Hydrogeochemical assessment of shallow aquifer in Chakdah, West Bengal for safe water supply

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ABSTRACT

The shallow aquifer hydrogeochemistry and arsenic exposure from drinking water in rural Bengal have been vividly investigated in the present study. It has been observed that shallow aquifers (<50 m) are often contaminated with arsenic, whereas deeper aquifers (≥100 m) are mostly free from arsenic contamination. In some pockets, deeper aquifers are contaminated which is surrounded by safer aquifers. Mostly, shallow aquifers (<50 m) are contaminated with arsenic surrounded by safe and/or deep aquifers (≥100 m) with low arsenic concentrations and are scattered throughout the study area with more heterogeneity. Furthermore, sedimentological (color of the sediment and its successions) and/or geomorphological features (land-use pattern and local recharge) are playing a key role to control the arsenic distribution pattern in groundwater from the study area. They control local hydrogeochemical factors thereby mobilizing arsenic into groundwater. It has also been found that yellow sand aquifers are mostly free from arsenic contamination. The deeper aquifers mainly consist of coarse to medium sand (mostly yellow sand) which incorporates the relatively lower concentration of arsenic in groundwater. For the long-term mitigation options, the findings from this investigation are very useful.

Introduction

Arsenic is an element which has both toxic and carcinogenic effect to mankind. The high concentration of arsenic in groundwater is frequently found and has been reported from the various parts of the world (BGS and DPHE, 2001; Bhattacharyya et al., 2003; Charlet & Polya, 2006; Chen et al., 1985; Nath et al., 2005; Smedley et al., 2002), especially from the two neighboring countries (West Bengal, India, and Bangladesh) of south Asia (BGS and DPHE, 2001; PHED, 1993). In this part of the world, the situation is worse concerning arsenic occurrence, its distribution and human exposure where millions of people are suffering from arsenic poisoning in groundwater and many patients with arsenic-induced diseases have been reported (Chakraborti et al., 2002; Chatterjee et al., 2003). The groundwater contaminated with high arsenic often exceeding the WHO guideline value (AsT < 10 µGL−1) has been used as the main source of potable water. The concentration of arsenic in groundwater is also exceeding the respective National standard (AsT < 10 µGL−1; Bhattacharyya et al., 2003; Chatterjee et al., 2005; McArthur et al., 2004).

The groundwater from the shallow aquifers (<50 m) is enriched with inorganic arsenic in BDP (Bengal Delta Plain, mainly in West Bengal, India, and Bangladesh) (Ahmed et al., 2004; Fendorf et al., 2010; Mukherjee et al., 2001; Nath et al., 2007; van Geen et al., 2008). So, the groundwater from the shallow wells (<50 m) was considered unsafe concerning groundwater quality (CGWB, 1999; PHED, 1993). The occurrence of arsenic in groundwater mainly depends on the local geology, hydrology, geochemical characteristics, land-use pattern, fresh organic matter contents in sediments, different anthropogenic activities, and many more (Chatterjee et al., 2005; Smedley & Kinniburgh, 2002).

The distribution pattern of arsenic in groundwater is heterogeneous showing several anomalies concerning spatial and vertical distribution patterns. The role of local conditions on arsenic release and/or mobilization in groundwater has been reported (Biswas et al., 2011; Neumann et al., 2010). In the present investigation, we are mainly focusing on the scale of arsenic heterogeneity in groundwater of BDP (especially in Nadia district, West Bengal, India). The correlation between the local conditions and the studied wells is examined clearly which often regulates the hydrogeochemical environment, especially the concentrations of the redox elements (Fe, Mn, and As).

The shallow aquifer (<50 m) hydrogeochemistry has been encountered to understand the actual scenario of groundwater arsenic contamination. The geospatial distribution maps of the study area for both shallow and deeper aquifers have been...
constructed to understand the spatial distribution of groundwater arsenic and area of contamination in the present study area. This investigation will help the planning agencies for the better management of the affected aquifers (mainly of shallow depth range, <50 m) to supply groundwater with arsenic lower than the potable water standards (As$_T$ <10 µgL$^{-1}$). Geochemistry and sedimentological control have also been studied to trigger safe aquifers.

**Study area**

**Physical settings**

The study area is Chakdah block in the district of Nadia, West Bengal (65 kms. north from Calcutta) which covers~ 400 sq.km of the area with latitude 23.02º-23.14ºN and longitude 88.49º-88.62ºE (as shown in Figure 1). It is situated in the central part of the BDP along Hoogli-Bhagirathi river, a main tributary of the river Ganga. This BDP encompasses an integral part of the Ganga-Brahmaputra basin with alluvial deposits. This alluvial plain is spreading southwards to the Bay of Bengal with the successions of an upward fining sequence consisting of occasional clay deposits. The main regional river Ganga has shifted its course to the west with the geological time scale during Holocene.

The study area is mainly flat and often intersected with rivers. It consists of many khals, bills, backwaters, marshy lands, river meanders, abundant channels, and oax-bow lakes with varying shape, size, and amplitudes. Different land-forms like natural levees, flood plains, inhabited areas have covered the whole area coverage. The slope of the area is generally toward the south and situated within the flood plain of the river Hoogli-Bhagirathi. It consists of a tropical climate, hot and humid (average relative humidity >

![Figure 1](image-url). The study area (Chakdah block, Nadia district) showing the bore-hole locations and cross-section lines.
65%) with an average temperature between 16°-41°C and moderate rainfall mostly in monsoon.

**Hydrogeological settings**

The aquifers of the study area can tentatively be categorized into three broad stratigraphic zones (Deshmukh & Goswami, 1973) as follows: (i) Shallowest part of the aquifer (<18 m) consists of topsoil, clay, and silt. (ii) The shallower part (18–50 m) comprises of fine to medium to coarse sand with clayey intercalations. (iii) The deeper aquifers (>50 m) mostly containing medium to coarse sand with occasional mixing of gravels and stones. The shallow wells have been installed for irrigation and domestic purposes, whereas deeper wells are installed for community water supply.

This area is mainly the Holocene sedimentary successions of fluvial deposits by the regional meandering rivers Hoogli-Bhagirathi with Fe-coated micaceous sand, silt, and clay with upward fining sequence (Bhattacharya et al., 1997; Pal et al., 2002; PHED, 1993). The aquifers (up to 250 m) are mainly constructed by sands overlain by surface silty clay. The shallow aquifers (<50 m) consist of silica sand (86%) with minor biotite, muscovite, illite, and Fe-oxides/oxi-hydroxides (Mukherjee et al., 2008; Nath et al., 2007). The shallow stratigraphic framework consists of different lithological features like brown clay, black clay, silt, yellow coarse sand, yellow medium sand, yellow fine sand, gray coarse sand, gray medium sand, gray fine sand, sandy clay, clayey sand and gravels/stones (Figure 2).

**Materials and methods**

**Groundwater sampling**

The groundwater samples have been collected from the number of affected villages from the Chakdah block of Nadia district (Figure 3). Mainly, the samples are procured from the younger aquifers of Holocene age. Sampling has been done by purging a standing volume of water for a few minutes to ensure sufficient flushing for each well (mostly hand-operated). Pre-washed poly-ethylene bottles have been used for the sampling of the capacity of 100 ml. A plastic funnel has been placed below the wellhead with the inlet connection to flow the water through a portable pre-calibrated pH-Eh meter (Radiometer, Copenhagen-PHM 80) to measure pH and Eh of the water samples onsite. A field multimeter (WTW, Germany) has also been used to measure dissolved oxygen, conductivity, and temperature in in-situ conditions. The very low dissolved oxygen content has also been rechecked by using the advanced Winkler method. The alkalinity of the water samples was measured using a portable kit (Merck) and is rechecked. The groundwater samples were then filtered by using membrane filter of sieve diameter 0.45 µm onsite and collected in two separate
big poly-ethylene bottles for the measurement of cations and anions respectively. The groundwater samples for cation measurement have been acidified with HNO$_3$ (0.1% v/v, pH 2) and another part of the groundwater samples was left unacidified for anion measurement. After sampling all the samples were preserved at 4°C (±1°) in ice-bags in the field. On returning from the field the samples have been stored in the refrigerator until the analyzes have been done.

**Sediment sampling**

The sediment samples have also been collected from different bore-holes (shown in Figures 1 and 3) in the study area (Chakdah block, Nadia district) to investigate the lithological pattern within the dealing depth (shallow depth, <50 m). The drilling of the bore-holes has been done by hand suction drilling technology (Ali, 2003), which is useful to reach up to 50 m depth below the ground. The sediments were collected from each 2 m interval to pursue the actual lithological distribution below ground level (bgl) and kept in polyethylene zipper packets and marked with location (name of the well owner, habitation, mouza and block names).

The geographical location (latitude and longitude) of each well as well as bore-holes have been recorded by using a handy GPS meter. The locations (latitude-longitude) of the boreholes which are considered for the present investigation are listed in Table 1.

**Groundwater samples analyses**

The concentrations of major cations (including arsenic) in the groundwater samples (stored in the refrigerator) were estimated by using a double-focusing High Resolution Inductively Coupled Plasma Atomic Absorption Spectrometry (Varian Inc., AA-240). The concentrations of the major anions are measured through the use of Ion Chromatography (761 Compact IC, Metrohm). The total iron (Fe$_T$) was estimated by using a Perkin Elmer, Lamda 20 UV-VIS Spectrophotometer by adding hydroxylamine hydrochloride as a reducing agent followed by the addition of 1,10-phenanthroline (510 nm) to it. The DOC of the collected groundwater samples were measured by a Shimadzu 5000 TOC analyzer.

For the sediment samples color, texture, and grain size were noted down with other relevant information just after procuring before atmospheric oxidation. Depending on the lithotypes, colors, lithologs of each

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**Figure 3.** Study area map showing all the groundwater samples (red bullets) and sediment samples (yellow triangles) locations.

**Table 1. Borehole locations appended in the present study.**

| Borehole ID | Location | Latitude | Longitude |
|-------------|----------|----------|-----------|
| BH28        | 23.015   | 88.437   |
| BH29        | 23.031   | 88.48    |
| BH31        | 23.08    | 88.524   |
| BH22        | 23.09    | 88.621   |
| BH32        | 23.003   | 88.509   |
| BH11        | 23.033   | 88.559   |
| BH20        | 23.043   | 88.622   |
| BH21        | 23.064   | 88.62    |
| BH12        | 23.069   | 88.475   |
| BH13        | 23.045   | 88.469   |
bore-hole was constructed. Organic carbon (C\textsubscript{org}) of the air-dried sediment samples have been measured by loss of weight (when heated at 550°C for more than two hours) and by reacting with the strong oxidizing agent as per standard protocol (Jackson and Richards, 1973). A few samples were analyzed with a CNS analyzer (Luco) after adding 10% HCl to eliminate inorganic carbon.

**Sediment samples analyses**

The sediment samples were opened in the anaerobic condition in LGIT, Grenoble, France and analyzed for particle sizes, mineralogical compositions by X-ray diffraction (XRD), acid digestion for total As content, ascorbate extraction for amorphous Fe-oxyhydroxides, organic carbon (C\textsubscript{org}), major and trace element concentrations including total arsenic (As\textsubscript{T}). The XRD analysis (Siemens) was also carried out using a Cu-K (alpha) radiation and operating (37.5 mA and 40 kV) with the help of a computer program DIFFRAC/AT version 3.3 by using the JCPDS database. Acid digestion for total As content (As\textsubscript{T}) in sediment was done by following the method from Roy Chowdhury et al. (1999).

**Boreholes interpretation method**

To construct the lithological section profile of the aquifer sediments of the study area (Chakdah, Nadia), software namely RockWorks, v.14 has been used. The lithological data have been incorporated with the GPS location of each bore-hole (bore-hole locations are shown in Figure 1). The lithological cross-sections (4 numbers) have been made by the above-mentioned software by applying an algorithm of the ‘litho-blending’ option. For each bore-hole, individual voxel was assigned with a lithology to a particular litho-type of the closest data point and the process continued both horizontally and vertically to the next voxel and so on. The cross-sections are optimized with the node spacing and finalized by less sensitivity in the grid size.

**Results and discussion**

**Groundwater geochemistry and statistical approach**

Among the studied wells, the chemical characteristics of the groundwater are shown in Table 2. In both shallow (< 50 m bgl) and deep (>100 m) aquifers, the groundwater samples show a narrow temperature range of Variation (25.1–30°C, Table 2). The pH of the sampled groundwater also has been recorded, which is often circum-neutral (5.95–7.98, Table 2). These mean that the groundwater composition is well buffered and also suitable for drinking purposes as per laid down Indian Standards (BIS-10500, BIS-10500, 2012). The electrical conductivities of the sampled water are medium to high even very high (up to 1514 µS cm\textsuperscript{-1}, Table 2). It is important to note that the electrical conductivities of the aquifers (shallow, <50 m bgl) are largely varying (450–1514 µS cm\textsuperscript{-1}, Table 2). The results indicate that groundwater in the two aquifers is fresh. The Eh of the groundwaters are also measured in shallow (<50 m bgl). The Eh value of the shallow groundwater samples shows highly reducing in nature (down to –187 mV, Table 2).

Several dissolved cations are also measured during the monitoring of the studied wells such as Ca\textsuperscript{2+}, Mg\textsuperscript{2+}, K\textsuperscript{+}, Na\textsuperscript{+} and NH\textsubscript{4}\textsuperscript{+}. Among the major cations, Ca\textsuperscript{2+} is always dominating the groundwater composition followed by Mg\textsuperscript{2+}, Na\textsuperscript{+} and K\textsuperscript{+}. Both bivalent alkali metals are possibly released during the dissolution of carbonate and/or mixed carbonate minerals (Nath et al., 2008a and 2008b; Biswas et al., 2011; Neidhardt et al., 2013). The study reveals that Ca\textsuperscript{2+} is always predominated over Mg\textsuperscript{2+} and Na\textsuperscript{+} predominated over K\textsuperscript{+}. Similarly, the high mobile monovalent alkali metals are possibly released from the dissolution of silicates which is usually common in BDP (Charlet et al., 2007; Chatterjee et al., 2004).

Among, the minor cations (Fe, Mn, and As), iron is the highest (0.32–6.41 mgL\textsuperscript{-1}, Table 2) and arsenic is the lowest (up to 340 µgL\textsuperscript{-1}, Table 2), whereas Mn is in between (up to 3.2 mgL\textsuperscript{-1}, Table 2). The study indicates the presence of several dissolved redox elements (Fe, Mn, and As), which is further supporting the anoxic nature of the aquifers (Ahmed et al., 2004; Bhattacharyya et al., 2003; Bhownick et al., 2013a). Among these redox elements, inorganic arsenic is more toxic in dissolved form and lower oxidation.

### Table 2. Summary of physical parameters and major elements concentrations of the groundwater samples from the study area (Chakdah, Nadia).

| Serial No. | Parameters | Minimum | Maximum | Average | Standard Deviation (%) |
|------------|------------|---------|---------|---------|------------------------|
| 1          | Temperature (°C) | 25.1    | 30      | 27.8    | -                      |
| 2          | pH         | 5.95    | 7.98    | -       | -                      |
| 3          | Conductivity (µS cm\textsuperscript{-1}) | 180     | 1514    | 871     | 57.7                   |
| 4          | E\textsubscript{h} (mV) | –187    | –26     | –75     | 64.3                   |
| 5          | HCO\textsubscript{3} (mgL\textsuperscript{-1}) | 154.8   | 320.5   | 244     | 34.4                   |
| 6          | Ca\textsuperscript{2+} (mgL\textsuperscript{-1}) | 78.2    | 173     | 113     | 92.6                   |
| 7          | Mg\textsuperscript{2+} (mgL\textsuperscript{-1}) | 19.2    | 36.3    | 26.7    | 2.81                   |
| 8          | Cl\textsuperscript{−} (mgL\textsuperscript{-1}) | 23.2    | 147     | 56.8    | 2.12                   |
| 9          | PO\textsubscript{4}\textsuperscript{3−} (mgL\textsuperscript{-1}) | 0.32    | 2.24    | 1.01    | 0.20                   |
| 10         | SO\textsubscript{4}\textsuperscript{2−} (mgL\textsuperscript{-1}) | bdl     | 4.20    | 0.89    | 0.33                   |
| 11         | Mn (mgL\textsuperscript{-1}) | 0.80    | 3.2     | 1.05    | 0.20                   |
| 12         | Na\textsuperscript{+} (mgL\textsuperscript{-1}) | 12.1    | 31.1    | 8.05    | 2.84                   |
| 13         | K\textsuperscript{+} (mgL\textsuperscript{-1}) | 2.54    | 9.49    | 4.35    | 1.70                   |
| 14         | Fe\textsubscript{h} (mgL\textsuperscript{-1}) | 0.32    | 6.41    | 4.88    | 0.40                   |
| 15         | As\textsubscript{T} (µgL\textsuperscript{-1}) | 1.0     | 340     | 273     | 12.2                   |
| 16         | DOC (mgL\textsuperscript{-1}) | 2.6     | 10.53   | 5.61    | 1.76                   |
| 17         | NH\textsubscript{4}\textsuperscript{+} (mgL\textsuperscript{-1}) | 0.12    | 4.5     | 2.90    | 0.6                    |
| 18         | NO\textsubscript{3}\textsuperscript{−} (mgL\textsuperscript{-1}) | bdl     | -       | -       | -                      |
| 19         | D.O. (mgL\textsuperscript{-1}) | bdl     | 0.3     | -       | -                      |
state [As(III)] is more harmful than high oxidation state [As(V)] (Guha Mazumder et al., 2010; Hopenhaynrich et al., 2000; Huges et al., 2001). The results reveal the range of arsenic concentration (1–340 µg L\(^{-1}\), Table 2) in groundwater is often exceeding WHO guideline value (As\(_T\) <10 µg L\(^{-1}\)) as well as the National safe limit (As\(_T\) <10 µg L\(^{-1}\)) (World Health Organization [WHO], 2011a and 2011b; BIS-10500, 2012). Among the anions (HCO\(_3\), Cl\(^-\), PO\(_4^{3-}\), SO\(_4^{2-}\), NO\(_3\)), bicarbonate is the highest (154.8–320.5 mg L\(^{-1}\), Table 2) and nitrate is the lowest (bdl). The rest are in between. The study suggests that bi-carbonate always have a base-line value (154.8 mg L\(^{-1}\), Table 2), which indicates that carbonate dissolution is the fundamental process in the aquifer and thereby maintaining the base-line concentration of bicarbonate (154.8 mg L\(^{-1}\), Table 2) in groundwater. Furthermore, the large variation of bi-carbonate also indicates that the source of bi-carbonate is multiple (Bhattacharyya et al., 2003; Harvey et al., 2006). In this context, the break-down of organic matter (notably fresh organic matter) is an important issue, because the microbial utilization of organic matter ultimately released high bi-carbonate. This further supports the dissolution of Fe-bearing host minerals (Fe-oxides and/or oxi-hydroxides) in the presence of organic matter. The nitrate is usually low even absent. This indicates the de-nitrification process is predominately in the aquifer under local reducing conditions. Moreover, the presence of NH\(_4^+\) (range 0.12–4.5 mg L\(^{-1}\), Table 2) and relatively high DOC (2.6–10.53 mg L\(^{-1}\), Table 2) and low sulfate (range bdl-4.20 mg L\(^{-1}\), Table 2) further support the pre-dominant reducing nature of the aquifers. The study specifically indicates that the monitored shallow aquifers (<50 m) are under moderate to strong reducing conditions along with the regular presence of several redox-sensitive elements (Fe, Mn, and As) as well as high bi-carbonate and medium DOC and NH\(_4^+\). The critical examinations of these results reveal that the reduction of Fe-bearing minerals (oxides, hydroxides, and oxi-hydroxides) is the major geochemical processes to explain the high occurrence of arsenic in the studied tube wells.

**Present water supply**

Four (2-dimensional) east-west, northeast-southwest, and northwest-southeast, lithological cross-sections have been constructed in the study area (Chakdah, Figure 1). Moreover, plan-view maps of sedimentation pattern which is representing the different lithological features (brown clay, black clay, silt, yellow coarse sand, yellow medium sand, yellow fine sand, gray coarse sand, gray medium sand, gray fine sand, sandy clay, clayey sand, and gravels/stone). The shallow hydro-stratigraphic lithological framework (Figure 2) represents the typical distribution pattern of sediment assembly which is usually complex and complicated (3D options not shown in Figure 2) within dealing depth (50 m).

Among the four lithological frameworks, in A-A’ (northern part, Chakdah to Natapuli) the topsoil is brown clay (3–4 m). In the western margin, gray fine sand (4–7 m) has been found. In the middle part, yellow fine sand has been observed where iron is possibly contributing to the yellow color of the sediment. In the eastern margin, silty gray sand has been observed (19–35 m). Grey medium sand (35–46 m) has been observed in the eastern margin. The rest of the lithology is dominated by gray fine sand and sandy clay.

Arsenic contaminated tube-wells are mostly installed in the gray fine sand and sandy clay layers. These tube-wells are often contaminated with arsenic and exceeding WHO guideline value (As\(_T\) <10 µg L\(^{-1}\)). The high arsenic yielding tube-wells (up to 210 µg L\(^{-1}\)) are installed in the gray fine sand aquifer which has been already designated as GSA (Grey Sand Aquifer) (Biswa et al., 2011). However, the spatial distribution of GSA is difficult to understand because of the limitation of the drilling data. The geospatial distribution of arsenic and iron is largely varying and indicates that the GSA is yielding high arsenic and the reducing nature of the aquifer is often noticed to support. But the wells in yellow sand aquifers are relatively least contaminated.

In B-B’ section, a silty sandy layer (22–35 m) has been observed below the gray sand which is absent in the southern part. The rest of the aquifer is gray fine sand in the northern part, gray coarse sand in the middle part, whereas yellow medium sand is found in the southern margin. The change in sedimentation pattern (gray fine sand to gray coarse sand) is possibly due to the change in drainage pattern and representing the paleo-channel sequence (MacArthur et al., 2008). Yellow fine to medium sand is the overbank deposits with varying thickness and is extensive along the southern transect.

Arsenic contaminated tube-wells are mostly found in gray sand as well as gray coarse sand. The high yielding tube-wells (up to 345 µg L\(^{-1}\)) has been observed in gray fine sand as well as gray coarse sand. It has also found that several wells are often yielding arsenic greater than WHO guideline value (As\(_T\) <10 µg L\(^{-1}\)). The safe wells (As\(_T\) <10 µg L\(^{-1}\)) are also noticed where yellow medium sand aquifers are existing.

In C-C’ section (Punglia to Khorgachhi), the uppermost part is mostly brown clay with varying thickness (4–30 m) and much thicker in the southern part. In the northern part, clayey sand has been noticed (4–12 m) and black clay deposition (4–9 m) in the middle part, whereas the southern margin is further extended with brown clay (up to 30 m). The clayey sand has been observed below the surface brown clay
in the northern margin, whereas yellow sand has been observed in the middle, whereas fine gray sand has been observed (25–32 m) in the rest of the part. The rest of the sedimentary column is mostly sandy clay with gray sand.

The arsenic-contaminated tube-wells are mostly installed in sandy clay and/or gray sand aquifer. The several drinking water wells have been found that are often exceeding WHO guideline value ($\text{As}_{\text{T}} <10 \mu\text{gL}^{-1}$). The high yielding arsenic tube-wells (up to 283 $\mu\text{gL}^{-1}$) have been observed in the sandy clay and/or GSA which is often reducing in nature. These aquifers can be designated as GSA which is already reported contaminated with arsenic. The extend of these aquifers and their exact formation (3-dimensional) are difficult to explain due to the paucity of exact information of the thickness of these aquifers.

In the section D-D’, the surface top layer is brown clay with relatively much higher thickness in comparison to other cross-sections (A-A’, B-B’ and C-C’), whereas in the eastern margin black clay with gray medium sand has been observed. The rest of the lithological column is gray sand (70%) along with yellow medium sand (30%).

Arsenic contaminated tube-wells (up to 163 $\mu\text{gL}^{-1}$) are found in mostly gray sand aquifers. However, the high yielding arsenic concentration tube-wells are relatively lesser in numbers when compared with the other three sections. Several safe tube-wells ($\text{As}_{\text{T}} <10 \mu\text{gL}^{-1}$) have been noticed in yellow medium sand where iron is in oxidized form (yellow color) in the sediment.

The XRD of the collected sediments from various depths (up to 50 m) has been conducted. The XRD results indicate that quartz and mica are the most dominating sediment minerals. Among mica, the usual occurrence of muscovite, biotite, and Chlorite has been observed. Among the minor constituents, feldspar, heavy minerals, kaolinite, and several Fe-bearing minerals are identified. The arsenic content of the sediments has also been determined. It has been found that non-magnetic as well as heavy magnetic minerals generally reported being arsenic-free. On the other hand, arsenic bearing several clastic minerals is usually contaminated with arsenic. Among these clastic minerals biotite, chlorite, illite, Fe-coated grains, and HFO, Fe$_2$O$_3$ and magnetite have been identified contaminated with arsenic. Moreover, the average organic carbon ($C_{\text{org}}$) is up to 1.5%. However, the organic content of the studied aquifers is relatively low (up to 0.4%), whereas silty and/or clayey rich sediments contain relatively higher organic matter. During the drilling campaign, the sediments’ colors are also determined in-situ. The arsenic-contaminated aquifers are generally containing gray sand whereas arsenic free aquifers are generally having brown sand. The off-white sand has also been found where arsenic concentration is usually low ($\text{As}_{\text{T}} <50 \mu\text{gL}^{-1}$). The orange/red/brown sands are generally oxidized aquifers where relatively oxic-environment is prevailing and tube wells are yielding arsenic-free water. On the other hand, gray, bluish gray, and sandy aquifers are often yielding high arsenic-containing groundwater. The environment is generally medium to strong reducing conditions. Off-white/white sands are also observed where arsenic contamination in groundwater is relatively low ($\text{As}_{\text{T}} <50 \mu\text{gL}^{-1}$) and the aquifer environment is oxic/anoxic zones even fluctuating.

**Arsenic levels in groundwater**

The arsenic distribution pattern in groundwater has also been studied. The study reveals that 70% of the wells often exceeding arsenic concentration above WHO guideline value and/or National guideline value ($\text{As}_{\text{T}} <10 \mu\text{gL}^{-1}$) and even usually also exceeding $\text{As}_{\text{T}} >50 \mu\text{gL}^{-1}$, while a few wells (10%) also exceeding arsenic concentration above 300 $\mu\text{gL}^{-1}$. However, arsenic concentration is usually decreasing with increasing depth. As a result, the deeper aquifer wells (>100 m bgl) are usually less contaminated with arsenic, even often found below WHO guideline value ($\text{As}_{\text{T}} <10 \mu\text{gL}^{-1}$). These deeper wells (>100 m bgl) can be successfully used for drinking water supply as well as for domestic purposes. The use of deeper aquifers (>100 m bgl) for community water supply is common practice in India and Bangladesh (Chatterjee et al., 2010; McArthur et al., 2001; McElhaney, 2002). The spatial distribution pattern of arsenic is patchy and varies from place to place in size, shape, and nature. It has also been found that the safe and/or low arsenic wells are generally situated in the peripheral part of the villages and/or near the agricultural lands that contain thick clay layer at the top (Biswa et al., 2011; Nith et al., 2008b). Furthermore, the land-use pattern has been found an important issue, and sanitation has been often coupled with highly contaminated arsenic wells. These have already been reported from several parts of the BDP (Bhattacharya et al., 1997; Bhattacharya et al., 2013a and 2013b, 2014).

The geospatial distribution map of groundwater arsenic in both shallow and deep aquifers (Figure 4 (a,b) respectively) shows that the distribution of arsenic in shallow groundwater is more heterogeneous and patchy than that in deeper aquifers groundwater. Though most of the shallow aquifers are arsenic contaminated with some scattered yellow patches which indicate the relatively lower extent of contamination (Figure 4a). South and south-eastern part of the study area is most affected (deep red patches in Figure 4a). But the arsenic contaminations in deeper aquifers are relatively lower. Safe zones (As <10 $\mu\text{gL}^{-1}$) are found in the western part and contaminated zones are on the eastern and north-eastern part of the study area.
(Figure 4b). It is very interesting to see that in deeper aquifers, distribution of groundwater arsenic is homogeneous.

Managing future water supply under present levels of arsenic

The spatial distribution of arsenic is patchy throughout the study area (Chakdah block, Nadia district, West Bengal) and arsenic ‘Hot-spots’ areas are often surrounded by the safe zones (As$_T$ <10 µgL$^{-1}$). The results indicate that the contaminated wells are surrounded by safe wells. This type of distribution is predominant in the low-lying areas (south and southeastern part). Safe groundwater wells are rarely found in the flood basins where sediment color is mainly gray to bluish-gray. The distribution pattern of arsenic in groundwater in the present study area solely depends on the site characteristics and land-use practices around the investigated wells.

The variation of average arsenic concentration in groundwater wells is very unique and interesting, where agricultural fields have the maximum average value (As$_T$ avg. 67 µgL$^{-1}$) and areas coupled with sanitary installations have the minimum average value (As$_T$ avg. 44 µgL$^{-1}$), whereas areas with surface water bodies (As$_T$ avg. 60 µgL$^{-1}$) and sanitation coupled with surface water bodies (As$_T$ avg. 49 µgL$^{-1}$) are in between. The safe wells (As$_T$ <10 µgL$^{-1}$) are generally situated in the peripheral part of the villages and/or near the agricultural fields, where a thick clay layer is found at the top of the sediment. The contaminated wells are denser in the southern part of the study area rather than the northern part. The frequency of the
contaminated wells is following an irregular fashion. It has also been noted that shallow aquifers (<50 m) are yielding high arsenic groundwater in comparison to deeper wells (>100 m), though deeper wells are also enriched with arsenic in some small pockets. During the field campaign, it has been observed that the high concentration of chlorides in groundwater wells are usually owned by private owners (household wells), whereas low chloride-containing wells are generally owned by local government (community wells). The previous studies showed that land-use patterns (sanitation installations, sanitation coupled with surface water bodies, agricultural fields and surface water bodies) are playing a key role in increasing both arsenic and iron concentrations in groundwater (Smith et al., 2000; Bhattacharya et al., 2002a and 2002b; Bhattacharyya et al., 2003). It has also been noticed that sanitary installations are the main factors among all these to control the aquifers’ environment by supplying fresh organic matter to it (reducing environment). The distribution of arsenic is found with iron in the south-eastern part and the same for manganese concentration in the north-western part of the study area. A competitive ion-exchange process is working where anthropogenic inputs are the controlling factor (groundwater wells near the agricultural fields) concerning high phosphate incorporation in the system from the locally used fertilizers containing phosphate as the chemistry of phosphate is nearly similar to arsenic oxy-anions’ chemistry. The presence of other oxy-anions (NO$_3^-$ and SO$_4^{2-}$) in the groundwater is very crucial as they can act as an electron acceptor in the aqueous chemistry. Arsenic concentration in groundwater (up to 9 µgL$^{-1}$) is very low where nitrate concentration is high (up to 12.68 mgL$^{-1}$). It indicates that the groundwater chemistry of the aquifers by and large influenced by local recharge and becoming more oxic due to man-made effects (anthropogenic inputs). The variation of redox species (Fe, Mn, and As) in the aquifers of the study area further indicates that there is a distinct variation of redox environment in the aquifers under different land-use patterns with specific local conditions. Therefore, a single mechanism is not enough to explain the actual scenario of the arsenic occurrence and the heterogeneous distribution arsenic in the groundwater of the study area. Multiple mechanisms are controlling the whole situation to maintain the release and distribution of arsenic in groundwater. The physico-chemical compositions of groundwater vary both locally and/or between aquifers. It has also been found that safe aquifers are ensured by sediment colors (gray/white- unfavorable; orange/red- favorable) along with the depth dependency and land-use pattern. A skillful protocol has been made to mitigate the options of safe water supply instead of articulated pipe water supply, which is often in vain in remote areas. A training schedule has been developed for villagers, tube well drillers, school teachers, and local leaders. These steps for the mitigation of the delineated problem are thus less eco-friendly, user-friendly, and cost-effective.

The groundwater wells from different land-use areas are tabulated in Table 3 to understand the role of land-use and/or land-cover to arsenic mobilization. The land-use pattern controls the local geochemical condition and influences mostly the shallow aquifer (<50 m) of the study area. Sanitation and sanitation coupled with water bodies promote the dissolution of Fe-bearing minerals and thereby mobilizing arsenic into shallow groundwater by supplying fresh and finely grained organic matter into the aquifers. The huge extent of groundwater uplifting in agricultural fields incorporates fluctuations in hydraulic gradient and phosphate inputs which influence the oscillation of redox zonation within the aquifers. Surface water bodies are also considered as a crucial geomorphological feature evident to be the source of organic matter. In the present study area, different geochemical processes are operating to mobilize arsenic with the aid of such local and anthropogenic factors.

**Conclusions and recommendations**

In BDP, groundwater is often contaminated with geogenic arsenic. Shallow aquifers (<50 m) are largely affected by geogenic arsenic and frequently exceeding WHO guideline value (As$_T$ <10 µgL$^{-1}$). In the present study, groundwater geochemistry and geospatial arsenic distribution pattern have been studied in and reported from arsenic ‘Hot-spots’ area (Chakdah block, Nadia district, West Bengal). Several field parameters (Temperature, pH, E$_{h}$, Electrical conductivities, D.O., TDS, HCO$_3^-$, Ca$^{2+}$, Mg$^{2+}$, Cl$^-$, PO$_4^{3-}$, SO$_4^{2-}$, NH$_4^+$, DOC, Fe$^{2+}$, Mn and As$_T$) are measured in in-situ condition. The results reveal that the pH of the

| Serial No. | Land-use                        | Number of wells | As$_T$ (µgL$^{-1}$) | Average As$_T$ (µgL$^{-1}$) | Number of wells (As$<50$ µgL$^{-1}$) | Percentage of affected wells |
|-----------|--------------------------------|----------------|---------------------|-----------------------------|-------------------------------------|-----------------------------|
| 1         | Sanitation                      | 74             | 0–217               | 44                          | 26                                  | 35                          |
| 2         | Sanitation and surface water bodies | 50             | 0–290               | 49                          | 17                                  | 34                          |
| 3         | Surface waterbodies             | 22             | 0–285               | 60                          | 9                                   | 41                          |
| 4         | Agricultural fields             | 35             | 0–340               | 67                          | 12                                  | 34                          |
groundwater is often circum-neutral in nature (5.95—7.98), which indicates the groundwater composition is well buffered and also suitable for drinking purposes as per laid down Indian National standard (As< 10 µgL⁻¹). The electrical conductivities of the studied groundwater samples are usually medium to high (up to 1514 µScm⁻¹) and indicate the freshness of the groundwater and also loaded with several dissolved elements. The E₈ values of the shallow groundwater samples are usually negative (down to ~187 mV) and are indicating reducing nature of the aquifers. The Dissolved Oxygen has been fixed up in the filled and later on measured in the laboratory, which is usually low to very low even absent. This further supports the reducing nature of the aquifers. Both anions (NO₃⁻, HCO₃⁻, SO₄²⁻ and Cl⁻) and cations (Ca²⁺, K⁺, Na⁺, NH₄⁺ and Mg²⁺) have been measured. Among the major cations, Ca²⁺ is always dominating in groundwater followed by Mg²⁺, Na⁺, and K⁺. The presence of bi-valent alkaline earth metals is possibly due to the dissolution of carbonate and mixed carbonate. On the other hand, the alkali metals are possibly released from the dissolution of silicates, which is usually common in the BDP sedimentary environment. Several minor cations (Fe, Mn, and As) have also been measured, where Fe is the highest (0.32–6.41 mgL⁻¹) and arsenic is the lowest (up to 340 µgL⁻¹), and Mn is in between (up to 3.2 mgL⁻¹). It is important to note that, all these minor elements are reducing in nature. The studied groundwater composition further reveals that the range of arsenic concentration (10–340 µgL⁻¹) is varying and is often exceeding both WHO guideline value as well as the National sage limit (As< 10 µgL⁻¹). This geospatial distribution pattern is patchy and varies from place to place in different sizes, shapes, and nature. Among the anions, HCO₃⁻ is the highest (154.8–320.5 mgL⁻¹) and NO₃⁻ is the lowest (bdl), and the rest are in between. The deeper scrutiny of the groundwater composition reveals that the dissolution of Fe-bearing host minerals (Fe-oxides and/or oxy-hydroxides) in the presence of organic matter is the principle release mechanism of arsenic in groundwater. The shallow (<50 m) lithological cross-sectional frame-work has been constructed. Among the four lithological frame-work, the section C-C’ (Punglia to Khorgachi) has been found the highest concentration of arsenic (As< 340 µgL⁻¹) in the monitored tube-well water. These aquifers are often loaded with gray sands (reducing in nature), represented as GSA (gray Sand Aquifer). A mineralogical study has been done. The XRD results indicate that the quartz and the mica are the most dominating sediment minerals. The arsenic content of the sediment has also been determined. The results indicate that nonmagnetic as well as heavily magnetic minerals are often arsenic-free, whereas several Fe-bearing clastic minerals are usually contaminated with arsenic. The average organic carbon is varying, which is relatively low (up to 0.4%) in the sandy aquifers (up to 4%), whereas silty and/or clayey sediments are generally rich in organic matter. During drilling, the lithology of the aquifers is also examined and it has been found that gray sediments are usually contaminated with arsenic, whereas orange, red, and brown sands are relatively free from arsenic. The distribution of arsenic is a function of the side characteristics and land-use pattern around the monitoring wells. It has been found that high arsenic wells (As≥ 50 µgL⁻¹) are generally associated with sanitary installation. Furthermore, agricultural field and surface water bodies are also playing an important role concerning high arsenic tube-wells (As≥ 50 µgL⁻¹). This is important because phosphate input into the aquifers can be possible both from the agricultural field and surface water bodies and thereby playing an important role to mobilize arsenic from the sediments by the competitive ion-exchange process because phosphate is very similar to arsenic oxy-anions both in charge distribution pattern and size. Finally, the study reveals that a single mechanism (Fe-reduction) may not be solely responsible for arsenic release in groundwater, whereas multiple mechanisms can be possible for high arsenic (As≥ 50 µgL⁻¹) in groundwater.

The present study enlightened that brown sand aquifers are relatively safe aquifers for community water supply. Moreover, deeper aquifers are safe from arsenic contamination so it can be utilized for future sources of safe groundwater (As< 10 µgL⁻¹). The policymakers should encounter these findings whenever making strategies for the community supply of safe groundwater.

Acknowledgments

The author declares no conflict of interest as there is no financial support against this present study. Author AD wants to thank Prof. DC of University of Kalyani for his potential discussion on a few topics. Moreover, the author wants to extend his thanks from the core of heart to the Editor-in-chief of the journal and the anonymous reviewers for their significant supports/comments which were helpful to shape the article in its current form.

References

Ahmed, K. M., Bhattacharya, P., Hasan, M. A., Akhter, S. H., Alam, S. M. M., & Bhuyian, M. A. H. (2004). Arsenic contamination in groundwater of alluvial aquifers in Bangladesh: An overview. Applied Geochemistry, 19(2), 181–200. doi:10.1016/j.apgeochem.2003.09.006

Ali, M. (2003). Review of drilling and tube well technology for groundwater irrigation. In A. A. Rahman & P. Ravenscroft (Eds.), Groundwater resources and development in Bangladesh—background to the arsenic crisis, agricultural potential and the environment (pp. 197–233). Dhaka, Bangladesh: Univ. Press.

BGS & DPHE. (2001). Arsenic contamination of groundwater in Bangladesh. In D. G. Kinniburgh & P. L. Smedley
Bhattacharya, P., Chatterjee, D., & Jacks, G. (1997). Occurrence of arsenic-contaminated groundwater in alluvial aquifers from delta plains, Eastern India: Options for safe drinking water supply. *International Journal of Water Resources Development*, 13(1), 79–92. doi:10.1080/07900629749944

Bhattacharya, P., Jacks, G., Ahmed, K. M., Routh, J., & Khan, A. A. (2002b). Arsenic in groundwater of the Bengal delta plain aquifers in Bangladesh. *Bulletin of Environmental Contamination and Toxicology*, 69(4), 538–545. doi:10.1007/s00128-002-0095-5

Bhattacharyya, R., Chatterjee, D., Nath, B., Jana, J., Jacks, G., & Vahter, M. (2003). High arsenic groundwater: Mobilization, metabolism and mitigation – An overview in the Bengal Delta Plain. *Molecular and Cellular Biochemistry*, 253(1/2), 347–355. doi:10.1023/A:1026001024578

Bhowmick, S., Halder, D., Kundu, A. K., Saha, D., Iqbal, A., Nriagu, J., … Chatterjee, D. (2013b). Is salinity a potential biomarker of arsenic exposure? A case–control study in West Bengal, India. *Environmental Science & Technology*, 47(7), 3326–3332. doi:10.1021/es303756s

Bhowmick, S., Halder, D., Nriagu, J., Guha Mazumder, D., Roman-Ross, G., Chatterjee, D., & Iqbal, M. (2014). Speciation of arsenic in salvia samples from a population of West Bengal, India. *Environmental Science & Technology*, 48(12), 6973–6980. doi:10.1021/es405614d

Bhowmick, S., Nath, B., Halder, D., Biswas, A., Majumder, S., Mondal, P., … Chatterjee, D. (2013a). Arsenic mobilization in the aquifers of three physiographic settings of West Bengal, India: Understanding geogenic and anthropogenic influences. *Journal of Hazardous Materials*, 262, 915–923. doi:10.1016/j.jhazmat.2012.07.014

BIS-10500. (2012). *Indian standard drinking water specification* (Second Revision). Bureau of Indian Standard.

Biswas, A., Majumder, S., Neidhardt, H., Halder, D., Bhowmick, S., Mukherjee-Goswami, A., … Chatterjee, D. (2011). Groundwater chemistry and redox processes: Depth dependent arsenic release mechanism. *Applied Geochemistry*, 26(4), 516–525.

CGWB. (1999). *High incidence of as in groundwater in West Bengal*. Central Groundwater Board, India. Ministry of Water Resources, Government of India.

Chakraborty, D., Mukherjee, S. C., Pati, S., Sengupta, M. K., Rahman, M. M., Chowdhury, U. K., … Basu, G. K. (2002). Doi:10.1289/ehp.5966 (available at http://dx.doi.org/): Arsenic groundwater contamination in middle ganga plain, Bihar, India: A future danger?

Charlet, L., Chakraborty, S., Appelo, C. A. J., Roman-Ross, G., Nath, B., Ansari, A. A., & Mallik, S. B. (2007). Chemodynamics of an As "hotspot" in a West Bengal aquifer: A field and reactive transport modeling study. *Applied Geochemistry*, 22(7), 1273–1292. doi:10.1016/j.apgeochem.2006.12.022

Charlet, L., & Polya, D. A. (2006). Arsenic in shallow, reducing groundwater in southern Asia: An environmental health disaster. *Elements*, 2(2), 91–96. doi:10.2113/gselements.2.2.91

Chatterjee, D., Chakraborty, S., Nath, B., Jana, J., Bhattacharya, R., Basu Mallik, S., & Charlet, L. (2003). Mobilization of arsenic in sedimentary aquifer vis-à-vis subsurface iron reduction processes. *Journal De Physique IV*, 107, 293–296. doi:10.1051/jp4:20030299

Chatterjee, D., Jana, J., Jacks, G., & Bhattacharya, P. (2004). Natural arsenic in groundwater of West Bengal, India: Examples from the districts of Nadia and South 24 Parganas. In: Proc 32nd IGC (pp. BWO 06–42). Florence, Italy.

Chatterjee, D., Majumder, S., Mukherjee-Goswami, A., Jana, J., Biswas, A., Halder, D., … Chatterjee, D. (2010). Young Bengal Delta plain and arsenic in groundwater: Distribution and geochemistry. In Das, S., Saha D., (Eds.), *Memoir 1 – Applied Geochemistry: Groundwater Quality Evaluation and Control* (pp. 170–185). Hyderabad: Indian Journal of Applied Geochemistry.

Chatterjee, D., Roy, R. K., & Basu, B. B. (2005). Riddle of arsenic in groundwater of Bengal Delta plain – role of noninland source and redox traps. *Environmental Geology*, 49(2), 188–206. doi:10.1007/s00254-005-0011-5

Chen, C. J., Chuang, Y. C., Lin, T. M., & Wu, H. Y. (1985). Malignant neoplasms among residents of a blackfoot disease-endemic area in Taiwan: High-arsenic artesian well water and cancers. *Cancer research*, 45(11 Pt 2), 5895–5899.

Deshmukh, D. S., & Goswami, A. B. (1973). *Geology and groundwater resources of alluvial areas of West Bengal* (Geol. Surv. India Bull. Series B, No. 34).

Fendorf, S., Michael, H. A., & van Geen, A. (2010). Spatial and temporal variations of groundwater arsenic in south and southeast Asia. *Science*, 328(5982), 1123–1127. doi:10.1126/science.1172974

Guha Mazumder, D. N., Ghose, A., Majumdar, K. K., Ghosh, N., Saha, C., & Guha Mazumder, R. N. (2010). Arsenic contamination of ground water and its health impact on population of District of Nadia, West Bengal, India. *Indian Journal of Community Medicine*, 35, 331–338.

Harvey, C. F., Ashfaq, K. N., Yu, W., Badruzzaman, A. B. M., Ali, M. A., Oates, P. M., … Ahmed, M. F. (2006). Groundwater dynamics and arsenic contamination in Bangladesh. *Chemical Geology*, 228 (1–3), 112–136. doi:10.1016/j.chemgeo.2005.11.025

Hopenhaynrich, C., Browning, S., Hertz-Picciotto, I., Peralta, C., & Gibbs, H. (2000). Chronic arsenic exposure and risk of infant mortality in two areas in Chile. *Environmental Health Perspectives*, 108, 667–673.

Huges, M. F., Beck, B. D., Chen, Y., Lewis, A. S., & Thomas, D. J. (2001). Arsenic exposure and toxicology: A historical perspective. *Toxicological Sciences*, 123(2), 305–332. doi:10.1093/toxsci/kfr184

Jackson and Richards, Standard Materials and Methods. (1973). New Delhi, India: Prentice Hall of India Pvt. Ltd. (pp. 498).

McArthur, J. M., Banerjee, D. M., Hudson-Edwards, K. A., Mishra, R., Purohit, R., Ravenscroft, P., … Chadha, D. K. (2004). Natural organic matter in sedimentary basins and its relation to as in anoxic ground water: The example of West Bengal and its worldwide implications. *Applied Geochemistry*, 19(8), 1255–1293. doi:10.1016/j.apgeochem.2004.02.001

McArthur, J. M., Ravenscroft, P., Safullah, S., & Thirlwall, M. F. (2001). Arsenic in groundwater: Testing pollution mechanism for sedimentary aquifers in Bangladesh. *Water Resources Research*, 37(1), 109–117. doi:10.1029/2000WR900270

McArthur, J.M., Ravenscroft, P., Banerjee, D.M., Milsom, J., Hudson-Edwards, K.A., Sengupta, S., Bristow, C., Sarkar,
A., Tonkin, S., Purohit, R., 2008. How paleosols influence groundwater flow and arsenic pollution: A model from the Bengal Basin and its worldwide implication. Water Resour. Res. 44, W11411.

Mcelhan, F. (2002). Arsenic contamination affects millions in Bangladesh. The Lancet, 359(9312), 1127–1129. doi:10.1016/S0140-6736(02)08179-5

Mukherjee, A., von Brömssen, M., Scanlon, B. R., Bhattacharya, P., Fryar, A. E., Hasan, M. A., … Sracek, O. (2008). Hydrogeological comparison and effects of overlapping redox zones on groundwater arsenic near the western (Bhairabati sub-basin, India) and Eastern (Meghna sub-basin, Bangladesh) margins of the Bengal Basin. Journal of Contaminant Hydrology, 99 (1–4), 31–48. doi:10.1016/j.jconhyd.2007.10.005

Mukherjee, M., Sahu, S. J., Jana, J., De Dalal, S. S., & Chatterjee, D. (2001). Scope of natural geochemical material in the removal of arsenic in drinking water. River Behavioral Contamination, 24, 1–7.

Nath, B., Berner, Z., Basu Mallik, S., Chatterjee, D., Charlet, L., & Stüben, D. (2005). Characterization of aquifers conducting groundwaters with low and high arsenic concentrations: A comparative case study from West Bengal, India. Mineralogical Magazine, 69(5), 841–853. doi:10.1180/00264610505690292

Nath, B., Berner, Z., Chatterjee, D., Basu Mallik, S., & Stuben, D. (2008b). Mobility of arsenic in West Bengal aquifer conducting low and high groundwater arsenic. Part II: Comparative geochemical profile and leaching study. Applied Geochemistry, 23(5), 996–1011. doi:10.1016/j.apgeochem.2007.11.017

Nath, B., Sahu, S. J., Jana, J., Mukherjee-Goswami, A., Roy, S., Sarkar, M. J., & Chatterjee, D. (2007). Hydrochemistry of arsenic-enriched aquifer from rural West Bengal, India: A study of the arsenic exposure and mitigation option. Water, Air, and Soil Pollution, 190, 95–113.

Nath, B., Stuben, D., Basu Mallik, S., Chatterjee, D., & Charlet, L. (2008a). Mobility of arsenic in West Bengal aquifers conducting low and high groundwater arsenic. Part I: Comparative hydrochemical and hydrogeological characteristics. Applied Geochemistry, 23, 977–995.

Neidhardt, H., Berner, Z., Freikowski, D., Biswas, A., Winter, J., Chatterjee, D., & Norra, S. (2013). Influences of groundwater extraction on the distribution of dissolved arsenic in shallow aquifers of West Bengal, India. Journal of Hazardous Materials, 262, 941–950. doi:10.1016/j.jhazmat.2013.01.044

Neumann, R. B., Ashfaque, K. N., Badruzzaman, A. B. M., Ali, M. A., Shoemaker, J. K., & Harvey, C. F. (2010). Anthropogenic influence on groundwater arsenic concentration in Bangladesh. Nature Geoscience, 3(1), 46–52. doi:10.1038/ngeo685

Pal, T., Mukherjee, P. K., & Sengupta, S. (2002). Nature of arsenic pollutants in groundwater of Bengal Basin – A case study from Baruipur area, West Bengal, India. Current Science, 82, 554–561.

PHED. (1993). National drinking water mission project on arsenic pollution on groundwater in West Bengal (Final report, Steering Committee on As investigation). West Bengal, India: Government of West Bengal.

Roy Chowdhury, T., Basu, G. K., Mandal, B. K., Biswas, B. K., Samanta, G., Chowdhury, U. K., … Chakrabarti, D. (1999). Arsenic poisoning in the Ganges delta. Nature, 40(6753), 545–546. doi:10.1038/44056

Smedley, P. L., & Kinniburgh, D. G. (2002). A review of the source, behaviour and distribution of arsenic in natural waters. Applied Geochemistry, 17, 517–568.

Smedley, P. L., Nicollli, H. B., Macdonald, D. M. J., Barros, A. J., & Tullio, J. O. (2002). Hydrogeochemistry of arsenic and other inorganic constituents in groundwaters from La Pampa, Argentina. Applied Geochemistry, 17(3), 259–284. doi:10.1016/S0883-9927(01)00082-8

Smith, A. H., Lingas, E. O., & Rahman, M. (2000). Contamination of drinking water by arsenic in Bangladesh: A public health emergency. Bulletin of the World Health Organization, 78, 1093–1103.

van Geen, A., Zheng, Y., Goodbred, S., Jr, Horneman, A., Aziz, Z., Cheng, Z., … Ahmed, K. M. (2008). Flushing history as a hydrogeological control on the regional distribution of arsenic in shallow groundwater of the Bengal Basin. Environmental Science & Technology, 42(7), 2282–2288. doi:10.1021/es702316k

WHO. (2011a). Guidelines for drinking-water quality (4th ed.). Geneva, Switzerland: World Health Organization.

WHO. (2011b). Selenium in drinking-water: Background document for preparation of WHO guidelines for drinking-water quality. Geneva, Switzerland: World Health Organization.