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ORIGINAL ARTICLE

Spatial relationship of groundwater arsenic distribution with regional topography and water-table fluctuations in the shallow aquifers in Bangladesh

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Abstract The present study has examined the relationship of groundwater arsenic (As) levels in alluvial aquifers with topographic elevation, slope, and groundwater level on a large basinal-scale using high-resolution (90 m × 90 m) Shuttle Radar Topography Mission (SRTM) digital elevation model and water-table data in Bangladesh. Results show that high As (>50 μg/l) tubewells are located in low-lying areas, where mean surface elevation is approximately 10 m. Similarly, high As concentrations are found within extremely low slopes (<0.7°) in the country. Groundwater elevation (weekly measured by Bangladesh Water Development Board) was mapped using water-table data from 950 shallow (depth <100 m) piezometers distributed over the entire country. The minimum, maximum and mean groundwater elevation maps for 2003 were generated using Universal Kriging interpolation method. High As tubewells are located mainly in the Ganges–Brahmaputra–Meghna delta, Sylhet Trough, and recent floodplains, where groundwater elevation in shallow aquifers is low with a mean value of 4.5 m above the Public Works Datum (PWD) level. Extremely low groundwater gradients (0.01–0.001 m/km) within the GBM delta complex hinder groundwater flow and cause slow flushing of aquifers. Low elevation and gentle slope favor accumulation of finer sediments, As-carrying iron-oxyhydroxide minerals, and abundant organic matter within floodplains and alluvial deposits. At low horizontal hydraulic gradients and under reducing conditions, As is released in groundwater by microbial activity, causing widespread contamination in the low-lying deltaic and floodplain areas, where As is being recycled with time due to complex biogeochemical processes.

Keywords Arsenic · SRTM digital elevation model · Spatial distribution · Groundwater gradient · Bangladesh

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Introduction

High level of dissolved arsenic (As) concentration in alluvial aquifers of Bangladesh and West Bengal, India has been recognized as the worst groundwater contamination in the world (Smith et al. 2000; British Geological Survey and Department of Public Health Engineering, Bangladesh 2001, hereafter referred as BGS and DPHE 2001). Millions of people are now exposed to the elevated As concentrations in groundwater, of which the majority population (~120 million) lives in the floodplains and low-lying Ganges–Brahmaputra–Meghna (GBM) deltaic areas of the south-central parts of Bangladesh and southern part of West Bengal, India (Mukherjee et al. 2007). Over the last few decades, residents have been using millions of hand-operated tubewells (estimated 10–12 millions) for extracting groundwater for drinking and approximately 1 million shallow (<100 m) wells for dry-season irrigation purposes from alluvial aquifers, of which many contain dangerously high levels of dissolved As (Smith et al. 2000; BADC 2003; Harvey et al. 2006). Geochemical data of 3,534 wells compiled in the National Hydrochemical Survey (NHS) in Bangladesh were collected by the Department of Public Health Engineering, Bangladesh and British Geological

Survey and Mott MacDonald Ltd. (UK) (BGS and DPHE 2001). Gaus et al. (2003), using the same dataset, have estimated that nearly 35 million people are drinking groundwater containing As of a concentration of more than 50 μg/l (Bangladesh standard) and nearly 57 million people are estimated to be exposed to a concentration exceeding 10 μg/l (World Health Organization standard). It has been shown in several national- and local-scale studies that distributions of As in alluvial aquifers in the country are not uniform (BGS and DPHE 2001; Yu et al. 2003; van Geen et al. 2003; Shamsudduha 2004; Hoque et al. 2008; Aziz et al. 2008). National-scale mapping of groundwater As concentrations shows that high As-contaminated tubewells are mostly located in the south-central, southeastern, western, and northeastern parts of Bangladesh (Fig. 1), whereas tubewells in the northern, northwestern, north-central, and eastern parts have lower concentrations of As in the groundwater (BGS and DPHE 2001; BAMWSP 2002).

High As groundwater occurrences are mostly seen within the fluvially influenced active and mature deltaic deposits, alluvial plains and valley deposits, and recent floodplains along the major rivers in the country (BGS and DPHE 2001). Many studies evaluated various aspects of As contamination in the groundwaters of Bangladesh over the last decade since the first detection of high As occurrence in groundwater reported in 1990s (Dhar et al. 1997; Nickson et al. 1998; Chakraborti et al. 1999; Smith et al. 2000; McArthur et al. 2001; Harvey et al. 2002; van Geen et al. 2003; Zheng et al. 2004; Ahmed et al. 2004; Saunders et al. 2005; Shamsudduha and Uddin 2007). The general consensus is that the reductive dissolution of As-bearing Fe- and/or Mn-oxyhydroxides is the principal mechanism leading to high As release in groundwaters in the alluvial aquifers (Nickson et al. 2000; McArthur et al. 2001; Zheng et al. 2004; Ahmed et al. 2004; Saunders et al. 2005; Ravenscroft et al. 2005). Although many studies have been conducted on the geochemical aspects of groundwater As in aquifers (Nickson et al. 2000; Zheng et al. 2004, Saunders et al. 2005), very few works focused on the control of regional-scale surface topography (Shamsudduha and Uddin 2007) and local-scale groundwater level dynamics on spatial As distributions (Ravenscroft et al. 2005; Harvey et al. 2006; Stute et al. 2007). Low surface elevation and sluggish groundwater movement within a narrow range of negligible hydraulic gradients can facilitate the accumulation of finer sediments enriched with As-adsorbing iron-oxyhydroxides minerals and organic matter that may lead to high As concentrations in groundwater (Harvey et al. 2002; Ravenscroft et al. 2005; Shamsudduha et al. 2006; Mukherjee et al. 2007). A preliminary study between spatial As distribution and surface elevation using an interpolated (300 m × 300 m horizontal resolution) digital elevation model (DEM) found that the surface elevation shows a negative relationship with groundwater As distribution (Shamsudduha 2004). Another recent study (Shamsudduha and Uddin 2007) has shown that high As (>100 μg/l) concentrations are observed in the south-central deltaic areas where the hydraulic gradients are very small (0.10–0.01 m/km). In this study, a more reliable and higher horizontal resolution (90 m × 90 m) DEM from the NASA Shuttle Radar Topography Mission (SRTM) is used to examine the spatial relationship between groundwater As, surface elevation and slope using Geographic Information System (GIS) techniques. In addition, spatial relationship between groundwater As concentrations and water-level fluctuations (yearly maximum, minimum and mean hydraulic head distributions) of 2003 within the shallow aquifers (<100 m) has been examined on the national-scale to improve our understanding of hydrological constraints on spatial As distributions in groundwater.

Description of study area

Bangladesh occupies much of the Bengal Basin, which has been the major depocenter of sedimentary flux from the Himalayas and Indo-Burman Ranges drained by the Ganges–Brahmaputra–Meghna river system (Goodbred and Kuehl 2000). The basin is bounded by the Himalayas to the distant north, the Shillong Plateau to the immediate north, the Indo-Burman Ranges to the east, the Indian Craton to the west, and the Bay of Bengal to the south (Fig. 1; Uddin and Lundberg 1998). The basin includes one of the largest delta complexes (GBM delta) in the world.

The alluvial plains of the GBM delta slope from north to south on a regional-scale, but are interrupted locally by ridges and tectonically developed depressions, such as Sylhet Trough and Atrai depression. The Bengal Basin is comprised of lowland floodplain and delta plain, and is surrounded by the Tertiary hills of various tectonic origins (Goodbred and Kuehl 2000; Ravenscroft et al. 2005). Within the Bengal Basin, the Madhupur and Barind tracts, which are the uplifted alluvial deposits of Pleistocene age, interrupt the regional surface gradient of the central basin (Morgan and McIntire 1959).

Surface elevation in the country ranges from less than 1.0 m in the south to about 1000 m in the southeastern Chittagong Hill Tracts (CHT). The elevation in northwestern parts (Teesta Alluvial Fan) of Bangladesh is higher than rest of the geomorphic units except for the CHT. The Himalayan foothills are extended up to the north of the Teesta Alluvial Fan. Elevation decreases gradually from the Teesta fan areas in the northwestern parts of Bangladesh towards the southeast in the lower GBM delta. The Madhupur and Barind tracts are also elevated areas (15–40 m) in the basin. The elevations of the Ganges–Brahmaputra–Meghna delta and

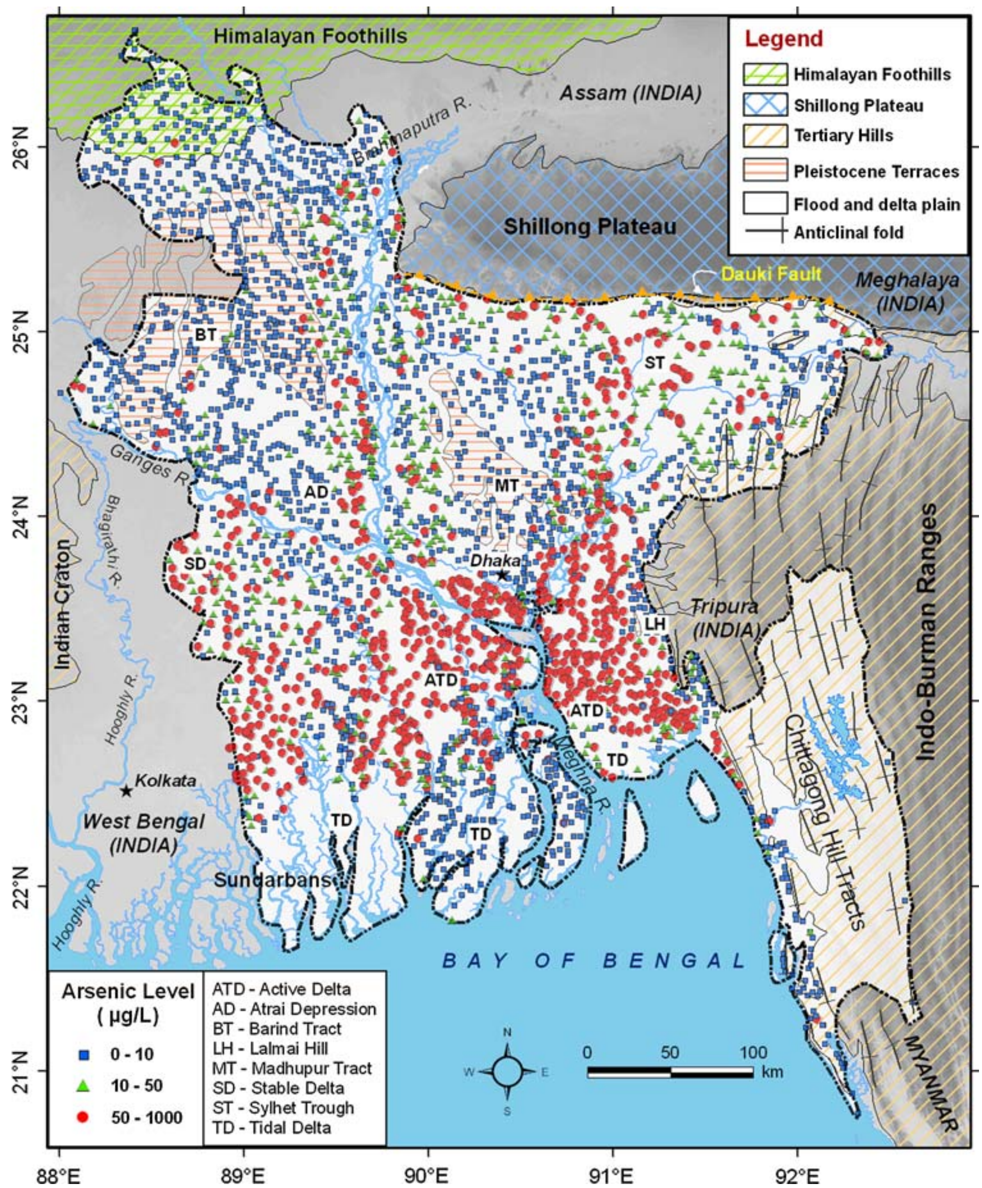


Fig. 1 Simplified geological map of the Bengal Basin. Groundwater wells from the National Hydrochemical Survey (BGS and DPHE, 2001) in Bangladesh with As concentrations are shown on this map

recent floodplains are fairly low (<1–10 m). Elevation in the Sylhet Trough, which is located between the Madhupur Tract and Eastern Fold Belt, is also low (Fig. 1). To the immediate north of the Dauki Fault in Sylhet (Fig. 1), the surface elevation increases abruptly to 500 m or more in the Shillong Plateau. In the eastern GBM delta, the surface elevation is less than 10 m, with a minimum of less than 1 m in the south.

Landforms in the floodplains and deltas are mainly characterized by natural levees, and crevasse splays, alluvial sands, and channel fill deposits. Large marshes and peat lands characterize the Sylhet Trough, which is frequently flooded during the monsoon (June–September). Shallow depressions and abundant peat basins are found in the central part of GBM delta. Numerous tidal creeks and mangrove forests characterize the southern delta plain.

Materials and methods

Groundwater arsenic dataset

Geochemical data from the National Hydrochemical Survey (NHS) (BGS and DPHE 2001) in Bangladesh are used in this study. This public-domain geochemical database is available online at http://www.bgs.ac.uk/arsenic/bangladesh/datadownload.htm (BGS and DPHE 2001). The survey analyzed a total of 3,534 tubewells of different depths in Bangladesh (Fig. 1). A total of 3,043 As-concentration data from the shallow (depth <100 m) tubewells have been used in this study. About 27% of these surveyed tubewells contain high groundwater As (>50 µg/l) concentrations (BGS and DPHE 2001). This dataset has been chosen because of its high reliability in terms of data collection, processing and analysis, and its country-wide coverage. This database contains location coordinates (geographic latitude and longitude) for all sampling sites that were taken by a hand-held Global Positioning System (GPS) during the survey. Details on water sampling and analytical procedures can be found in BGS and DPHE (2001).

SRTM digital elevation dataset

The Shuttle Radar Topography Mission (SRTM) digital elevation data, produced by NASA originally, is a major breakthrough in digital mapping of the world, and provides a major advance in the accessibility of high-quality elevation data for large portions of the tropics (CGIAR-CSI 2008). The NASA SRTM has provided digital elevation data (DEMs) for over 80% of the globe (USGS 2002). This high-resolution digital elevation dataset is particularly useful in mapping topography in the developing countries like Bangladesh where expensive digital elevation data acquisition is not always possible. The SRTM was tasked to collect 3D measurements of the Earth's surface in 2000. The objective of the SRTM mission was to obtain elevation data on a near-global scale and generate the most complete high-resolution digital topographic database of the Earth (USGS 2002). Initially, SRTM data (3-arc second, 90-m resolution) were available to freely download from the National Map Seamless Server of the USGS public-domain repository (online at http://seamless.usgs.gov). In the unfinished SRTM product, there were numerous voids in space that are mostly associated with mountain valleys, water bodies, and sand dunes around the world. Although many voids were filled in the finished product, yet there was a significant amount of voids still present, which can cause substantial problem in deriving slopes and groundwater modeling. The CGIAR-Consortium for Spatial Information (http://csi.cgiar.org) has filled all the gaps in the SRTM data using TOPOGRID algorithm with auxiliary DEM and made available for download as $5° \times 5°$ tiles, in the geographic coordinate system with WGS84 datum (Jarvis et al. 2006; CGIAR-CSI 2008). In this study, a total of four SRTM tiles (version 3) were downloaded (as GeoTiff file format) to cover all of Bangladesh (Fig. 2). The vertical accuracy of the finished 3-arc SRTM images was within 16 m depending on types of terrain. However, in the CGIAR-CSI version 3, the SRTM has significantly improved the vertical accuracy of the DEM to around 10 m after void filling (Jarvis et al. 2006; Gorokhovich and Voustianiouk 2006). However, the error in elevation can be as high as 15 m depending on the presence of dense forest (e.g., Sundarbans mangrove), where canopy heights can reach up to 15–20 m from the ground surface. The surface elevations in the Sundarbans are generally less than a few meters (WARPO 2000). In this study, the elevation values within the Sundarbans have been disregarded since there are no groundwater As data available for that part of the country in the NHS database (Fig. 1).

Groundwater elevation dataset

Hydraulic head data were collected from the Bangladesh Water Development Board (BWDB) for the year 2003. BWDB has a network of about 1,256 water-table monitoring stations throughout the country where the water-table (hydraulic head below the piezometer top) is measured once a week. Each well is established with a reference level, known as Public Works Datum (PWD). This horizontal PWD was originally thought to be located at the mean sea level (msl), but there is a difference between these two reference levels (PWD is approximately 0.45 m below the msl; see http://www.ffwc.gov.bd/). Water-table data from 950 shallow (well depth $<$100 m; mean depth $\sim$20 m) piezometers for the year of 2003 have been used for creating water level elevation maps on the national-scale (Fig. 3). Reading of the water-table at each piezometer is converted into groundwater elevation by subtracting from the reference level (PWD) before GIS analysis and mapping.

Water-table elevation data for normal hydrological year (2003) were used in this study since there was not any major and extensive flood event or drought in Bangladesh (FFWC 2007) that could possibly affect the natural groundwater levels in the shallow aquifers. However, it has been reported that high irrigation (deep tubewells and motor-driven shallow pumps) during the dry water-stressed period (December–April) can impact the groundwater levels (Harvey et al. 2006; Klump et al. 2006), although the actual impacts and their spatial extents have not been fully investigated. Maximum, minimum and mean water-level elevations during 2003 were mapped over the entire country to compare the spatial relationship between hydraulic head distributions and groundwater As levels.

Spatial GIS and statistical analyses

A database of groundwater As concentrations with *XY* coordinates (Universal Transverse Mercator projection in Zone 46 North) was used to create a vector point map of the 3,043 shallow tubewells. Four separate SRTM images were mosaiced after re-projecting into the UTM system with the above-mentioned zonal attributes to provide a single DEM of Bangladesh with the original horizontal resolution of SRTM (Fig. 2). The original image contains elevation information in each cell as floating-points, in which the cell values commonly represent continuous surfaces, assigned as decimal points (USGS 2002). The SRTM surface elevation data, which are remotely sensed,

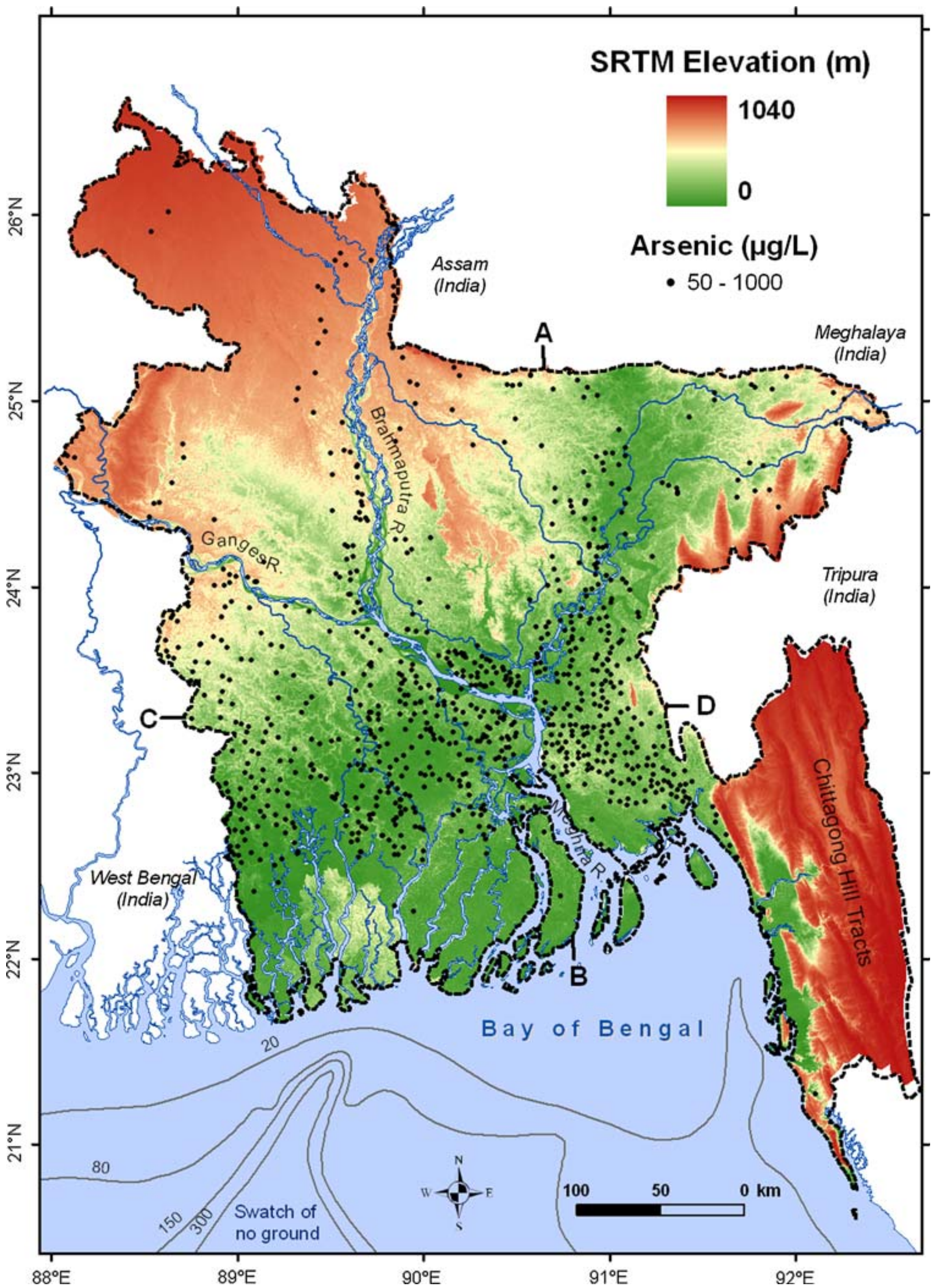


Fig. 2 Digital elevation model (DEM) of Bangladesh and groundwater As concentrations in the National Hydrochemical Survey tubewells. DEM was created from SRTM data from the Seamless Data Distribution System of USGS. Wells exceeding As concentrations of 50 µg/l are used for mapping. High As wells are mainly located within topographically low areas. Transects *A*–*B* and *C*–*D* show the relationship between As and elevation in Fig. 7

are not highly accurate for areas of dense forests and very flat topography such as Bangladesh. One of the major problems with the SRTM data for flat areas is the presence of sinks or depressions in low-lying areas that are not necessarily associated with small river channels, shallow swamps and lakes in floodplains. Before using the SRTM data for any spatial GIS analysis, the depressions were filled using the fill-sink function under hydrology tool in the spatial analyst extension of ArcGIS 9.2 program. After removing negative values (associated with river channels) and artificial topographic sinks from the SRTM data, a more reliable DEM was generated with the same spatial resolution of 90 m × 90 m for GIS analysis (Jarvis et al. 2006). The NHS tubewell data have GPS coordinates but do not have the surface elevation at their locations. The tubewell coordinates were used to extract specific elevation for each sample location by extracting DEM values (m) to tubewell coordinates by bilinear interpolation (within a 2 × 2 neighborhood of cells) from the DEM. Elevation values for each of the 3,043 shallow tubewell locations were stored in a data file (.dbf) for statistical analysis.

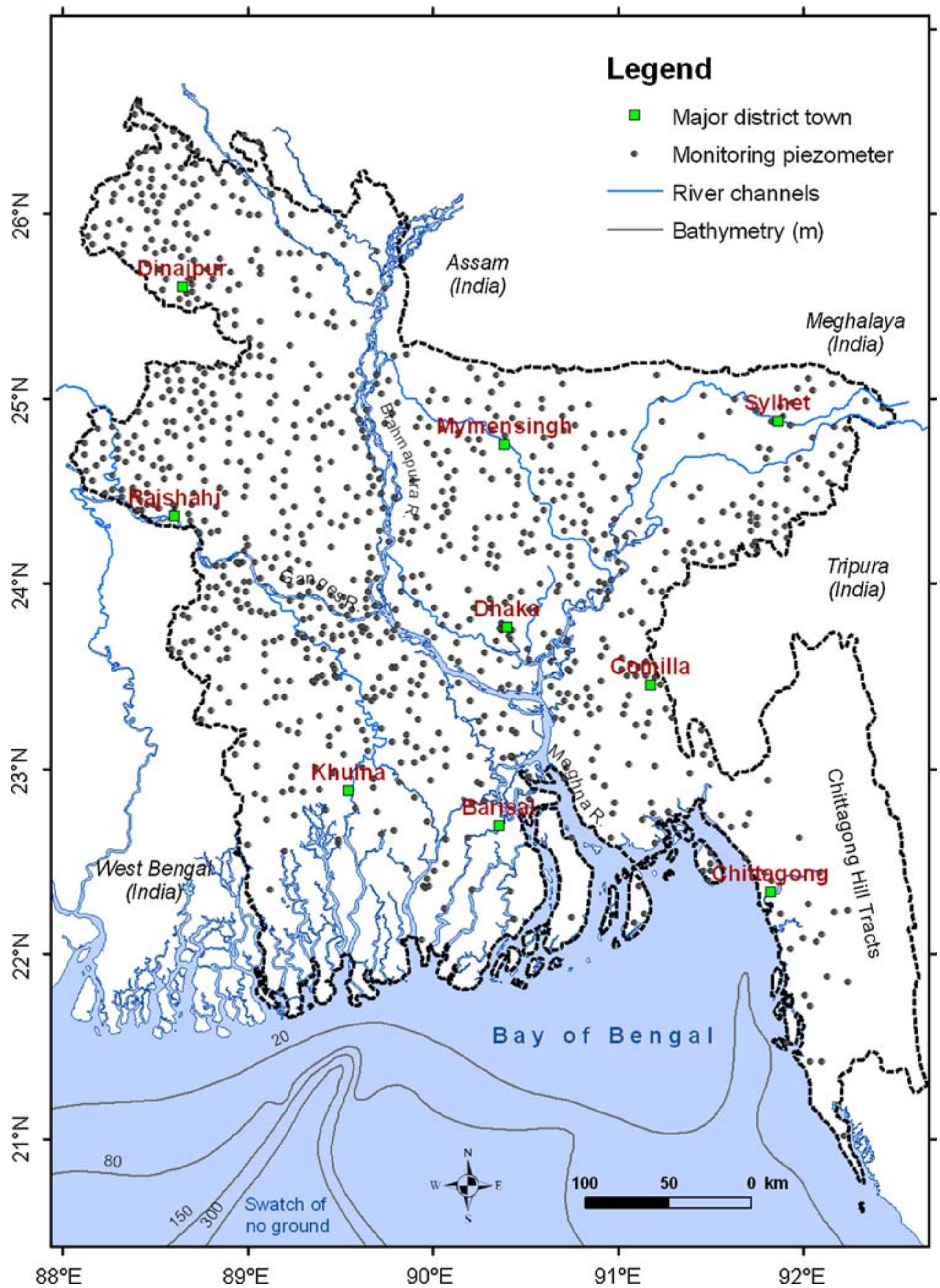


Fig. 3 Map showing the locations of 950 shallow (mean depth $\sim$20 m) groundwater monitoring piezometers from the Bangladesh Water Development Board water-table monitoring network. Water-table data in 2003 were used for generating hydraulic head distribution maps. The locations of some major district towns are also shown on this map

Digital elevation model can be used to derive slope and aspect of any area of interest within the extent of the DEM raster dataset. In this study, topographic slope (0–90°) was derived from the DEM for Bangladesh using the surface analysis tool in the ArcGIS program (Fig. 4). Since a major portion of the country is covered by low-lying floodplains and delta plains, the resulting slope is very small except for the eastern part where the surface topography is rugged due to folding of the Cenozoic sediments. However, minor variations in the slope distributions are noticed within the central and northwestern Bangladesh in the Madhupur and Barind Tract areas, respectively (Fig. 4). Slope at each NHS tubewell has been extracted by the same GIS method described in the previous section.

Groundwater elevation data from the shallow aquifers were used to create water level surface maps by interpolating from 950 data points using Universal Kriging (UK) method with an exponential semivariogram model. The Universal Kriging is one of the most appropriate interpolation methods for contouring groundwater level, which is generally a non-stationary variable (Gundogdu and Guney 2007). Since the regional groundwater flow in Bangladesh

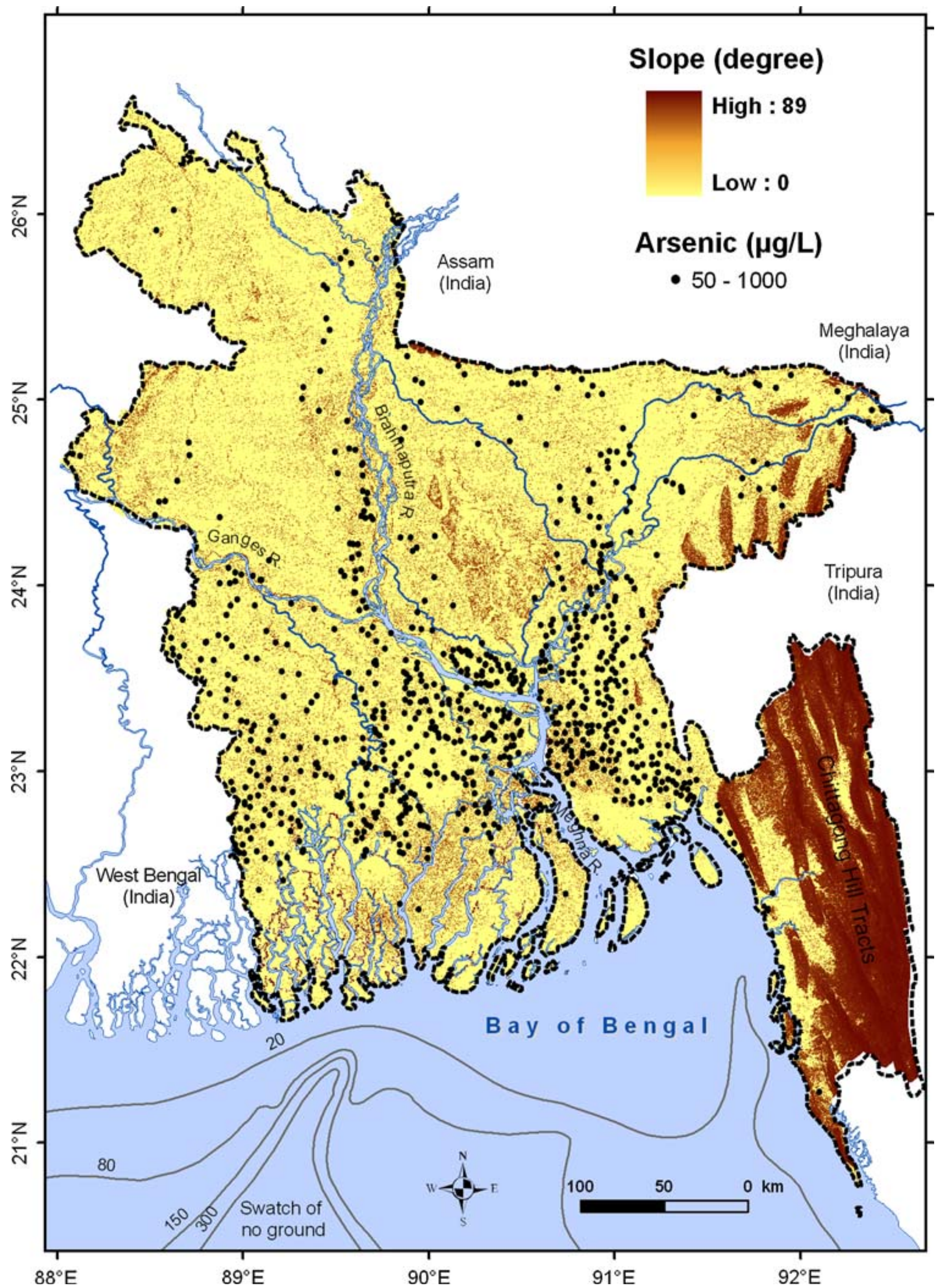


Fig. 4 Topographic slope distributions in Bangladesh as derived from DEM. Tubewells containing groundwater As more than 50 µg/l are concentrated within the GBM delta, Sylhet Trough and recent floodplains

is mainly driven by topography (variations in elevation), there is a general trend (from north to south) in the groundwater levels. Groundwater level data were detrended using a first-order polynomial regression before modeling the semivariances and applying for geostatistical interpolation. Three interpolated groundwater elevation surface maps (Fig. 5) were generated for three different hydrological phases during a calendar year: (i) groundwater elevation map for the maximum water depth during 2003, which corresponds to the lowest water-table that is generally reached during the driest or highest irrigation period (March–April); (ii) groundwater elevation map for the minimum depth during 2003, which corresponds to the highest water-table that is generally reached during the peak of monsoon rainfall and flood event (August–September); and (iii) mean groundwater elevation map for 2003, which corresponds to either the onset of monsoon rainfall or rapidly rising groundwater level (June–July) or to the natural recession of groundwater level (November–December). The gridded raster datasets of groundwater level were clipped within the international boundary of Bangladesh using a vector dataset of the political boundary

(Fig. 5). Interpolated water level elevations at the NHS tubewell locations were extracted from the mean water level elevation raster dataset using the extraction function in spatial analyst extension.

In this study, both descriptive and bivariate statistical methods were applied to evaluate the relationships between groundwater As, elevation, slope and groundwater levels. The descriptive statistical method was applied to summarize the basic statistical parameters of surface elevation, slope, and groundwater levels for given thresholds (10, 10–50, and >50 µg/l) of groundwater As concentrations. The bivariate statistics determine the nature of relationships between variables and ascertains the strength of their statistical association. Pearson correlation coefficients were calculated to evaluate the relationships between groundwater As, surface elevation, slope and groundwater levels. Emphasis was given more on the descriptive statistics than the correlation analysis since the relationships between the variables are mostly non-linear.

Results and interpretations

Surface elevation and groundwater arsenic

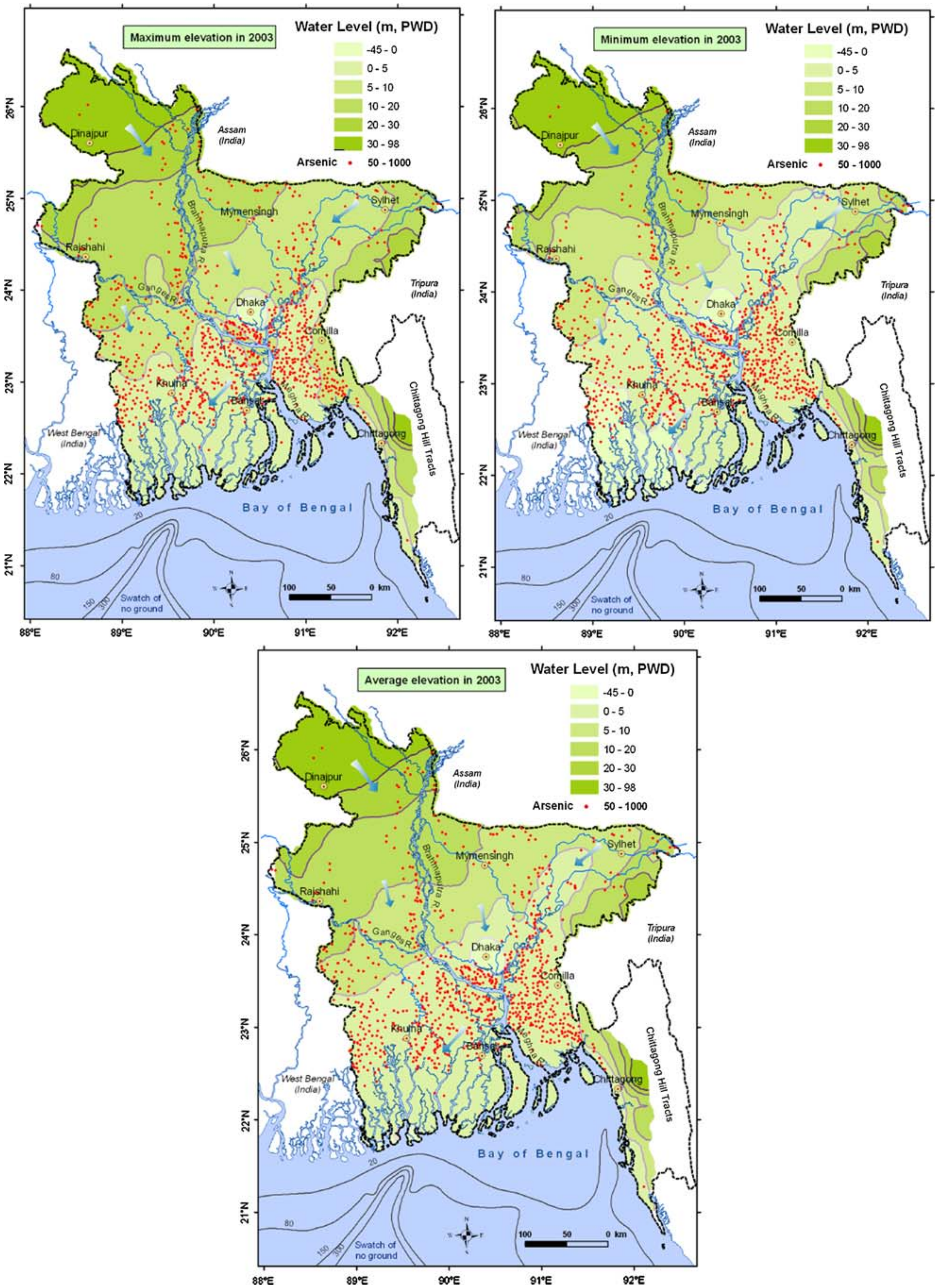
Variations in surface topography and groundwater As levels are shown in Fig. 2 using DEM and a total of 3,043 shallow tubewells from the NHS database. High As (>50 µg/l) tubewells are located mostly within the low-lying GBM delta and in Sylhet Trough area (Fig. 2). The surface elevations of these areas vary from <1 m to as high as 15 m. Some high As tubewells are located over the northwestern stable delta parts (south of the Ganges river), Brahmaputra river floodplains and Atrai depression where elevation can reach as high as 25–30 m. It should be noted that the relationship between groundwater As and surface elevation is non-linear (Fig. 6a). The Pearson correlation coefficient (r) between As and surface elevation is −0.30 ($P < 0.0001$), which suggests that these two variables are negatively correlated. However, both high (>50 µg/l) and low (<50 µg/l) groundwater As concentrations are found within low (<15 m) elevation in the country (Fig. 6a). Two regional transect lines across the country show the spatial relationship between groundwater concentrations and variation in surface elevation (Fig. 7). From these N–S and E–W trending profiles, it is apparent that the relationship between surface elevation and groundwater As distribution is negative on regional scales. High groundwater As values are found within low topographic areas. Within the As hotspots, subtle change in surface elevation seems to have noticeable influence on As concentrations (Fig. 7). Descriptive statistical analysis (Table 1) shows that 56% of NHS tubewells with As concentrations of <10 µg/l (in estimated area of 39,055 km^2 excluding the Chittagong Hill Tracts and the Sundarbans) are located within the elevated areas with a mean elevation of 22 m (above msl). Arsenic concentrations of 10–50 µg/l (in estimated area of 35,536 km^2) are located in slightly elevated areas where the mean elevation is approximately 14 m with a standard deviation of 8.5 m. Areas with the surface elevation of 10 m or less tend to be highly contaminated (>50 µg/l) with groundwater As, which covers an area of approximately 54,235 km^2 (Table 1). However, the standard deviation of SRTM elevation within these low-lying areas is approximately 5 m.

Fig. 5 Groundwater hydraulic head distribution maps of Bangladesh ▶ as interpolated from a total of 950 shallow piezometers. Universal Kriging (UK) method with exponential semivariogram models was applied for creating these gridded maps. Tubewells with As concentrations exceeding 50 µg/l are superimposed on these hydraulic head maps for visual comparison. The maximum, minimum and mean hydraulic heads during 2003 are shown here with the general directions for groundwater flows (*arrows* on maps) in the shallow (depth <100 m) aquifer system. High As wells are mostly located in south-central Bangladesh where hydraulic heads are very low with no significant variations in the horizontal hydraulic gradients

Slope and groundwater arsenic

The spatial relationship between groundwater As distributions and topographic slope in Bangladesh is shown in Fig. 4. For more than 90% area of Bangladesh, the topographic slope is below 4°. Slopes are higher (10–80°) in the elevated areas in the Chittagong Hill Tracts and Sylhet in eastern Bangladesh. In the central part, slopes are as high as 10° only in the Madhupur Tract, which is a Pleistocene highland. Within the GBM delta, Sylhet Trough, and alluvial floodplains, the average slope is below 1.0°, sometimes ranging from 0.1 to 1.5°. In the southern GBM delta, slopes are slightly higher than the rest of the delta complex.

Arsenic-contaminated tubewells (NHS dataset) are located within the low-slope areas, such as GBM delta, Sylhet Trough and alluvial floodplains in Bangladesh (Fig. 4). Although the variations in As concentrations with the variations in slope (all samples, $n = 3{,}040$) are not significant on a regional-scale as suggested by the correlation coefficient ($r = -0.05$, $P < 0.10$), the correlation between As concentrations and particularly high slopes (>1.5°; $n = 200$) is negative ($r = -0.17$, $P < 0.05$). A scatterplot between groundwater As and topographic slope in Fig. 6b shows the association of high As with very low surface slope in the country. Tubewells with low concentrations of As are also found within low slope areas, but high As wells are not found in the areas of high slope (>1.0°). Table 1 shows the relationship between slope and groundwater As with other statistical attributes. Wells with


Maximum elevation in 2003
Water Level (m, PWD)
-45 - 0
0 - 5
5 - 10
10 - 20
20 - 30
30 - 98
Arsenic 50 - 1000
Dinajpur
Assam (India)
Brahmaputra R.
Mymensingh
Sylhet
Rajshahi
Ganges R.
Dhaka
Tripura (India)
Comilla
Khulna
Barisal
Meghna R.
West Bengal (India)
Chittagong
Chittagong Hill Tracts
Bay of Bengal
20
80
150
300
Swatch of no ground
100 50 0 km
88°E 89°E 90°E 91°E 92°E
21°N 22°N 23°N 24°N 25°N 26°N
Minimum elevation in 2003
Water Level (m, PWD)
-45 - 0
0 - 5
5 - 10
10 - 20
20 - 30
30 - 98
Arsenic 50 - 1000
Average elevation in 2003
Water Level (m, PWD)
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30 - 98
Arsenic 50 - 1000

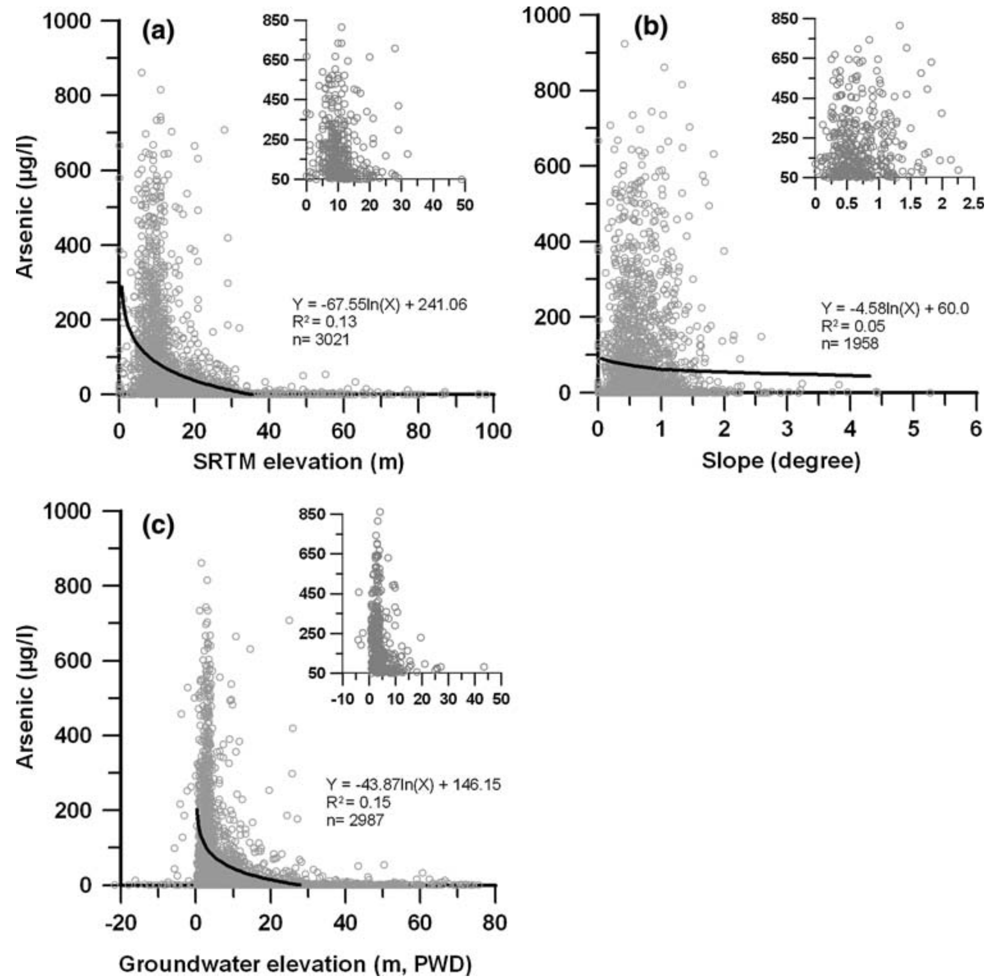

Fig. 6 Bivariate scatter plots with best fit lines show relationship between groundwater As, SRTM elevation, slope and groundwater levels in shallow aquifers. **a** shows the non-linear relationship between groundwater As and surface elevation. The overall relationship is negative. High As concentrations (>50 µg/l) are mainly found at low elevations (<10 m above msl; see *inset graph*); **b** scatterplot shows the non-linear relationship between groundwater As and slope. The overall relationship is negative. High As concentrations are found at low slopes (<1°; see *inset graph*); and **c** scatter plot shows the non-linear relationship between groundwater As and groundwater levels (m, PWD). The overall relationship is similar to that seen between groundwater As, surface elevation and slope. High As concentrations are found at low groundwater elevations (<10 m above PWD; see *inset graph*)

As levels exceeding 50 µg/l are located in areas where mean slope is approximately 0.60° with a standard deviation of 0.35°. Low concentrations (<10 µg/l) of As are found in areas of slightly higher slopes where the mean slope is ~0.70°.

Groundwater elevation and arsenic

Three water-level gridded maps (maximum, minimum and average hydraulic heads) in the shallow aquifers of Bangladesh for the year 2003 have been generated from the BWDB monitoring piezometers (Fig. 5). Hydraulic heads are reported as groundwater elevation (m) with respect to the PWD, which is located approximately at the mean sea level. Groundwater elevation maps (Fig. 5) show that the water levels are higher in the northwestern part of Bangladesh, where surface elevations are also high. Groundwater elevations are fairly low (<10 m above PWD) in the GBM delta plains and display broad depressions in the northeastern Sylhet region of the country. There is a broad circular (~30 km in diameter) cone of depression surrounding Dhaka city where groundwater abstraction has been exponentially increasing since the early 1980s (Hoque et al. 2007). From these national-scale maps, it is seen that the groundwater flow paths in the shallow aquifers are towards the general direction of south–southwest. Hydraulic head distribution maps suggest that groundwater (depth <100 m) flows toward the deep submarine canyon of the "swatch of no ground" in the Bay of Bengal (Fig. 5), but this requires further investigation and substantiation. Other than variations in seasonal magnitude of groundwater heads, there are no strong variations in the regional patterns of groundwater head distributions. Overall, groundwater flow in the country is mainly topography-driven and varies with precipitation, interaction with river channels and irrigation abstractions (BGS and DPHE 2001; Harvey et al. 2006). Around Dhaka city, groundwater elevation is exceptionally low (less than −30 m) due to extremely high withdrawal (domestic and industrial water supplies) of groundwater that exceeds the natural recharge rate by several orders of magnitude (Hoque et al. 2007). High As tubewells are located within the areas of low groundwater levels in Bangladesh (Fig. 5). Relationship between groundwater As and shallow piezometer hydraulic heads is non-linear (Fig. 6c) and inverse as suggested by the

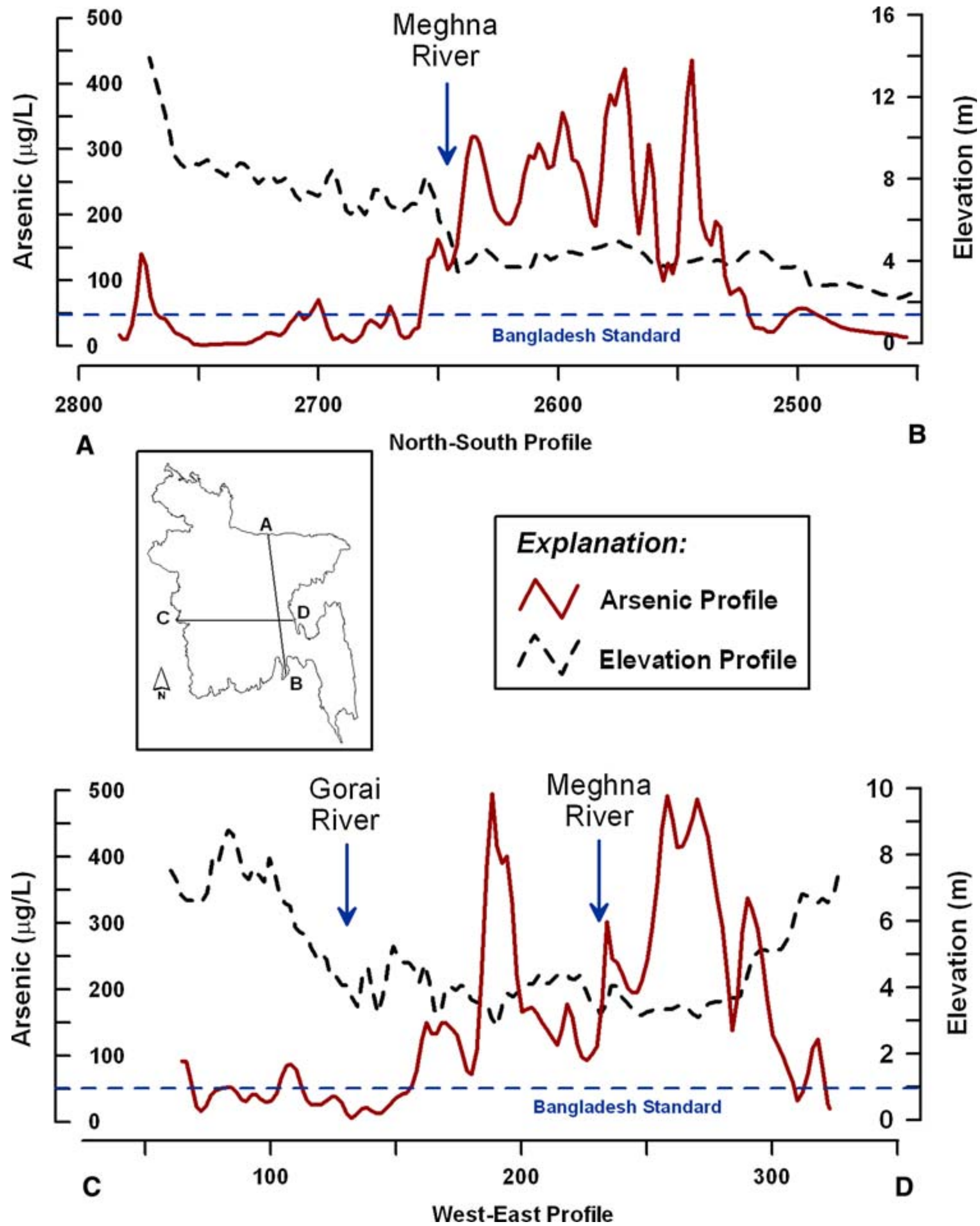

Fig. 7 Two regional transects (**a**) *A*–*B* (north–south) and (**b**) *C*–*D* (west–east) across Bangladesh show the variations in groundwater As concentrations against surface elevation (modified from Shamsudduha and Uddin 2007). In south-central Bangladesh, where surface elevation is very low, most wells are contaminated with high As levels

negative Pearson correlation coefficient ($r = -0.28$, $P < 0.0001$). High As values are mostly found within very low (<10 m) groundwater level areas, although co-existence of both high and low As wells is not uncommon. Descriptive statistical analysis shows (Table 1) that approximately 27% of NHS tubewells with As concentrations exceeding 50 µg/l are located within areas where the mean water-table elevation is approximately 4.5 m with a median of 3.25 m. Low As (<10 µg/l in estimated 39,055 km^2) tubewells are located in the areas where the mean hydraulic head in 2003 was 16 m (above PWD) with a median of 11 m. Tubewells with moderate As concentrations (10–50 µg/l) are found where the mean hydraulic head is 9.2 m with a median of 7.0 m above the PWD (Table 1).

Discussion and conclusions

In this study, high levels (>50 µg/l) of As are generally found in areas of low surface elevation, gentle slopes, and low groundwater levels on a regional-scale in the Bengal Basin. All these components are inter-related and are controlled by geology, geomorphology, precipitation and abstraction (irrigation and urban water supplies). Surface elevation and topographic slopes, and to a lesser extent, heterogeneity in fluvial geology, are the main factors that greatly control regional-scale groundwater flow within the shallow alluvial aquifers in the basin. Although the negative correlation coefficients between groundwater As, surface elevation and slope are not statistically significant,

Table 1 Descriptive statistics on the relationships within surface elevation, topographic slope, groundwater elevation, and arsenic concentrations in Bangladesh

Surface elevation (SRTM, m) and groundwater arsenic			
Statistical parameters	Elevation at As < 10 μg/l	Elevation at As 10–50 μg/l	Elevation at As > 50 μg/l
Number of As data points	1687	539	813
As-affected area cover (in km^2)	39,055 (30%)	35,536 (28%)	54,235 (42%)
Range (surface elevation)	0–98	0–77	0–55
Mean elevation (m)	22.2	14	10.6
Median (m)	18	13	10
95% confidence interval	0.68	0.72	0.35
Standard deviation	14.2	8.51	5.16
Variance	203	72	27
Percentage (NHS shallow tubewells)	56%	18%	26%
Slope (degree) and groundwater arsenic			
	Slope at As < 10 μg/l	Slope at As 10–50 μg/l	Slope at As > 50 μg/l
Number of As data points	1687	539	814
As-affected area cover (in km^2)	39,055 (30%)	35,536 (28%)	54,235 (42%)
Range (topographic slope)	0–5.3	0–3.8	0–2.6
Mean slope (degree)	0.70	0.67	0.60
Median (degree)	0.62	0.62	0.61
95% confidence interval	0.022	0.032	0.024
Standard deviation	0.45	0.38	0.35
Variance	0.21	0.15	0.13
Percentage (NHS shallow tubewells)	55%	18%	27%
Groundwater elevation (average in 2003, in meter with respect to PWD) and arsenic			
	Water elevation at As < 10 μg/l	Water elevation As 10–50 μg/l	Water elevation As > 50 μg/l
Number of As data points	1677	536	811
As-affected area cover (in km^2)	39,055 (30%)	35,536 (28%)	54,235 (42%)
Range (groundwater elevation)	−21 to 75	−16 to 67	−5 to 50
Mean water level (m)	16	9.2	4.5
Median (m)	10.95	6.9	3.25
95% confidence interval	0.72	0.73	0.31
Standard deviation	15	8.7	4.5
Variance	226	76	21
Percentage (NHS shallow tubewells)	55%	18%	27%

Variations in SRTM elevation, slope and groundwater elevation within three categories of As concentrations (safe As level <10 μg/l; moderate As level 10–50 μg/l and high As level >50 μg/l) are given above. Areas within these three categories of As concentrations in the country are estimated from gridded As map produced by spatial GIS method. The Chittagong Hill Tracts and Sundarbans are excluded from the area estimation

nevertheless, it is clear from the results of both bivariate correlation and descriptive analyses that high concentrations of As are associated with low elevation and low slope. Similar relationships have been reported in the Pannonian Basin of Hungary (Varsanyi and Kovacs 2006), and the Bassac and Mekong River banks and alluvium deposits in Cambodia (Buschmann et al. 2007), where most of the high As wells are located within topographically low areas. Coexistence of high and low As tubewells within short spatial distances and even in the same aquifer suggests greater spatial heterogeneity of sediments in the shallow aquifers as discussed in Weinman et al. (2006). Their study also described how high-energy rivers during the Holocene time in the GBM delta interacted with the low-lying floodplains and deltaic landforms and created a complex sedimentological framework, which accounts for the arsenic heterogeneity over very small spatial scales (i.e., within 100 m). Moreover, heterogeneity in sediment size controls the variations in permeability and hydraulic conductivity in aquifers (Hoque et al. 2008; Aziz et al. 2008). Generally, hydrologic flushing rates are higher in coarser sediments (e.g., sand bar), and lower in low-energy deposits (e.g., overbank floodplain deposits) and these variable fluxes can cause small-scale variations in groundwater As concentrations.

Groundwater As distributions are shown to be associated with the groundwater elevation of shallow aquifers as depicted from the piezometer water levels. GIS analysis shows that the distribution of groundwater hydraulic heads follows the regional surface elevation. High As tubewells are found within the areas of low (<10 m above PWD) groundwater elevations. Results suggest a negative correlation between high As concentrations and low groundwater levels in the country. Variations in hydraulic heads are relatively higher in the high abstraction areas (e.g., Rajshahi district; Fig. 5) between monsoon and summer periods (Fig. 5). Shallow groundwater heads fluctuate within 10's of centimeters to a few meters (up to 10 m with a median of 3.5 m) in most of the country. Within the As-affected (>50 μg/l) areas (Fig. 5), the annual fluctuation (based on the range of hydraulic head distributions in 2003) of shallow groundwater heads is smaller where the mean head is 3.0 m with a standard deviation of 1.5 m. Groundwater levels in shallow aquifers in the GBM delta areas rise almost to the surface level during the monsoon seasons, although differences between the dry season and monsoon hydraulic heads in the other parts of the country are higher than in the GBM areas (Aggarwal et al. 2000). Shallow aquifers in most of the country reach the full saturation condition almost every year with heavy monsoon rainfall and flooding, particularly in the low-lying areas (Harvey et al. 2006). Groundwater flow within the shallow aquifers varies from a local- to intermediate-scale (1,000 m to 10 km) to a regional-scale (10–100 km), which is mainly driven by variations in topographic elevation, slope and irrigation abstractions (Ravenscroft et al. 2005; Mukherjee et al. 2007). The natural groundwater flow is thought to be greatly disrupted by large-scale irrigation pumping during the dry period when vertical flow overtakes the lateral groundwater flow (Ravenscroft et al. 2005; Harvey et al. 2006). Regional geomorphic features such as the Tertiary hills, Pleistocene terraces and major rivers control the groundwater flow-system within the country (BGS and DPHE 2001).

Groundwater flow is greatly dependent on variations in the regional hydraulic gradients, except where the natural groundwater flow is disrupted by dry-season irrigation pumping (Harvey et al. 2006; Klump et al. 2006). In general, hydraulic gradients are small throughout the country in the absence of dry-season irrigation pumping (Harvey et al. 2006). Hydraulic gradients in the shallow aquifers seem to vary both in time and space due to precipitation, evapotranspiration and variations in aquifer hydrogeology and hydraulic parameters. BGS and DPHE (2001) reported that the hydraulic gradients vary in Bangladesh from about 1.0 m/km in the northern part to 0.01 m/km in the south. In a different study, the hydraulic gradients were reported as 2.0–0.5 m/km in the north, and 0.10–0.01 m/km in the south of Bangladesh (BAMWSP 2002). Lateral groundwater flow within these alluvial aquifers is slow within the Holocene floodplains where the hydraulic gradient is commonly very low (0.0001) and the Darcy velocity is about 2 m/year (Burgess et al. 2002; Ravenscroft et al. 2005). From hydraulic head distribution maps (Fig. 5), the average horizontal hydraulic gradients of shallow aquifers in different regions in Bangladesh have been estimated as follows: (i) hydraulic gradient (dh/dl) in the northwestern part is 0.35–0.25 m/km (northwest to southeast direction); (ii) 0.05–0.01 m/km (northwest to southeast direction) in the central part; and (iii) 0.01–0.001 m/km (north to south–southwest direction) in the southern part. During floods in the wet season, very little groundwater flow occurs as the hydraulic gradients become negligible in most low-lying places (Harvey et al. 2002). In the GBM delta, As-rich (>50 μg/l) groundwaters in shallow (<100 m) aquifers mostly occur in broad depressions and low-lying floodplains of the major rivers, where groundwater elevation (regardless of seasonal variations) is hardly above 5 m relative to the PWD.

Low hydraulic gradients in shallow aquifers can greatly slow down the aquifer-flushing process and obstruct regular replenishment by new oxic groundwater (Mukherjee et al. 2007). Gentle slope and low-energy conditions in surface water systems favor accumulation of finer sediments and organic matter within the low-lying delta and floodplains areas. Consequently, As and other dissolved metals can be adsorbed by iron-oxyhydroxides, which are flocculated as fine-grained sediments within low-energy deltaic and floodplain environments (Dowling et al. 2002). Arsenic is released in groundwater of the shallow aquifers by the reductive dissolution process aided by iron-reducing microbes (Islam et al. 2004), which occurs more completely where abundant organic matter has accumulated and groundwater flushing is slow. In addition, sluggish groundwater flow and low topographic gradients can cause recycling of As-rich groundwater over a long period of time within the same shallow aquifers (mostly in the GBM deltaic areas and floodplains), which are already contaminated (Zheng et al. 2004; Harvey et al. 2006; Mukherjee et al. 2007).

The national-scale spatial distributions of groundwater As are constrained within the shallow aquifers in low-elevation areas with extremely low topographic relief and negligible hydraulic gradients. Results suggest that spatial distributions of As in the lowland deltas and floodplains are controlled by regional topography and slow flushing. Results from this study along with proper information on surface and sub-surface geology, and aquifer distributions can be used to locate areas of possible low groundwater As in shallow aquifers at the regional scale. However, it would be interesting to investigate the relationship between groundwater As, topography and groundwater level dynamics at the local scale (e.g., 1–10 km) to better understand the small-scale heterogeneity in groundwater As distributions and its mobilization in the shallow aquifers in Bangladesh.

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