# Chapter 1
# Overview of the Groundwater of South Asia

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**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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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),

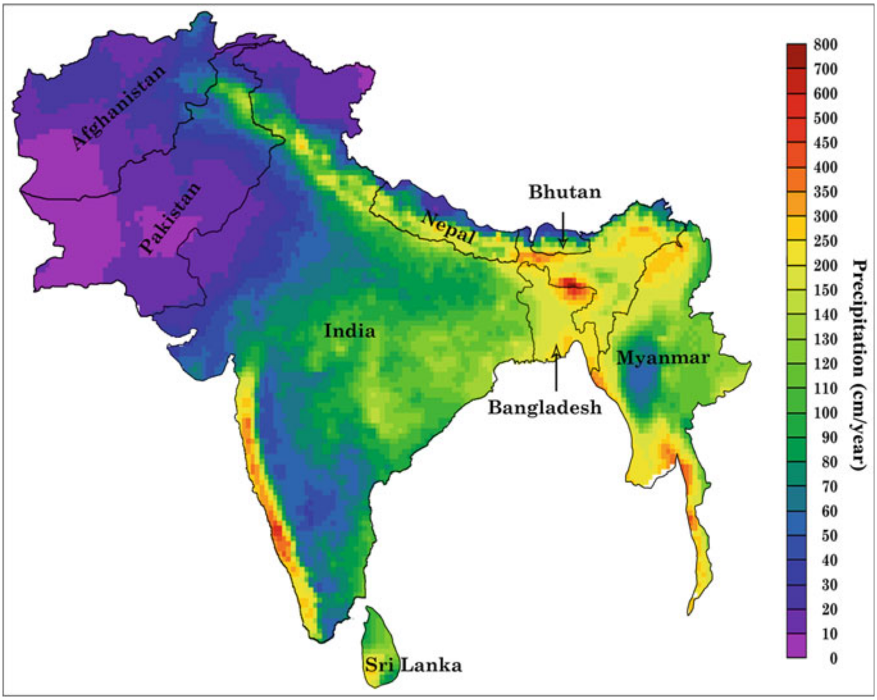


**Fig. 1.1** Map of South Asia showing the range of mean annual precipitation distributions (1961–2011). *Source* APHRODITE database. The figure is not to scale, and the country boundaries are for illustrative purpose only

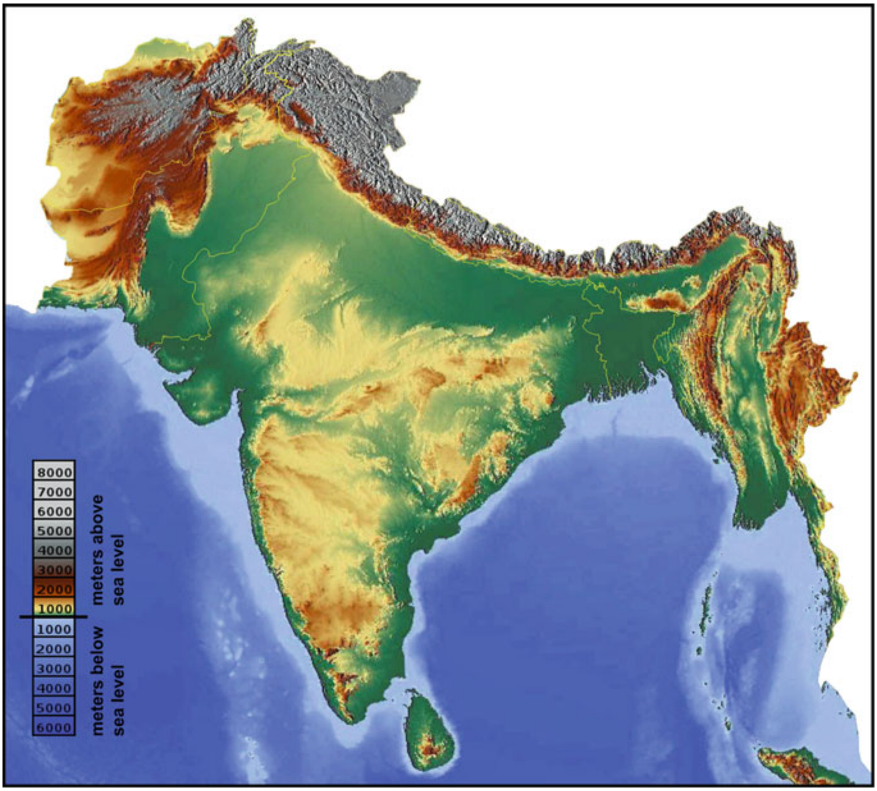


**Fig. 1.2** Topographic and geomorphic map of South Asia, demonstrating the major topographic features visible in the area. The figure is not to scale, and the country boundaries are for illustrative purpose only

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 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):

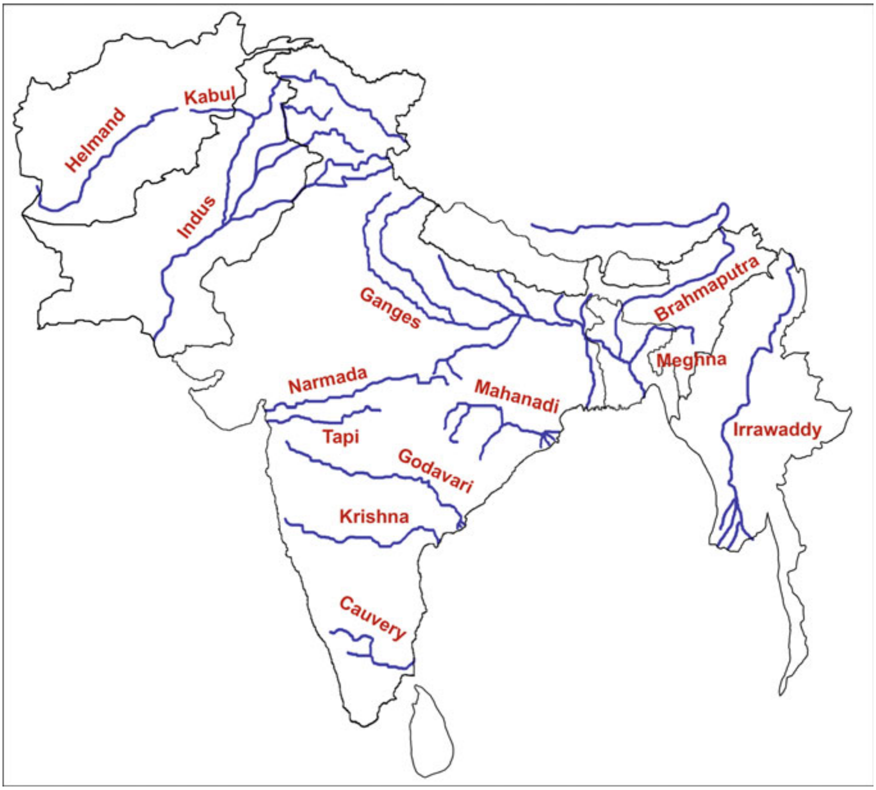


**Fig. 1.3** Map of major river systems of South Asia. The figure is not to scale, and the country boundaries are for illustrative purpose only

- 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

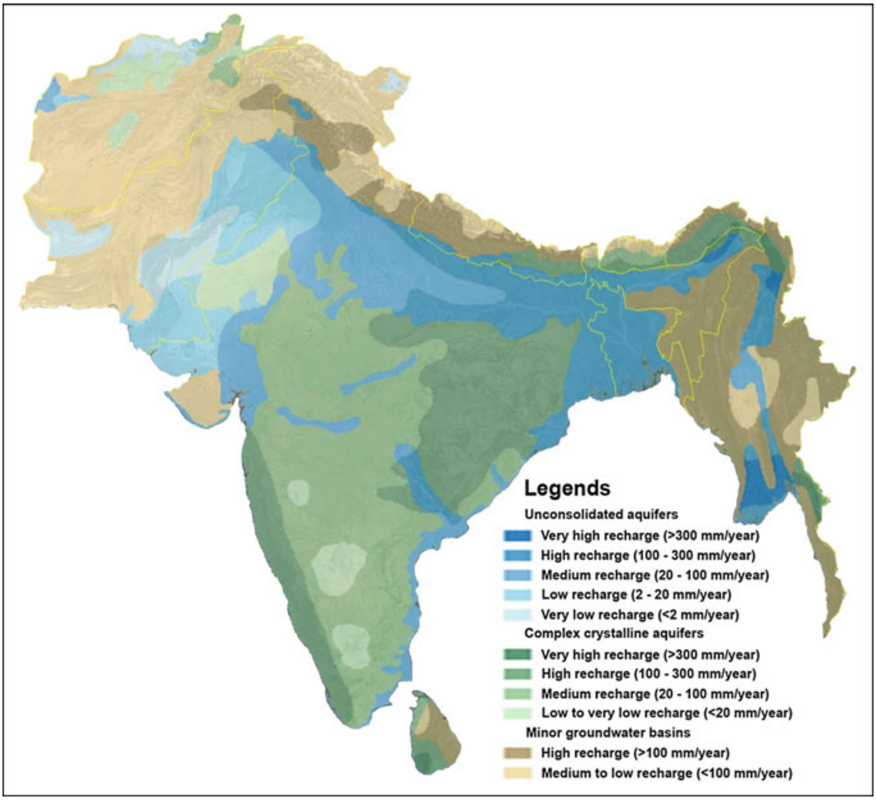


**Fig. 1.4** Hydrogeological map of South Asia, showing major river channels and distribution of groundwater recharge rates (modified from WHYMAP database, www.bgr.de). The figure is not to scale, and the country boundaries are for illustrative purpose only

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, $\sim$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

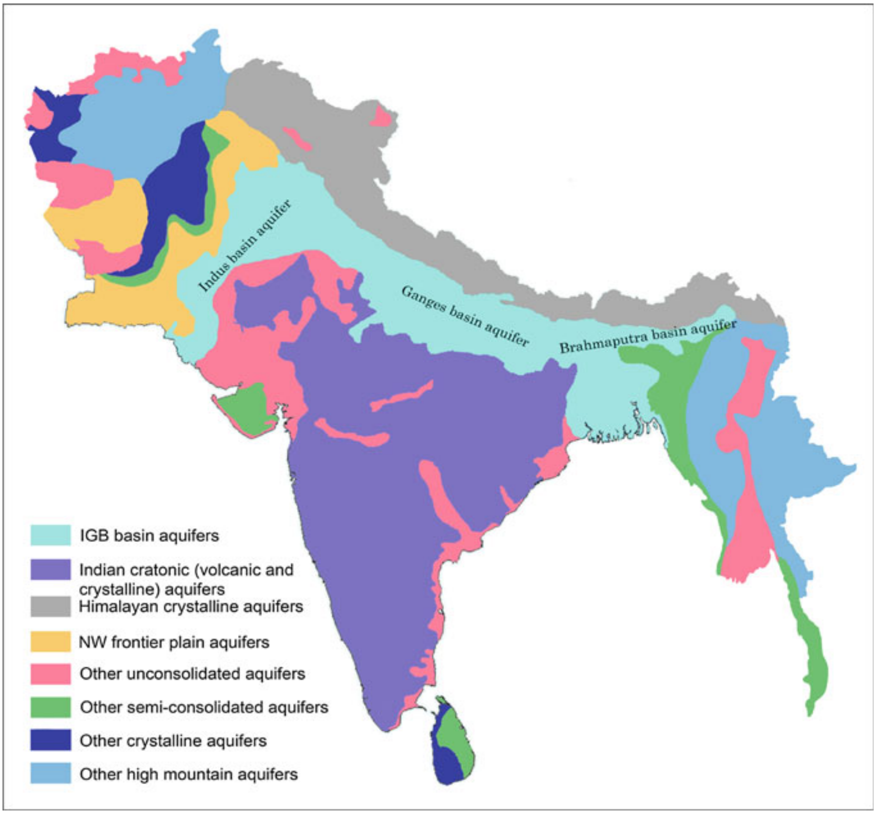


**Fig. 1.5** Major aquifer map of South Asia. The map demonstrates the major aquifer types that are found in the area and generally used for groundwater abstraction. The figure is not to scale, and the aquifer and country boundaries are for illustrative purposes only

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 ~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 ~430 bcm, with annual groundwater draft of ~243 bcm in 2009. Of these, ~221 bcm of groundwater was used for irrigation, and the rest ~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, $\sim$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 $\sim$495 $km^3$/year, respectively. The groundwater use in Myanmar is mostly for agriculture purposes, ranging up to $\sim$90%, the rest $\sim$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 $\sim$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).

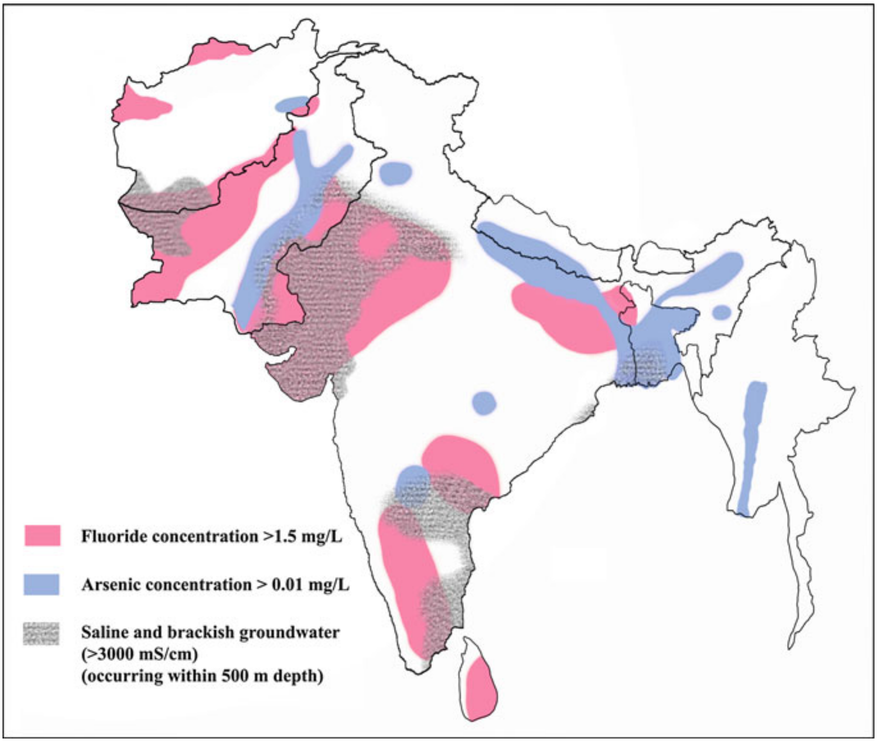


**Fig. 1.6** Map of major geogenic groundwater contaminants of South Asia. The figure is not to scale, and the aquifer and country boundaries are for illustrative purposes only

## 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.

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