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Groundwater systems of the Indian Sub-Continent

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ABSTRACT

The Indian Sub-Continent is one of the most densely populated regions of the world, hosting ~23% of the global population within only ~3% of the world's land area. It encompasses some of the world's largest fluvial systems in the world (River Brahmaputra, Ganges and Indus Basins), which hosts some of the highest yielding aquifers in the world. The distribution of usable groundwater in the region varies considerably and the continued availability of safe water from many of these aquifers (e.g. Bengal Basin) is constrained by the presence of natural contaminants. Further, the trans-boundary nature of the aquifers in the Indian Sub-Continent makes groundwater resource a potentially politically sensitive issue, particularly since this region is the largest user of groundwater resources in the world. Indeed, there is considerable concern regarding dwindling well yield and declining groundwater levels, even for the highly productive aquifers. Though irrigation already accounts for >85% of the total ground water extraction of the region, there is a mounting pressure on aquifers for food security of the region. Highly variable precipitation, hydrogeological conditions and predicted, impending climate change effects provide substantial challenges to groundwater management. The observed presence of natural groundwater contaminants together with the growing demand for irrigated food production and predicted climate change further complicate the development of strategies for using groundwater resources sustainably. We provide an introduction and overview of 11 articles, collated in this special issue, which describe the current condition of vulnerable groundwater resources across the Indian Sub-Continent.

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1. Overview of the groundwater systems in the Indian Sub-Continent

The Indian Sub-Continent (ISC) comprises six countries: Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka (Fig. 1). The ISC occupies ∼3.2% of the global land area but hosts ∼23.2% of the world's population (FAO, 2013). The region is arguably the most densely populated region in the world. Precipitation varies spatially and temporally over the region, with the lowest national mean occurring in Pakistan (494 mm/year; WBA, 2015) and the highest in Bangladesh (2600 mm/year; WBA, 2015) (Fig. 1). The ISC is drained by the rivers Indus, Ganges and Brahmaputra Basins, which collectively form the Indo-Gangetic Basin (IGB) (Figs. 2 and 3) and include some of the highest yielding aquifers of the world (Figs. 2 and 3). The aquifers associated with these river basins cross international borders of the contiguous ISC countries, forming numerous transboundary aquifers, including the Indus basin aquifers (between India and Pakistan), Ganges and Brahmaputra basin aquifers (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).

At the beginning of every hydrologic year, >4000 billion cubic meters (bcm) water enters the ISC hydrological systems, of which almost half is lost by poorly understood and un-quantified processes (e.g. overland flow, surface discharge through rivers to oceans, submarine groundwater discharge, evaporation and evapo-transpiration, etc.) (Verma and Phansalkar, 2007). Annual groundwater

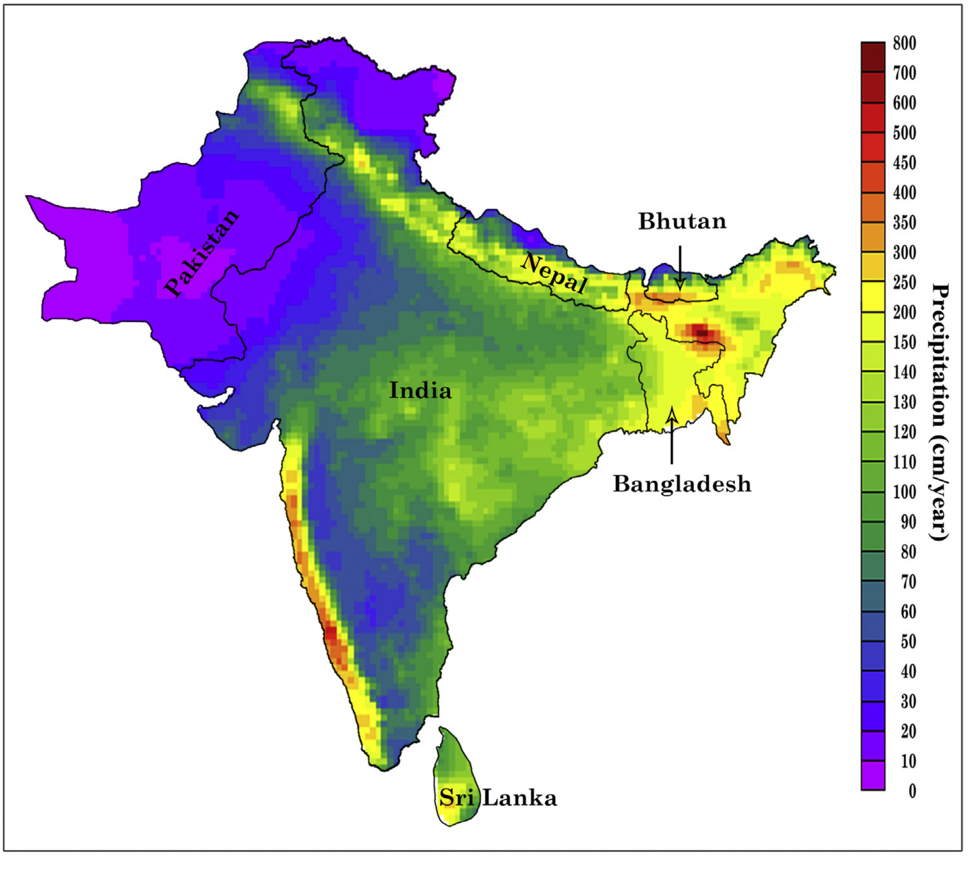

Fig. 1. Map showing mean annual precipitation distributions (1961–2007) across the Indian Sub-Continent (*source*: APHRODITE database). The figure is not to scale and the country boundaries are for illustrative purpose only.

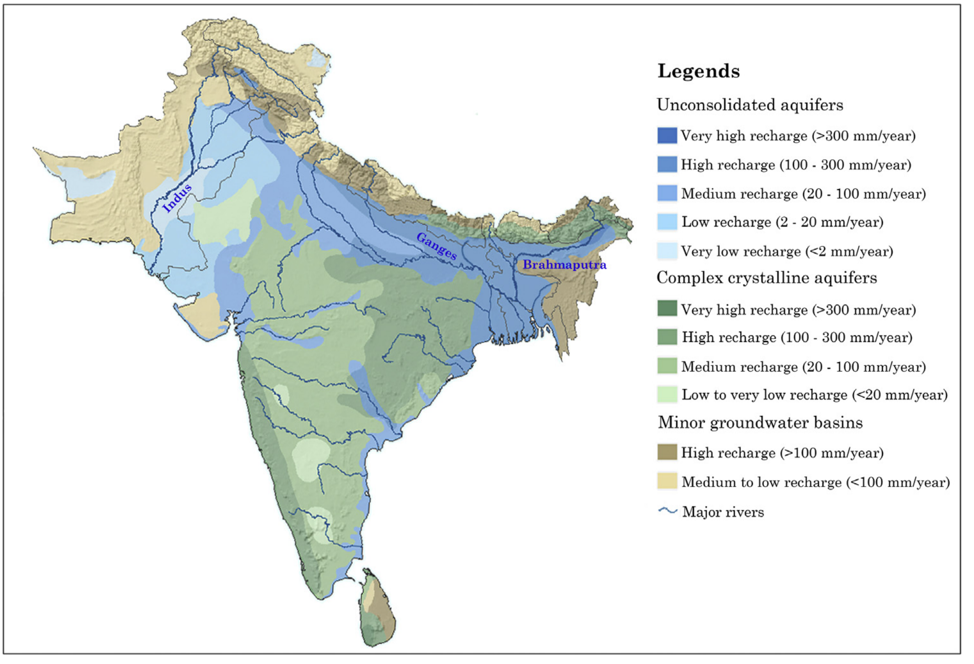

Fig. 2. Map of the Indian Sub-Continent, showing major rivers and distribution of recharge rates (modified from WHYMAP database, www.bgr.de). The figure is not to scale and the country boundaries are for illustrative purpose only.

withdrawals in the ISC are estimated to exceed a 340 bcm (Table 1), and represent the most voluminous use of groundwater in the world (FAO, 2013; Siebert et al., 2013). The ISC faces acute shortage of drinking water and other usable waters in many areas, as it is witnessing rapid rise in water demand and change in societal water use pattern because of accelerated urbanization and change in lifestyle (Scanlon et al., 2010). In many urban and rural areas of the ISC, surface waters have been historically used as receptacles of sewage and industrial waste rendering them unfit for domestic use, prompting a switch to groundwater and rainwater sources to meet drinking and agricultural water needs (Mukherjee et al., 2011). Presently, about 60–80% of the domestic water supplies across the ISC are met by groundwater (e.g. Bangladesh, India, Pakistan). Irrigation accounts for >85% of groundwater withdrawals in the ISC (FAO, 2013) and are considered to be the primary contributor to groundwater depletion (Rodell et al., 2009; Tiwari et al., 2009; Shamsudduha et al., 2012; Bhanja et al., 2014) with maximum possible groundwater footprint observed in the Gangetic aquifers (Gleeson et al., 2012). Moreover, the distribution of usable, potable groundwater in ISC is not uniform and there is a growing concern about the availability of safe water in many areas due to presence of natural contaminants. Of these, the widespread presence of elevated concentrations of dissolved arsenic (As) and fluoride (F), and high salinity have caused much concern (Fig. 4). Arsenic contamination of groundwater in the Bengal Basin has been called ‘the largest mass poisoning in human history’ (Smith et al., 2000). The extent and effect of other emerging and unidentified groundwater contaminants (e.g. nitrate, pesticides, radiogens, antibiotics, etc.) are yet to be fully accounted for (CGWB, 2014a). Large areas of the Ganges aquifers have been recently found to be vulnerable to groundwater pesticide pollution (Saha and Alam, 2014). Intensive agriculture in the IGB basins are associated with generous input of chemical fertilizers and synthetic pesticides that potentially infiltrates to the groundwater systems. Consequently, most of ISC has been marked as highly water stressed areas (Bates et al., 2008), primarily because of extensive irrigational abstraction in the alluvial aquifers of the IGB basin, low yielding crystalline aquifers in the Indian craton, and wide-spread presence of natural groundwater contaminants. Reduction in precipitation trends over the region analyzed between 1979 and 2005

Table 1
Summary of land area, population, precipitation, irrigated land area, renewable groundwater resources, groundwater withdrawal and total water uses in ISC.

Country	Land area estimates (as of 2009)[a]		Population estimates (as of 2011)[a]		Annual precipitation (1962–2011 mean)[b] (mm/year)	Irrigated land[a] (thousand ha)	Renewable Groundwater resource (as of 2014)[c] (bcm/year)	Groundwater abstraction (as of 2010)[d]				Total water uses (as of 2010)[a,f] (bcm/year)
	Million ha	Global %	Thousands	Global %				Total abstraction (bcm/year)	A[e] (%)	D[e] (%)	I[e] (%)	
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	433.0[g]	245.00[g]	89	9	2	761.00 (2010)
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	411	3.16	1,620,824	23.24	9655	93,766	545.0	344.15				1003.40

N.A., data not available.

[a] FAO (2013).

[b] WBA (2015).

[c] FAO (2015).

[d] Margat and Van der Gun (2013).

[e] Percentage contribution to total groundwater withdrawal from: A: Agriculture; D: Domestic; I: Industry.

[f] Total water uses: uses of all naturally available water (groundwater, surface water, etc.).

[g] CGWB (2014c).

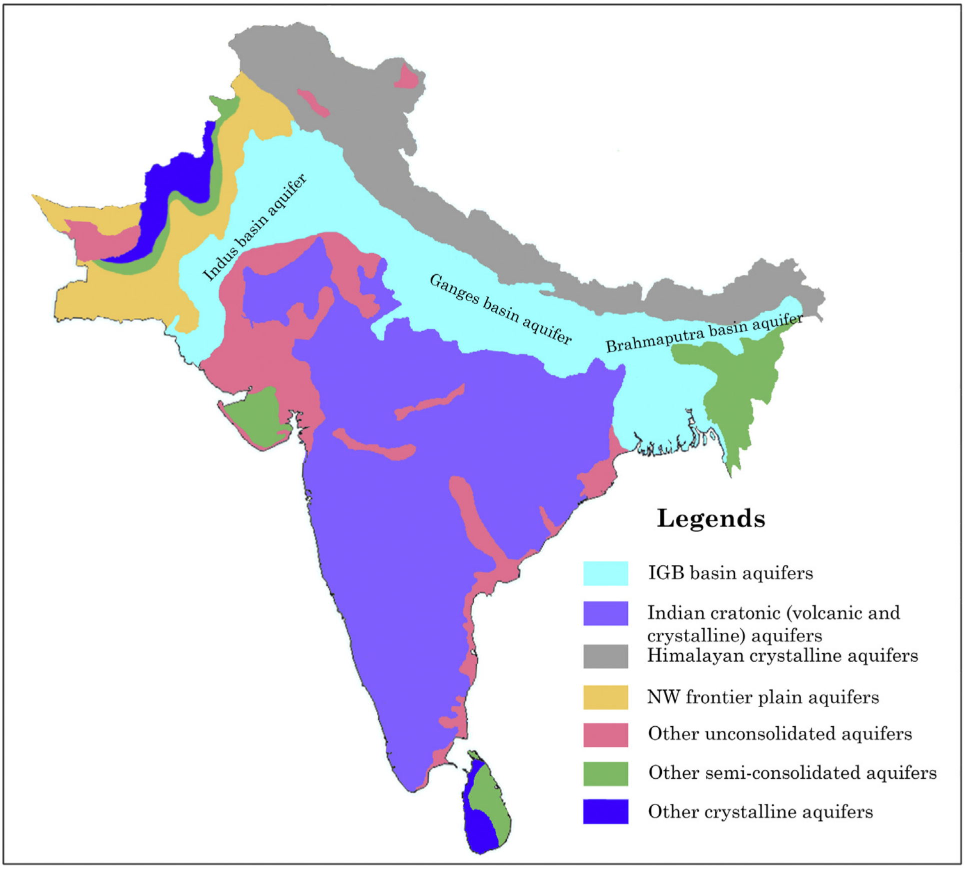

Fig. 3. Map of the major aquifers of the Indian Sub-Continent. The figure is not to scale, and the aquifer and country boundaries are for illustrative purposes only.

(Bates et al., 2008) suggests further decrease in per capita availability of groundwater in the region. With the present-rate of increasing population, the availability of usable groundwater is expected to seriously decline in near future, if not managed properly with immediate attention.

These aforesaid groundwater conditions may be further complicated by the projected impacts of impending climate change. Headwaters of the river basins in the ISC are supplied by meltwater flows from high-altitude glaciers. Glacial lake outburst floods have increased in recent years (at a rate of 0.38 events/year in 1950s to 0.54 events/year in 1990s; Bates et al., 2008) in the Himalayas within Bhutan, India and Nepal. Higher surface runoff is projected for the 2090–2099 period in comparison to 1980–1999, as an effect of global warming (Bates et al., 2008), enhancing potential of flood risks downstream. While high recharge rates (>300 mm/year; Fig. 2) have been observed in the eastern side of ISC owing to higher present-day precipitation in the region (Fig. 1), much of the western ISC receives little recharge (Scanlon et al., 2010).

In the following sections, synopses of country-wise groundwater resources of the six member countries of the ISC are outlined (*in alphabetical order*) as a prelude to this special issue.

1.1. Bangladesh

Nationally, Bangladesh receives highest rate of precipitation within ISC (Fig. 1 and Table 1). About 80% of the total precipitation occurs in the monsoon months of June to September (FAO, 2015). Very

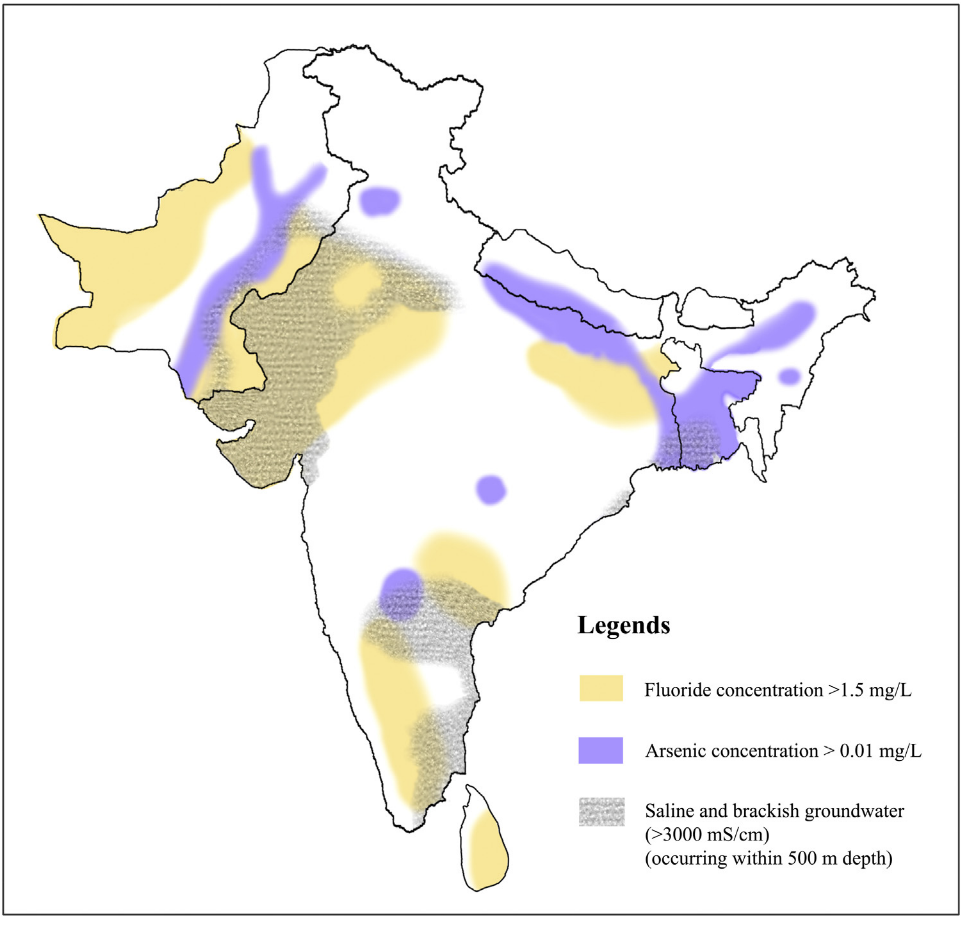

Fig. 4. Generalized groundwater contamination map of the Indian Sub-Continent (*data source*: IGRAC archive; BGS archive; Mukherjee et al., 2009b; Ravenscroft et al., 2009; Bhattacharya et al., 2014; CGWB, 2014a; Ramanathan et al., 2015). The extent of the groundwater contamination is for indicative purpose. The figure is not to scale and the country boundaries are for illustrative purpose only.

high annual precipitation, subdued topography in much of the country and discharge of regional flow systems produced the largest deltaic system in the world (Figs. 2 and 3). The central and southern part of 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 of drained by 230 streams, which are either tributaries or distributaries of the GBM system (FAO, 2015). As a result, ~80% of the land mass 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 the cultivable lands are cropped two or more times each year (FAO, 2015). Intense irrigation accounts for 79% of groundwater withdrawals (FAO, 2015), placing immense pressure on groundwater resources and has led to depletion of groundwater storage of estimated from 2003 to 2007 to be in the range of −0.5 to −0.8 km^3/year, with accelerating depletion rates in recent years (Shamsudduha et al., 2012). A substantial decline in groundwater levels has been observed in the area surrounding the densely populated capital, Dhaka (Ahmed, 1994; Alam, 2006). In general, the regional groundwater flow is from north to south (Michael and Voss, 2008) with local variations in the vicinity of the river systems, which are mostly effluent. Shallow groundwater flows, in recent times, have been largely affected by extensive pumping, which has greatly increased recharge rates through the increase in available storage (Shamsudduha et al., 2011). Furthermore, existence of widespread, elevated concentrations of geogenic As in groundwater has largely reduced the usable groundwater resources of the country (Ahmed et al., 2004). More than 80% of tube-wells within shallow aquifers of the major river basins in southern and coastal aquifers have been detected with high As concentrations (Ahmed et al., 2004). The natural As pollution may have been further exacerbated by wide-spread groundwater abstraction by pumping (Harvey et al., 2002). The anoxic, shallow aquifers are also prone to microbiological contamination in many parts of the country (BGS, 2001a). Water logging is a critical issue in the southern areas as most of the areas were flooded during monsoon time (FAO, 2015). The coastal areas also are at risk from seawater intrusion and storm surges that serve to increase groundwater salinity.

1.2. Bhutan

Bhutan is the smallest country within the ISC in terms of population and land area (Table 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. 2 and 3). Annual precipitation pattern is highly variable throughout the country with minimum value of 477 mm at Gidakhom in Thimpu district and maximum value of 20,761 mm at Dechenling in Samdrup Jhongkhar district (FAO, 2015) (Fig. 1 and Table 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 very localized and depends on fractures and joints related to the tectonic activity of various scale of the Himalays. Hence, the yields of the aquifers are extremely variable, and much of the population depends on surface water and groundwater discharging as spring waters from the mountains.

1.3. India

India is the largest country within the ISC, both in terms of land area and population (Table 1). Major parts of the country receive precipitation between 750 and 1500 mm/year, with extremely low precipitation in the western parts (<150 mm/year) and some of the world's highest rainfall in the north-eastern parts (>2500 mm/year) (Fig. 1 and Table 1). Most of the total precipitation occurs during the south-west monsoon season from June to September (CGWB, 2014b). The major aquifers are related to the major river basins that drain the country (Figs. 2 and 3). The total land of the country can be divided into 20 major river basins (CWC, 2010), which may be further separated 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 (Mahanadi, Godavari, Krishna, Pennar, Cauvery, Narmada and Tapi) are mostly rain-fed and strive on baseflow; (iii) the coastal rivers, mostly non-perennial; and (iv) rivers of the western dessert originate within small fluvio-aeolian basins, and are rain-fed ephemeral and disconnected from the groundwater systems (FAO, 2015).

The Ganges basin system is the largest 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 regional alluvial aquifer system that is regarded as one of the most productive aquifers of the world. In contrast, groundwater is available in a limited extent within the weathered zone and underlying fractured aquifers within the remaining two-thirds of the country. The northern porous and permeable aquifers are both of unconsolidated and semi-unconsolidated alluvial sedimentary type whereas fractured aquifers are mostly composed of Pre-Cenozoic crystalline rocks, consolidated sedimentary formations and multi-layered basalt flows of the Indian craton (CGWB, 2014b). Intense irrigational activities are prevalent in the highly fertile IGB basin, which is also the most populous part of the country. Renewable groundwater resources have been estimated to be ∼433 bcm, with annual groundwater draft of ∼245 bcm in 2011. Of these, ∼223 bcm of groundwater was used for irrigation, and the rest ∼23 bcm were used for domestic and industrial purposes

(CGWB, 2011, 2014c). Increasing agricultural demand for a rising population has resulted in a four-fold increase in production of crops (50–204 million tons) between 1950s to 2000 (Kumar et al., 2005) severely stressing groundwater resources. Rapid depletion in groundwater storage has been observed in the intense agricultural regions in the ISC (Rodell et al., 2009; Tiwari et al., 2009; Bhanja et al., 2014; CGWB, 2014b). More than a 4 m decline in groundwater levels with respect to decadal mean groundwater level has been observed in several parts of the country (CGWB, 2014b). Additionally, similar to its eastern neighbor Bangladesh, groundwater in large parts of the north Indian shallow alluvial aquifers are anoxic, and are enriched with elevated As concentrations (Mukherjee et al., 2008; Saha et al., 2010; Bhattacharya et al., 2011, 2014). Elevated groundwater As concentrations have been identified in groundwaters of 86 districts in 10 Indian states (CGWB, 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). Elevated levels 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 been observed in many of the coastal aquifers adjoining the Bay of Bengal and Arabian Sea, however, highly brackish groundwater are also prevalent in the inland aquifers of several states (CGWB, 2015). Such inland salination may be linked with mineral dissolution and/or agricultural pollution. Frequent, wide-spread floods, caused by intense precipitation and rejected recharge are common in parts of eastern India.

1.4. Nepal

Nepal is characterized by the Himalayan crystalline aquifers in the north and piedmont alluvial fan and flood plain aquifer in the south (BGS, 2001b). The southern part, called the Terai, is comprised of relatively low topography alluvial deposits between the Siwalik hills of the Himalayas in the north and the Gangetic alluvial plains of India in the south, and are formed from Quaternary fluvial sedimentation (Figs. 2 and 3). The Terai region also serves as the source of sediment and solute for many of the north Indian rivers. Almost half of the population of Nepal resides in this region. The unconfined, Quaternary aquifers, which are on the order of ∼300 m thick, are exploited by almost a million tubewells. These wells supply water to about 90% of the residents of the Terai. The groundwater systems in fractured basement aquifers are mostly replenished from precipitation during monsoon time (Andermann et al., 2012), which eventually discharge through numerous mountain springs (Fig. 1 and Table 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) possibly from baseflow.

1.5. Pakistan

The river Indus and its five major tributaries (Jhelum, Chenab, Ravi, Beas and Sutlej) form the major fluvial system of Pakistan which hosts the most exploited aquifers of the country (Figs. 2 and 3). The Indus river basin covers ∼65% of the land area in the country (FAO, 2015). The Indus alluvial aquifers of Punjab and Sindh provinces in Pakistan are of Quaternary age, and are similar to the Gangetic alluvial systems of India and Bangladesh. The sediments of the plain have their provenance in the western Himalayas, transported by the River Indus and its tributaries. The alluvial deposits are widespread and thick, mostly forming unconfined aquifers with fresh groundwater (Mukherjee et al., 2009b). The area also differs in having a more arid climate and greater proportion of Pleistocene aquifers. Two-thirds of the total precipitation occurs within three months, July to September.

The climate is characterized as semi-arid to arid, with low to very low annual precipitation. Average annual precipitation ranges from less than 100 mm to over 750 mm in parts of the lower Indus plain and upper Indus plain near the foothills, respectively (Fig. 1 and Table 1). More than 20 million ha land was cultivated in 2009 (FAO, 2015). Groundwater withdrawals for irrigation amount to ∼94% of the total water demand (FAO, 2013). Rapid agriculture demand requires accelerated groundwater abstraction which is taking place through more than 500,000 tubewells in the country (Kahlown and Majeed, 2003). The North West frontier province has experienced groundwater level declines associated with intense groundwater withdrawals, and also effected by high groundwater salinity (>3000 mg/L). In contrast to the Ganges–Brahmaputra basin aquifers, the Indus basin aquifers are relatively oxic. Availability of high amount of nitrate in groundwater facilitates the pathogenic pollution in the groundwaters around the cities of Karachi, Lahore, Rawalpindi and Islamabad (Chilton et al., 2001). High concentrations of dissolved fluoride are also observed in groundwater in Punjab, Sindh and Baluchistan (Tariq, 1981). Groundwater in the recent alluvial and deltaic aquifers of Indus plain, specifically in Punjab and Sindh regions have been reported to be widely contaminated with As (Smedley, 2005).

1.6. Sri Lanka

As an island in the Indian Ocean, Sri Lanka is physically disconnected from landmass of the other countries of the ISC. Consequently, it does not share any transboundary aquifer with any of the other ISC countries. It features a seasonally humid climate dominated by the South-West monsoon season extending from May to September (FAO, 2015) (Fig. 1 and Table 1). Sri Lanka has 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, ~90% of the sub-surface area of the country is composed of crystalline, metamorphic rocks of Precambrian age. The remainder is underlain by disconnected, Miocene limestone and Quaternary sedimentary deposits (Cooray, 1984) (Figs. 2 and 3). The weathered sediments, generated from crystalline formations, exist at variable depths (<10–35 m) owing to favorable weathering conditions (Dharmagunewardene, 2003). Six types of aquifers are found in the country e.g. shallow karstic aquifers, deep confined sandstone and Miocene limestone aquifers, shallow Quaternary coastal sand aquifers, alluvial aquifers of variable depths, confined or semi-confined lateritic aquifers and the shallow regolith aquifers (Panabokke, 2001). Total cultivated area in the country exceeds 2 million ha (FAO, 2015). Intensive irrigation relies upon groundwater with the vast majority (87.4%) of withdrawals associated with agriculture (FAO, 2013). Rapid development of groundwater facilitated by advanced drilling techniques and low-cost pumps has led to large-scale groundwater depletion (Senaratne, 2002). Intensive groundwater use has led to seawater intrusion in regions amplifying the salinity of groundwater (Rajasooriyar et al., 2002). Nitrate contamination of groundwater is also a serious groundwater pollution issue in some of the areas, where an effective sanitation system is absent (Villholth and Rajasooriyar, 2010).

2. Section 2: layout of the special issue

In light of substantial interest in water resources and hydrology of specific regions, the *Journal of Hydrology: Regional Studies* decided to have one of its first special issue to be focused on the groundwater quality and quantity of the Indian Sub-continent, and invited us (*Abhijit Mukherjee*, *Dipankar Saha*, *Charles F. Harvey*, *Richard G. Taylor* and *Kazi Matin Ahmed*) to serve as the Guest Editors for this special issue. The articles selected for this special issue focus on recent findings from groundwater studies of the ISC, broadly on the following themes:

a) *Groundwater quantity and exploration*
b) *Groundwater quality and pollution*
c) *Groundwater economics, management and policies*

2.1. Groundwater quantity and exploration

There are three articles in this section that provides a glimpse of status of available groundwater resource in parts of the ISC.

The first article of this section by Papa et al. (2015) discusses multi-sensor based measurements to estimate the surface freshwater storage (SWS) and subsurface water storage (groundwater + soil moisture) variations over parts of the Ganges–Brahmaputra river basin and its aquifers. Monthly surface water storage variations for the period 2003–2007 show a mean annual amplitude of ~410 km^3, which contributes to ~45% of satellite-derived total water storage variations. The variations of groundwater storage were found to have average annual amplitude estimated to be ~550 km^3. This dataset provides a new insight to the water storage variations in one of the largest fluvial aquifer system of the world.

The article by Van Steenbergen et al., 2015 describes the groundwater resources in the western boundary of the ISC, at Balochistan Province Pakistan and how the alluvial aquifer of the Kuchlagh area experienced groundwater depletion after three decades of intense groundwater abstraction. However, no active intervention was undertaken by authorities to manage or restore the unsustainable resource. Rather, the losses of agricultural opportunities were traded with urban employment, switching agricultural bases to other parts of the Province or drilling deep. The authors have described this situation as a ‘socio-institutional void’ in which the groundwater resource in the study area was drastically reduced.

The final article in this section by Hameed et al. (2015) discusses the nature and quantity of recharge in the Chaliyar river basin, Kerala state of India based on isotopic fingerprinting and mass balance. Spatio-temporal variations in the stable isotope compositions of oxygen were used to delineate surface water-groundwater interactions, thus to estimate the groundwater recharge from river water in the studied water-shed. The oxygen isotope conditions were found to be effective to quantify the variation of volume of recharge from rainfall in the various physiographic parts of the watershed. The variation of isotopic composition across the seasons for groundwater was found to be rather limited than that of river water.

2.2. Groundwater quality and pollution

Five articles are selected for this section, which deals with studies of description of groundwater quality, evolution of groundwater chemistry and geogenic pollution with natural contaminants like arsenic (As), fluoride (F^-), manganese (Mn).

The first article in this section by Diwakar et al. (2015) examines the mechanisms of As, F and Mn mobilization in the Terai plains in vicinity of the Siwalik Hills within the piedmonts of the Himalayas in Nepal. The Ca-HCO_3 type groundwater was found to be polluted with As, Mn and F in 80%, 70% and 40% of the samples. Hyporheic-zone reductive processes produce baseflow enriched in As, Fe, F and Mn to the streams. The authors suggest that the geochemical conditions of the groundwater regime are indicative of oxidation of organic matter, precipitation of authigenic Fe minerals, along with microbial mediated reductive processes as important As mobilizing mechanisms.

In the second article, Machiwal and Jha (2015) conduct spatio-temporal variations of groundwater quality schematic plots and multivariate statistical analyses coupled to GIS-based groundwater quality index analyses. The authors note that cluster analyses were able to identify the control on modification or degeneration of groundwater quality by water–rock interactions and rainfall recharge. The spatial distribution of the solutes is suspected to be affected by anthropogenic processes. They show that major-ion and soil leaching pollution factors govern overall evolution of geochemical processes in their study area.

The presence of elevated concentrations of aqueous fluoride in the crystalline aquifers of the ISC is a widely discussed groundwater quality issue. Hallet et al. (2015) assess the distribution of fluoride across eight crystalline phases and between the bedrock and the regolith at eleven sites in three catchments at the Maheshwaram and Waipally of Andhra Pradesh state of India, and the Plonnaruwa of north-central parts of Sri Lanka. Partial or total erosion of the primary fluoride-bearing bedrock minerals and consistent depletion of F in the remnant minerals result in reduced total F content in the regolith and a consequent increase in groundwater concentrations. Laboratory experiments and field relationships in this study indicate a greater potential for F mobilization to groundwater from the regolith than the bedrock.

Verma et al. (2015) provide an account of chemical evolution of groundwater and geomorphic influences on As distribution in the tectonic-controlled, fluvial aquifers that extend from the foothills of the eastern Himalayas to the Brahmaputra river valley in the northeastern parts of India. The authors identified four different geomorphologic units in the study area and found out that, unlike the aquifer along the River Ganges, groundwater residing in the older aquifers of the Brahmaputra river basin is more prone to As pollution. They conclude that while reductive dissolution of metal-oxide/hydroxide reduction are dominant mechanism of As mobilization, other metal dissolution processes e.g. ion-exchange and pH-dependent desorption may have also influenced groundwater As enrichment.

In the final article of this section by Mahanta et al. (2015) examined the origin, distribution and processes of As release by investigating the salient groundwater chemistry and subsurface sedimentological characteristics in low-industrialized areas of Brahmaputra floodplains in Assam, India. The authors concluded that considering the absence of anthropogenic sources in the study area, the causes for As release to groundwater in the study area appear to be natural and influenced by redox-dependent dissolution, although As release and fate in specific locations are also influenced by advection–dispersion transport and retardation along groundwater flow.

2.3. Groundwater economics, management and policies

Three articles selected for this section outline general groundwater management strategies of India and Pakistan, along with detailed discussion on the densely populated and severely groundwater stressed Delhi region.

The first article by Kulkarni et al. (2015) highlights the requirement of development of a robust groundwater governance framework for a highly groundwater-dependent country like India. The authors describe the groundwater typology of an area as a combined function of hydrogeological aspects and socio-economic influences that defines dependency on groundwater resources. Groundwater management using 'aquifer-based, common pool resource' approaches is becoming popular in India. The authors stress that participation at all levels is important in management decisions as well as in the development of a governance framework. Developing a regulatory framework, which supports protection of the resource and promotes the good practices of participatory groundwater management, is essential for groundwater governance.

Watto and Mugera (2015), in the second article in this section, provide an econometric estimation of groundwater irrigation efficiency of cotton cultivation farms in parts of Punjab province in Pakistan. This study estimates irrigation water-use efficiency of groundwater irrigated cotton farms in the study area. The authors define water-use efficiency based on water conveyance efficiency, efficiency in water application at the farm and the amount of water actually utilized by the crop compared to the amount of water supplied to that crop. Hence, these irrigation water efficiency calculations have integrated hydrological principles with economic pragmatism that is an essential tool to improve irrigation efficiencies.

In the final article of this special issue, Shekhar et al. (2015) discusses an interesting hydrogeological scenario, where the densely populated north district of Delhi in India is having a groundwater surplus zone, in stark contrast to the groundwater-stressed, over-exploited aquifers in the vicinity. The surface runoff and flood waters during monsoon season in the district either causes water logging in lower elevation areas or they join drains and rivers as rejected recharge. The present study tries to understand the groundwater dynamics in three distinct hydrogeological domains of the region. The authors also decipher the geochemical conditions that lead to deterioration of groundwater quality of the area. Based on this physical and chemical groundwater dynamics information, the authors propose groundwater management techniques for the study area involving the viability of limited dewatering of shallow aquifers and its replenishment by enhanced recharge from surface runoff and flood waters during the monsoon period have been established.

The above-noted 11 articles, selected in this special issue, illustrate studies of groundwater quantity and exploration from basin-scale to watershed-scale, discuss groundwater chemical evolution and pollution in the tectonic-controlled, porous fluvial aquifers to crystalline Himalayan or Cratonic aquifers, and finally discuss emerging groundwater management and policy development strategies. Hence, this special issue should be of much interest to scientists, planners and policy makers, who are interested to further explore and understand the vulnerable groundwater resource of the ISC.

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