Chapter 13
An Overview of Groundwater Quality in Bangladesh

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Abstract Groundwater is one of the most valuable natural resources of livelihood and food security of millions of rural people across Bangladesh. Groundwater availability in Bangladesh is governed by its subtropical monsoon climate, aquifer storage capacity, consumption rate along with changes in volume and distribution of groundwater recharge conditions. Groundwater withdrawal from the shallow alluvial aquifer (depth <150 m) is the country's source of the arsenic-enriched waters. In Bangladesh, millions of people are suffering from severe and chronic arsenic poisoning due to consumption of drinking water from contaminated groundwater sources. The groundwaters with elevated levels of arsenic abstracted from the shallow aquifers are of natural origin, which has likely been present in the groundwater for thousands of years. However, arsenic is not the only water-quality problem in Bangladesh's groundwater. In many parts of the country, the groundwaters are characterized by elevated levels of dissolved iron, manganese, and boron. Additionally, dissolved uranium concentrations appear to be a water-quality problem in certain areas; however, the nature and extent of the problem is poorly defined due to lack of sufficient data. Furthermore, climate change and rising sea levels will likely contribute to an increase in salinity in the coastal groundwater systems of the country. Consequently, access to safe drinking water is one of the greatest environmental threats in this predominantly rural country.

13.1 Introduction

Until the 1970s, surface water resources were primarily used for drinking water source in Bangladesh. However, microbial contamination of stagnant surface water resources resulted in water-borne diseases, such as cholera and dysentery that led to millions of deaths in this region alone (Nickson et al. 2000; Chakraborti et al. 2002;

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Ravenscroft et al. 2005). In an effort to prevent morbidity and mortality from water-borne diseases, during the 1970s, Department of Public Health Engineering (DPHE) of Bangladesh worked with the United Nations Children's Fund (UNICEF) to install hand-pumped tube wells to provide what was then considered a safe source of drinking water for Bangladesh's rural population (Smith et al. 2000; Kinniburgh et al. 2003). Groundwaters are generally less susceptible to microbial contamination compared to surface waters. As of 1999, roughly 97% of the population depended on groundwater for drinking water supplies along with agricultural and industrial usage (BGS and MML 1999).

Groundwater is abundant in Bangladesh. Water tables vary across the country but are relatively shallow at a depth of approximately 1–10 m below the ground surface (BGS and WaterAid 2001). In addition, the unconsolidated sediments of Bangladesh are easy to drill manually to depths of at least 50 m or more within 48 h (DPHE/BGS/MML 1999). The exact number of tube wells in Bangladesh is not known but an estimated 10 million hand-pumped tube wells have been installed across the country (van Geen et al. 2003; Cheng et al. 2004). Consequently, easy accessibility to freshwater from underground aquifers has led to indiscriminate and sometimes excessive use of groundwater (Jahan et al. 2010; Shahid 2011; Shahid et al. 2015). As of 2010, total abstraction of groundwater was 30.21 bcm annually, and 79% of groundwater withdrawal was for intense irrigation usage (Margat and Van der Gun 2013; Mukherjee et al. 2015). During the dry season (November to May), surface water supplies are inadequate to meet irrigation water demand. As a result, groundwater-fed irrigation through installation of shallow tube wells is widely used for cultivation of high-yielding rice during the dry seven months of the year (Scott and Sharma 2009). Between 1972 and 1999, the area irrigated by groundwater as a fraction of the total irrigated area, increased from 4% to 70% (Mainuddin 2002). During the past four decades, the growing demand and excessive use of groundwater has led to substantial drawdown of aquifer, and groundwater levels have reportedly receded by approximately 20–30 m (Zahid and Ahmed 2006; Jahan et al. 2010; Sumiya and Khatun 2016). In particular, significant annual decline in groundwater levels has been reported in the area neighboring the densely populated capital, Dhaka (Ahmed 1994; Alam 2006).

Climatic variations, changing river courses, poor management of water bodies along with contamination from natural and anthropogenic sources as well as saltwater intrusion in the coastal aquifers have rendered the groundwaters from some areas unfit for human consumption or agricultural uses (Zahid and Ahmed 2006; McBean et al. 2011; van Geen et al. 2011; Bodrud-Doza et al. 2016). This is alarming considering the vital role groundwater plays to support rural economies within Bangladesh. Thus, it is crucial to safeguard both the quality and the quantity of the country's groundwater, and to further understand the concerns and challenges of groundwater depletion in Bangladesh. This chapter presents a review of the existing literature and data to assess the quality of groundwaters in Bangladesh. More related information regarding groundwater of South Asia is available in Mukherjee (2018).

13.2 Geology and Landform

Bangladesh is a low-lying riverine country that lies within the Bengal Basin in Southern Asia. The total land area in Bangladesh is approximately 143,998 km^2. Geographically, the country extends from 20° 34′N to 26° 38′N latitude and from 88° 01′E to 92° 41′E longitude (Fig. 13.1). Bangladesh shares international land borders with two nations: to the east, west, and north with India and to the southeast with Myanmar (Burma), and to the south, it is bounded by the Bay of Bengal, which opens into the Indian Ocean. Most of Bangladesh is less than 10 m above sea level,

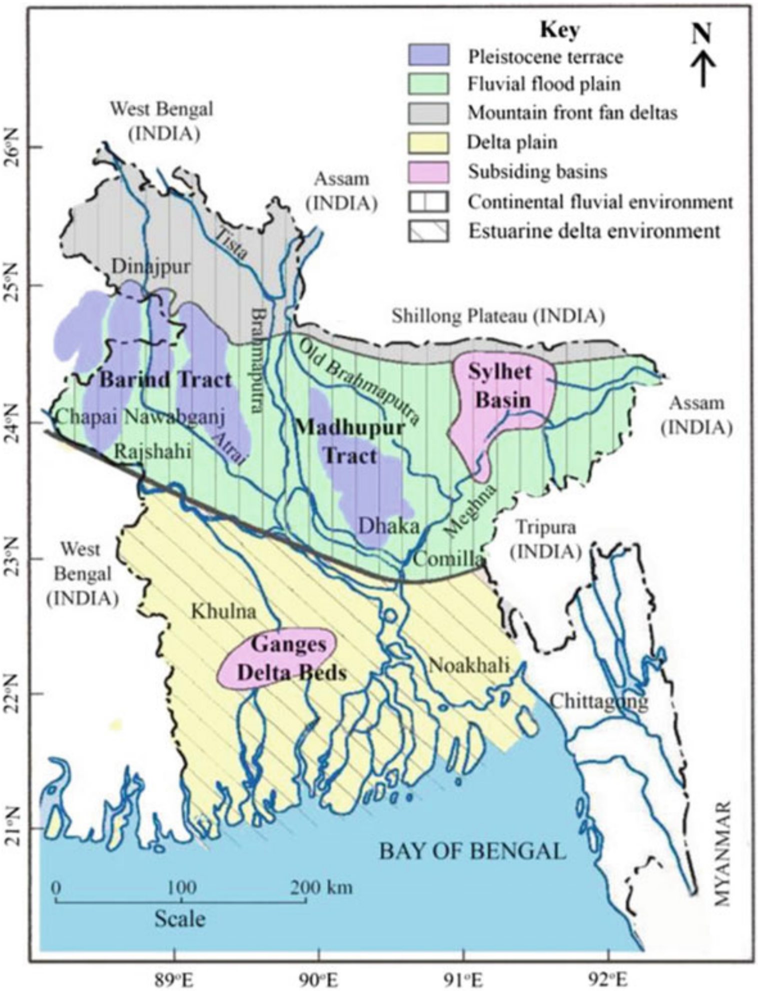

Fig. 13.1 Geology and geomorphology of Bangladesh. Map modified from BGS and DPHE (2001)

excluding the uplifted Pleistocene terraces of Barind and Madhupur Tracts, the Chittagong Hill Tracts, and the hilly area in the northeast (Datta et al. 2009; Fig. 13.1). The central and the southern region of the country is located within the floodplains of the Ganges, Brahmaputra, and Meghna (GBM; locally known as Padma-Jamuna-Meghna) river systems (Lindsay et al. 1991; Goodbred and Kuehl 2000; Mukherjee et al. 2009) and their tributaries, such as the Teesta, Dharla, Dudhkumar, Kushiayra, and Surma. The GBM river systems drain the Himalayas and Tibetan Plateau, slope from north to south, and drain into the Bay of Bengal through Bangladesh. The GBM subsurface delta mineralogy is predominantly composed of quartz, with lesser amounts of plagioclase, potassium feldspar, and volcanic, metamorphic, and sedimentary fragments (Uddin and Lundberg 1998a, b).

The Bengal Basin, which covers most of Bangladesh, is bounded by tertiary rocks of the Himalayas and Shillong Plateau to the north, the Indo-Burman ranges to the east, the Indian craton to the west, and the Bay of Bengal to the south (Morgan and McIntire 1959; Nandy 2001). The western and northwestern parts of the Bengal Basin are composed of Permian to Pleistocene age sedimentary rock sequence (Ball et al. 1981). The surface area of present-day Bangladesh is predominantly covered by Holocene fluvio-deltaic sediments of the meandering GBM river system, much of it deposited between ca 6000 BP and 10,000 BP (Morgan and McIntire 1959; BGS and DPHE 2001). During the Quaternary, sediment deposition in major river systems of the Bengal Basin was largely controlled by climatic changes and sea-level oscillation pertaining to glacial cycles (Umitsu 1993). The Quaternary alluvial sediments primarily formed aquifers in Bangladesh, except in the southeastern hilly areas of the country, where aquifers are composed of tertiary age deposits (Ravenscroft 2003; Zahid and Ahmed 2006; Shamsudduha and Uddin 2007).

The surface geology of the country can be classified into four major physiographic units: (i) tertiary sediment in the northern and eastern hills, (ii) uplifted Barind (located to the northwest) and Madhupur Tracts (located in central Bangladesh) of Pleistocene, (iii) Holocene (i.e., recent) floodplains of the GBM River Basin, and (iv) delta covering the remainder of the country (Morgan and McIntire 1959; Zahid and Ahmed 2006).

13.3 Hydrogeological Setting

Several classification schemes have been proposed to differentiate aquifers in Bangladesh (e.g., UNDP 1982; Umitsu 1993; Acharyya et al. 2000; Uddin and Abdullah 2003); however, the architecture of the aquifers is yet to be fully determined (Mukherjee et al. 2009). The first systematic classification of the aquifer systems was proposed by UNDP (1982). According to the UNDP threefold classification, the aquifers of Bangladesh, up to a depth of 140 m, were divided into:

(1) upper or composite aquifer, (2) main aquifer, and (3) deep aquifer. In a more recent study of Bangladesh aquifers, Uddin and Abdullah (2003) proposed a new classification scheme of the aquifer systems based on the sedimentological parameters and the depositional history of the aquifer sediments. Based on this new classification scheme, the major aquifers are divided into: (1) Plio-Pleistocene aquifers, (2) Late Pleistocene—Early Holocene aquifers, (3) Middle Holocene aquifers, and (4) Upper Holocene aquifers.

The Plio-Pleistocene Aquifers of the Dupi Tila Formation is overlain by the Pleistocene Madhupur Clay Formation. This aquifer consists of yellowish-brown to light gray, medium to coarse sand with pebble beds. The sediments are very weakly consolidated and depleted in mica and organic matter (Ravenscroft et al. 2005).

The Late Pleistocene-Early Holocene Aquifers are discontinuous in some areas of the country. A 10-m-thick gravel bed marks the bottom surface of the Late Pleistocene-Early Holocene, and the upper surface is formed of oxidized sediment layer. The aquifer is composed of gray micaceous, medium and coarse sand to silt with organic mud and peat (Ravenscroft et al. 2005).

Middle Holocene Aquifer overlies the Late Pleistocene-Early Holocene aquifer. The Middle Holocene is composed of mostly fine sand, and the sandy sequence varies significantly both in vertical and horizontal directions. Sediments in the uppermost part consist of clay, silt, and peat layers and were deposited in a transgressive phase of the sea level. The groundwater has been dated ca 3000 BP. Groundwater in Bangladesh is mostly extracted from this aquifer.

Upper Holocene Aquifers represent the upper most part of the sedimentary column of the delta and the recent flood plains of the GMB delta complex. The aquifers' sediments are composed of clay, silt, and fine sand. These aquifers contain a stack of several sandy layers that are interconnected and create leaky conditions. Water from this aquifer has been dated as ca 100 BP. Groundwater is available within 10 m below surface.

13.4 Hydrogeological Properties

The subtropical monsoon climate coupled with favorable geologic and hydrogeologic settings indicates high groundwater storage potential in the aquifers of Bangladesh (Zahid and Ahmed 2006). Numerous pumping tests carried out throughout Bangladesh found that in a regional scale, the near-surface Quaternary alluvium acts as a single hydraulically connected aquifer unit with reasonably good transmission and storage properties (Michael and Voss 2009; Rajmohan and Prathapar 2013). Aquifer tests conducted by the Bangladesh Water Development Board (BWDB) give hydraulic conductivity (K) values ranging from 3×10^{-5} to 1×10^{-3} m/s (Hussain and Abdullah 2001). Pumping tests reported that the shallow aquifer system in most parts of the country has a mean transmissivity of 1,270 $\pm$ 770 m^2/day and a specific yield of 0.01–0.20 (UNDP 1982; BWDB 1994; Shamsudduha et al. 2011). According to Domenico and Schwartz (1998), specific storage values typically range from roughly 10^{-5} per m (dense sandy gravel) to 10^{-2} per m (plastic clay) for materials in the Bengal Basin aquifer system.

In the dry season, groundwater levels across Bangladesh become depressed. The aquifers are replenished by heavy rainfall and flooding during monsoon season (Kahlon et al. 2012). However, the rate of recharge is variable and controlled by the properties of the overlying soil and geology of the area. According to the Bangladesh Bureau of Statistics (2005), an estimated 21.1 bcm of groundwater resources is produced within the country. In addition, an important, but unknown, quantity of groundwater flows into Bangladesh through horizontal flow paths from the Himalayan system (BanDuDeltAS 2015). During dry season, the shallow groundwater discharges to major rivers within Bangladesh (Datta et al. 2009).

13.5 Groundwater Geochemistry of Bangladesh

Most of the groundwater of Bangladesh is characterized by circum-neutral pH (6.5–7.6), and the oxidation-reduction potential (Eh) varies between +594 and −444 mV (Mukherjee and Bhattacharya 2001). Dowling et al. (2002) found that the groundwater is calcium carbonate rich, contains some sodium chloride-type water, no sulfate and background concentrations of most trace metals, except for strontium, barium, iron, manganese, and arsenic. Overall, these groundwater geochemistry results are consistent with the findings of the other investigations of groundwater of Bangladesh (e.g., BGS and DPHE 2001; Mukherjee and Bhattacharya 2001; Harvey et al. 2002; van Geen et al. 2003; Anawar et al. 2011). These past investigations found that the groundwater exhibits low dissolved oxygen concentrations, characteristically high concentrations of iron and manganese, and low levels of sulfate that are consistent with characteristics of reducing environments (Ahmed et al. 1998; Bhattacharya et al. 2002; Harvey et al. 2002; Chatterjee et al. 2013). The reducing conditions are likely due to presence of organic matter-enriched peat layers, which are interspersed throughout the aquifer sediment (McArthur et al. 2001). It is also possible that dissolved organic matter is brought to depth during recharge from surface water sources (Harvey et al. 2002). Note that in some parts of the country, conditions are even sufficiently reducing for methanogenesis (Ahmed et al. 1998; Hoque et al. 2003).

13.6 Arsenic

The discovery of widespread arsenic contamination in groundwaters of Bangladesh has linked the country with what has been dubbed "the largest mass poisoning in history" (Smith et al. 2000). An estimated 35–77 million people have been chronically exposed to arsenic through drinking water from shallow aquifers containing up to 100 times the World Health Organization's (WHO) drinking water limit of 0.01 mg/L (Smith et al. 2000; Smedley and Kinniburgh 2002; Burgess et al. 2010; Edmunds et al. 2015). In 1983, the first cases of arsenic induced dermal lesions were identified in Kolkata in neighboring West Bengal, India (Saha 1995), and by 1997, numerous other cases were identified in neighboring Bangladesh (Smith et al. 2000; Smedley and Kinniburgh 2002). Clinical manifestations of arsenic poisoning begin with various forms of skin diseases and progress by damaging internal organs, which ultimately lead to cancer and death. These symptoms of long-term arsenic poisoning may take five to fifteen years to appear. In late 1990s, it was established that the affected population were mainly drinking water from tube wells, which tapped into shallow alluvial aquifers that were laced with arsenic (Jakariya et al. 1998; Smith et al. 2000; Ravenscroft et al. 2005). Public concerns over arsenic in drinking water from groundwater sources have increased in the past few decades owing to widespread evidence of chronic arsenic poisoning from consumption of high arsenic-contaminated groundwater (Smedley and Kinniburgh 2002; Haque et al. 2008). The widespread arsenic crisis prompted many studies of hydrogeochemical processes governing the mobilization of arsenic into the groundwaters of the Bengal Basin.

In an effort to evaluate the extent of arsenic problem, the National Hydro-chemical Survey (NHS), which is the most comprehensive water-quality dataset for Bangladesh, was carried out by the Department of Public Health Engineering (DPHE), the British Geological Survey (BGS), and Mott MacDonald Ltd., UK. Between 1998 and 1999, NHS surveyed 61 of the 64 administrative districts of the country (except for the Chittagong Hill Tracts, which are mostly arsenic-free) and analyzed water samples from 3534 tube wells for arsenic and other elements. The NHS reported the aqueous concentration of arsenic range from <1 to 1,500 μg/L (Fig. 13.2); the arsenic concentrations exceeded the Bangladesh standard of 50 μg/L in approximately 27% of the tube wells, and roughly 42% of the tube wells exceeded the 10 μg/L WHO standard for arsenic in drinking water (BGS and DPHE 2001; Kinniburgh et al. 2003). More recently, the Bangladesh National Drinking Water Quality Survey (BNDWQS) of 2009 was conducted by the Bangladesh Bureau of Statistics (BBS), with participation from UNICEF. In this survey, drinking water samples were collected from 15,000 households that were randomly selected from all geographic areas of Bangladesh. The distribution of arsenic found in BNDWQS (2009) agrees with that found in the previously conducted NHS by BGS and DPHE (2001), with 13.4% of samples exceeding the Bangladesh standard and 32.0% of samples exceeding the WHO guideline value for arsenic in drinking water (UNICEF 2011).

Arsenic is now recognized to be the most important groundwater-quality problem in the GBM delta region of Bangladesh and the neighboring Indian state, West Bengal. It is well documented that the majority of the shallow (depth <150 m) alluvial aquifers under the recent floodplain are enriched with arsenic, whereas groundwater from Pleistocene and older aquifers is largely free of arsenic (e.g., BGS and DPHE 2001; Mukherjee and Bhattacharya 2001; Nordstrom 2002;

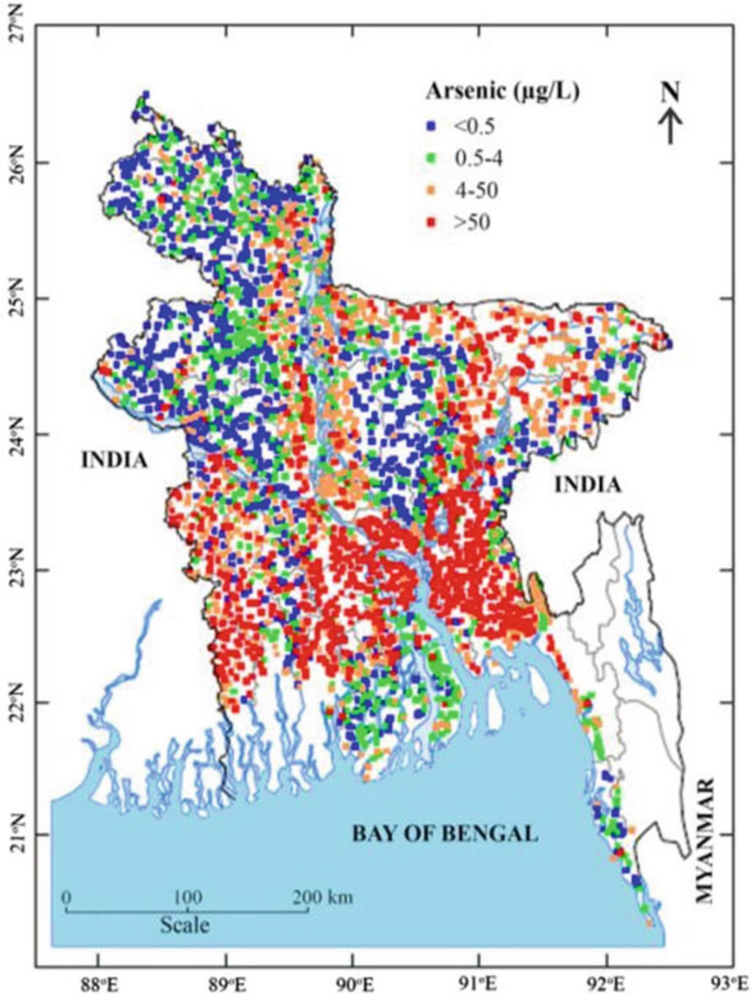

Fig. 13.2 Distribution of arsenic in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

Ravenscroft et al. 2005). It is generally agreed that the arsenic is geologic in origin, deriving from the sediments from the upland Himalayan catchments (McArthur et al. 2001; Nickson et al. 2000; Harvey 2001; Harvey et al. 2002). In particular, delta plains and flood plains of the Ganges–Brahmaputra river system exhibit moderate-to-severe arsenic enrichment with more than 60% of the tube wells affected. The worst-affected shallow aquifers lie below the Meghna floodplains and coastal plains with more than 80% of the tube wells affected (Ahmed et al. 2004). Aquifers within the Pleistocene uplands and tertiary hills and their adjacent Piedmont plains are low in arsenic (Ahmed et al. 2004).

The aquifer matrix serves as the primary source of arsenic, which under favorable condition release arsenic into the groundwaters (Hoque et al. 2009; Chakraborty et al. 2015). Past studies have reported that the arsenic-rich groundwaters are characterized by reducing aquifer conditions with notably high dissolved iron concentrations and low nitrate and sulfate levels (BGS and DPHE 2001; Nordstrom 2002). Numerous biogeochemical processes have been advanced to explain the elevated levels of arsenic in these aquifers, and it is presumed to reflect reductive dissolution of ferric oxides/oxyhydroxides as coatings on sand grains as well as biotite and release of sorbed and/or co-precipitated arsenic into the groundwaters (Nickson et al. 2000; McArthur et al. 2001; Dowling et al. 2002; Harvey et al. 2002; Haque and Johannesson 2006; Haque et al. 2008).

It is important to note that only 1% of the tube wells tapping the deep aquifers (depth >150 m) in the Bengal Basin are arsenic-enriched (BGS and MML 1999). Additionally, Ravenscroft et al. (2013) reported that between 1998 and 2011, groundwater composition remained stable in 46 tube wells from depths of more than 150 m from across the arsenic-contaminated region of southcentral Bangladesh. Moreover, there is no evidence of water-quality deterioration with respect to arsenic, iron, manganese, barium, boron, or salinity during these 13 years. Therefore, tube wells tapping the deep aquifers are likely to provide a safe and economic means of arsenic mitigation in the country.

13.7 Iron

High levels of dissolved iron are common in tube well water samples collected from various parts of Bangladesh (Fig. 13.3; BGS and DPHE 2001; Frisbie et al. 2009; Islam et al. 2015). The NHS reported that the maximum dissolved iron concentration was 61 mg/L with a median value of 1.1 mg/L. Additionally, the survey found that 23 and 10% of the tube well waters contain more than 5 and 10 mg/L dissolved iron concentrations, respectively. Whereas out of the 2896 tube well water samples analyzed by BNDWQS (2009), 60% of the samples meet the Bangladesh standard for iron in drinking water of 0.3–1.0 mg/L (Department of Environment 1991; UNICEF 2011). The notable difference in iron concentrations in the BGS and DPHE (2001) and BNDWQS (2009) may have resulted from difference in the sampling techniques employed. The BGS and DPHE survey aimed for a statistically representative sample of groundwater, whereas the BNDWQS survey targeted household water for drinking. Note that on contact with air during storage in the household, iron can react with oxygen and form insoluble precipitates (UNICEF 2011). A possible explanation is that users prefer to collect drinking water from sources which taste better (i.e., groundwater with lower levels of dissolved minerals).

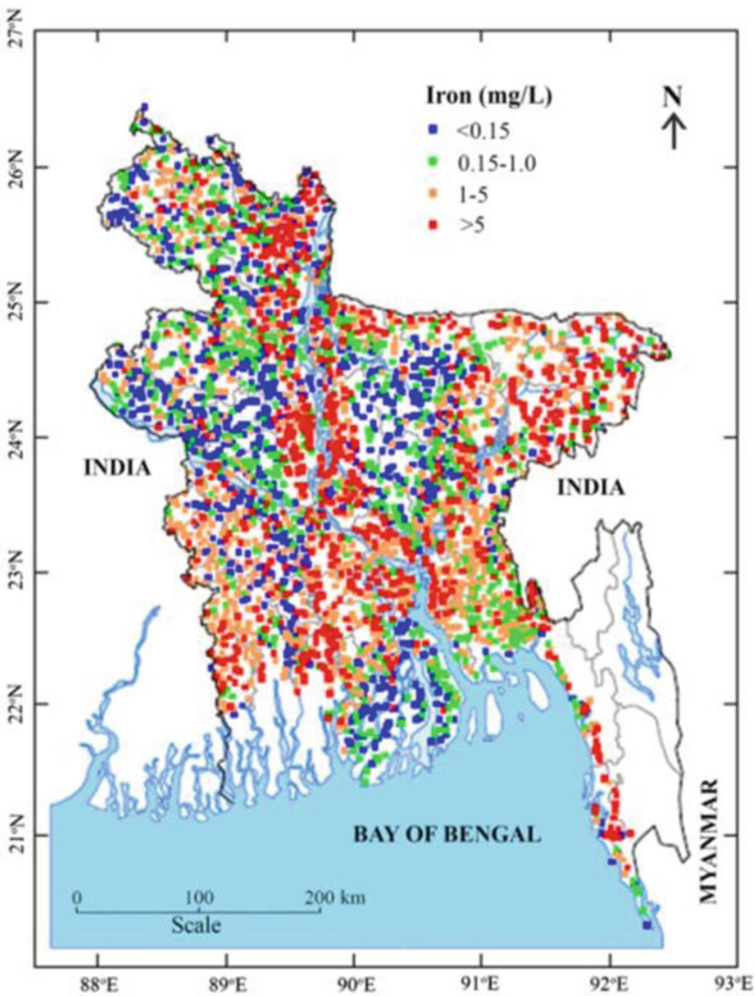

Fig. 13.3 Distribution of iron in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

Hossain and Huda (1997) analyzed well water samples from roughly 1000 deep tube wells of the 56 districts out of 64 districts, covering 86% of total area of Bangladesh. These investigators reported that 41 and 22.5% of the studied area exceed dissolved iron concentrations of 1.0 and 5.0 mg/L, respectively. Studies have linked extended exposure to dissolved iron with hemochromatosis, a disorder of iron regulation in human body (WHO 1996a; Rajappa et al. 2010).

13.8 Manganese

Roughly 39% and 65% of the BNDWQS (2009) samples met the Bangladesh standard for manganese of 0.1 mg/L and the WHO guideline value of 0.4 mg/L for manganese in drinking water, respectively (UNICEF 2011). The 3534 wells surveyed in the BGS and DPHE (2001) study found the maximum concentration of dissolved manganese at 10 mg/L with a median value of 0.3 mg/L (Fig. 13.4). Additionally, the dataset indicates that the deeper wells contain much less manganese compared to the shallower wells. Elevated manganese levels are reported in

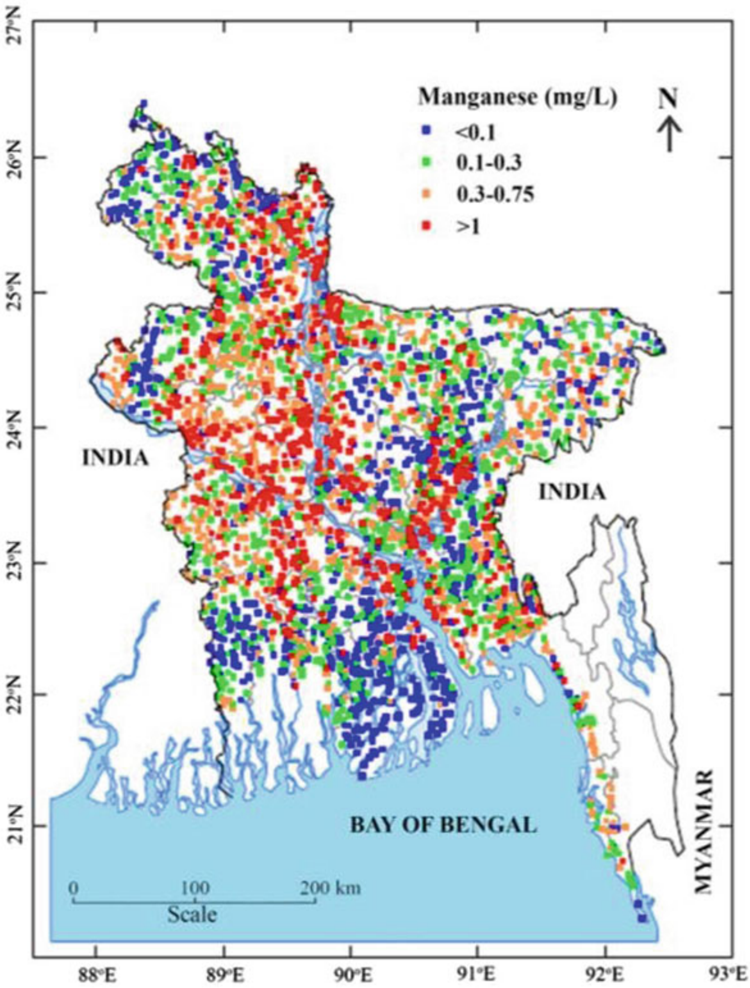

Fig. 13.4 Distribution of manganese in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

most areas of the country. However, notably high-manganese groundwaters are commonly associated with the present-day Brahmaputra and Ganges floodplains (i.e., the central, northern, and western regions of Bangladesh; Zahid and Ahmed 2006). An estimated 60 million people in Bangladesh are drinking water with manganese concentrations exceeding the WHO's guideline value (BGS and DPHE 2001; Frisbie et al. 2009; Hasan and Ali 2010). Manganese-induced neurotoxicity following prolonged exposure to very high levels of manganese in drinking water is well documented (Bouchard et al. 2007, 2011; Wasserman et al. 2006). Many studies have reported link between chronic ingestion of manganese and adverse neurological effect, such as Parkinsonian disorder in humans (e.g., Kondakis et al. 1989; Dorsey et al. 2007; Ferri et al. 2005). Manganese is also known to cause learning disabilities in children (Wasserman et al. 2006).

In the context of arsenic, numerous studies have reported a positive correlation between low arsenic and high manganese concentrations (Fig. 13.5; BGS and WaterAid 2001; Hoque 2006; Hasan and Ali 2010). Furthermore, the BNDWQS found that roughly 93% of deep tube wells meet the Bangladesh standard for arsenic; however, only 60% of deep tube wells meet the Bangladesh standards for arsenic, manganese, and iron (UNICEF 2011). This is an important finding not only in terms of well switching but also the presence of high levels of manganese further complicates an already difficult drinking water supply scenario in rural Bangladesh (Hasan and Ali 2010).

13.9 Nitrate and Ammonia

In a recent investigation by Parvez et al. (2014), groundwater samples collected from central Bangladesh were analyzed for levels of reactive nitrogen species, nitrate, and ammonia. These authors reported that levels of nitrate present in analyzed water are generally low. Majumder et al. (2008) investigated the spatial distribution of nitrate in groundwater samples in west central region of Bangladesh. This study found that in groundwater of the shallow and deep aquifers, nitrate levels range from <0.10 to 75.12 mg/L and <0.10 to 40.78 mg/L, respectively. Others have also found low levels of nitrate (4 mg/L or less) in ground water samples in Chapai Nawabganj, Faridpur, Laksmipur, and Comilla (BGS and DPHE 2001; Rasul and Jahan 2010). Additionally, high nitrate levels reported by NHS were usually restricted to a few shallow wells that had evidence of surface pollution (BGS and DPHE 2001).

Parvez et al. (2014) reported that ammonia levels in most of the ground water samples from central Bangladesh were less than 5 mg/L. Note that natural levels of ammonia in groundwaters are commonly below 0.2 mg/L (WHO 1996b). There is no WHO health-based guideline for ammonia as it is not considered to be of direct importance for human health in the concentrations to be expected in drinking water (WHO 1996a, b). However, the presence of ammonia may impart unpleasant odor to drinking water.

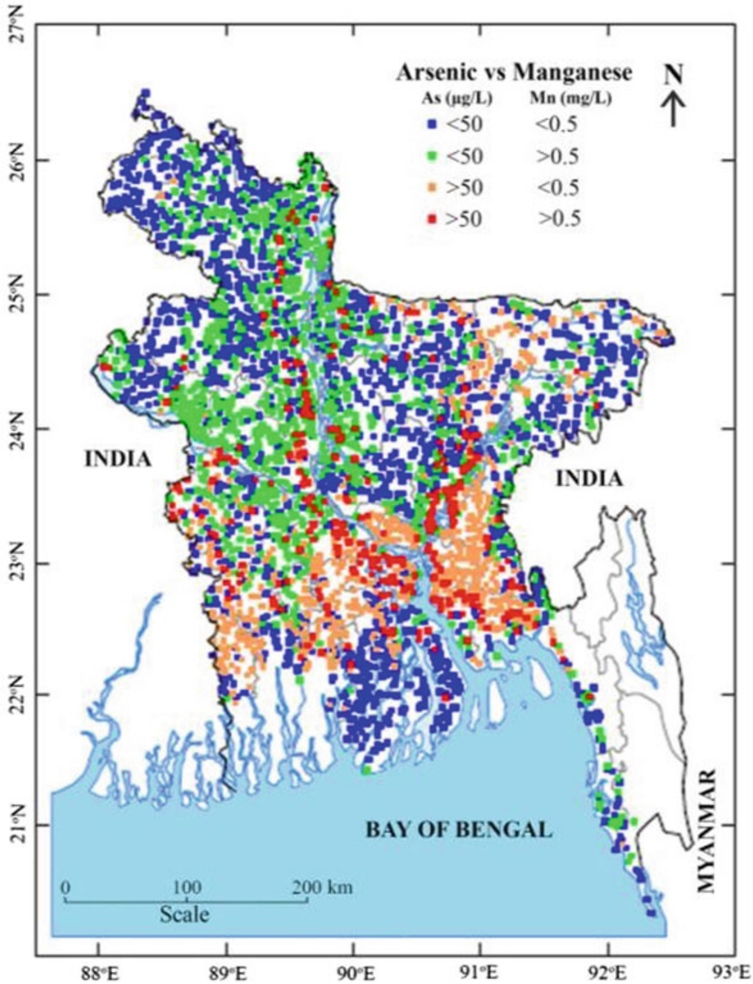

Fig. 13.5 Distribution of arsenic versus manganese in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

13.10 Sulfate

The BGS and DPHE (2001) countrywide data set reported low concentrations of sulfate with a minimum less than 0.4 mg/L and with a median value of 1 mg/L. The dataset also shows a trend of rapidly decreasing sulfate with depth that is consistent with cyclical sulfide weathering with water-table fluctuations (Harvey et al. 2006). Harvey et al. (2002) found an inverse correlation between arsenic and sulfate in the young Holocene aquifers of Bangladesh, suggesting that it is unlikely that arsenic could be liberated from sulfide minerals.

13.11 Methane

Widespread occurrence of biogenic methane has been reported in groundwaters from most parts of the country, as well as in some areas of the southeastern region (Ahmed et al. 1998; Hoque et al. 2001; McArthur et al. 2001). Biogenic methane is the ultimate end-product of microbially mediated reductive fermentation (Whiticar and Schoell 1986; Harvey et al. 2002). Ahmed et al. (1998) reported that the deltaic region of the Bengal Basin hosts conditions, such as the amount of total organic carbon and organic matter, burial depth, hydrothermal gradient along with degree of compaction, which are conducive for methane gas generation. Furthermore, the authors state that areas containing highly saline groundwater generate more methane gas than the rest of the country, suggesting an estuarine depositional environment of the aquifer materials in the areas of high salinity (Ahmed et al. 1998).

13.12 Boron

The NHS survey found that the boron-enriched groundwater samples are mostly found in the coastal region along with low-lying areas near Netrokona and Kishorganj (Fig. 13.6; BGS and DPHE 2001). The dataset shows that in 5.3% of well water samples, concentrations of boron exceed the earlier WHO health-based guideline value of 0.5 mg/L. Note that the revised WHO guideline value for boron (borate) in drinking water is 2.4 mg/L (WHO 2011). The revision is based upon a review of the toxicological data and studies in areas with high background exposures. Boron distribution of the BNDWQS (2009) shows that 94% well water samples meets the Bangladesh standard of 1.0 mg/L.

Ravenscroft and McArthur (2004) reported that concentrations of boron in groundwater reached 2.1 mg/L in the study areas from southwestern (Khulna) and coastal (Barisal, Khulna and Chittagong) regions of Bangladesh. Additionally, boron levels exceeded 0.5 mg/L across roughly 3000 km^2 of the shallow aquifer and 6700 km^2 of the deep aquifer. Typically, the high boron levels are accompanied by high levels of sodium, which is possibly due to saltwater intrusion in the southwestern region (Hassan et al. 1998; Rahman et al. 2000), or due to the presence of residual seawater in the underground aquifers (BGS and DPHE 2001; Acton 2013; Bañuelos 2015).

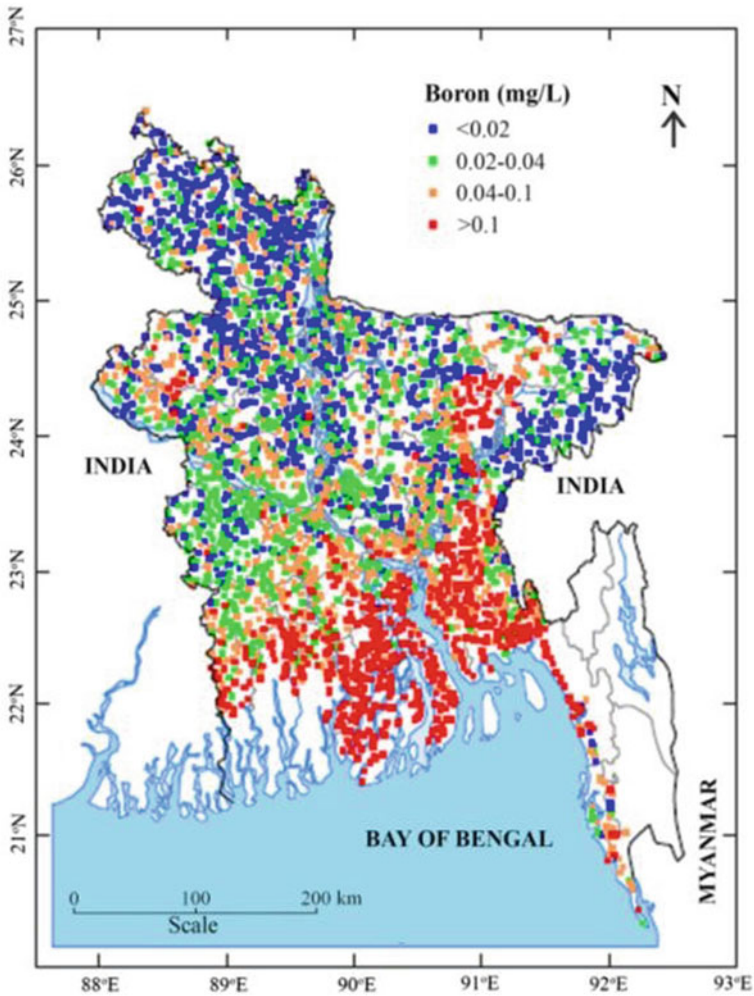

Fig. 13.6 Distribution of boron in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

13.13 Fluoride

BGS and DPHE (2001) reported that concentration of fluoride is comparatively low in the groundwater of Bangladesh, ranging from 0.01 to 0.73 mg/L, with none of samples exceeding the WHO guideline value for fluoride in drinking water of 1.5 mg/L and Bangladesh standard of 1.0 mg/L. The lowest concentrations are found in northwestern parts of the country and the Chittagong coastal region. About 99% samples of the BNDWQS (2009) meet the Bangladesh standard for fluoride, and low concentrations of fluoride were reported across the country. Approximately

1% of the BNDWQS samples exceeds the Bangladesh standard and ranged between 1.1 and 1.5 mg/L. It is important to note that fluoride deficiency-related health problems, such as dental carries, especially in children, may result in areas with low fluoride concentrations (Chouhan and Flora 2010), whereas excess intake of fluoride can lead to discolouration and dental fluorosis (UNICEF 2011).

13.14 Iodide

There is little information available about the iodide levels in the groundwater of Bangladesh. BGS and DPHE (2001) reported that the distribution of iodide levels in groundwaters is varying, ranging from 0.004 to 5.84 mg/L. The higher concentrations are usually found in the coastal region aquifers, and the iodide is seawater derived. In some parts of northern Bangladesh, the iodide levels are low (<3 μg/L) and problematic as this could cause iodine-deficiency disorders, such as high incidence of goiter (BGS and DPHE 2001). Additionally, iodine deficiency during pregnancy and infancy could cause mental retardation (Sack et al. 2000).

13.15 Barium

The WHO guideline value for barium is 0.7 mg/L, and the Bangladesh standard for barium is 0.01 mg/L, which is reportedly a typographical error (UNICEF 2011). The BGS and DPHE (2001) report that barium levels have a nearly similar range in both the shallow and deep groundwaters of Bangladesh, ranging from <0.06 to 1.4 mg/L and <0.06 to 1.0 mg/L, respectively (Fig. 13.7).

The highest concentrations are observed in the southwestern regions along with occasional highs in the Brahmaputra Valley and the Sylhet Basin. In addition, the highest concentrations roughly correspond to those of other alkaline earth elements (e.g., calcium, magnesium, and strontium). The BNDWQS (2009) dataset shows that 99% of the well water samples meet the WHO guideline value for barium (UNICEF 2011). However, barium distribution in the BNDWQS and that in BGS and DPHE (2001) samples are considerably different, with a probability of 55.4% that the BNDWQS distribution is greater than the BGS and DPHE (2001) distribution.

Significant correlations have been observed between concentrations of arsenic and barium in urine ($r = 0.774$), nail ($r = 0.719$), and hair ($r = 0.773$) samples collected from residents of the Indian State of West Bengal and Bangladesh ($n = 31$–59; Chakraborti et al. 2003). Chronic exposure to high levels of barium in drinking water has the potential to cause hypertension (WHO 2004). However, the combination of toxicity resulting from high levels of arsenic and barium in drinking water is yet to be studied for the Bangladesh population.

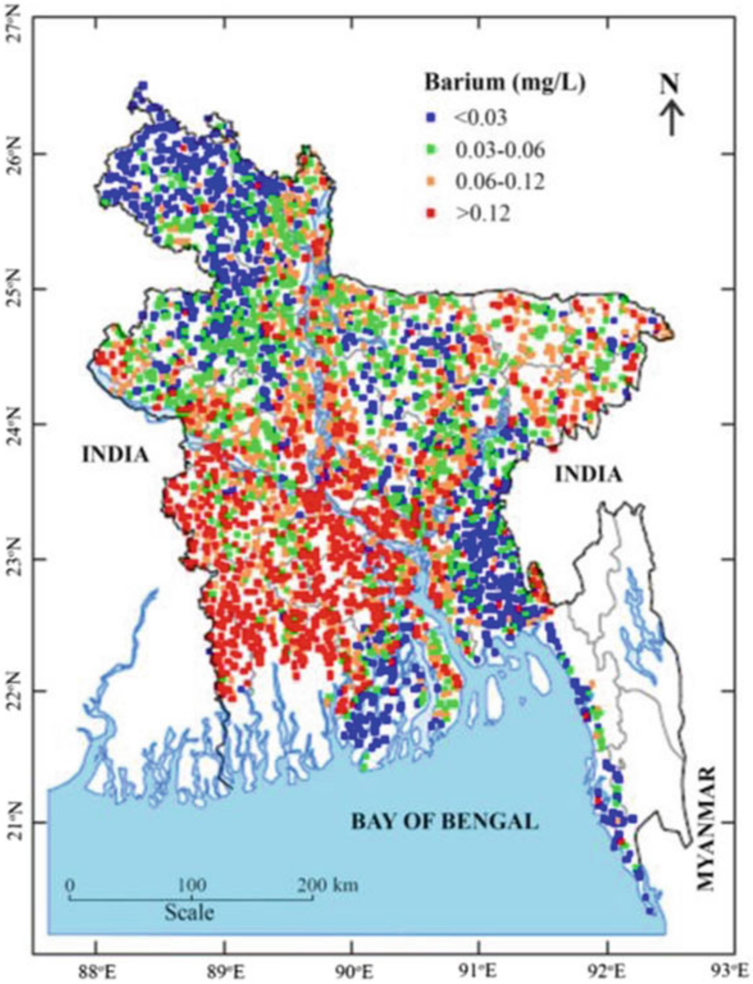

Fig. 13.7 Distribution of barium in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

13.16 Strontium

At this time, there is neither a Bangladesh standard, nor a WHO guideline value for strontium in drinking water. The BGS and DPHE (2001) reported concentrations range from <0.2 to 1.6 mg/L and <0.2 to 3 mg/L in the groundwater of the shallow and deep aquifers, respectively (Fig. 13.8). The survey reported that the regional distribution in the groundwater reflects dissolution of carbonate minerals in the aquifer matrix. Additionally, the observed increase in strontium concentrations in the southern coastal region is ascribed to seawater intrusion. The lowest

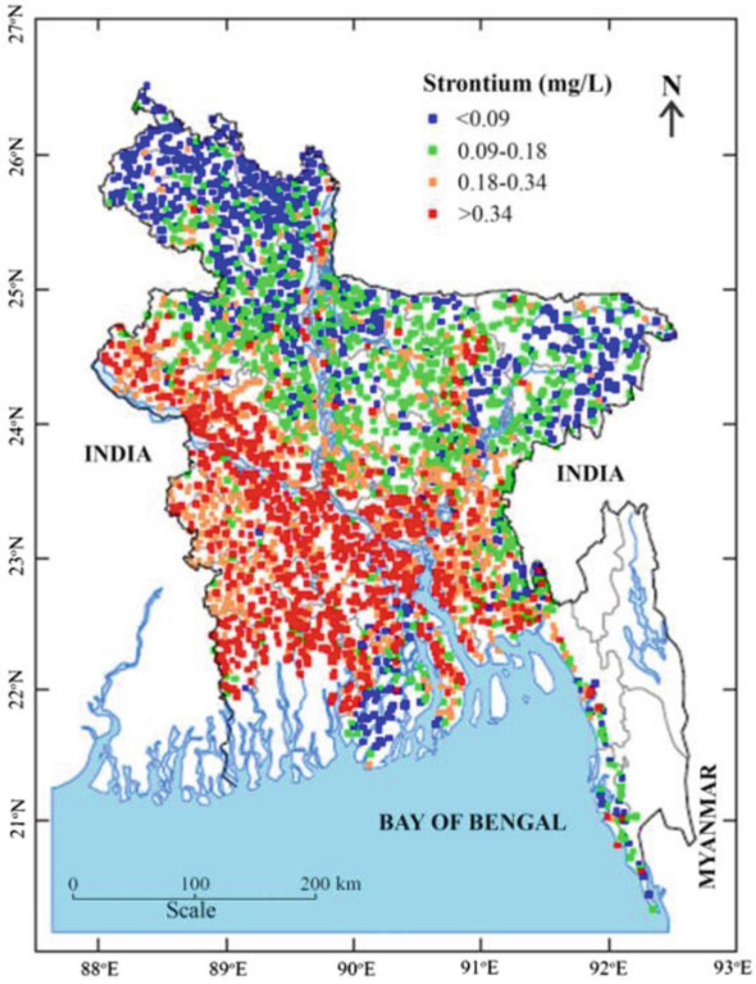

Fig. 13.8 Distribution of strontium in the groundwaters of Bangladesh from the NHS. Modified from BGS and DPHE (2001)

concentrations are found in the groundwater of the Tista Fan and Sylhet Basin. In general, low concentrations are observed in the deep aquifers of the extreme south coastal area. In these deep waters, strontium concentrations appear to follow a trend similar to that of calcium concentrations. There is a small difference in the magnitude of strontium contents between BNDWQS (2009) and BGS and DPHE (2001) distributions (UNICEF 2011).

13.17 Uranium

The sedimentary successions of Bangladesh have continental sandstones along with lignite and organic matter, a lithology that is favorable for uranium occurrence in sandstones (Majumder 2014). BGS and DPHE (2001) reported that well water samples collected from Chapai Nawabganj, Faridpur, and Lakshmipur showed uranium concentrations up to 47 μg/L and the average concentration found was 2.8 μg/L. The reported concentrations of uranium in BNDWQS (2009) and BGS and DPHE (2001) samples are not significantly different. Frisbie et al. (2009) analyzed groundwater samples collected from western Bangladesh and found that the uranium concentrations range from <0.2 to 10 μg/L, with 48% of the tube wells exceeding the previous 2 μg/L WHO guideline for uranium in drinking water. Note that recently, the guideline value for uranium in drinking water has been revised upward and the new provisional guideline value is 30 μg/L. The new standard is derived from epidemiological studies on human populations exposed to high levels of uranium from drinking water sources (WHO 2011). There is no Bangladesh standard for uranium.

Sultana et al. (2014) analyzed 261 well water samples from 54 administrative districts in Bangladesh to investigate the dissolved uranium. The authors report that uranium concentration ranges between 0.5 and 10 μg/L in 27% of tube well samples, 11–20 μg/L in 38% of tube well samples, 21–30 μg/L in 16% of tube well samples, and 19% of the samples exceeded the recent WHO provisional guideline for uranium in drinking water. Based on the findings of these studies, detailed investigations of uranium occurrence in the aquifers of Bangladesh are required to assess the potential for adverse human health effects of uranium-contaminated drinking water.

13.18 Fecal Contamination of Groundwater

Three past studies exploring microbial contamination of shallow tube wells of the Bengal Basin found that more than 40% of water samples collected were contaminated with human fecal organisms (Hoque 1999; Islam et al. 2001; Luby et al. 2006). Luby et al. (2006) reported that groundwater samples collected from 207 tube wells located in the flood-prone districts of Comilla, Brahmanbaria, and Sirajganj were microbiologically contaminated with total coliforms (41%), thermo-tolerant coliforms (29%), and *Escherichia coli* (13%). The study further found that 86% of tube wells were located within close proximity ($\sim$10 m) of a latrine and 70% had some source of pollution within 10 m. Cow barns, fertilizer, and surface water ingress appear to be the possible sources of contamination of the tube well waters.

More recently, van Geen et al. (2011) found that a high proportion of shallow tube wells from Araihazar and Matlab upazilas contained detectable levels of fecal indicator *E. coli* almost throughout the year. The key finding of this study is that shallow tube wells that meet the WHO standard for arsenic are more likely to contain detectable levels of *E. coli*. The significance of this inverse relationship between fecal contamination and aqueous arsenic is that well switching may expose the users of rural Bangladesh to higher levels of diarrheal disease pathogens.

13.19 Groundwater Pollution from Urban Industrial Areas

Rapid urbanization coupled with industrialization is responsible for increased heavy metal concentrations in soils and sediments in many parts of the country. High levels of chromium, aluminum, and iron have accumulated in topsoils (up to 6 m) of Hazaribagh leather processing area of Dhaka city (Zahid et al. 2004). Moreover, significant amounts of manganese, zinc, nickel, and copper are present in shallow groundwater of this area (Zahid and Ahmed 2006). Approximately 1% of tube wells exceed the 10 μg/L WHO health-based drinking water guideline for lead. Bodrud-Doza et al. (2016) reported that ceramics, brick, and pottery industries are located in the study area likely contribute to heavy metals, such as nickel and zinc in groundwaters of Faridpur district located in central Bangladesh.

13.20 Agrichemicals

Intensive agricultural practice along with generous application of commercial fertilizer and pesticides are widespread in the country. Runoff and infiltration of agrichemicals (i.e., commercial fertilizers and pesticides) from farmlands into water bodies should be considered a serious concern with respect to their impact on groundwater quality. In Bangladesh, between 1975 and 1976, fertilizer consumption was 0.36 kg/ha of agricultural land, whereas by 2007 it had increased to 298 kg/ha (Basak 2011). In the central-west region of Bangladesh, the shallow and deep groundwater nitrate concentrations range from <0.10 to 75.12 mg/L and <0.10 to 40.78 mg/L, respectively (Majumder et al. 2008). The WHO's maximum contaminant level (MCL) for nitrate is 50 mg/L. Nitrates are highly soluble, mobile, and not readily biodegradable. The source of both nitrate and ammonium-N in groundwaters of Bangladesh has been ascribed to excessive application of nitrogenous fertilizer (Kurosawa et al. 2008; Majumder et al. 2008).

Recent studies of pesticide in groundwaters of Bengal Basin have found a large area of the Ganges aquifers to be susceptible to pesticide pollution (e.g., Anwar and

Yunus 2013; Saha and Alam 2014). An investigation of the mobility and leaching potential of various pesticides in a shallow unconfined aquifer in northwest Bangladesh reported that topsoils are found to be vulnerable to organochlorine pesticide accumulation (Anwar and Yunus 2013). Additionally, low concentrations of heptachlor and dichlorodiphenyltrichloroethane (DDT) were detected in some parts of the country (Zahid and Ahmed 2006). Furthermore, Hossain (1997) reported higher concentration of ammonium and nitrate in shallow aquifers. Because of its solubility, excessive ammonia may infiltrate into deeper soils and ultimately reach groundwater.

13.21 Saltwater Intrusion

Most groundwater in Bangladesh is fresh, except in parts of the southern coastal region where salinity is the highest in groundwater due to ingress of seawater (Ahmed 1994; Ravenscroft 2003). In coastal plain aquifers of southern Bangladesh, a sequence of aquifer layers containing saline or brackish groundwater overlies deeper aquifers containing freshwater (DPHE-DANIDA 2001). During the dry season, moderate-to-strong saline groundwaters are encountered within 1–2 m below the soil surface at all locations (Datta and Biswas 2004; Rasel et al. 2013). The coastal communities in the southern region are particularly vulnerable to salinity intrusion due to increasingly shrinking quantities of freshwater (Rasel et al. 2013). Note that salinization of groundwater is a serious threat to aquifer sustainability as there is no natural attenuation mechanism (UNEP-DEWA 2003).

13.22 Consequences of Groundwater Overdraft

It is widely documented that during the last decade, long-term excessive exploitation of groundwater has led to substantial drawdown of aquifers (McArthur et al. 2001; Jahan et al. 2010; Shahid 2011). The worst-affected areas in terms of declining water table lie in the northwestern (i.e., Barind Tract) and northcentral (Madhupur Tract) regions (Shamsudduha et al. 2009). These are areas of *Boro* rice cultivation and intensive groundwater-fed irrigation in the dry season. An estimated 3,000–5,000 L of water is required to produce one kilogram of rice (Biswas and Mandal 1993). The irrigation water supply primarily comes from shallow aquifers. Bangladesh Agricultural Development Corporation (BADC 2003) reported that between 1979 and 2003, groundwater-fed irrigation for dry season rice cultivation has increased annually by around 875 million m^3. Numerous studies have reported that in the northwestern regions, water tables are declining steadily at a rate of 0.1–0.5 m/year (e.g., Shamsudduha et al. 2009; Dey et al. 2013). In contrast, rising groundwater levels (0.5–2.5 cm/year) are observed in the southern coastal region, albeit slow, a consequence of seawater intrusion (Shamsudduha et al. 2009;

Brammer 2014). Groundwater use in the coastal region remains unexploited due to salinity concerns in shallow and lower shallow aquifers (Qureshi et al. 2014).

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