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Near surface lithology and spatial variation of arsenic in the shallow groundwater: southeastern Bangladesh

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Abstract This study investigated the relationship between near-surface lithology and the spatial variability of As concentrations using sediment grain-size analysis and electromagnetic induction survey in the southeast Bangladesh. It has been observed that the aquifers overlain by finer sediments have higher concentrations of As in groundwater, whereas As concentrations are remarkably low in aquifers having permeable sandy materials or thinner silt/clay layer at the surface. The near-surface lithology acts as a controlling factor for spatial distributions of groundwater As within the very shallow depths (<15 m). Shallow alluvial aquifers can provide low-As drinking water in many areas of the country when tube wells are properly installed after investigation of the overlying near-surface sediment attributes and hydraulic properties.

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Introduction

Groundwater is generally considered as the best-quality water for drinking and irrigation around the world. In many parts of the world, surface water sources, such as lakes, streams, and springs are no longer considered suitable because they are vulnerable to pollution and can contain harmful pathogens. In Bangladesh, groundwater has been widely used in household, agriculture, and for industrial purposes since the early 1970s when groundwater abstraction by hand-operated pumps, mainly in the rural areas, started replacing the exploitation of polluted surface waters. Consequently, millions of tube wells were installed in the Ganges–Brahmaputra–Meghna (GBM) delta in the last four decades to provide pathogen-free water for domestic and irrigation purposes in Bangladesh and West Bengal (Smith et al. 2000; BGS and DPHE 2001). This major switch to groundwater abstraction saved hundreds of lives from waterborne acute diseases, but exposed a majority population to high concentrations of groundwater As and its slow poisoning over time. Millions of people of Bangladesh and neighboring Indian state, West Bengal have been affected by the excessive presence of dissolved As in groundwater. An extensive national-scale survey in Bangladesh by the Department of Public Health Engineering (DPHE) and the British Geological Survey (BGS) found that nearly 35 million people are drinking groundwater containing As of a concentration of more than 50 µg/L (Bangladesh standard) (BGS and DPHE 2001; Gaus et al. 2003).

Since the discovery of groundwater As in the early 1990s, there have been many studies carried out by the national and international scientists to understand the complex nature and occurrence of the As-contamination. From these studies, it has been understood that the sources and causes of widespread occurrences of groundwater As

are natural through geological processes; however, its mobilization and patchy spatial distributions are not fully understood (Bhattacharya et al. 1997; Dhar et al. 1997; Nickson et al. 1998; Acharyya et al. 2000; BGS and DPHE 2001; McArthur et al. 2001; Mukherjee and Bhattacharya 2001; Khan et al. 2003; van Geen et al. 2003; Ahmed et al. 2004; Horneman et al. 2004; Hasan et al. 2007; Shamsudduha and Uddin 2007; von Brömssen et al. 2007). From these studies, it is also clear that high concentrations of As occur within the alluvial aquifers of Holocene age up to a depth of approximately 100 m below ground level. These aquifers are mostly composed of sand, silt, clay, and/or their combination (BGS and DPHE 2001).

Occurrence and distributions of As in the aquifers largely depend on local geology. It has been agreed by the scientific community that the principal mechanism of As release in groundwater is the reductive dissolution of iron oxy-hydroxides (FeOOH) and manganese oxy-hydroxides (MnOOH) (Nickson et al. 1998, 2000; McArthur et al. 2001; Horneman et al. 2004; Zheng et al. 2004).

BGS and DPHE (2001) studied the local and regional scale spatial variability of groundwater As and suggested that dissolved As is relatively low (<50 μg/L) at a depth of 150 m and below in alluvial aquifers. In contrast, the Pleistocene aquifers (Dupi Tila sandy aquifers) are entirely As safe (McArthur et al. 2001). van Geen et al. (2003) discussed depth and spatial variations of groundwater As concentrations in a small area ($\sim$25 km^2, Araihazar Upazila, Narayanganj district, Bangladesh). In that study, they explained spatial variations between the Holocene and older sediments and mentioned about the variation of arsenic at very shallow depths, particularly in the Holocene sediments. In later studies, by the same group (van Geen et al. 2006; Aziz et al. 2008), they linked these variations with surface soil conductivity (electromagnetic induction) i.e. higher As concentrations with higher EM values of the surface soils and vice versa. A recent study (von Brömssen et al. 2007) showed that aquifers composed of yellow to brown or brownish-red sediments contain low As as opposed to grey to dark-grey sediments. An earlier work (Khan and Hoque 2002) showed that high As in the very shallow depths (<50 m) and local-scale variability are closely linked with geomorphology and landform development. Several other recent studies (Hasan et al. 2007; Shamsudduha and Uddin 2007) showed that spatial distributions of groundwater As are well-linked with regional geomorphological units, near-surface geology, delta building processes and migration of the GBM delta lobes with time.

A national survey (BGS and DPHE 2001) data showed that 63% of the wells (n = 3,208, <150 m depth) do not exceed the Bangladesh standard (50 μg/L) for arsenic in drinking water and 54% of the wells comply with WHO guideline (10 μg/L) (*cf.* Gaus et al. 2003), among which a significant number of the wells are in very shallow zone of the aquifers. Finding the explanation behind the low arsenic content of these very shallow wells may lead to a low cost arsenic safe source of groundwater exploration and further development. This study examines the spatial and depth distribution of As concentrations at very shallow (<15 m below ground level) alluvial aquifers and relates to near-surface (depth < 3 m) sediment attributes as revealed by shallow subsurface auger-boring and electromagnetic investigations (EM31) in an area located within the southeastern Bangladesh. In addition, efforts have been made to improvise simple and low-cost near-surface geological investigation to target low As wells.

Geology and landform

Bangladesh is a lowland country where three major rivers, the GBM, formed one of the largest delta complexes in the world (Coleman 1969; Lindsay et al. 1991; Goodbred and Kuehl 2000). Fluvio-deltaic unconsolidated alluvial sediments of the Quaternary period mainly formed aquifers in Bangladesh, except in the southeastern hilly areas (Fig. 1), where older deposits of Tertiary period occasionally form aquifers (e.g. Ravenscroft 2003; Shamsudduha and Uddin 2007).

Neotectonically uplifted Barind Tract located to the northwest and Madhupur Tract in the central Bangladesh is composed of highly oxidized clay and sand of Pleistocene age (Morgan and McIntire 1959). Underneath the Pleistocene tracts, there is yellowish-brown sandy aquifer, formed within the Pliocene–Pleistocene Dupi Tila sand (e.g. BGS and DPHE 2001).

The study area (approximately 15 km^2) is located in Laharkandi union of Lakshmipur Upazila (sub-district) in southeastern Bangladesh, which is one of the severely As-affected areas (Fig. 1), located in the Meghna Floodplain unit. The landforms of the southeastern parts of Bangladesh are geomorphologically different from the other parts of the Bengal basin. Elevated Tertiary hill ranges in the east and the location of the dynamic Meghna river accompanied by a number of active channels in the west formed a gently dipping (towards west) floodplain (Fig. 1). Several earlier studies (e.g. Morgan and McIntire 1959; Bakr 1977; Rashid 1991; Shamsudduha and Uddin 2007) classified the landforms into several categories (Fig. 1, right) and showed that the fluvio-deltaic landforms in this region are constrained by the tectonically active Teriary hills and Tippera surface in the east and Meghna estuary in the southwest.

Shamsudduha and Uddin (2007) explained that this part of the country has the longest history of delta-building

Fig. 1 The study area in Bangladesh with generalized distribution of As in groundwater (data from BGS and DPHE 2001) and major landforms (*left*); Sub-regional landform (after, Bakr 1977) shows how westward topographical gradient and landforms developed and a more detail classification of the landforms by Rashid (1991) is overlain to show the differential variation of the landforms in the area (*right*)
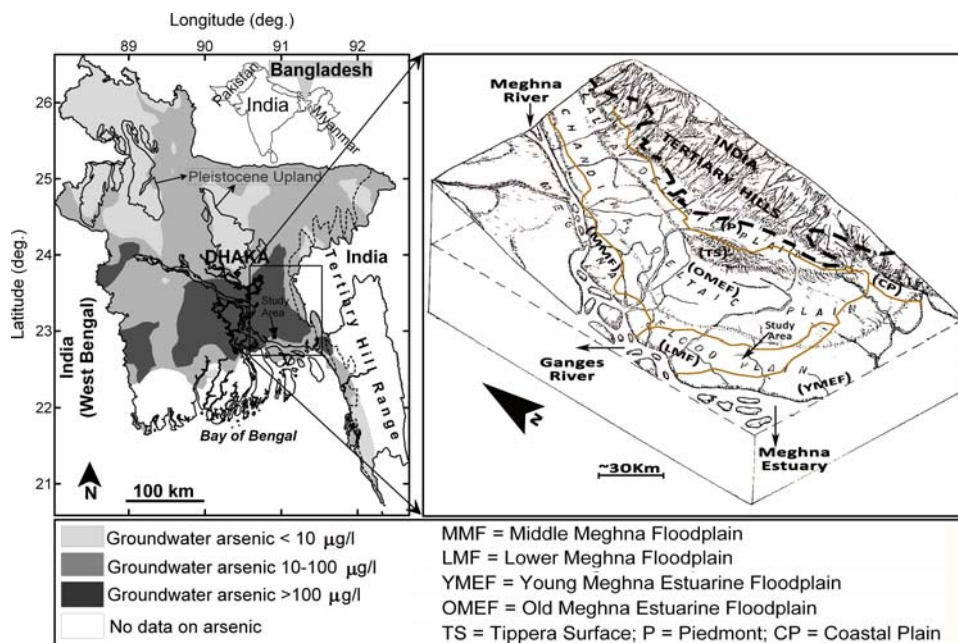
processes and neotectonic activities. The drainages in these flood plain areas are mainly of the meandering type, although numerous man-made narrow canals (locally known as 'khal') are abundant in this area. One of the major tributaries of the Meghna river flows through this study area known as 'local Meghna', which is also meandering by nature (Fig. 2). The common geomorphological features are natural levees, meandering channel bars, channel cut-off, and back-swamps of various shapes and sizes. The surface elevation of this area ranges from <2 m to approximately 7 m above mean sea level with an average of 3.5 m. Elevation is low in the northeast and southeast marshy areas, whereas the central part of the study area is slightly higher elevated. The surface sedimentary deposits are mainly floodplain silts, clay and fine-sands.

Hydrogeology and arsenic distribution

Unconsolidated fluvio-deltaic sediments of Quaternary age formed the hydrogeological framework in the area. By and large, the study area is characterized by two major aquifer zones: the shallow aquifer zone (depth <50 m) and the deep aquifer zone (depth >130 m). There are no wells screened between 50 and 130 m, because the intervening strata contain brackish water (DSC 1996). The deep aquifer zone is free of groundwater As, while the shallow aquifer zone is extensively affected by As. The aquifers, mostly within 30 m below ground level, contain As at concentrations up to 750 µg/L in this area (Khan et al. 2001), although As-concentrations vary laterally. Shallow aquifer
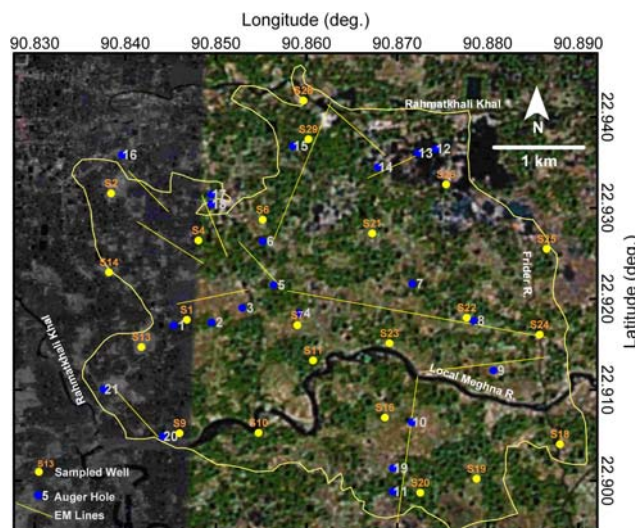

Fig. 2 Location of the groundwater sampling points and auger drill-holes are shown on (Google Earth at http://www.earth.google.com/ accessed on 10 December 2007) satellite image of the area. Different geomorphological features—marshy land and channel patterns can be observed on the image. On the image sample points for Auger-holes and Tube-wells' location for known arsenic concentration and lines of EM survey are shown

is largely semi-confined in nature as it is covered by floodplain silts of variable thicknesses and occasionally these silts contain significant amount of sands. Depth of the As-safe deep aquifer is reported to be at about 240 m by Khan et al. (2001). In addition, some biogenic gas pockets have also been reported in the intermediate zone in between shallow and deep aquifer. The groundwater table varies between 1.5 and 4 m with fluctuation ranging between 1.25 and 3 m in the shallow aquifer. In this area,

groundwater is considered as the main source for drinking water and dry season irrigation and industrial uses.

For this study, a total of 22 very shallow (<15 m) tube wells from (Khan et al. 2001) that are distributed uniformly throughout the study area (Fig. 2), were chosen. Arsenic distribution in the shallow aquifer shows some distinct patterns. Highest level As-wells (>200 μg/L) are found in the northwest corner, several intermediate to high (100–200 μg/L) As-wells are located in the east and southeast, whereas low As-wells (<100 μg/L) are located in the central part of the study area (Fig. 3).

Materials and methods

Sediment sampling and grain-size analyses

An Eijkelkamp[TM] (Nijverheidsstraat 30, 6987 EM Giesbeek, Netherlands) hand-operated auger was used to collect near-surface sediments. There was a total of 21 auger holes (Fig. 2); each were drilled to a maximum depth of 3 m below the ground level, and sampled, which provided representative spatial coverage of the study area. The location of each auger-hole was recorded by a hand-held 12-Channel Garmin global positioning system (GPS) unit.

Sediment types were logged continuously and samples were taken from each auger-hole at depths 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 m. Boring was mainly focused on the topmost lithological unit and therefore, drilling was stopped at the top of the second lithological unit even if it was

found at shallower depths (<3 m). Thicknesses of the lithological units (e.g. silt or silty-clay layer) were recorded at each auger-hole to generate surface contour maps. Samples from 0.5 to 1.5 m were mixed-up proportionally to make a bulk sample representative of 1.5 m slab. These samples were dried and plant debris were removed before grain-size analysis. Sediments were sieved by a mechanical sieving machine and results were recorded carefully for each sample. Samples were pre- and post-weighted and any sieve loss was also recorded. Grain-size analysis was performed to determine the dominant particles sizes ranging from very coarse sand (>1.0 mm), coarse sand (0.5–1.0 mm), fine to medium sand (0.063–0.5 mm) and silt (<0.063 mm) fractions.

Electro-magnetic induction (EM31) survey

A ground conductivity instrument (in this study, EM31) induces currents, generated by varying electromagnetic fields, into the ground in such a manner that their amplitudes are linearly proportional to the ground conductivity. A Geonics® (Mississauga, Ontario, Canada) EM31 hand-held electro-magnetic (EM) meter (vertical resolution of zero to 3–6 m below surface) was used to conduct EM induction (expressed in milliSiemens/meter, or mS/m) survey, in which the amount of clay or finer contents of lithological units were correlated with the bulk conductivity of near-surface deposits. That is, the higher the clay contents the higher the conductivity (McNeill 1990; van Geen et al. 2006; Aziz et al. 2008).

EM induction survey was carried out along a number of transects to cover the different landforms and zones of As concentrations in groundwaters. About 300 EM data were acquired covering most of the study area. To avoid the interference from metallic household substances, the survey was restricted to the open fields and open areas in the villages. The ground conductivity was measured in vertical mode, approximately 1 m from the ground (e.g. McNeill 1990). The location of the data points were collected using a hand-held GPS unit during the survey. EM meter was calibrated prior to field operation following the calibration instructions by the manufacturer (Geonics Ltd. 1992).

Results

Sediments and grain-size distributions

Auger drill-hole data show a distinct pattern in the thickness of the top silt layer. The top silt layer is relatively thin in the mid-west, whereas, this layer thickens towards south and northeast of the survey area (Fig. 4).
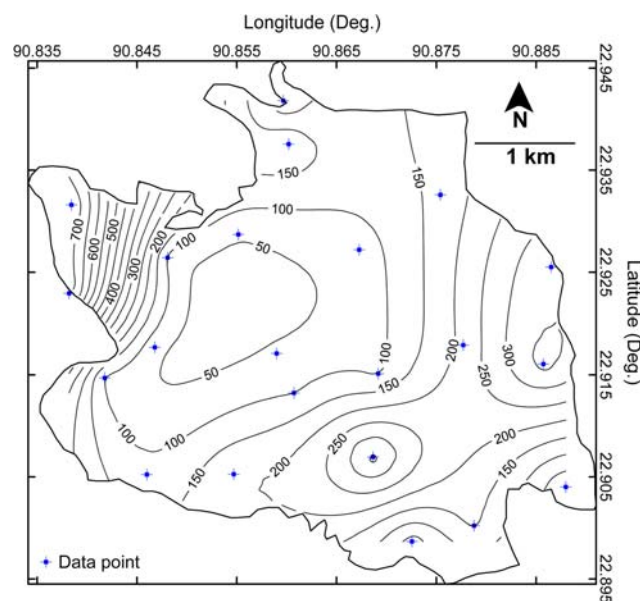

Fig. 3 Groundwater As concentration (in μg/L) contours of the area show the high and low arsenic zones
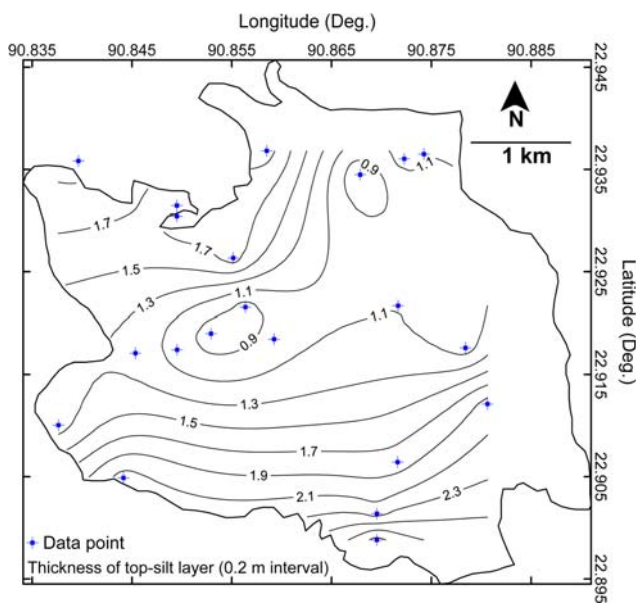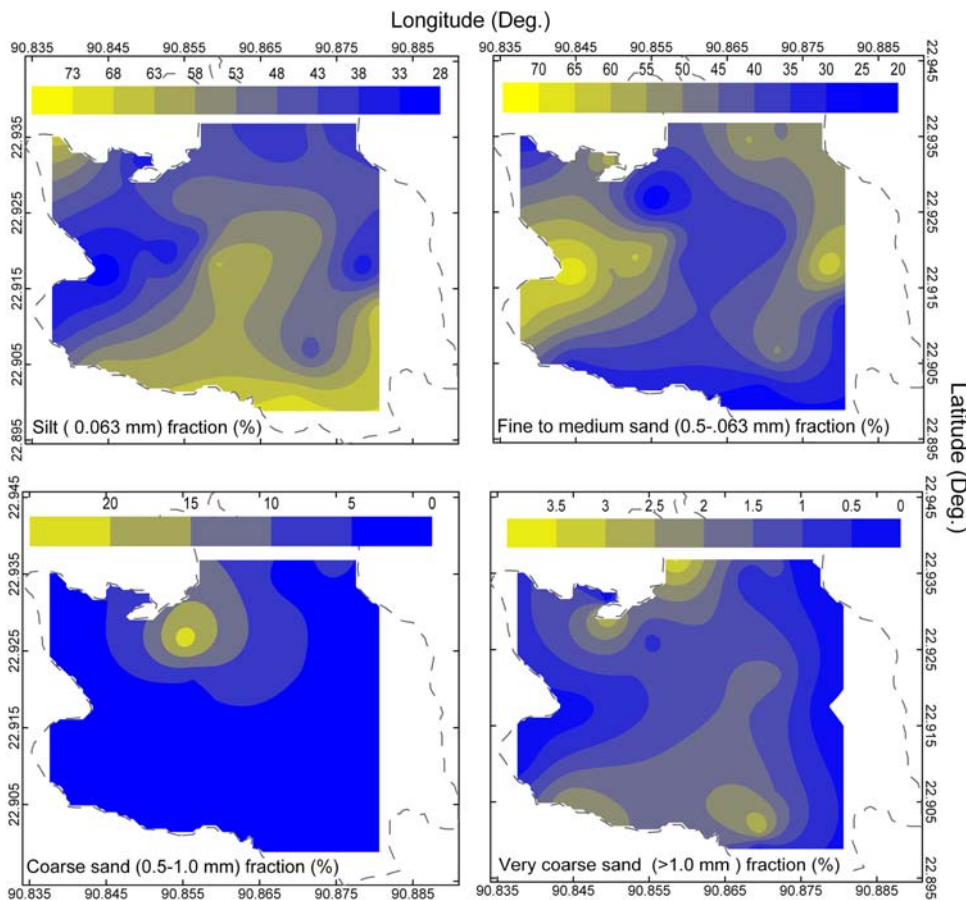
Fig. 4 Contour of thickness (in m) of the top silt layer over the area

Sediment grain-sizes at sampled locations show a distinct spatial distribution pattern. The study area is mostly covered by silt to silty-clay and less frequently with sand.

However, the thickness of the silt layer varies spatially from a few centimetres to more than 2 m (Fig. 4). The bottom of the silt layer consists of fine sand at all 21 sampling locations. The area is generally covered by almost equal quantity of silts and fine to medium sands, whereas coarser sands are insignificant in amount. The northwestern part of the area has coarser particles, whereas the rest of the area is characterised by finer particles (Fig. 5). Close observation of the grain-size analysis of the top 1.5 m sediments reveals that middle-west area has higher contents of sand fraction compared to other parts.

Electro-magnetic induction survey results

Electro-magnetic conductivity values (Fig. 6) are highly variable and thus indicate greater spatial variability in clay to sand ratios. The EM values are generally low in the mid-west, but high in other areas. The bulk sediment contents and the thickness of the top silt layer have been reflected in EM values. The greater the thicknesses of top silt layer the higher the recoded EM values. Very high conductivity was observed in the northeast and southeast, whereas low to intermediate conductivity values were seen in the other areas. These variations in the EM values are due to the
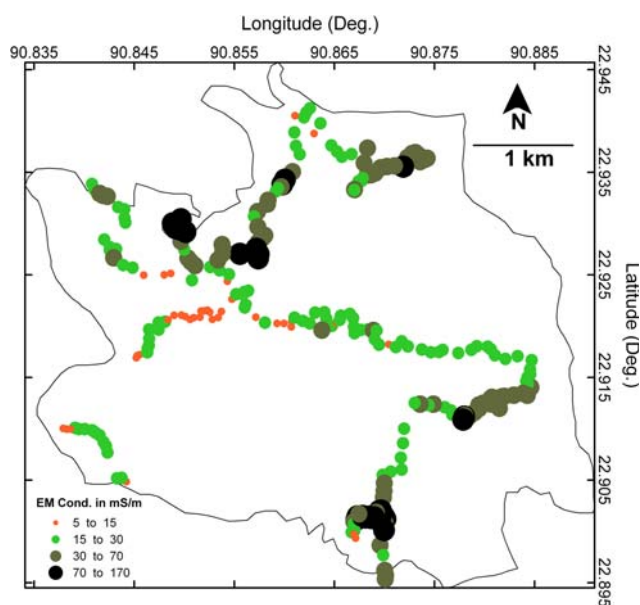
Fig. 5 Grain size fractionation surfaces (in percentage) constructed from the sieve analysis data for the top 1.5 m slab. Samples (as of Fig. 4) were collected using hand-held auger drilling. The area is generally covered by almost equal quantity of silts and fine to medium sands, and coarser sands are significantly low

Fig. 6 Electromagnetic (EM) conductivity measurement points with classified values (in mS/m). Lower range values indicate coarser or thinner top silt layer or their average and higher values represent the reverse. Very high values (70–170 mS/m) may be influenced by surface soil salinity

variations in the thickness of top silt layer and the grain-size. In some parts of the surveyed area, particularly, in the south and northeast, the higher EM values (70–170 mS/m) are probably indicating the presence of higher surface soil salinity

Discussions

Role of lithology in As-distributions

In this study, near surface lithological information was derived directly by auger drilling that was compared with

the electromagnetic (EM) survey results. The investigations show that the area is covered mostly by finer sediments, except some parts in the mid-west, where top silt layer is thin and contain sands particles as well. Relatively low EM conductivity values recorded in the mid-west area indicate average effects of coarser materials and thinness of top silt layer. Sieve analysis results from the auger-drilled sediment samples, compares the same lithological attributes.

Aquifer in the area occurred at very shallow depth, semi-confined in nature as covered by floodplain silt with sandy materials. The thickness of the top layer varies laterally from a fraction of a meter to a couple of meters. The expected rate of recharge would be low where the thickness of the finer materials is high, while the rate is higher in the areas with a thin cap of finer particles above aquifers or presence of sands up to the surface. The principal recharge comes from rainfall and/or return flows from the un-used discharges from both irrigation and drinking water wells. The spatial variability of recharge may be acting as a mechanism to the variation of the redox state of the aquifer hence dissolved As concentration (due to reductive dissolution) in the very shallow aquifer zone. Stute et al. (2007) proposed recharge rate of shallower aquifers as a possible dominant factor controlling As concentrations in groundwater, based on paired measurements of groundwater As concentrations and groundwater age by ^{3}H–^{3}He dating. The overall variability of dissolved As in the very shallow groundwater could be conceptually linked with fluvial landform and aquifer structure as illustrated in Fig. 7. In fluvio-deltaic regions like this study area, shallow aquifers are commonly composed of point bars, channel bars and overbank deposits. These deposits are significantly different in grain sizes and thickness. Syndepositional landforms determine their positions in the aquifer architecture. For instance, in Fig. 7, a well with low-As concentration, can be found to be screened within a sandy body (i.e. point-bar

Fig. 7 A conceptual cross-section shows how the surface lithology deposited by the meandering streams influence the aquifers' redox condition. In the figure 'HA' 'LA' and 'MA' are the locations of three hypothetical wells. Among the wells' water from 'HA' and 'LA' would contain highest and lowest concentration of As, respectively, while 'MA' would have medium concentration of As in comparison to others. For details please see the text
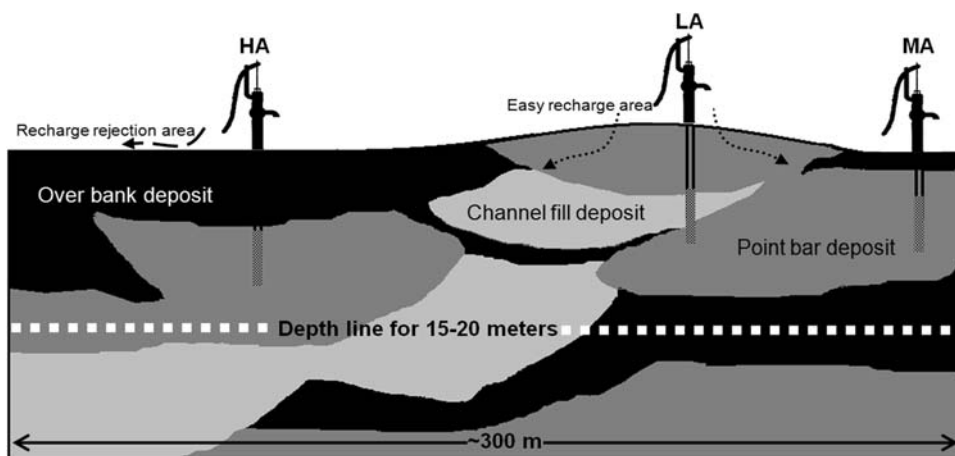
or channel bar), which is generally exposed to the ground surface and thus receiving easy recharge and active flushing. On the other hand, a neighbouring well may contain high-As if it is screened within an aquifer (made of point-bar or channel bar) but overlain by floodplain deposits (i.e. predominantly silt and clay). Moreover, grain size variability within the aquifer materials also has an effect on the As content; that is depth-specific As source zones principally associated with fine-grained floodplain sediments (Burgess et al. 2002).

In Bangladesh, shallow aquifers are commonly developed and modified by fluvio-deltaic processes. It is observed that sandy surface area in fluvial terrain remain slightly elevated (*ca. 1* m) than that of areas with finer sediments. This may lead to the exploitation of groundwater from these areas maintaining the local hydrodynamic equilibrium to meet at least household scale demand (1 m^3/day) without drawing water from the nearby high As area. Cuthbert et al. (2002) modelled a shallow tube-well catchment, which indicates increase of As content at the tube well (with a discharge 10 m^3/day) by 10–15 years, but they considered a flat topography. However, consideration of the real topography, even if the spatial variations in surface elevation are very small, would have made some differences in the As breakthrough time, which could have been more than the modelled result.

Implications for As-mitigation

In a fluvio-deltaic terrain it is obvious that clay or silty clay and/or finer materials are generally deposited by channel chute cut-off, chute bar and swamp/oxbow lake. Sandy and/or coarser materials are deposited in the channel bars, point bars and natural levees (e.g. Miall 1996). Clay and finer materials act as barriers for natural groundwater recharge, while sandy materials ease the recharge to the underlying aquifer. In entire Bangladesh, aquifers are composed of fluvio-deltaic sediments (Ravenscroft 2003), where the shallow aquifers developed or modified over the Quaternary time by sea-level dynamics and fluvial processes.

In most part of Bangladesh, household drinking water is tapped from aquifers that are located within the upper 50 m below the ground surface. However, the pumping depths vary across the country depending on the suitability of aquifers and/or drop of water level due to irrigation pumping during dry season. A large part of the country's household drinking water comes from aquifers located within depths of 20 m below the ground, indicated by BGS and DPHE (2001) survey results. In these areas, shallow groundwater exploration and further development could be considered an additional source of As safe drinking water for millions of peoples.

Hand-held EM survey and auger drilling techniques are very simple to use to explore the near surface lithology. Since our research shows close association of near-surface lithology and groundwater As in the very shallow aquifers, the methods described in this study can be applied to locate areas with low As in very shallow aquifers. In addition, intended wells could be tested for dissolved As using field test kits, before boring a well by 'needle sampler' (van Geen et al. 2004). Successful sinking of such low As shallow tube wells can serve thousands of people in the rural areas at least for another decade. Published groundwater As data sets from BGS and DPHE (2001) and Bangladesh Arsenic Mitigation and Water Supply Project (BAMWSP) can be used to find out background As distribution of a particular area of interest, where further investigation of near-surface lithological attributes through EM conductivity and/or manual auger-hole survey can aid in targeting "low-As" very shallow (<15 m) aquifers in Bangladesh. A massive well arsenic-testing programme could be conducted in those shallow aquifer areas so that people can switch to the safe wells as it is reported in Araihazar area of Narayanganj district in Bangladesh (van Geen et al. 2002).

Conclusions

The present study has examined the spatial variations in groundwater As concentrations at very shallow (depth <15 m) alluvial aquifers and attempted to link between near-surface (depth <3 m) sediment attributes and As-distributions in tube wells. Electromagnetic (EM31) investigations and sediment grain-size results from shallow subsurface auger-boring from a small area in the southeastern Bangladesh indicated that the variations in As concentration within the very shallow Holocene aquifers are constrained by the heterogeneity in near-surface sediments that seems to control recharge and rate of aquifer flushing at shallow depths. This study has shown that low-As aquifers are located underneath the areas with relatively thinner top-silt layer or sandy surface materials with higher permeability and hydraulic conductivity at slightly higher topography. Finer materials on the surface act as potential barriers to downward percolation and infiltration of oxygenated water from precipitation and runoff into the shallow aquifers and thus control groundwater As mobilization in the very shallow aquifers. Since shallow aquifers in Bangladesh are also providing low-As drinking water in many areas, it is recommended to carry out further investigations to understand the controlling mechanism of spatial As-variations within the very shallow aquifers.

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