Zone (ITCZ) moves in. This change results in depressions in the Bay of Bengal which brings in rain from June to September (Olive 2005).

2 Hydrogeological Framework

The behaviour of groundwater in South Asia is highly complicated due to the occurrence of diversified geological formations with considerable lithological and chronological variations, complex tectonic framework, climatological dissimilarities and various hydrochemical conditions. Studies carried out over the years have revealed that aquifer groups in alluvial/soft rocks even transcend the surface basin boundaries. The hydrogeological framework of the countries of South Asia is briefly described below.

2.1 India

In India groundwater occurs broadly in two groups of rock formations depending on characteristically different hydrogeological and hydrodynamical conditions. They are porous formations (unconsolidated and semi-consolidated) and fissured formations.

The unconsolidated formations are alluvial sediments of river basins, coastal and deltaic tracts where groundwater occurs in primary porosity. These are by far the most significant groundwater reservoirs for large scale and extensive development.

The hydrogeological environment and groundwater regime conditions in the Ganga-Brahmaputra basin indicate the existence of potential aquifers having enormous fresh groundwater resources. Bestowed with high incidence of rainfall and covered by a thick pile of porous sediments, these groundwater reservoirs get replenished every year and are being used heavily. The semi-consolidated formations normally occur in narrow valleys or structurally faulted basins. The Gondwanas, Lathis, Tipams, Cuddalore sandstones and their equivalents are the most extensive productive aquifers. Under favourable situations, these formations give rise to free flowing wells. In select tracts of northeastern India, these water-bearing formations are quite productive. The Upper Gondwanas, which are generally arenaceous, constitute prolific aquifers.

The fisssured formations occupy almost two-third of the country. Groundwater in these formations occurs in secondary porosity except vesicular volcanic rocks where it occurs in primary porosity. From the hydrogeological point of view, fissured rocks are broadly classified into four types. They are (i) igneous and metamorphic rocks excluding volcanic and carbonate rocks, (ii) volcanic rocks, (iii) consolidated sedimentary rocks and (iv) carbonate rocks. The first type consists of granites, gneisses, charnockites, khondalites, quartzites, schists and associated phyllites, slates, etc. These rocks possess negligible primary porosity but develop secondary porosity and hydraulic conductivity due to fracturing and weathering. Groundwater yield depends on rock type, grade of metamorphism and degree of weathering and fracturing. The predominant types of the volcanic rocks are the basaltic lava flows of Deccan Plateau. The Deccan Traps have usually poor to moderate hydraulic conductivity depending on the presence of primary and secondary porosity. The consolidated sedimentary rocks occur in Cuddapahs, Vindhyans and their equivalents. The formations consist of conglomerates, sandstones, shales, slates and quartzites. The presence of bedding planes, joints, contact zones and fractures control the groundwater occurrence, movement and yield. The carbonate rocks consist of mainly limestones and dolomites in the Cuddapah, Vindhyan and Bijawar group of rocks. In carbonate rocks, the circulation of water creates solution cavities. The solution activity leads to widely contrasting permeability within short distances through which turbulent flow of groundwater takes place.

The estimated replenishable groundwater resources in India as estimated by the Central Ground Water Board is 432 billion cubic metres (BCM) of which nearly 60% of the resources has already been developed. Major utilization of groundwater resources, nearly 80%, is in the agriculture sector.

2.2 Pakistan

The lndus Plain in Pakistan was formed by sediment deposits from the River lndus and its tributaries, and it is underlain by a highly transmissive unconfined aquifer. In the Punjab, most groundwater supplies are fresh. The main exceptions are the areas of saline groundwater in the centre of the interfluviums (‘doab’), particularly those between Multan and Faisalabad, around Sargodha, and in the south-eastern part of the province. In the southern part of the lndus Plain, in Sindh, groundwater supplies are more problematic. With the exception of a small strip along the River Indus, groundwater supplies are highly saline. The discharge from the aquifers in Sindh is generally less than that in Punjab (Survey of Pakistan 1989). Supplies are even less in the eastern deserts and the western limestone ridges bordering the lndus Plain. Balochistan and North West Frontier Province are geologically more complex. In Balochistan, land formations consist of limestone, sandstone, and shale formations alternating with sand, silt, and gravel deposits. The aquifers are confined and generally yield only limited quantities of water. The quality of groundwater is unsuitable for agriculture in parts of Balochistan, particularly in some of the coastal areas, in patches in the large, alluvial Kacchi plain in the east, and in several valleys in the uplands. Although the picture for North West Frontier Province resembles that of Balochistan, irrigation with groundwater in North West Frontier Province is more recent and, until recently, less extensive. This is due to the less arid conditions and ample surface water resources. Another difference is in the areas around Bannu and Mardan, where there are thick and extensive aquifers. In Bannu, however, the fresh water is overlain by saline water.

Total groundwater resources in Pakistan has been estimated to be 57 BCM out of which 30 to 40% is considered unsuitable for agriculture. Nearly 1.1 million tubewells (agricultural wells) are among the major causes of rapidly depleting groundwater levels. The over-exploitation of the confined aquifer has caused such an alarming situation that in the forseeable future the supply from groundwater may dry up in Quetta, the capital of Baluchistan. Large scale groundwater abstraction has posed considerable threat to soil and groundwater quality.

2.3 Bangladesh

The deposits of thick unconsolidated Pliestocene and Holocene alluvial sediments of the Ganga-Brahmaputra-Meghna (GBM) delta system form one of the most productive aquifer systems in the world. The aquifer gets fully recharged each year by monsoonal rains and floods. Deeper aquifers below the shallow zones of saline water intrusion are exploited in the coastal regions. Jones (1985) suggested that fresh water may also be available from older Tertiary rocks down to depths of 1800 m. The main aquifers in Bangladesh are (i) Late Pliestocene to Holocene coarse sands, gravels and cobbles of the Tista and Brahmaputra mega fans and basal fan delta gravels along the incised Brahmaputra channel (MMP 1977; UNDP 1982; MMP 1983), (ii) Late Pliestocene to Holocene braided river coarse sand and gravels deposited along the incised palaeo-Ganga, lower Brahmaputra and Meghna main channels (UNDP 1982; MMP 1983; Davies et al. 1988; Davies and Exley 1992; MMI 1992), (iii) Early to Middle Pliestocene stacked fluvial main channel made of medium to coarse sand at >150 m depth in the Khulna, Noakhali, Jessore/Kushtia and western moribund Ganga delta areas in the subsiding delta basin (UNDP 1982), (iv) Early to Middle

Pliestocene red-brown medium to fine sands that underlie grey Holocene medium to fine sands in the Old Brahmaputra and Chandina areas (UNDP 1982; MMP 1983; MMI 1992; Davies and Exley 1992), and (v) Early to Middle Pliestocene coarse to fine fluvial sands of the Dupi Tila Formation that underlie the Madhupur and Barind Tracts, capped by deposits of Madhupur Clay Residuum (Welsh 1966).

In most of the groundwater studies undertaken in Bangladesh, the aquifer system has not been divided stratigraphically. Conceptual models of hydrogeological conditions based on simple lithological units have been used to assess the hydraulic properties of aquifers and tubewell designs to depth of about 150 m. The aquifers have been divided into two groups according to colour and degree of weathering (Clark and Lea 1992). They are (i) the grey sediments mainly deposited during the last 20 ka, and (ii) the red brown sediments mainly older than 100 ka with iron oxides cements and grey smectitic clays. Hydraulic conductivities determined for grey sediments are estimated to be in the range 0.4–100 m/day. Those for red brown sediments are in the range 0.2–50 m/day (UNDP 1982). These give a ratio of hydraulic conductivities of 2:1 for grey-brown sediments. In general, the regional groundwater flow in the aquifers of Bangladesh is from north to south with local variation near major rivers. National Water Plan Phase-II estimated average groundwater as 21 cubic kilometres in 1991 (Sengupta et al. 2012). More than 60 per cent of the groundwater in Bangladesh contains naturally occurring arsenic, with concentration levels often significantly exceeding World Health Organisation's (WHO) standard of 10 μg/L.

2.4 Afghanistan

According to United Nations Department of Technical Cooperation for Development (United Nations 1986) the aquifers in Afghanistan can be divided into three categories. They are (i) alluvial and colluvial unconsolidated to semi-consolidated aquifers comprising about 20% of the total mapped aquifers and containing about 70% of the available groundwater resources, (ii) limestone and dolomite aquifers making up only 15% of the total mapped aquifers and containing about 20% of the available groundwater resources, and (iii) the remaining 65% of aquifers are low permeability units that contain about 10% of the available groundwater resources.

The three hydrogeological regions in Afghanistan are the Great Southern Plain (Siestan Basin) in the south, the Central Highland Region including the Hindu Kush mountain range and its associated ranges, and the Northern Plain (Amu Darya Basin) (United Nations 1986).

The intermontane stream basins of the Central Highland Region are hydrogeologically most significant (Gellasch 2014). These basins are fault controlled and filled with a variety of unconsolidated materials ranging from alluvial, colluvial, lacustrine and glacial deposits. The aquifers in these basins contain good amount of fresh water. The most important of the intermontane basins include those near the cities of Ghazni, Khowst (Khost), Jalalabad and Kabul (United Nations

1986). Of these basins, the Kabul Basin has been studied most extensively since 2001 (Broshears et al. 2005; Akbari et al. 2007; Lashkaripour and Hussaini 2008; Houben et al. 2009a, b; Mack et al. 2010). The Kabul Basin geology consists of consolidated rocks in the mountains surrounding the basin with unconsolidated sediments in the basin serving as the principal aquifer system. There are four aquifers in the Kabul Basin consisting mainly of sand and gravel which become slightly cemented with increasing depth. The Paghman-Darulaman basin has two aquifers lying along the course of River Paghman and the upper course of River Kabul. The other two aquifers are located in Logar Basin and the southern part of the Kabul Basin and follow the course of River Logar and the lower course of River Kabul.

The general groundwater flow direction is from western or south-western basin margin, through the basin centre, to the eastern basin margin. Locally the thickness of the aquifer can be up to 80 m (Bockh 1971). The Kabul, Paghman and Logar aquifers provide most of the drinking water to the residents of Kabul. The hydraulic conductivity of the aquifers varies from 2.3×10^{-5} to 1.3×10^{-3} m/s and can be classified as permeable to very permeable (Himmelsbach et al. 2005). Each of these three aquifers near Kabul is capped by a loess layer that varies between 1 and 5 m in thickness and helps to protect groundwater from contaminants migrating downward from the surface. The loess also inhibits infiltration and impacts recharge. The Kunar River valley in eastern Afghanistan is another basin that contains an important aquifer system. According to Banks and Soldal (2002), these intermontane basins are similar to two other thoroughly studied locations: the intermontane trough between the Greater and Lesser Caucasus in Azerbaijan and the intermontane trough of the Altiplano, between the Cordilleras Oriental and Occidental of Bolivia. The total groundwater recharge has been estimated to be $10{,}650 \times 10^6$ m^3/year and the total groundwater usage is 2800×10^6 m^3/year (Uhl 2003).

2.5 *Nepal*

Nepal is among the richest in terms of water resource availability. Water resources are abundant throughout the country in the form of snow covers, rivers, springs, lakes and groundwater. The total renewable water resource of the country is estimated to be 237 km^3/year (225 km^3/year for surface water sources and 12 km^3/year for groundwater sources) and per capita water availability for 2001 was 9600 m^3/capita/year (http://www.wepa-db.net/policies/state/nepal/state.htm, accessed on February 2017).

Groundwater is abundant in the aquifers of the Terai and the Kathmandu Valley. About 50% of the water used in the city of Kathmandu is derived from groundwater. Groundwater availability is more limited in the populated hilly regions because of the lower permeability of the indurated and crystalline rock types. In the Kathmandu Valley (area around 500 square kilometres), groundwater is abstracted from two main aquifers within the thick alluvial sediment sequence. A shallow unconfined aquifer occurs at >10 m depth and a deep confined aquifer occurs at around 310–370 m (Khadka 1993). The transmissivity value ranges between 163 and 1056 m^2/day for the shallow aquifer and 22.5 and 737 m^2/day for the deep aquifer (Pandey and Kazma 2011) indicating that the shallow aquifer has a better capacity to transmit water. Exploitation of these aquifers, especially the shallow aquifer, has increased rapidly in recent years as a result of the increasing urbanisation of the region. Recent abstraction of groundwater from the deep aquifer has led to a decrease in the groundwater level by around 15–20 m since the mid 1980s (Khadka 1993). Below the alluvial sediments in the Kathmandu Valley, karstic limestone aquifers also exist. A small number of natural springs issue from these and are used for water supply in the southern part of the valley. The limestone aquifer has not been developed and has received little hydrogeological attention. Shallow and deep aquifers are also present in the young alluvial sediments throughout most of the Terai region (Jacobson 1996). The shallow aquifer appears to be unconfined and well developed in most areas, although it is thin or absent in Kapilvastu and Nawalparasi (Upadhyay 1993). The deep aquifer of the Terai region is reported to be artesian (Basnyat 2001).

2.6 Sri Lanka

Six main types of groundwater aquifers have been identified and characterized in Sri Lanka. They are (i) shallow karstic aquifer of Jaffna Peninsula, (ii) deep confined aquifer, (iii) coastal sand aquifers, (iv) alluvial aquifers, (v) shallow regolith aquifer of the hard rock region, and (vi) south western lateritic (Cabook) aquifer. In 1985, the internal renewable groundwater resources were estimated at 7.8 km^3, most (estimated at 7 km^3/year) returning to the river systems and being included in the surface water resources estimate of 50 km^3/year (http://www.eoearth.org/view/article/156991/, accessed on February 2017).

The shallow karstic aquifer of the Jaffna peninsula is composed of Miocene limestone and is intensively used. The aquifer is 100 to 150 m thick, distinctly bedded and well jointed. The shallow groundwater forms mounds or lenses floating over the saline water. These water mounds or lenses reach their peak during the monsoon rains of November–December (Panabokke and Perera 2005).

The deep confined aquifers occur within the sedimentary limestone and sandstone formations of the northwest coastal plain and are least utilized. These aquifers are more than 60 m deep and have a relatively high recharge rate. The deep aquifer is highly faulted and it separates the aquifer into a series of isolated blocks thus forming seven distinct groundwater basins. The shallow coastal sand aquifer occurs on the coastal beaches and spits in the Kalpitiya Peninsula and the Mannar Island in the north west of Sri Lanka and on raised beaches of Nilaveli-Kuchchaweli, Pulmoddai and Kalkuda in the north-eastern region. The shallow coastal aquifers occupy about 1250 sq. km and are intensively used for drinking, domestic, agriculture and tourism industry.

The alluvial aquifers occur on both coastal and inland flood plains, inland river valleys of varying size, and old buried river beds and is unconfined in nature. The deeper and larger alluvial aquifers occur along the lower reaches of the major rivers that cut across the various coastal plains. Rivers such as Mahaweli Ganga, Kelani Ganga, Deduru Oya, Mi Oya, Kirindi Oya and Malwathu Oya have broad and deep alluvial beds of variable texture and gravel content in their lower reaches. Old buried riverbeds with high groundwater yield are present in the lower part of River Kelani. The alluvial formations of these larger rivers may vary between 10 and 35 m thickness, and may extend to several hundreds of meters on either side of the riverbeds. A reliable volume of groundwater can be extracted from these alluvial aquifers throughout the year and are intensively used at present.

Groundwater potential in the hard rock region of Sri Lanka is limited because of the low groundwater storage capacity and transmissivity of the underlying crystalline basement hard rock (Sirimanne 1952). Groundwater is found in the weathered rock zone, or the regolith, as well as in the deeper fracture zone. The weathered zone generally ranges from 2 to 10 m in thickness, while the fracture zone is located at depths of more than 30–40 m (Panabokke 2003). This shallow regolith aquifer is mainly confined to a narrow belt along the inland valley systems of this undulating mantled plain landscape, and despite its low yield and transmisivity, it has provided the basic minimum water needs for village settlements. The average thickness of the regolith is not more than 10 m in this region. Recent developments in agro-well farming in the north central provinces of the country are wholly dependant on this shallow groundwater (Karunaratne and Pathmarajah 2002).

The laterite or cabook, aquifers which occur in southwestern Sri Lanka have considerable water holding capacity depending on the depth of the Cabook Formation and is unconfined in nature. Due to the highly dissected nature of the macro landscape in this region, the aquifer is highly fragmented into a number of discreet, low mounds, within the residual landscape which is separated from each other by intervening valley floors. This aquifer has been highly exploited due to rapid expansion of industrial estates, urban housing schemes and bottled water projects especially in the area of outer Colombo and adjacent districts.

2.7 *Maldives*

Groundwater in Maldives is found in freshwater lenses underlying the atolls and floating on top of the saline water. Heavy abstraction of this as the main source of drinking water has depleted the freshwater lenses, especially in the capital city of Male, causing salt water intrusion. Groundwater is recharged by rainfall but becomes contaminated while percolating through the soil, which is generally polluted with organic and human wastes. A rough estimate of the groundwater resources, based on an assumed 0.1 m/year recharge throughout the country (300 km^2), is 0.03 km^3/year, which would be the only renewable resource of Maldives, though hardly exploitable because of seawater intrusion and pollution (http://www.eoearth.org/view/article/156968/, accessed on February 2017).

2.8 Bhutan

Very little hydrogeological work has been done in Bhutan. A reconnaissance hydrogeological work was carried out by Sikdar (2014) in Samdrup Jongkhar town. The town shares border with Indian state of Assam in the South, Arunachal Pradesh in the East, Pemagatshel Dzongkhag of Bhutan in the west and Trashigang Dzongkhag of Bhutan in the north. The area consists of low to moderate altitude denudation structural hills and is characterised by high run off, low infiltration to the groundwater body and development of springs. Groundwater occurs under unconfined condition within the weathered residuum of the underlying semi-consolidated formation consisting of claystone/siltstone/sandstone. Groundwater also occurs under semi-confined conditions within the fractures, joints and bedding planes of the semi-consolidated formation. Geophysical investigation up to a depth of 60 m by PRCS and ATWMC in 2010 reveals that in the northern part of the town in the Pinchina area the aquifer comprising fine to coarse sand mixed with gravels, pebbles and boulders (weathered/fractured sandstone?) extends up to a depth of 30 to 40 m followed by a low permeability bed made of clay (claystone or siltstone?). In the industrial area of the town the aquifer extends up to a depth of 60 m. In the southern part of the town the aquifer is thinner, extending up to a depth of 20 m followed by a low permeability bed. At Dredulthang the aquifer has not been recorded and the low permeability bed occurs at a depth of 3.5 m only. Central Ground Water Board of India has reported the existence of two to three promising aquifer zones down to the depth of maximum 200 m below ground level and the aquifer shows various degree of lateral and vertical variation in the adjoining area of Assam. It is expected that similar hydrogeological condition prevails in Samdrup Jongkhar town. The master slope of the land surface is towards south and hence the regional groundwater flow is also towards south.

3 Problems of Groundwater

South Asia is home to about a quarter of the global population, but has less than 5% of the world's annual renewable water resources. Low groundwater recharge (Fig. 1.1), low per capita water availability, coupled with a very high relative level of water use (dominated by irrigation), makes South Asia one of the most water scarce regions of the world, and a region where scarcity impacts on economic development (Fig. 1.2).

Since the 1970s, groundwater extraction has increased greatly in South Asia especially for food security. For example, in India, groundwater irrigated areas witnessed a spectacular increase from around 11.9 million hectare in 1970–1971 to 33.1 million hectare in 1998–1999, an increase of over 178%. The number of groundwater extraction mechanism rose from less than one million in 1960 to almost 26–28 million in 2002. In Pakistan Punjab, the number of mechanized wells and tube

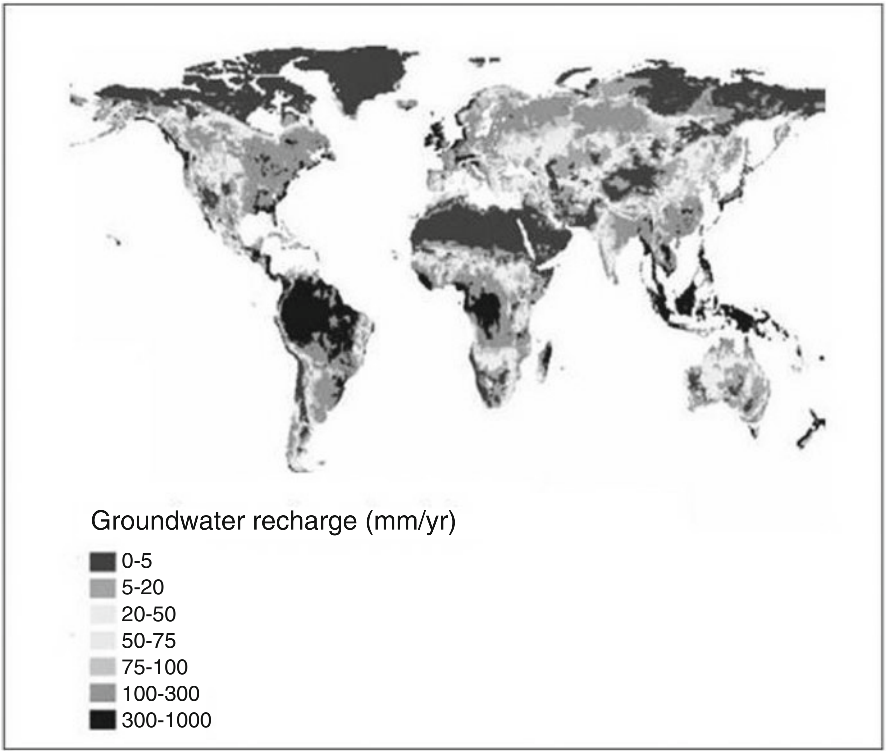

Fig. 1.1 Long-term average groundwater recharge. (*Source:* Döll et al. 2002)

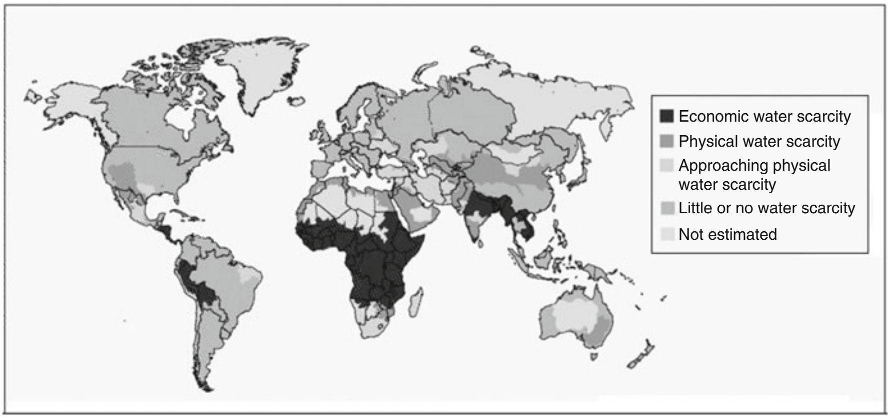

Fig. 1.2 Global water stress. (*Source:* UNWWDR 2012)

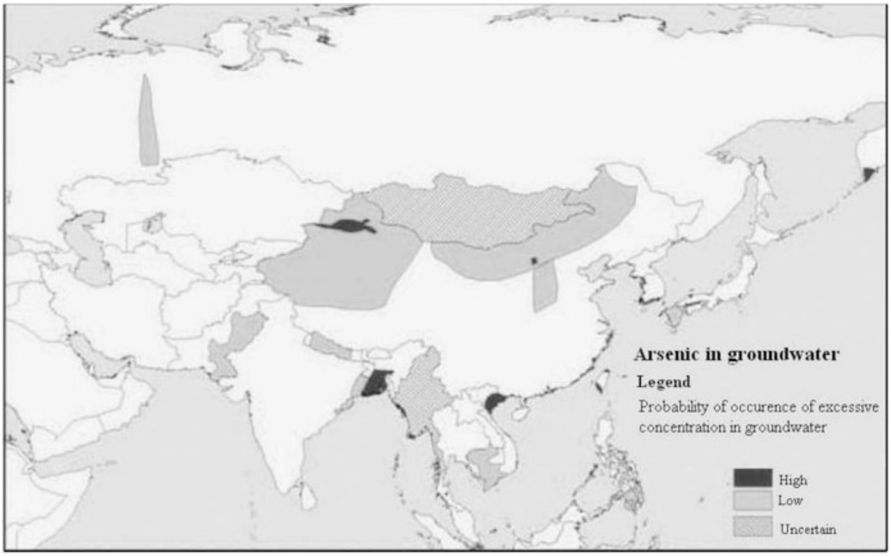

Fig. 1.3 Distribution of arsenic in groundwater in Asia. (*Source:* Brunt et al. 2004a)

wells increased from barely a few thousand in 1960 to 500 thousands in 2000. Bangladesh saw an increase in the number of tube wells, from 93,000 in 1982–1983 to almost 800,000 in 1999–2000. The beneficial impacts of groundwater use are increased productivity, food security, increased recharge, decreased flood intensity, job creation, livelihood diversification, poverty alleviation and general economic and social improvement. But in the long run, the impact of groundwater extraction might be negative especially in over-exploitation situation, such as permanent lowering of the water table, deterioration of water quality, saline intrusion in coastal areas, etc.

3.1 Groundwater Quality

Groundwater quality in South Asia has progressively deteriorated due to increasing withdrawals for various uses, increased use of agrochemicals, discharge of untreated domestic sewage and industrial effluents. In parts of India, Bangladesh, Nepal and Pakistan, high concentration of arsenic in groundwater is a menacing problem and estimated 500 million people are at risk of being exposed to arsenic poisoning through drinking water (Fig. 1.3). Long-term exposure to low levels of arsenic in food and water produces adverse effects on human health that are often described by the term arsenicosis. Early symptoms are non-specific effects such as muscular weakness, lassitude and mild psychological effects. These are followed by characteristic skin ailments such as changes in skin pigmentation and progressively painful

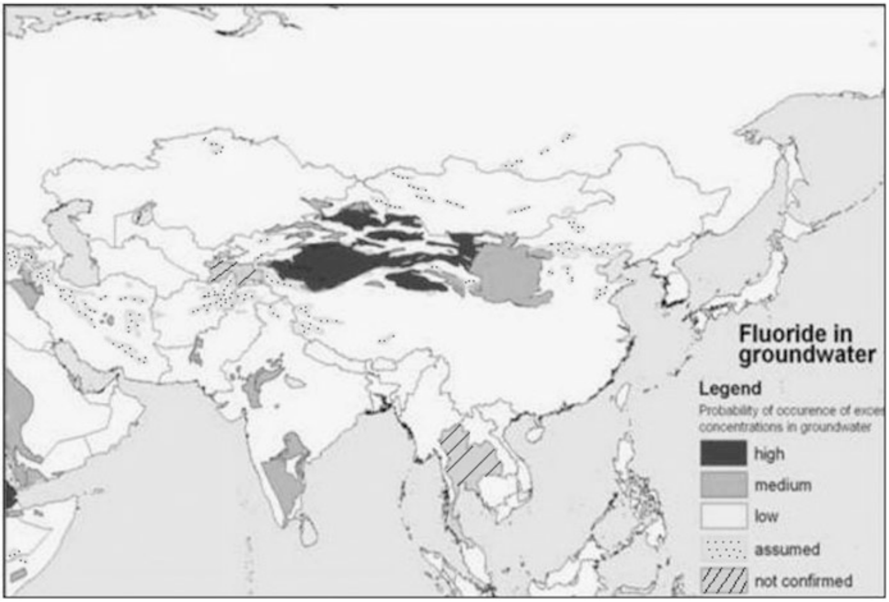

Fig. 1.4 Distribution of fluoride in groundwater in Asia. (*Source:* Brunt et al. 2004b)

skin lesions, known as keratosis. At the same time, arsenic causes a wide range of other effects on health, including diseases of the liver and kidney, cardio-vascular and peripheral vascular diseases, neurological effects, diabetes and chronic and acute lung disease. Continued exposure to arsenic can lead to gangrene, cancers of the skin, lung, liver, kidney and bladder, and thereby to death. High fluoride in groundwater is another problem in India and Pakistan (Fig. 1.4). Consumption of water having excess fluoride over a prolonged period leads to a chronic ailment known as fluorosis. Dental fluorosis, also called “mottled enamel”, occurs when the fluoride level in drinking water is marginally above 1.0 mg/L. Typical manifestations of dental fluorosis are loss of shining and development of horizontal yellow streaks on teeth. Since this is caused by high fluoride in or adjacent to developing enamel, dental fluorosis develops in children born and brought up in endemic areas of fluorosis. Skeletal fluorosis affects both adults and children and is generally manifested after consumption of water with fluoride levels exceeding 3 mg/L. Typical symptoms of skeletal fluorosis are pain in the joints and backbone. In severe cases this can result in crippling the patient. Recent studies have shown that excess intake of fluoride can also have certain non-skeletal health impacts such as gastro-intestinal problems, allergies, anemia and urinary tract problems. Nutritional deficiencies can enhance the undesirable effects of arsenic and fluoride. Anthropogenic contamination in the form of heavy metals such as Cr, Pb, Mn and bacteriological parameters has already made the groundwater unacceptable at many places.

3.2 Over-Exploitation of Groundwater

Groundwater over-exploitation has occurred in most countries of South Asia which has resulted in fall in groundwater levels, reduction of well yields, sea water intrusion in coastal aquifers, land subsidence and transport of polluted water into the aquifer. Generally, the fall of groundwater levels results in increased cost of groundwater owing to the expenditure involved in deepening the wells and pumping up water from the correspondingly increased depths. In some cases, over-exploitation can lower the water table to such depths that the existing wells have to be abandoned. Countries which are facing problems related to excessive withdrawal of groundwater in certain locations include India, Bangladesh, Pakistan, Maldives and Sri Lanka. For example, in Quetta, the state capital of Baluchistan over-exploitation due to large scale development through private tube wells of the confined aquifer has caused such an alarming situation that in the foreseeable future even the supply from deep groundwater may dry up. In Kolkata, India (Sikdar et al. 2001) and Dhaka, Bangladesh (Hoque et al. 2007) because of over-abstraction of groundwater from deep aquifers water level fails to recover fully due to monsoonal recharge resulting in a long-term water level decline in the post-monsoon period and change in groundwater flow pattern.

3.3 Seawater Intrusion

Seawater intrusion into coastal fresh water aquifers is another serious groundwater problem. Since a large portion of South Asia's population is located along the coasts there are many problems of this kind in this region. When groundwater is pumped from aquifers that are in hydraulic connection with the sea, the gradients that are set up may induce a flow of salt water from the sea towards the well. The migration of salt water into freshwater aquifers under the influence of groundwater development is known as seawater intrusion. There is a tendency to indicate occurrence of any saline or brackish water along the coastal formations to sea water intrusion. Although seawater intrusion is a slow process, in an area where pumping is continuous, it tends to be an irreversible process. As groundwater is extracted from the wells, the salt water slowly moves through the water-bearing formations in the direction of the wells and, unless corrective measures are taken, the salt water will ultimately begin to contaminate the fresh water in the wells. Such contamination manifests itself in a gradual increase in the salt content of the water being pumped. In India, sea water intrusion is observed along the coastal areas of Gujarat and Tamil Nadu.

3.4 Land Subsidence

Land subsidence occurs when large amounts of groundwater have been withdrawn from certain types of rocks, such as fine-grained sediments. The sediment compacts because the water is partly responsible for holding up the ground. Decline of water table or piezometric surface results in vertical compression of the subsurface materials (Bouwer 1977). Along with vertical compression, lateral compression may also take place due to initiation or acceleration of lateral flow of groundwater. This lateral movement also results in subsidence of the land surface. Any flow or overdraft of groundwater in unconsolidated material should produce some movement of the land surface. This movement is generally small, but may become very significant where subsurface materials are thick and/or compressible and the groundwater level declines appreciably (Sikdar et al. 1996). Land subsidence may not be noticeable because it can occur over large areas rather than in a small spot. Over-exploitation of groundwater in India, Pakistan and Bangladesh requires to be controlled so that possibilities of land subsidence, a vulnerable environmental threat, can be avoided.

4 Groundwater Legislation

Groundwater legislation is concerned with the provision for the quantification, planning, allocation and conservation of groundwater resources, including water abstraction and use rights. It is also concerned with providing cooperative interaction between water administrators and water users.

In India, groundwater is treated as a state subject as the Constitution of India does not empower Central Government to directly deal with its management. The Government of India prepared a Model Bill for regulation of groundwater in 1970 and circulated it to all states for implementation which advocated the view that government has the right to regulate the extraction of groundwater which, therefore, should not be regarded as private property like land. The bill was revised in 1992, 1996 and 2005. The main thrust of all the versions of the Model Bill is to constitute a state groundwater authority which would identify the critical areas and would notify them for regulation. Eleven states (Andhra Pradesh, Goa, Tamil Nadu, Kerala, West Bengal, Himachal Pradesh, Bihar, Jammu-Kashmir, Karnataka, Assam and Maharahtra) and three Union Territories (Lakshadweep, Pondicherry and Dadra-Nagar Haveli) have so far enacted legislation for regulation of groundwater in their states. A Central Ground Water Authority has also been constituted as a statutory body under Environment (Protection) Act, 1986 from January 1997 to regulate and control development and management of groundwater resources in the country. The Authority has been given wide powers including power to impose penalty on any person, company, Government Department etc. The Authority has notified 162 places/blocks/mandals/talukas for control and regulation of groundwater.

In Bangladesh the first effort towards management of groundwater was in the form of 'Groundwater Management Ordinance 1985'. The ordinance was primarily meant for management of groundwater used for irrigation purpose. In 2013 Water Act 2013 has been enacted and is designed for integrated development, management, extraction, distribution, usage, protection and conservation of water resources in Bangladesh. As per Water Act 2013 groundwater in Bangladesh belong to the government and a permit or a license is required for any large scale withdrawal of water by individuals and organizations beyond domestic use.

In Pakistan, Balochistan is the only provincial government to issue legislation to control groundwater mining. In 1978 the Groundwater Rights Administration Ordinance was announced. The objective of the Ordinance was 'to regulate the use of groundwater and to administer the rights of the various persons therein.' The Ordinance established the procedures and framework within the district civil administration to issue permits for the development of new karezes, dug wells and tubewells.

In Maldives, as per the Maldives Tourism Act (Law No. 2/99) groundwater cannot be extracted for the purpose of construction in an island or land leased for the development of tourism. In Sri Lanka, Nepal, Afghanisthan groundwater has practically remained an unregulated resource.

5 Challenges for Groundwater Management

The present system of groundwater management is based on political and administrative boundaries. This approach may be faulty as flow of water ignores political boundaries. Therefore, the first challenge for effective groundwater management is to advocate the importance of managing water at catchment or river basin scales. Database on groundwater systems are either poor or haphazardly maintained. Hence, the second challenge is to improve and share basic data and generate and transfer scientific knowledge. In many parts of the region the aquifer system is not well understood. Therefore, the third challenge is to map the aquifer at river basin scale which should also include the quality aspect. A nationwide programme of regular water-level and water-quality monitoring of the stressed aquifer systems would both characterize the state of water quality in the aquifer and serve as an early-warning system for the impending arrival of contaminants in water supply wells. Therefore, developing a framework of monitoring of the groundwater level and quality is the fourth challenge for effective groundwater management. The fifth challenge is to evolve an effective legal and institutional framework for groundwater governance which would include well-defined groundwater use rights, water pricing and energy pricing. The sixth and the final challenge is to train a group of hydrogeologists into 'social hydrogeologists' or 'ecological hydrogeologists' who will have the capacities to comprehend a sustainable system that combines not only the technical, but also financial, social and environmental aspects and their impacts.

Therefore, challenges for groundwater management in South Asia are huge, and perhaps, more importantly, that there is an urgent need for all professionals working with water-related management to realize their personal responsibilities in creating an accountable and conscious stewardship of water for present and future generations.

6 Conclusion

A review of hydrogeological situation in South Asia reveals several alarming trends of over-exploitation of groundwater causing long-term decline of groundwater level, ingress of saline water and deterioration of groundwater quality. This calls for a new institutional framework for groundwater management. There should be a clear shift from focusing on the unsustainable exploitation of groundwater towards an approach centered on providing incentives to different stakeholders for better and more equitable management of groundwater resource. Providing incentives may not be enough. An empowering environment and a fine-tuned combination of top-down and bottom-up approaches are also required. This new groundwater management framework will focus not only on groundwater use rights and groundwater pricing but also on the users themselves including low income users and other vulnerable groups, and to develop a group of ‘social hydrogeologists’ or ‘ecological hydrogeologists’ who would have the skills to better understand not only the technical, but also financial, social and environmental aspects and their impacts. There is dire need to evolve workable methods and approaches to synchronize the demand and supply gap. In order to improve water supply in urban areas, the installation of water meters need to be encouraged. Building a near social framework including community participation at all levels of water system is necessary. The community participation in water pumping policies, incentives of efficient use, affordability by low income users and other vulnerable groups, water awareness, especially among women and children are prime factors for success of any domestic water project.

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