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Groundwater-fed Irrigation and Drinking Water Supply in Bangladesh: Challenges and Opportunities

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Abstract: Groundwater is critical to both drinking and irrigation water supplies in Bangladesh. Today, approximately 97% of all drinking water supplies comes from groundwater via hand-operated tubewells tapping from primarily the shallow (<150 m below ground level) groundwater. Groundwater-fed irrigation has been sustaining the dry-season rice (*Boro*) cultivation in Bangladesh since the 1970s that has made the country nearly self-sufficient in food grains. Currently, the shallow groundwater is facing two major challenges: (1) widespread contamination by elevated (exceeding the WHO Standard of 10 µg/L) arsenic (As) concentrations, and (2) rapid decline in groundwater storage in major cities (e.g., Dhaka) and intensely irrigated areas (e.g., Barind Tract region in northwestern Bangladesh). Nearly 50 million people in Bangladesh are currently threatened by chronic consumption of elevated As concentrations. Continuous decline in shallow groundwater levels is currently leading towards an unsustainable condition for low-cost pumping technologies (e.g., shallow irrigation wells) and threatening food security. As a practical and economic mitigation response to the on-going As crisis, the deep (>150 m bgl) groundwater resource, which is almost uniformly free of As is currently being utilized in many parts of Bangladesh. However, very little is known about deep groundwater and its interactions with shallow groundwater. This study presents a critical review of groundwater resources in Bangladesh highlighting the areas where this vital resource is facing challenges and how these difficulties can be overcome to sustain the continuing economic growth and social development.

Key words: Groundwater resources, irrigated agriculture, arsenic contamination, climate change, Bangladesh

1 INTRODUCTION

Groundwater is an essential part of public water supply and food production in Bangladesh. Groundwater-fed irrigation, which has been sustaining the dry-season (January to May) *Boro* rice cultivation in large parts of Bangladesh since the 1970s, has nearly made the country self-sufficient in food grains (Rahman and Parvin 2009). Currently, the high-yielding *Boro* rice is grown (Figure 1) in nearly 4 million hectares of net cultivable land (total of 7.7 million ha) in the country that is primarily groundwater-fed (BBS, 2008). The dry-season groundwater-fed irrigation represents ~80% of total groundwater use in Bangladesh. Groundwater also provides a year-round, pathogen-free drinking water supply to 97% population in the country. However, Bangladesh is currently facing two grave crises relating to the shallow (<150 m below ground level) groundwater resource: (1)

widespread contamination of shallow groundwater with dangerous levels of arsenic (As) concentrations, and (2) rapid decline of shallow groundwater storage in many parts (e.g., Dhaka City, Barind Tract region) of Bangladesh.

Firstly, a total of 77 million people of Bangladesh are exposed to toxic levels of As (WHO Standard of (10 μg/L) in their drinking water (Argos et al., 2010) that primarily comes from shallow groundwaters. A recent study (Flanagan et al., 2012) reports that over the next 20 years As-related mortality in Bangladesh (1 of every 18 deaths) could lead to a loss of US $12.5 billion assuming a steady economic growth and an unchanged population exposure to As contamination. The second problem is considered as an imminent threat to the food security of Bangladesh as declining groundwater levels in shallow aquifers in the northwestern parts of the country have already rendered many low-cost pumping technologies (e.g., shallow irrigation pumps, hand tubewells) inoperable particularly during the dry season when water table is too deep (>10 m bgl). Declining groundwater levels beneath Dhaka City is currently costing the city water supply authority (DWASA) a lot more than the previous years as the high-cost pumping technologies have now been utilized to provide domestic water supply to its 12 million people.

This study presents a critical review of groundwater resources development in Bangladesh over the last four decades and highlights the current challenges and opportunities.

2 DEVELOPMENT OF GROUNDWATER IN BANGLADESH

2.1 Groundwater-fed Drinking Water Supply

Before 1970s, surface water (e.g., pond, river) was the main source of drinking and domestic water supplies in Bangladesh. Dug wells were also commonly used in many parts of the country except in coastal areas where near-surface (very shallow) groundwater is mostly saline. During the late 1970s and early 1980s, in order to avoid surface water sources, which were mostly contaminated with pathogenic micro-organisms, the use of groundwater was introduced in Bangladesh. Thousands of hand-operated tubewells were installed in rural areas of Bangladesh by the government aided by international donor agencies to provide pathogen-free groundwater-fed drinking water supply. During the International Drinking Water Decade (1980 - 1990) several millions of such hand-operated tubewells were installed to tap shallow (<150 m bgl) groundwater for domestic usage. The exact number of hand tubewells in Bangladesh is not known but an estimated 10 million tubewells exit in the country. The vast majority of these tubewells are private, which penetrate the shallow parts of alluvial aquifers down to depths typically of 10–60 m bgl (BGS and DPHE, 2001).

In large urban areas of Bangladesh there are city water-supply and sewerage authorities that are responsible for providing drinking water supplies to the city dwellers. For instance, in Dhaka City there is the Dhaka Water Supply and Sewerage Authority (DWASA) that supplies water to the city dwellers. At present, DWASA has a network of several hundred deep (>150 mbgl) groundwater wells and a couple of surface water treatment plants. DWASA covers more than 360 km^2 service area with production of nearly 2,110 million liters of water every day of which 87% comes from groundwater and the rest from surface water treatment plants. In addition to DWASA water-supply wells there are several hundreds to a thousand unlicensed groundwater abstraction wells in Dhaka City. There are similar water-supply and sewerage authorities operating in other big cities in Bangladesh such as the Chittagong Water supply and Sewerage Authority in Chittagong and the Khulna Water Supply and Sewerage Authority in Khulna. Like DWASA these water-supply authorities are also heavily dependent upon groundwater resources.

In many semi-urban, district and upazila towns in Bangladesh there are local water-supply and sanitation authorities known as municipalities who are responsible for providing public water supply through pipe networks. These municipal water-supply systems are also groundwater-fed. The Department of Public Health Engineering (DPHE) and Bangladesh Water Development Board (BWDB) are the two government organizations that provide technical support to local municipality to setup their water-supply system. In addition to the government initiatives, many private sectors and NGOs also provide financial support and some technical assistants to develop water-supply systems in many rural parts of Bangladesh.

2.2 Groundwater-fed Irrigation Water Supply

Groundwater is essential for food production in Bangladesh. Irrigated agriculture is the largest consumer of groundwater in the country. Nearly 80% of all irrigation water supplies come of groundwater of which shallow groundwater-fed irrigation dominates (Figure 1). Small-scale groundwater-fed irrigation (known as the minor irrigation) has been sustaining the high-yielding *Boro* rice cultivation in Bangladesh since the 1970s. *Boro* rice is grown during the dry season (January to May) throughout Bangladesh except some areas in the south (Figure 2). Besides *Boro* rice cultivation, groundwater-fed irrigation is applied to other non-dry season rice (e.g., *Aman*) in drought-prone parts of northwestern Bangladesh.

Groundwater-fed irrigation first started during a period of 1963 to 1966 in Bangladesh (then East Pakistan) with installation of a few hundred deep irrigation wells. Although these wells were installed at a depth ranging from 75 to 100 mbgl they are popularly known as ‘deep’ wells as the pump (submersible) is set below the static water table. A good description to the development of groundwater-fed irrigation is Bangladesh can be found in several literatures (Rahman and Ravenscroft, 2003; Ahmed et al., 2012).

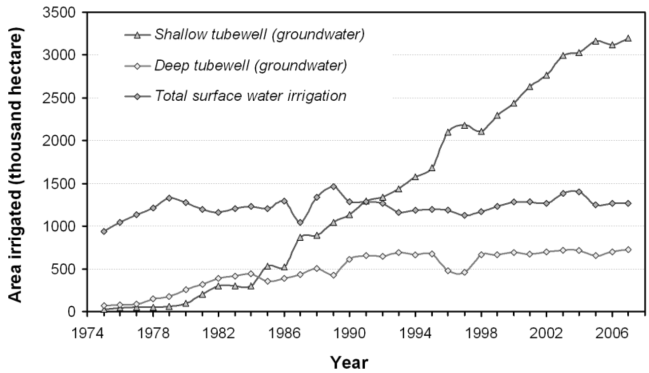

Figure 1. Development of groundwater and surface water-fed irrigation in Bangladesh since the early 1970s (Shamsudduha et al., 2011).

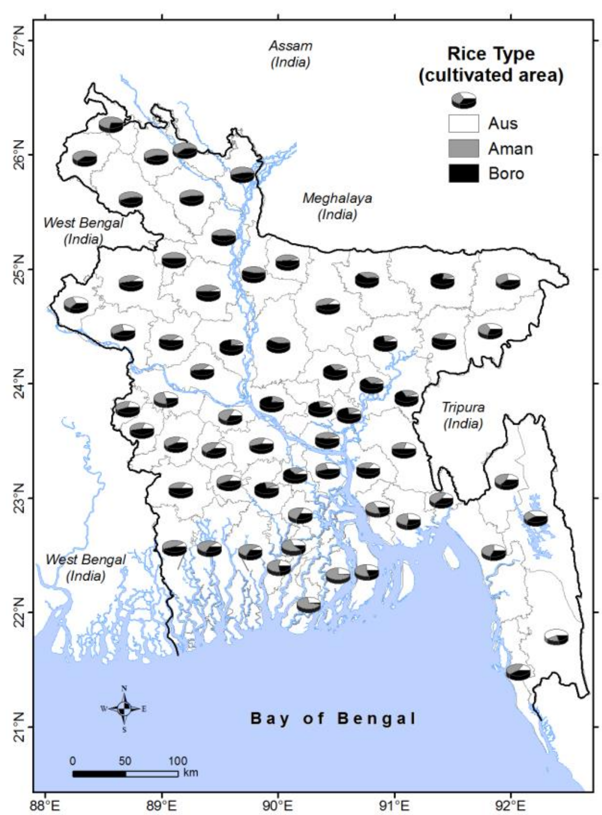

Figure 2. District-wise summary of cultivated area (percentage of net cultivated land) under three main rice in Bangladesh (data from BBS Agricultural Census, 2008).

Currently, nearly 90% of the total irrigation in Bangladesh is operated under “minor irrigation” or small-scale irrigation scheme primarily involving groundwater-fed shallow tubewell (STW), deep-set shallow tubewell (DSSTW), deep tubewell (DTW), and force mode tubewell (FMTW), and surface water-fed low lift pumps (LLT). According to BADC irrigation statistics, a total of 1.2 million STW, nearly 30,000 DTW, and 50,000 LLP operated during the Boro rice season in 2007. It was very clear from Figure 1 that STW-based irrigation has dramatically increased over the last three decades in Bangladesh.

3 MONITORING OF GROUNDWATER RESOURCES

3.1 Development of Groundwater-level Monitoring Network

Today, there are several organizations in Bangladesh that have established national groundwater-level monitoring networks throughout the country. These organizations are BWDB, DPHE, and Bangladesh Agricultural Development Corporation (BADC). Amongst these three national organizations BWDB is the key organization responsible for monitoring both surface water and groundwater resources and implementation of water-related development projects in Bangladesh. To monitor water resources of the region the East Pakistan Water and Power Development Agency (EPWAPDA) was established in the late 1950s. Subsequently, BWDB emerged following the independence of Bangladesh in 1971 replacing the former EPWAPDA. A detailed account of the development history of groundwater-level monitoring in Bangladesh can be found in several literatures (Nishat et al., 2003; Zahid and Ahmed, 2006).

Currently, BWDB manages a total of about 1250 monitoring boreholes or piezometers across the entire Bangladesh. Most of these boreholes are shallow (depth <50 m bgl); a few boreholes in the southern Bangladesh are deep (>150 m bgl). The depth to groundwater levels is measured manually once a week (i.e. every Monday). Depth from the well head (also known as the parapet height) to groundwater level at each station is referenced to a common horizontal datum known as the Public Works Datum (PWD), originally set approximately at the mean sea level (msl) with a vertical error of ±0.45 m (Shamsudduha et al., 2009).

In the early 1970s, BWDB started their monitoring with a few hundred boreholes mostly inherited from the former EPWAPDA (Figure 3). During the 1960s most of these monitoring wells were dug wells; many of these were subsequently replaced by boreholes. The total number of monitoring wells that operated from 1961 to 2006 is 2154; 735 were dug wells and 1419 were boreholes (Figure 3). Most dug wells have been replaced by boreholes at the same location; faulty boreholes have also been replaced throughout the recording period. In some cases, newly installed boreholes were drilled deeper or shallower than those they replaced. The total number of active boreholes in the database is 1267 (Figure 4) (Shamsudduha et al., 2009).

DPHE has its own network of about 4500 monitoring wells throughout Bangladesh. However, DPHE only measures the depth to the dry-season groundwater levels once a year that generally corresponds to the deepest annual groundwater levels in most locations in Bangladesh.

BADC has a network of more than 3000 monitoring wells throughout Bangladesh. Little is known about their monitoring frequency and observation technique. BADC has published groundwater-level maps dubbed as "groundwater zoning map" for two seasons (2004 and 2010) (Alam, 2011).

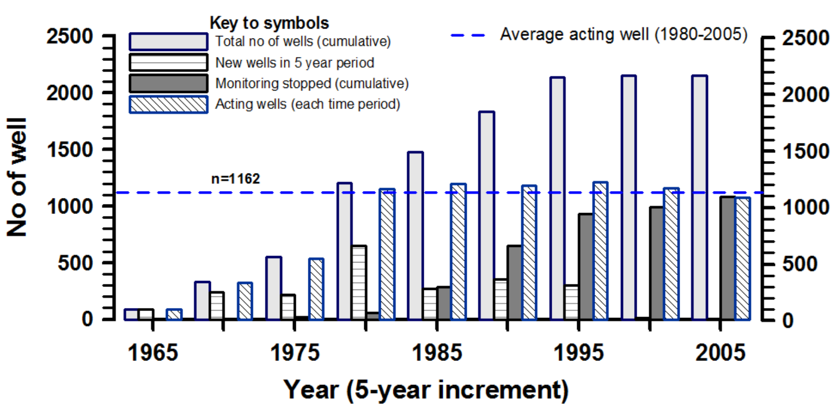

Figure 3. Development of groundwater-level monitoring network by BWDB.

3.2 Long-term Trends in Shallow Groundwater Levels

Long-term trends in shallow groundwater levels reflect the sustainability of abstraction abstractions primarily used for dry-season irrigation in Bangladesh. This study has estimated that nearly 30 km^3 of groundwater was abstracted for irrigation throughout Bangladesh during the *Boro* rice season in 2006. Considering an average daily groundwater use of 50 liters per person for both drinking and domestic uses (total population of 150 million in 2006) an estimated domestic groundwater use is approximately 3 km^3 which is an order of magnitude less than irrigation abstraction in Bangladesh. Irrigation water supplies predominantly come from shallow groundwater. During each *Boro* rice season in Bangladesh about a million STWs operate that withdraw a substantial amount of groundwater which is not fully recharged during the following monsoon season. As a result of this unsustained groundwater abstraction for irrigation and municipal water supplies shallow groundwater levels are declining at high rates in many areas of Bangladesh.

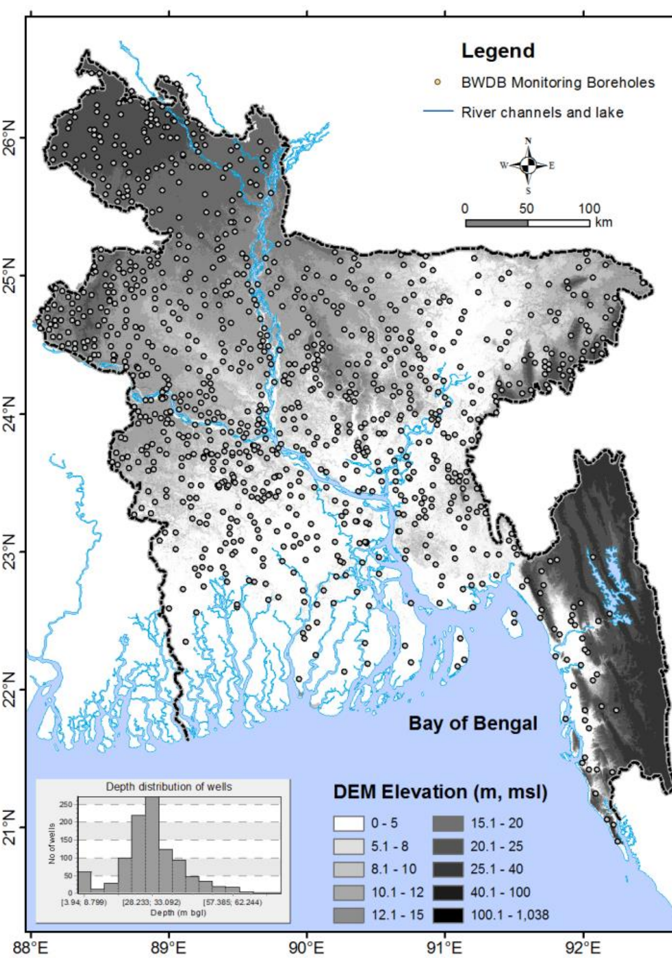

Figure 4. Map showing the spatial distribution of BWDB groundwater-level monitoring boreholes in Bangladesh. The background map is a digital elevation model (DEM) constructed from the NASA's Shuttle Radar Topography Mission data. The histogram on the lower left-hand side of the figure shows distribution of intake depth of BWDB boreholes. The average depth of monitoring boreholes is approximately 33 mbgl.

Using weekly monitoring records of groundwater levels from a network of 454 boreholes throughout Bangladesh (Shamsudduha et al., 2009) shows that shallow groundwater levels are declining a high rates in the recent time (1985 – 2005). Declining rates are highest (exceeding −0.5 m/year) in and around Dhaka City and Barind Tract region, and high (0 to −0.05 m/year) in areas south of the River Ganges (Figure 5). In the coastal areas, shallow groundwater levels are showing stable to slightly rising trends (0 to +0.1 m/year) over the same period.

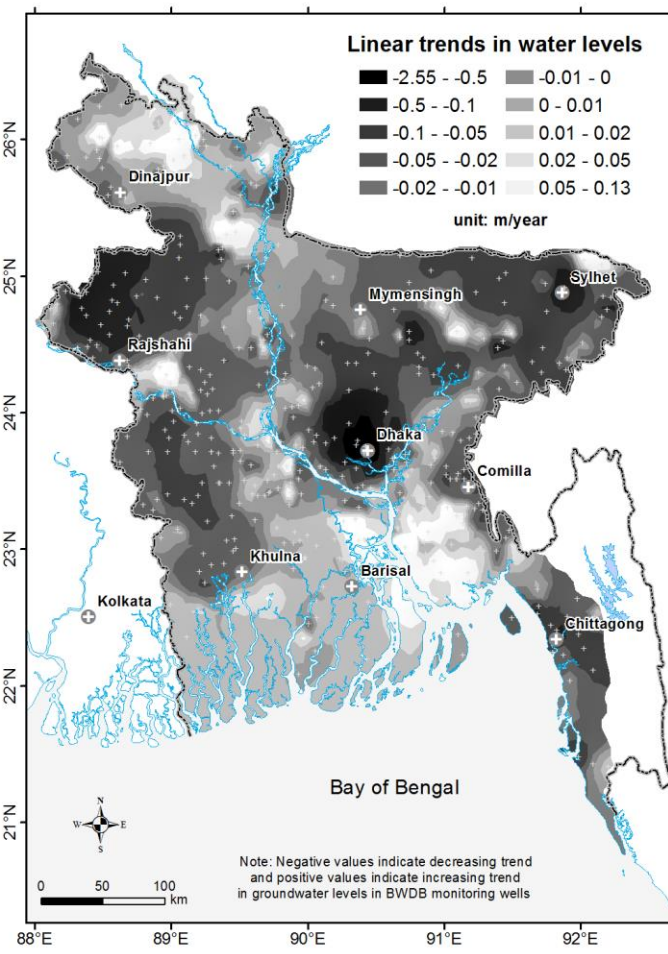

Figure 5. Long-term (1985 – 2005) trends in shallow groundwater levels throughout Bangladesh (Shamsudduha et al., 2009). Groundwater levels are declining over dark areas but stable to rising over light-gray to white areas.

3.3 Long-term Trends in Deep Groundwater Levels

Unlike detailed monitoring of shallow groundwater levels throughout Bangladesh, deep (>150 mbgl) groundwater-level monitoring is very limited. A total of 13 deep monitoring boreholes is found in the BWDB weekly groundwater-level monitoring database of which monitoring has stopped at 7 boreholes. Time-series of deep groundwater levels from three continuously monitored boreholes in southern Bangladesh are shown in Figure 6. Borehole

BA025 is as deep (281 mbgl) monitoring well located in Mathabaria Upazila of Pirojpur District of southern Bangladesh. Long-term time-series data show a slightly rising trend until 1990 but a declining trend in the recent decade (1995-2005). Borehole CT041 (291 mbgl) and CT042 (168 mbgl) both are located in Sandwip Upazila of Chittagong District in southeastern Bangladesh. Long-term time-series data do not show any discernible trends. A number of deep monitoring boreholes has already been installed in several coastal districts in Bangladesh by BWDB (Zahid et al., 2012).

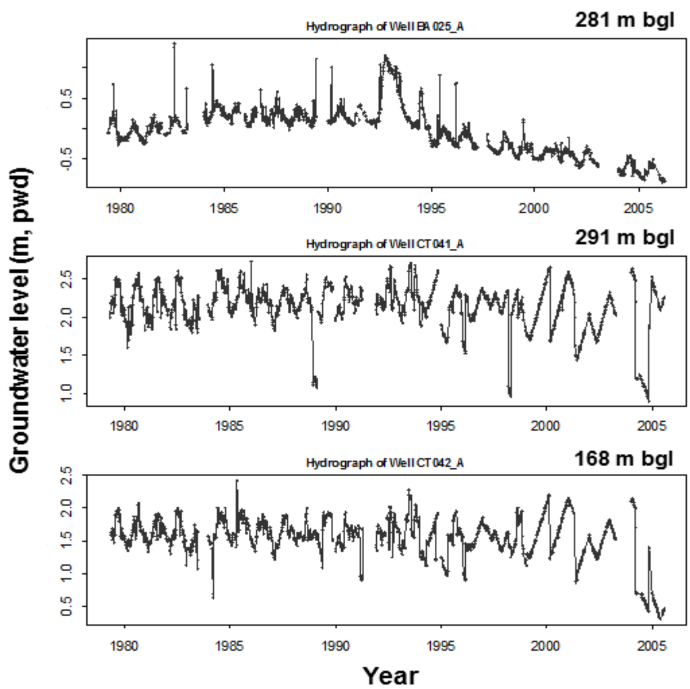

Figure 6. Long-term monitoring records of deep (>150 m bgl) groundwater levels in the coastal region of Bangladesh.

4 MONITORING OF GROUNDWATER QUALITY

4.1 Arsenic Contamination of Shallow Groundwater

Geogenic arsenic (As) contamination of shallow groundwater in Bangladesh (Figure 7) is the greatest environmental problem in the recent history. Nearly 50 million people are currently exposed to dangerous levels (exceeding the WHO standard of 10 µg/L) of As concentrations in drinking water supplies. Numerous studies have been conducted on As since it was first detected in groundwater in southwestern Bangladesh during the early 1990s (BGS and DPHE, 2001; Ravenscroft, 2001; van Geen et al., 2003; Ahmed et al., 2004;

Zheng et al., 2004; Ravenscroft et al., 2005; Shamsudduha et al., 2008; Burgess et al., 2010; Neumann et al., 2010; Ravenscroft et al., 2013).

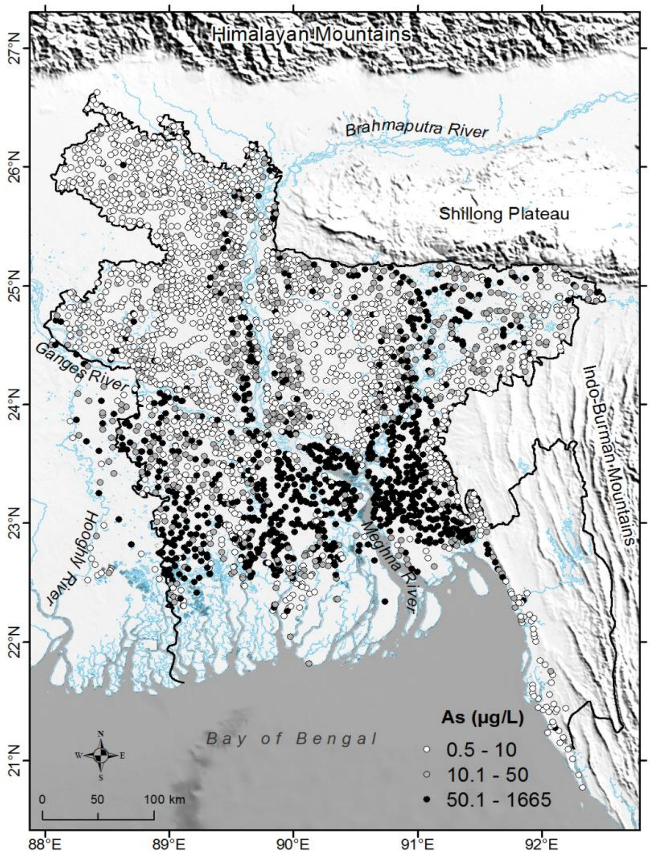

Figure 7. Spatial distribution of As concentrations in shallow (<150 m bgl) groundwater in the Bengal Basin (BGS and DPHE, 2001; Mukherjee, 2006).

Over the last two decades, several national-scale surveys of water wells (e.g., hand-operated tubewells, irrigation wells, dug wells) have been conducted that reveal regional patterns in groundwater As concentrations (Figure 7). The pioneering survey known as the National Hydrochemical Survey (NHS) of Bangladesh (DPHE, 1999; BGS and DPHE, 2001) sampled some 3,534 wells, mostly of shallow depths (<150 m bgl), of which 25% wells contain As concentrations of >50 µg/L (Bangladesh Standard). Under the supervision of the National Arsenic Mitigation Information Centre (NAMIC) nearly 5 million tubewells were surveyed throughout Bangladesh using field kit tests on the spot and the survey revealed that approximately 20% wells contain groundwater As concentrations exceeding the Bangladesh standard (BAMWSP, 2004). Recently, another national-scale survey was conducted by Bangladesh Bureau of Statistics (BBS) with technical support from UNICEF under the Multiple Indicator Cluster Survey (MICS) and published as the Bangladesh National Drinking Water Quality Survey Report of 2009 with total records of 14,442 household drinking-water samples (UCL, 2013). Nearly 14% samples collected from shallow tubewells exceed As concentrations of 50 μg/L (BBS and UNICEF, 2011).

4.2 Salinity Contamination of Groundwater

Salinity contamination of groundwater is another critical water quality issue in Bangladesh, particularly in the coastal region. There has been very little monitoring of groundwater salinity in Bangladesh in the past. BWDB has a network of some 110 monitoring stations throughout the country except three districts in the Chittagong Hill Tracts and Sunamganj district in the northeast. These monitoring wells range in depth from as shallow as 10 mbgl to around 300 mbgl. BWDB samples groundwater from these wells twice every year and analyze major and minor chemical composition including salinity. As part of the national survey in 1998-1999 chloride (Cl) concentrations were measured along with many other chemical parameters. High Cl concentrations (>100 mg/L) in groundwater are found in the coastal areas of Bangladesh (BGS and DPHE, 2001). A detailed national-scale map of groundwater salinity (electrical conductivity, EC) (Ravenscroft, 2003) shows the spatial distribution of high salinity (EC >2000 μS/cm) in shallow (<150 mbgl) aquifers in the Sundarbans. However, high EC concentrations in shallow groundwater are also observed in isolated pockets located in the southern greater Comilla region. Salinity in groundwater is much lower (<500 μS/cm) in the northern half of Bangladesh.

Recently, BWDB has established a network of around 500 shallow and 10s of deep monitoring wells in 19 coastal districts of Bangladesh where groundwater levels are currently being recorded manually once a week (Zahid et al., 2012). In addition to taking of manual readings, at a number of locations automatic data loggers have been installed where high-frequency (hourly interval) groundwater levels and salinity (EC levels) are being recoded. Besides, these multilevel borehole locations, there are more than 500 locations where shallow groundwater levels are monitored manually once a week. For baseline survey, groundwater and surface ware chemistry including salinity have been analyzed in a few hundred locations in these 19 coastal districts of Bangladesh.

Groundwater salinity (expressed as chloride concentration) in deep aquifers was measured in more than 20,000 deep (>150 m bgl) public water-supply wells in Barisal, Patuakhali and Noakhali regions as part of a DPHE – Danida Water Supply and Sanitation project in coastal Bangladesh (Figure 8) (BAMWSP, 2004; DPHE/DANIDA, 2006; Yu et al., 2010). Several thousand additional salinity data have been collated from other projects (e.g., DPHE Deep Groundwater Quality Project, Bangladesh Arsenic Mitigation Water Supply Project) and plotted in Figure 8. Spatial distribution of observed Cl concentrations in deep groundwater shows that high (>300 mg/L) concentrations of Cl are observed in west of Barisal, north of Noakhali, and around Khulna districts.

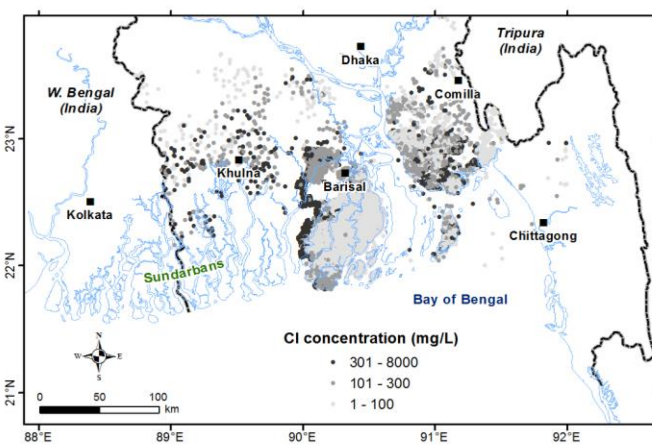

Figure 8. Spatial distribution of salinity in deep (>150 m bgl) groundwater in the Bangladesh (data from many sources, see reference list).

4.3 Other Chemical Contamination of Groundwater

High concentrations of dissolved manganese (Mn) in groundwater is another groundwater quality issue in Bangladesh (BGS and DPHE, 2001; Hasan and Ali, 2010). NHS reports that about 73% of surveyed water wells have Mn concentrations exceeding 0.1 mg/L, and nearly 42% water wells exceed a concentration of 0.4 mg/L. Although adverse neurological effects of inhaled Mn have been well documented in humans the quantitative and qualitative details of exposure necessary to establish direct causation are lacking (WHO, 2011). Adverse neurological effects (i.e., reduced children's intellectual function) as well as infant mortality with high exposure to Mn through drinking water have recently been reported from long-term monitoring of Mn exposure and public health impacts in central Bangladesh (Wasserman et al., 2006; Hafeman et al., 2007).

High concentrations of dissolved iron (Fe) is common in groundwater in many areas of Bangladesh (BGS and DPHE, 2001). Fe is an essential element in human nutrition. Estimates of the minimum daily requirement for Fe depend on age, sex, physiological status, and iron bioavailability and range from about 10 to 50 mg per day (WHO, 2003). There are no reported public health effects of high Fe in drinking water. However, turbidity and color may develop in piped water systems at concentrations >0.05–0.1 mg/L;

laundry and sanitary wares usually stain at concentrations >0.3 mg/L. NHS reports that the median Fe concentrations in Bangladesh groundwater is 1.1 mg/L and the maximum concentration was recorded at 61 mg/L. In Bangladesh, groundwater is commonly treated for high Fe concentrations in drinking and industrial water supplies because of aesthetic reason.

5 IMPACTS OF CLIMATE CHANGE ON GROUNDWATER

5.1 Projected Temperature Change in Bangladesh

According to the IPCC's Fourth Assessment Report (AR4) the global average surface temperature has increased especially since 1950s (IPCC, 2007). The rate of global warming averaged over the last 50 years (0.13 ± 0.03 °C per decade) is nearly twice that for the last 100 years. Based on AR4 multi-model ensemble an increase is projected in global mean air temperature of 1.8, 2.8 and 3.4 °C in various climate change scenarios (e.g., B1, A1B and A2) by 2090-2099 relative to 1980-1999. Climate models have been improved substantially since AR4. IPCC's AR5 multi-model ensemble projects rises in global surface temperature with maximum ranging from 1.2, 2.4 to 5.4 °C in various scenarios (RCP2.6, RCP4.5 and RCP8.5); the corresponding rise in minimum temperature ranges from 1.7, 3.2, and 6.2 °C in the above mentioned scenarios (Kharin et al., 2013).

An analysis of historical surface temperature data from the Bangladesh Meteorological Department shows an increase in observed surface temperature of approximately 1 °C from 1976 to 2008 (Basak et al., 2013). According to CMIP5 (Coupled Model Intercomparison Project Phase 5) climate models (Note: IPCC's Fifth Assessment Report – AR5 is due in September 2013), surface air temperature in Bangladesh is going to increase for the period of 2071-2095 compared to a period of 1980-2004 (Figure 9) (Hostetler et al., 2011).

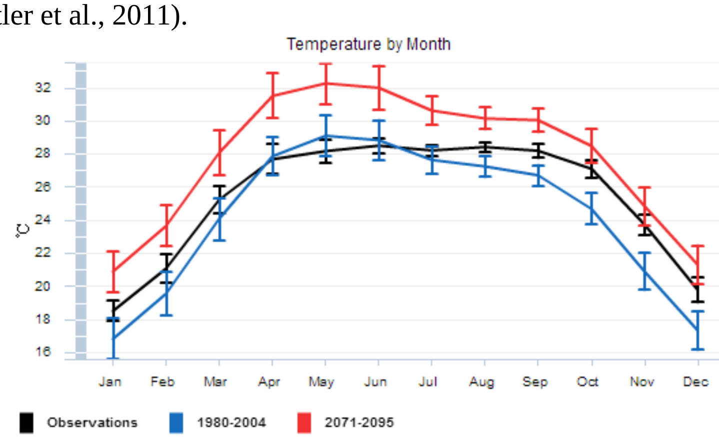

Figure 9. Projected rise in seasonal surface temperature in Bangladesh based on CMIP5 scenario RCP8.5.

5.2 Rainfall Variability and Groundwater Recharge

One expected impact of global climate change is increase in precipitation (i.e., rainfall) intensity (Meehl et al., 2005). The global mean precipitation may increase by several percent within the next hundred years. Climate models predict an increase of approximately 7% until 2100 (IPCC AR4 emission scenario A1B). The spatial and temporal distribution of the rainfall is also going to change (Figure 10). In Bangladesh, both volume and intensity of monsoon rainfall is going to increase in the future. An increase in heavy rainfall events has already been observed during monsoon seasons in the recent past (Shahid, 2010).

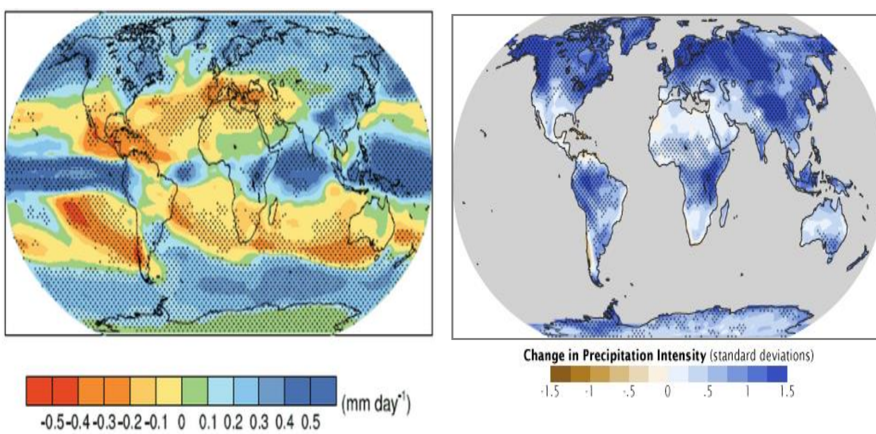

Figure 10. Projected changes in global rainfall quantity (left) and intensity (right) (IPCC Fourth Assessment Report).

There is a consensus that changes in projected precipitation and temperature extremes will intensify global hydrological system (Taylor et al., 2013a). An analysis of recently compiled groundwater-level observations in an aquifer of central Tanzania reveals that groundwater recharge is highly episodic and closely associated with anomalously intense seasonal rainfall (Taylor et al., 2013b). However, how changes in magnitude and intensity of the monsoonal rainfall will impact groundwater recharge in the Bengal Basin is not fully understood. Shallow groundwater recharge in Bangladesh is greatly dependent on surface geology and the timing and magnitude of groundwater recharge has been greatly modified by anthropogenic development (i.e., intensive pumping) (Shamsudduha et al., 2011).

5.3 Sea-level Rise and Salinity Intrusion in Coastal Aquifer

Recent sea-level rise in the Bay of Bengal is going to affect coastal ecosystems and influence salinity intrusion in coastal shallow aquifers in

Bangladesh. Rising sea levels will affect salinity-sensitive coastal bionetworks and aquatic ecosystems including the world's largest mangrove forest – the Sundarbans located in southwestern Bangladesh and West Bengal of India. Rising sea levels forces groundwater levels to rise in shallow aquifers within low and flat deltaic environments (Barlow, 2003). Shamsudduha et al. (2009) reported long-term (1985 to 2005) rising trends (0.5 to 5.0 cm/year) in coastal groundwater levels in Bangladesh. Monthly mean tidal gauge records (1980 to 2000) at four locations in coastal Bangladesh also show rising trends (0.4 to 1.7 cm/year) that are higher than the average global sea-level rise of 0.2 and 0.3 cm/year over two periods of 1961-2003 and 1993-2003 respectively (IPCC, 2007).

How will climate change (i.e., sea level rise, coastal storm surges) impact shallow groundwater in coastal Bangladesh? The exact answer is currently unknown partly due to lack of long-term monitoring of groundwater salinity in coastal aquifers. However, there are several pathways through which saline water can intrude shallow groundwater in the coastal region:

(1) rising sea levels can ultimately increase shallow groundwater levels and thus increase groundwater salinity by raising the freshwater-saltwater interface (current position is unclear) in the shallow aquifer,

(2) rising sea levels can increase groundwater salinity in coastal river channels which can increase groundwater salinity by recharging the aquifers,

(3) increased coastal storm surges and cyclones can frequently flood coastal region including the areas that are currently protected by polders or embankments and this can ultimately cause salinity rise in groundwater,

(4) localized recharge to shallow aquifers from brackish-water based shrimp farms can further increase salinity in shallow groundwater, and

(5) intensive pumping of fresh groundwater in the coastal aquifer will accelerate saltwater intrusion and degradation of groundwater quality (Yu et al., 2010).

6 WAY FORWARD

Managing groundwater resources is critical for sustaining long-term, safe public water-supply and food security in Bangladesh. For continuing social and economic development there is no alternative to sustainable development of groundwater resources. Currently, nearly one-fourth of the national Gross Domestic Product comes from the agricultural sector that largely dependents on groundwater resources. However, declining water storage in many parts of Bangladesh is posing a threat to its economic development from the agriculture sector. Municipal and public water supplies are also affected by the shortage of groundwater storage (e.g., Dhaka City). On the other hand, the health of millions of people in Bangladesh is at greater threat due to the chronic exposure to dangerous levels of As and salinity.

The utilization of deep (>150 m bgl) groundwater in Bangladesh has been recognized as the most popular and economic mitigation measure for As over the last decade. Deep groundwater has long been used in the coastal region to provide fresh drinking water as shallow groundwater is mostly saline. In the last decade, thousands of deep tubewells have been installed in southern Bangladesh to provide As-safe water supply. Studies using both time-series data on groundwater chemistry from coastal areas (Ravenscroft et al., 2013) and numerical groundwater modeling (Michael and Voss, 2008; UCL, 2013) show that deep groundwater in most places is safe to develop for domestic water supply for >100 years.

There is no alternative to monitoring of groundwater levels and chemistry of both shallow and deep groundwater. Thanks to large government initiatives (e.g., BWDB Climate Change Trust Fund Project) for establishing monitoring network of groundwater levels and salinity in several coastal districts of Bangladesh. In addition to government and donor initiatives, private companies should be encouraged to engage themselves more in the water sector development and management. Private sector can invest in developing urban water supply systems in provincial towns where there is need and growing demand for safe drinking water. For example, in India a private company, Piramal Water Ltd. (http://www.sarvajal.com/) has created a micro-franchise business strategy known as the 'Water ATM' which allows customers to buy clean drinking water at a minimum price. In six states of India this company currently supplies 200 million liters of water to communities where safe drinking water is scarce. This model can effectively work in urban slumps, rural schools, and isolated communities in remote parts of Bangladesh where freshwater is not readily available.

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