Regional hydrostratigraphy and groundwater flow modeling in the arsenic-affected areas of the western Bengal basin, West Bengal, India

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Abstract The first documented interpretation of the regional-scale hydrostratigraphy and groundwater flow is presented for a ~21,000-km^2 area of the arsenic-affected districts of West Bengal [Murshidabad, Nadia, North 24 Parganas and South 24 Parganas (including Calcutta)], India. A hydrostratigraphic model demonstrates the presence of a continuous, semi-confined sand aquifer underlain by a thick clay aquitard. The aquifer thickens toward the east and south. In the south, discontinuous clay layers locally divide the near-surface aquifer into several deeper, laterally connected, confined aquifers. Eight 22-layer model scenarios of regional groundwater flow were developed based on the observed topography, seasonal conditions, and inferred hydrostratigraphy. The models suggest the existence of seasonally variable, regional, north–south flow across the basin prior to the onset of extensive pumping in the 1970s. Pumping has severely distorted the flow pattern, inducing high vertical hydraulic gradients across wide cones of depression. Pumping has also increased total recharge (including irrigational return flow), inflow from rivers, and sea water intrusion. Consequently, downward flow of arsenic contaminated shallow groundwater appears to have resulted in contamination of previously safe aquifers by a combination of mechanical mixing and changes in chemical equilibrium.

Résumé Pour la première fois une interprétation de l'hydrostratigraphie à l'échelle régionale et de l'écoulement des eaux souterraines est présenté sur une zone de ~21,000-km^2 des districts affectés par l'arsenic dans l'Ouest du Bengal en Inde (Murshidabad, Nadia, Parganas Nord 24 et Parganas Sud 24 (incluant Calcutta)). Un modèle hydrostratigraphique démontre la présence d'un aquifère continu et semi-captif recouvrant un aquitard épais argileux. L'épaisseur de l'aquifère augmente vers l'est et le sud. Au sud, des couches discontinues d'argile partagent localement l'aquifère proche de la surface en plusieurs aquifères captifs, plus profonds et connectés latéralement. Huit scénarios de modèle d'écoulement régional à 22 couches ont été développés sur la base de la topographie, des conditions saisonnières et de l'hydrostratigraphie déduite. Les modèles suggèrent l'existence d'un écoulement régional variable selon les saisons, orienté nord-sud à travers le bassin avant l'intensification des pompages dans les années 1970. Le pompage a sévèrement modifié les lignes d'écoulement, induisant des gradients hydrauliques verticaux élevés au droit de larges cônes de rabattement. Le pompage a également augmenté la recharge totale (recharge par irrigation inclue, l'eau d'irrigation provenant des aquifères), l'écoulement par les rivières et l'intrusion d'eau de mer. Par conséquent, l'écoulement descendant des eaux phréatiques contaminées par l'arsenic apparaît comme le résultat de la combinaison de mécanismes de mélange et de changements des équilibres chimiques.

Resumen Se presenta la primera interpretación documentada de hidroestratigrafía y flujo de agua subterránea a escala regional para un área de ~21,000-km^2 de los distritos afectados con arsénico en Bengala Occidental (Murshidabad, Nadia, Parganas 24 Norte y Parganas 24 Sur -incluyendo Calcuta-, India. El modelo hidroestratigráfico demuestra la presencia de un acuífero de arena continuo semi-confinado que sobreyace un acuitardo grueso de arcilla. El acuífero aumenta su espesor hacia el oriente y el sur. En el sur, las capas discontinuas de arcilla dividen localmente el acuífero cercano a la superficie en varios acuíferos confinados más profundos conectados lateralmente. Se desarrollaron ocho escenarios de modelos con 22 capas de flujo regional de agua subterránea en base a la topografía observada, condiciones estacionales, e hidroestratigrafía inferida. Los modelos sugieren la existencia de flujo regional norte-sur con variación estacional a través de la cuenca antes del inicio de bombeo extensivo durante los 1970s. El bombeo ha distorsionado fuertemente el patrón de flujo induciendo

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gradientes hidráulicos verticales altos a través de anchos conos de depresión. El bombeo también ha incrementado la recarga total (incluyendo el flujo de retorno por riego), entrada de ríos, e incursión de agua de mar. En consecuencia, el flujo descendente de flujo de agua subterránea somera contaminada con arsénico parece dar por resultado la contaminación de acuíferos previamente seguros mediante una combinación de mezcla mecánica y cambios en equilibrio químico.

Keywords India · Hydrostratigraphy · Groundwater flow · Arsenic · Western Bengal basin

Introduction

More than 2% (120 million) of the total population (6 billion) of this planet lives in an area of ~200,000 km^2 covering the eastern part of the state of West Bengal (India) and most of Bangladesh. This area, known as the Bengal basin (Morgan and McIntire 1959), is the world's largest fluvio–deltaic system (Coleman 1981; Alam et al. 2003). The basin is drained jointly by the River Ganges, River Brahmaputra (also known as River Jamuna in Bangladesh), River Meghna and their numerous tributaries and distributaries, and hence is also known as the Ganges–Brahmaputra–Meghna (GBM) basin.

Indiscriminate use of the rivers and streams as pathways of sewerage and industrial waste by the Bengal basin inhabitants has made the surface water impotable. Moreover, the introduction of high-yielding dry-season rice (Boro) (Harvey et al. 2005) accelerated the demand for irrigation. This led to the shift of water supply policy from surface water to groundwater in both West Bengal and Bangladesh during the early 1970s. As a consequence, several million wells (ranging from low yielding hand-pumped to heavy-duty motor-driven) were installed in order to meet drinking, irrigation, and industrial water demands (Smith et al. 2000; BGS/DPHE/MML 2001; Harvey et al. 2005; Horneman et al. 2004). However, by the 1990s, a large part of the Bengal basin groundwater was determined to have elevated concentrations of arsenic (As), which can impact human health at concentrations of 10 μg/l in drinking water (WHO 1993). It has been hypothesized that the non-point source, geogenic As, mostly occurs in the Holocene shallow aquifers of the Bengal basin and probably has been mobilized from the sediments by redox reactions (e.g., Saha 1991; Bhattacharya et al. 1997; CGWB 1997; Nickson et al. 1998; BGS/DPHE/MML, 2001; McArthur et al. 2001, 2004; Ravenscroft et al. 2001; Harvey et al. 2002; Mukherjee 2006). Estimates show that at present about 25% (McArthur et al. 2004) to 33% (Horneman et al. 2004) of the wells have been identified to be contaminated by As. Consequently, several hydrogeologic studies have been conducted in the Bengal basin (mostly in Bangladesh) to evaluate the groundwater resources and to understand the role of groundwater dynamics (local to regional scale) in influencing the movement of As-contaminated water within the alluvial aquifers (e.g., MPO 1987; Burgess et al. 2002; Harvey 2002; JICA 2002; Cuthbert et al. 2002; Nishant et al. 2003; Ravenscroft 2003; van Wonderen 2003; Ravenscroft et al. 2005; Harvey et al. 2006).

In the western part of the Bengal basin (West Bengal), in spite of district-level surveys of groundwater resources by the Central Ground Water Board (CGWB 1994a, b, c, d, e) and State Water Investigation Directorate (SWID 1998), detailed hydrogeologic studies are lacking. This report provides the results of a multiyear hydrogeologic study in four districts of West Bengal investigating groundwater flow within the arsenic-affected alluvial aquifers. The objectives of the study were to delineate the regional aquifer–aquitard framework of the study area and to evaluate the hydrostratigraphic controls, the effects of seasonal variability, and the effects of pumping (primarily for irrigation) on the spatial and temporal patterns of groundwater flow. The study focused on the deeper regional-scale flow (Tóth 1963) instead of the shallower, local-scale flow, on the premise that understanding sub-basinal scale hydrodynamics is important for evaluating the possibility of arsenic movement from contaminated shallow aquifers to the as-yet uncontaminated deep aquifers (e.g., van Geen et al. 2003). Efforts were also made to understand the interaction between the local and regional flow systems, along with estimating and understanding the control of recharge and hydraulic parameters on the regional flow.

Study area setting

Extent

Figure 1 shows the study area, which comprises ~21,000 km^2 of the As-affected areas of four districts of West Bengal, India. These include the eastern part of Murshidabad, Nadia, North 24 Parganas and South 24 Parganas. About 40 million people reside in this area, which includes the city of Kolkata (formerly Calcutta) and several other important towns. The area represents an interfluvial delta plain (Fig. 1b,c), bounded by the main channel of the River Ganges in the north, the River Bhagirathi-Hoogly in the west, the rivers Jalangi, Bhairav, Ichamati, Raimangal and Kalindi in the east, flowing almost along the Indo-Bangladesh border, and the Bay of Bengal in the south. The River Churni diverges from the River Ichamati and flows toward the River Bhagirathi-Hoogly, and the River Matla drains the southern parts of South 24 Parganas (Survey of India 1971). These rivers are the most important geomorphic features in the study area.

In general, the topography of the study area is very flat [maximum elevation of about 35 m above mean sea level (MSL) near Jangipur, Murshidabad, sloping toward the Bay of Bengal in the south], with a gradient of ~0.1 m/km from north to south. In order to obtain detailed elevations, a digital elevation model (DEM) was acquired from the Shuttle Radar Topography Mission (SRTM 90) of the US National Aeronautics and Space Administration (NASA;

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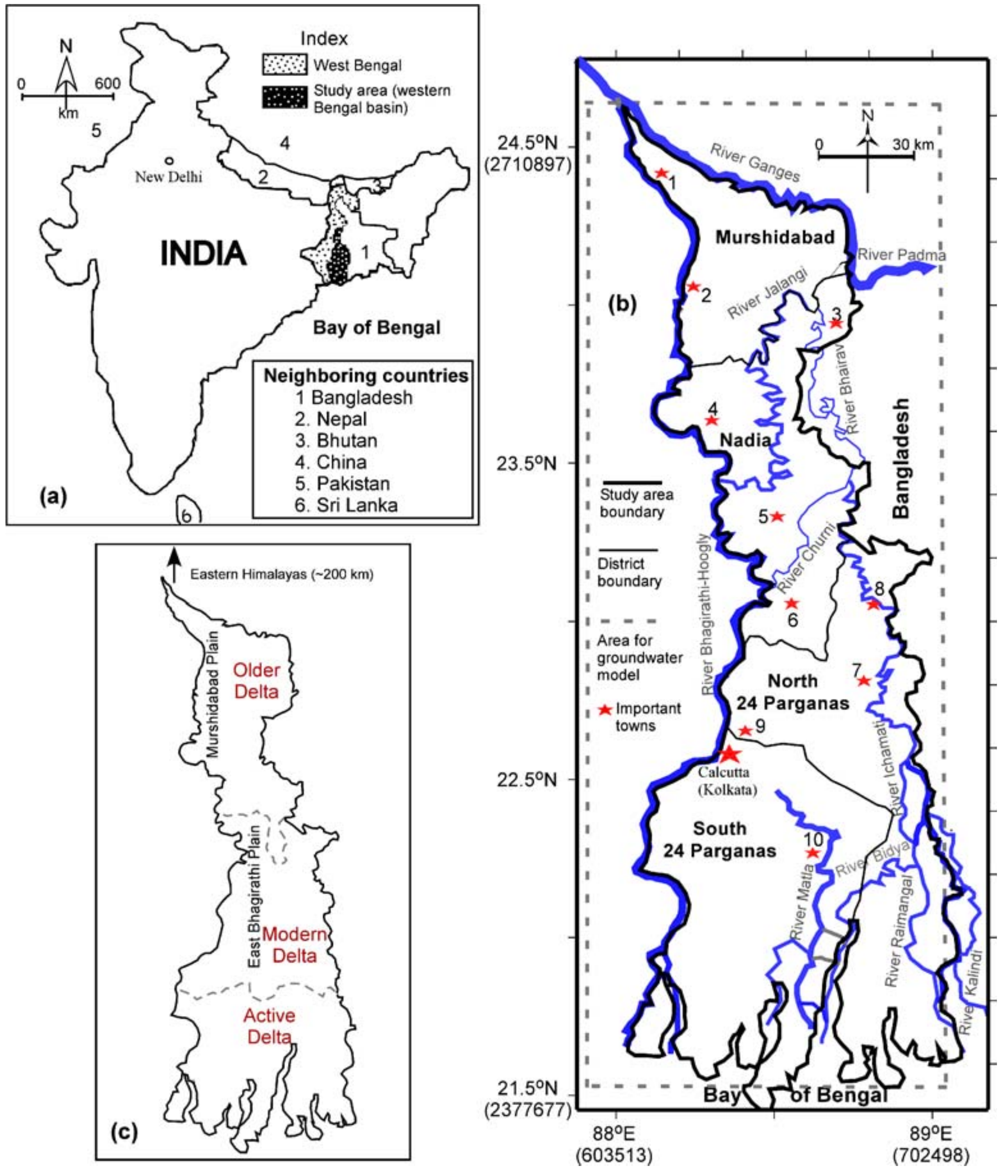

Fig. 1 Map of the study area (**a**) showing its location within West Bengal in India, and neighboring countries. **b** The extent of the groundwater model and the important rivers (*in blue*) and towns (*red stars*) within the study area: *1* Raghunathganj, *2* Behrampur, *3* Tehatta, *4* Debagram, *5* Krishna Nagar, *6* Ranaghat, *7* Bashirhat, *8* Bongaon, *9* Barasat, *10* Canning. The UTM coordinates (in parentheses) are listed beside the respective latitude and longitude coordinates. **c** The broad geomorphic divisions of the study area (after CGWB 1994e)

horizontal resolution of 3 arc-sec/90 m; vertical resolution of 1 m) and processed for the study area (ESM Fig. 1).

Coordinate system

The locations of the reference points within the study area were measured in the field by a Trimble® hand-held GPS using a spherical coordinate system of latitude and longitude (datum WGS84). To minimize the distortion for discretization of the grids for the lithologic and groundwater models, the location data were projected to Universal Transverse Mercator (UTM 1983), Zone 45 (central meridian 87, spheroid GRS 80, reference latitude 0, scale factor of 0.9996, false easting 500,000, false northing 0). The coordinates of origin of the modeled area for both type of modeling were easting 600,000, northing 2,380,000.

Background

Geology

The Bengal basin is a peripheral foreland basin formed as a consequence of subduction of the Indian plate below the Eurasian (Tibetan) and the Burmese plates. The basin is located at the junction of the three plates. It is bounded by the Peninsular shield of India in the west, Chittagong hills in the southeast, and the Dauki fault zone (Evans 1964) and Naga thrust in the north and northeast (Sengupta 1966). At present, about 1–8 km of Permian to Recent clastic sediments are thought to rest on the western part of the basin (study area) (Imam and Shaw 1985).

The stratigraphy of the study area [after Biswas (1963) and Lindsay et al. (1991)] starts with the deposition of the pre-Jurassic Gondwana deposits, which are overlain by the Late Jurassic to Early Cretaceous amygdaloidal basalts

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and andesites and the ~250-m-thick Late Cretaceous alternating sandstone–mudstone sequence of the Rajmahal Group. The Rajmahal Group is followed upward by a thick, uninterrupted, arenaceous-argillaceous sedimentary sequence from the early Paleocene to the end of the Pliocene, comprising the Jaintia Group (Paleocene–Eocene) and Bhagirathi Group (late Eocene to late Pliocene). The only interruption in this sandstone–shale sequence is the deposition of the basin-wide, fossiliferous Sylhet Limestone in the mid-Eocene. The sediments of the Bhagirathi Group are unconformably overlain by the late Pliocene–Pleistocene Barind Formation. These Pleistocene clays have a distinct yellow-orange hue and are found as elevated outcrops in the Barinds north of the study area and Madhupur Hills in central Bangladesh (Morgan and McIntire 1959). In turn, the Barind Formation is uncomformably overlain by the unconsolidated Holocene sediments of the Bengal Alluvium, which forms most of the surficial lithostratigraphic and geomorphic units throughout the Bengal basin.

In the study area, fluvial processes have resulted in the formation of extensive Holocene flood plains with a dominance of coarser grained sediments, representing the overlapping of a number of sub-deltas (Morgan and McIntire 1959). Avulsion of the major streams in the area, which are tributaries or distributaries of the River Ganges, within a time scale of 100 years, has resulted in a thick layer of tens of meters (Allison et al. 2003) of Recent overbank silts and clays incised by channel sands (Coleman 1969; Umitsu 1987; Goodbred and Kuehl 2000). The coastal region in the south has a mixture of fine-grained sand and mud deposits with peat layers, which have resulted from eustatic influence (Goodbred et al. 2003). Deposition of the lowest parts of the Bengal Alluvium began at the onset of the Pleistocene glacial maximum (Islam and Tooley 1999), with sea level (i.e., regional base level) at least 100 m below present MSL. Thus, the rivers draining the plain during that time must have scoured through the earlier plains (Umitsu 1993). Around 11,000 to 10,000 years before present (BP), deposition of lower delta mud over low-stand oxidized sand units started, suggesting sea level rise (Goodbred and Kuehl 2000) to about 45 m below present MSL (e.g., Fairbanks 1989). The present GBM delta began to prograde into the Bay of Bengal at this time (Lindsay et al. 1991; Goodbred and Kuehl 2000). From ~10,000 to ~7,000 years BP, rapid marine transgression occurred (Umitsu 1993; Islam and Tooley 1999; Goodbred and Kuehl 2000), resulting in the deposition of fine sediments. Since ~7,000 years BP to the present, the general trend of the eustatic sea-level curve shows continuing sea-level rise, although with a decreased gradient (Umitsu 1993; Islam and Tooley 1999; Goodbred and Kuehl 2000).

Hydrogeology

The western Bengal basin groundwater system is strongly influenced by the rainfall caused by the southeast monsoon wind. There are distinct dry seasons (October/November to May/June) and wet seasons (June/July to September/October). Annual rainfall ranges from about <1,200 mm to 1,600 mm (CGWB 1994e). Everywhere on the delta, precipitation exceeds annual potential evapotranspiration (Allison 1998). The heavy rainfalls during the monsoon period together with snow melt from the Himalayas cause extensive flooding in the Bengal lowlands.

There are very few published systematic descriptions or stratigraphic classifications available for the alluvial aquifers for the study area (for exceptions, see AIP/PHED 1991 and CGWB 1994e). However, several such studies have been done in the Bangladesh part of the basin (e.g., UNDP 1982; MPO 1987; Davies 1995; BGS/DPHE/MML 2001; Islam and Uddin 2002; Ravenscroft 2003; Uddin and Abdullah 2003; Ravenscroft et al. 2005). The British Geological Survey, Department of Public Health Engineering (Government of Bangladesh), and Mott MacDonald Ltd (UK) did the most extensive hydrogeologic study of Bangladesh and recognized five potential aquifers based on lithology (BGS/DPHE/MML 2001). Following their nomenclature, aquifers in the West Bengal part of the basin probably belong to (1) Late Pleistocene to Holocene Ganges sediments and (2) Early to Middle Pleistocene coastal and moribund Ganges delta deep aquifers composed of stacked, main-channel, medium to coarse sands at depths more than 130 m. CGWB (1994e) suggested that the aquifers of South 24 Parganas district at more than 250 m depth are of late Tertiary age. Many workers (e.g., BGS/DPHE/MML 2001; Horneman et al. 2004; Ravenscroft et al. 2005; von Bromssen et al. 2007) have suggested that the older (probably Pleistocene) sediments of Bangladesh are generally yellow-brown in color, in contrast to the more recent (Holocene) grey sediments, and the older sediments generally have lower hydraulic conductivity (K) values. However, such strata with distinctive color have not been reported from the study area (Mukherjee 2006).

The aquifers of the study area are highly productive, with the water table mostly encountered within 15 m below ground level (bgl). Groundwater levels tend to be similar from year to year at the beginning of each irrigation season, which suggests sufficient recharge replenishing the groundwater systems (BGS/DPHE/MML 2001). CGWB (1994a, b, c, d) and SWID (1998) estimated that transmissivity (T) values (in m^2/day) vary from 3,300 to 7,000 in Murshidabad, 5,000 to 8,800 in North 24 Parganas, and 500 to 3,000 in South 24 Parganas, with an average storativity (S) of 0.03. Values of porosity (n) were assumed to be 0.2 for the Bangladesh part of the basin (Harvey 2002; JICA 2002). BGS/DPHE/MML (2001) suggested that the K values for Gangetic sediments in Bangladesh could vary from 10 to 100 m/day. In their site-specific model of Faridpur (central Bangladesh), they classified the sediment as sandy silt (K=4 m/day), fine sand (8 m/day), medium sand (25 m/day), and coarse sand (46 m/day). The hydraulic gradient is about 1 m/km in the northern part of the Bengal basin and about 0.01 m/km in the southern Bengal basin (BGS/DPHE/MML 2001). The present-day, natural, regional ground-

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water flux to the Bay of Bengal has been estimated by mass-balance calculations to be 2×10^{11} m^3/year (equal to about 19% of the total surface water flux of 1.07×10^{12} m^3/year) (Basu et al. 2001) and $1.5\pm0.5\times10^{11}$ m^3/year (equal to about 15% of the Ganges-Brahmaputra river flux) (Dowling et al. 2003).

The groundwater flow systems for the study area have been conceptualized [after Tóth (1963) and Ravenscroft et al. (2005)] to consist of (1) shallow flow systems (over lateral distances of a few kilometers) between local topographic features and (2) intermediate- to regional-scale flows (tens to hundreds of kilometers long) between major topographic features or basin boundaries. In light of the low elevations throughout the study area, intermediate-scale flow may not be distinguishable from regional-scale flow. Groundwater movement in areas of flat topography in the Bengal basin may be mostly vertical and lateral flow may be limited to local scale (J. van Wonderen, Sir Mott Macdonald Ltd, personal communication, 2006). Sikdar et al. (2001) reported the presence of north–south regional flow near Calcutta in the 1950s, but flow had dramatically changed by the 1980s. Harvey (2002) argued against the persistence of any regional flow system in view of the extensive irrigation pumping currently practiced in the Bengal basin. Surface water–groundwater interaction generally occurs within local flow systems. The River Bhagirathi-Hoogly is a losing stream along most of its length and recharges the shallow aquifers (Ghosh and Mukherjee 2002). Deeper groundwater generally has insignificant interaction with the surface water bodies, and the deeper aquifers have restricted recharge (Mukherjee et al. 2007).

Hydrostratigraphy

Previous studies

AIP/PHED (1991, 1995), CGWB (1994a, b, c, d, e, 1997), SWID (1998), Acharyya et al. (2000), Goodbred and Kuehl (2000) and Goodbred et al. (2003) are the only publicly-available publications on the sedimentary framework of part of or the entire study area. All of these reports tend to provide brief descriptions of the lithology without specifying the relations between the individual aquifers at the local or regional scale.

Data acquisition and sediment classification

Lithologic data for this study were collected from 143 lithologs of drinking-water, irrigation and observation wells [sources: B.M. Engineering (KrishnaNagar, West Bengal), unpublished data (2005); CGWB 1994d; SWID 1998; PHED 2003a, b, c, d] drilled in and around the study area as shown in Fig. 2 and Electronic Supplementary Material (ESM Table 1) (see also Mukherjee 2006). Depth of the lithologs ranges from 50 to 612 m bgl (mean 240 m, and median 231 m bgl). They are distributed throughout the area (horizontal spacing varying between <1 km to ~10 km) except for some areas near the active delta front and near the eastern border of central Nadia district. To fill the data gap in this latter area, five logs were collected from the adjoining part of Bangladesh (JICA 2002). In the absence of reliable dates for aquifer sediments from various depths, the hydrostratigraphy of the study area in this report has been based on sediment grain size, and older sediments have not been differentiated from younger sediments for hydrologic classification.

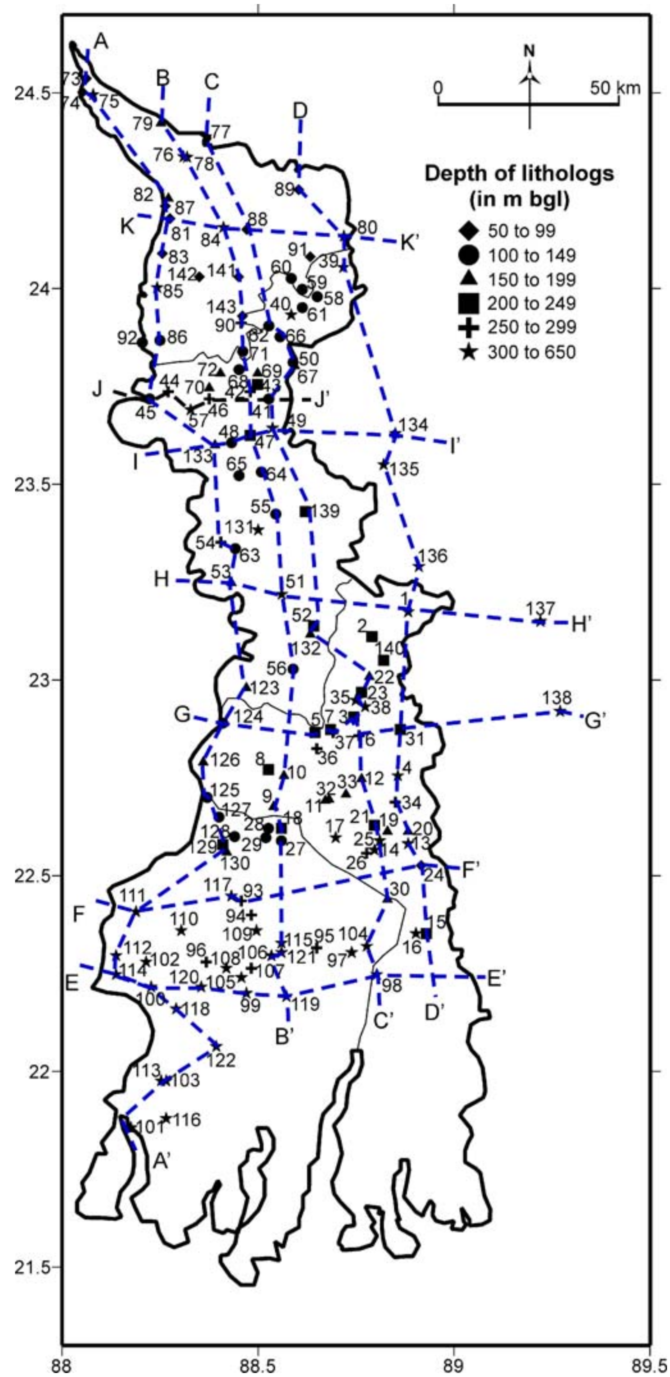

Fig. 2 Map showing location of the 143 lithologs used for lithologic interpolation and orientation of the cross-sections shown in Figs. 3a–d and 4

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The lithology of the logs has been recorded at sub-meter vertical resolution and consists of four major types of unconsolidated sediment: gravel, sand, sandy clay and clay. A number of lithologs from various localities have recorded further subdivision of sands in terms of grain size (very coarse, coarse, medium, fine). Description of the color of these sediments and their scope of use in the related studies has been documented by Mukherjee (2006). For the purpose of this study, only the major sediment types were used. A relatively thin soil horizon with a general thickness of 2–4 m covers the study area. The soil types are Entisols (Udifluvents) (north of Calcutta), Alfisols (Tropaqualfs) (in most of South 24 Parganas) and Aridisols (in the delta front) (CGWB 1994e). These soils have not been included in the modeling or the description of the hydrostratigraphy.

From a general hydrogeologic point of view, these sediments have been categorized as aquifer (sand and gravel) and aquitard (clay). The position of the sandy clay is ambiguous: it can act as either less permeable aquifer or higher-permeability aquitard. Its exact category will vary from locality to locality based on the sand/clay ratio and permeability. Although the less permeable sediments like clay transmit some groundwater, they separate the overlying aquifer(s) from lower aquifer(s) by hydraulic conductivity (K) contrast. In the study area, the extent, thickness and K of these clay or aquitard layers are very important as they govern the three-dimensional flow of groundwater at the regional scale. In this report, the names of the sediment types and hydrogeologic categories will be used interchangeably for the description of both hydrostratigraphy and groundwater flow modeling.

Lithologic modeling

Based on the acquired lithologs, a lithologic model was developed with RockWorks (RW) version 2004® (RockWare, Golden, Colo., USA). The lithologic solid model was created using a block-centric finite-difference grid. The gridding was done by eight nearest-neighbor methodology with 3-D interpolation by average minimum distance. The solid model was developed to a depth of 300 m below MSL and the topographic elevation was defined by the SRTM 90-DEM grid. The sensitivity of the model was tested by varying the horizontal and vertical spacing of the nodes and an optimized final model was constructed that was least sensitive to changes in spatial resolution (i.e., smaller grid sizes). The resolution of the final model was 1000 m (x)×1000 m (y)×2 m (z). The resulting discretization consisted of 135×nodes×335 y nodes×165 z nodes, thus having 7,462,125 solid model nodes, each with a voxel volume of 2,000,000 m^3. Four nodes were assigned around each interpolated datapoint. It should be noted that the results of the modeling are not free from uncertainties (which may improve with an increase in datapoints), but illustrate one of the most probable scenarios. The smallest scale of variation that the model is able to depict is equal to the resolution of one voxel.

Four north–south and 25 east–west manually interpolated lithologic cross-sections (11 of which are shown in Fig. 2) were developed from the map of the study area, visually compared with their modeled counterparts, and corrected for any obvious error or noise. The interpolation of the final model was verified by using 14 randomly-spaced lithologs (10% of the total number of lithologs), which were not used in the construction of the model, and was found to be satisfactory by visual comparison. A number of profile sections and fence diagrams were developed from this final model. It was observed that the modeled transects were closely comparable to the manually interpolated transects, except that the computer-generated ones seemed to demonstrate/simulate the 3-D extent of the lithologic bodies to a greater extent. Several plan-view maps have also been developed for specific depths in order to visualize the nature of the aquifers and aquitards at those depths.

Results

The lithologic modeling suggests the presence of a very complex 3-D hydrostratigraphic framework in the subsurface of the western Bengal basin. A detailed description of the study area at the block scale is provided here to illustrate the general spatial trends in aquifer thickness and spatial variability. The cross-sections in Figs. 3a–d and 4 and depth maps (ESM Fig. 2) provide detailed depictions of the aquifer framework. The names of the localities mentioned henceforth represent the respective blocks (not shown on the map) or towns. These names are followed by numbers in parentheses corresponding to the locations of lithologs shown in Fig. 2, listed in ESM Table 1. At a depth of ~300 m below MSL (the base of the model), a thick clay deposit covers the whole area. In the northernmost part of Murshidabad (from west to east, the blocks are Raghunathganj-II, Lalgola, Bhagwangola-I and -II and Raninagar-II), the topmost sand layer extends from near the surface to a depth of about 65–75 m (locations 73, 79). Below this unconfined aquifer is a basal clay aquitard extending from ~80 m to more than 300 m in the west (73, 74, 75), and dividing into multiple layers toward the east (80, 89). Near Raninagar-II, the upper clay layer is very thin and is mostly replaced by a sandy clay horizon, which lies between thick sand layers. In the west, this thick aquitard extends to near Beldanga (86) and Kaliganj (45), while it diminishes to form an extensive sand layer toward Karimpur-I and -II in the east to a depth of 110 m (58, 59, 60), gradually increasing to about 190 m (61, 62). The most noteworthy thing about this area is the presence of isolated aquifers at depths of ~200 to 230 m and ~240 to 265 m extending from Bhagwangola (76, 77) to Behrampur (84) through Murshidabad-Jiaganj, with the possibility of southward extension. These isolated aquifers have water chemistry distinct from the shallower aquifer (Mukherjee 2006; Mukherjee and Fryar 2007). Towards the south, the unconfined sand aquifer thickens to a depth of about 190 m in Nakashipara (near Bethuadahari in the west, 47) and to a depth of about 230 m in Tehatta (67,

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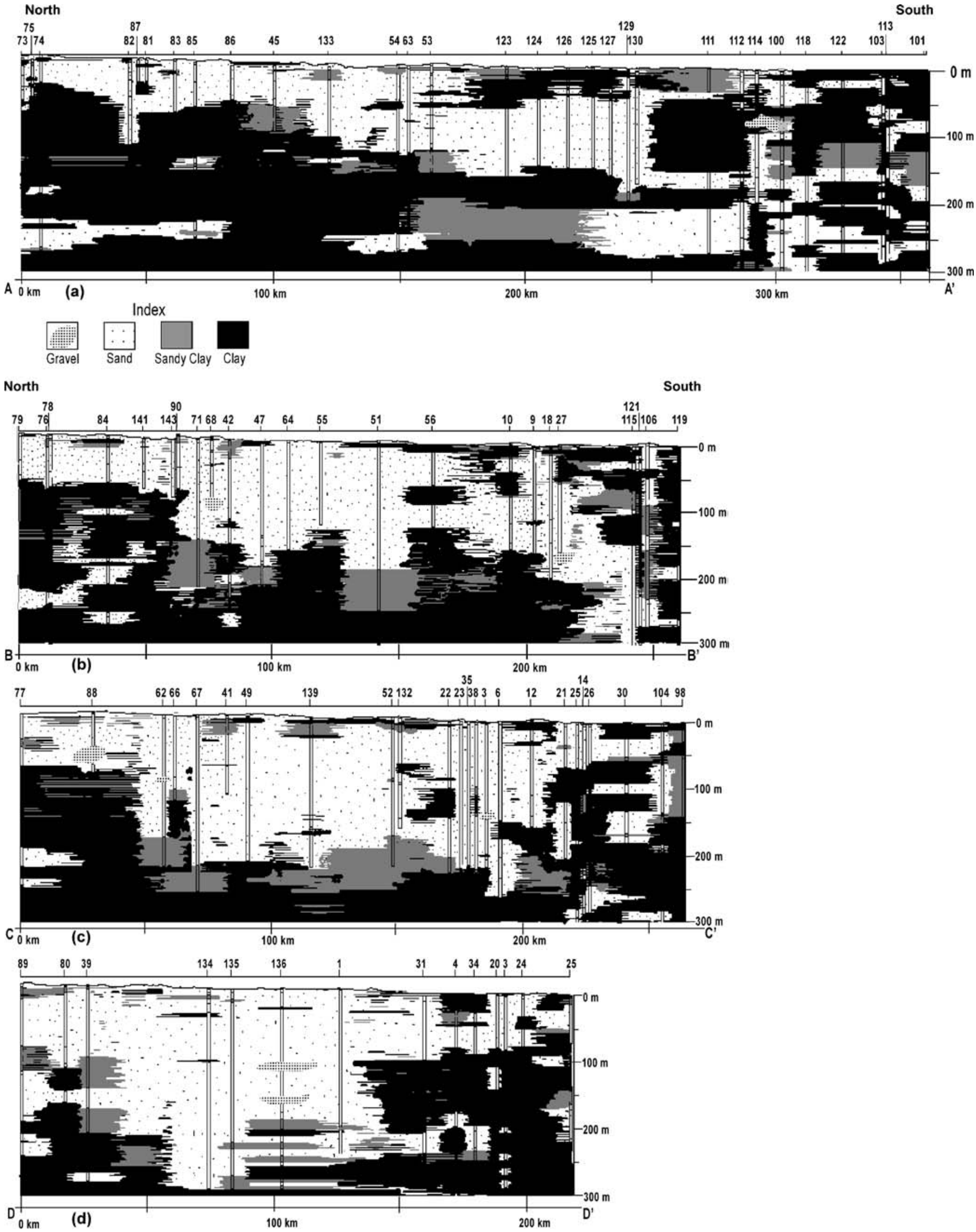

Fig. 3 **a–d** Modeled cross-section along transects AA', BB', CC', and DD' in Fig. 2 (vertical exaggeration=265×). Litholog numbers are labeled along the top of the sections

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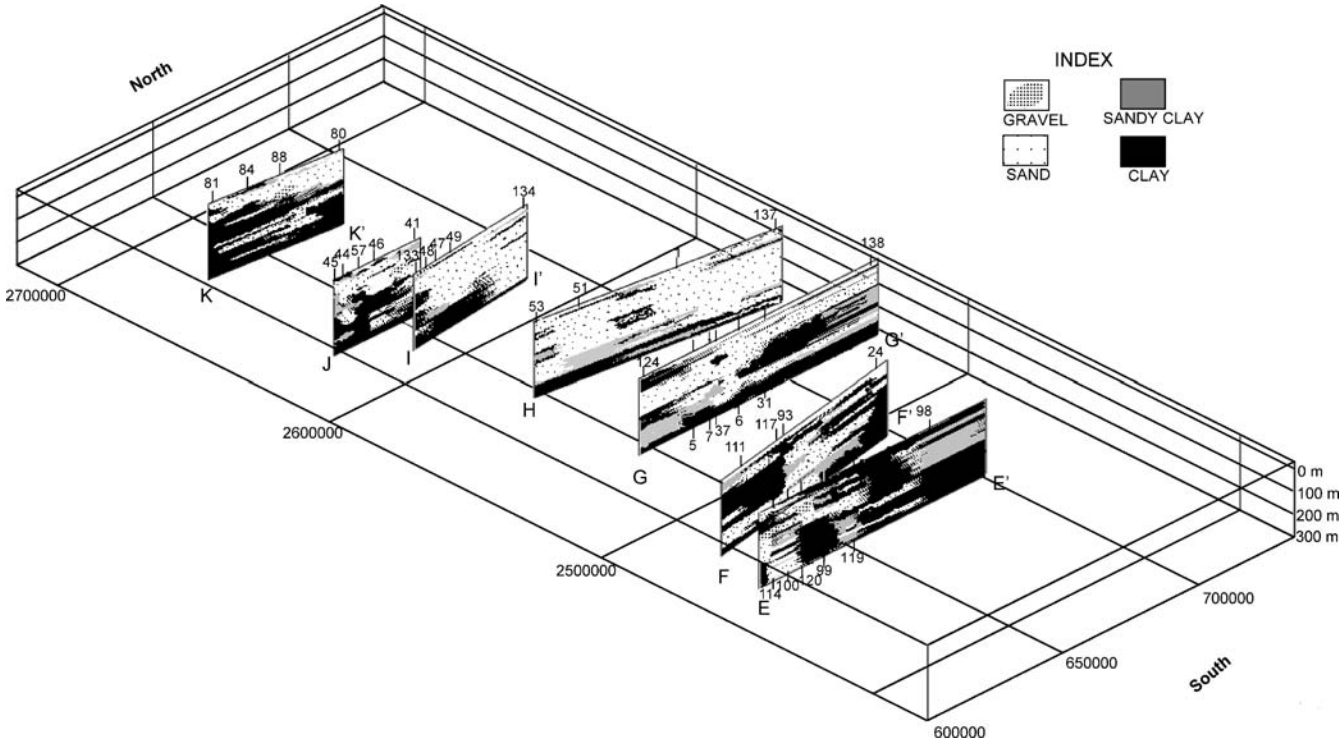

Fig. 4 Modeled cross-sections along transects EE', FF', GG', HH', II', JJ', and KK' in Fig. 2 (vertical exaggeration=80×)

70). The basal aquitard exists from ~230 m to more than 300 m depth. There are also some isolated aquifers in Tehatta from a depth of ~120 to 160 m (42, 43).

The unconfined aquifer changes to a confined/semi-confined aquifer south of Shantipur (53) because of thick clay layers from near surface to a maximum depth of 60 m. These layers thin to the east, toward Ranaghat-II (52), and ultimately vanish toward the Bangladesh border (137, 138). In the west, near the town of Kalyani (123), this surficial aquitard extends to about 65 m bgl, extending south to the north-northeast of Calcutta, where it is thin (12 to 25 m bgl) near South Dumdum (129) and Bidhannagar (130), and continues toward Diamond Harbour (100, 102). In the east, toward Ranaghat (51, 52) and eastern Chakdah (56), this aquitard thins to about 10–12 m before it disappears near the western border of Bagda (1). Near the India-Bangladesh border, two gravel horizons exist at depths of about 110 to 120 m and 160 to 180 m, as observed in Krishnachandrapur (136). These gravel horizons, probably indicating paleo-channels, thin toward the west, and only the top horizon is observable at a depth of about 75–100 m at Palashipara, Tehatta (68). The basal aquitard exists at 170–200 m depth in south Nadia (51, 52, and 123). In the western part of North 24 Parganas, the extensive basal clay layer splits to form a sandwiched confined aquifer, which continues to the Bay of Bengal. This aquifer starts in the north of Calcutta and is prominently visible in Budge Budge (111) at a depth of 212–280 m. Some gravel horizons are visible near the Bangladesh border of northern North 24 Parganas at a depth of 138–148 m (3) and in Jessore, Bangladesh (115–120 m, 185–190 m, and 260–280 m).

Two thick clay lenses occur farther south of Calcutta, toward Budge Budge (111) (52–151 m) in the west and Swarupnagar block (82–204 m) in the east (4, 31), continuing toward south-central South 24 Parganas. The hydrostratigraphy of southern South 24 Parganas is dominated by multiple aquitards (100, 118, 119, 121, and 126). Many of these clay layers contain fragments of invertebrate fossils, indicating a marine origin. These clay layers separate a succession of fresh–brackish–fresh aquifers. The brackish aquifers exist at depths of 22–168 m in southern South 24 Parganas (CGWB 1994d). Around Karaibaria, Diamond Harbour (114) area, a gravel horizon is visible at a depth of 98–150 m. This gravel bed is a marker horizon between the overlying brackish aquifer and fresh water below (CGWB 1994e).

Discussion and proposition of hydrostratigraphic nomenclature

Hydrostratigraphic units have been defined as bodies of rock with considerable lateral extent that compose a geologic framework for distinct hydrologic systems (Maxey 1964). Based on the hydraulic properties of rocks/sediments, they were supposed to be practical mappable fundamental units for describing hydrologic systems in the field (Seaber 1988).

As mentioned in the Background section, the general nature of the aquifer system in Bangladesh has been discussed by many workers, but for the western Bengal basin there is a scarcity of such published studies. Thus, based on the discussion so far, a hydrostratigraphic nomenclature for the study area is proposed here. Seaber

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(1988) commented that because of the lack of physical material in Maxey's (1964) definition of hydrostratigraphic units (dynamics of hydrologic regime), hydrostratigraphic units have not been formally adopted by the North American Commission on Stratigraphic Nomenclature. Hence the proposed nomenclatures in this study are also intended to be informal.

In summary, the study area is dominated by a major single-aquifer system, which is mostly unconfined/semi-confined except in the southernmost part. In several localities, this main aquifer has been locally divided into multiple layers by the presence of discontinuous aquitards (with a lateral extent of one to a few kilometers), but except in the southernmost part (southern portion of North 24 Parganas and South 24 Parganas), the chemistry is generally similar throughout (Mukherjee 2006; Mukherjee and Fryar 2007; Mukherjee et al. 2007), supporting the interpretation of a single hydrostratigraphic unit. The deeper, isolated aquifers are differentiable from the semi-confined portions of this main aquifer on the basis of groundwater chemistry (Mukherjee 2006). The name Sonar Bangla (Golden Bengal) aquifer is proposed for the main aquifer in the study area as shown in Fig. 5, after the poetic description of Bengal by Tagore (1905). The thick, extensive, basal clay layer that marks a definite division between the Sonar Bangla aquifer and any other aquifer present below −300 m below MSL is named as the Murshidabad aquitard due to its best development in the Murshidabad area (Fig. 5). The Sonar Bangla aquifer probably formed over the Murshidabad aquitard as a major shift in the delta-building process of the Ganges-Brahmaputra. The top surface of the Murshidabad aquitard deepens toward the east and south, but it can be vertically traced to a depth of at least 300 m. In the southernmost part of the study area, distinct intermediate-depth aquitards extend northward from the active delta front in the south and pinch out northward about the middle of North 24 Parganas. These aquitards have divided the main aquifer into multiple but occasionally connected (at intervals of tens of kilometers) layers, which have some differences in chemistry (Mukherjee 2006). While the upper and lower portions of the aquifer in this area contain fresh water, the intermediate portion contains brackish water (CGWB 1994e), probably as a result of sea water intrusion from the Bay of Bengal (Mukherjee et al. 2007). These aquitards have confined a part of the Sonar Bangla aquifer from near a line between Calcutta and Bashirhat (34), and thicken toward the south. They are named as the Ichamati-Bhagirathi-Hoogly aquitard system, after the two major rivers that drain the area (Fig. 5).

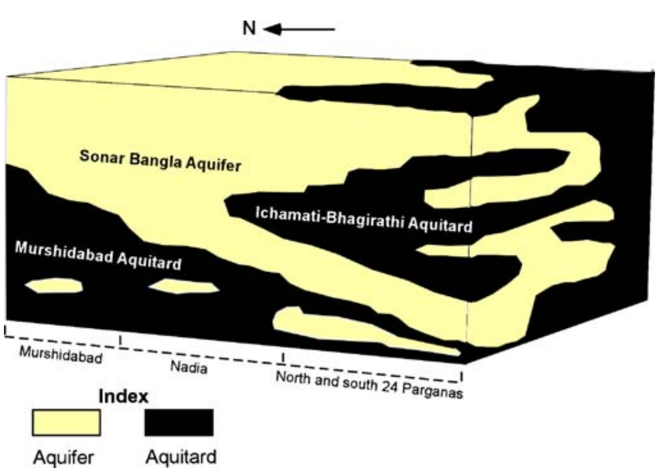

Fig. 5 Conceptual block diagram showing the proposed hydrostratigraphic units (not to scale)

Groundwater flow modeling

Previous modeling efforts

Except for some local-scale models that have been developed (e.g., for the Yamuna subbasin in North 24 Parganas; Ghosh et al. 1999; Mukherjee 2004), no report of comprehensive modeling was found for the study area. However, multiple hydrological modeling studies have been undertaken in the Bangladesh part of the basin, including northwestern Bangladesh (MMP 1982), Faridpur and Chapai Nawabganj (BGS/DPHE/MML 2001), southwestern Bangladesh (Hassan 1992), Jennaidah and Jessore (JICA 2002), the Jamuneswari, Lower Atrai and Barind basins and the Dhaka area (Hossain et al. 2003), and the country as a whole (MPO 1990; van Wonderen, 2003).

Methodology and model design

Because of the heterogeneities and complexities associated with the study area (e.g. local-scale variations of aquifer properties, presence of numerous surface water bodies etc.), several generalizations, simplifications and assumptions were made to construct the regional-scale model.

The modeled study area is bounded in the north, west, and east by the Rivers Ganges, Bhagirathi-Hoogly and Jalangi/Ichamati, respectively, and to the south by the Bay of Bengal. The study area is 335 km in length and 110 km in width. However, the total modeled area encompasses the study area along with surrounding areas as shown in Fig. 1b in order to prevent edge effects. The 3-D, constant-density groundwater flow was simulated by a block-centric, finite-difference grid model using MODFLOW (McDonald and Harbaugh 1988). Microsoft Windows® based Groundwater Vistas® (GV) version 4 (Environmental Simulations International, Reinshold, Pa., USA) was used as the pre and post-processor.

Ideally, the modeling should have been done in transient mode to show the continuous time-variant nature of flow under seasonal variations in recharge and abstraction rates. However, estimates of total inflow and seasonal surface water-groundwater interaction are poorly constrained, given the near-absence of time-variant field data (e.g., seasonal groundwater levels and stream stage) from the study area. Therefore, construction of detailed transient models was unsuccessful, so steady-state

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(dynamic-equilibrium) models were developed for individual seasons. However, a very simplified transient model (with approximated, seasonally varying groundwater levels, inflows, and aquifer properties) was developed for hypothesis testing. A plot of hydraulic heads versus time for this simplified transient model has a seasonally-periodic wave form (similar to observations by Michael and Voss, unpublished). The maxima and minima of the plot occur at the ends of wet and dry seasons (definitions of the seasons are given later), respectively, visually matching with the simulated steady-state heads for those seasons. This visual match suggests that the steady-state models are snapshots of the transient mode during the peak of each season, and thus indicates suitability of the present approach.

Discretization and hydraulic parameters

For each of the models, the study area was horizontally discretized as 335 (x)×110 (y) (36,850 horizontal grid cells) with each grid cell having dimensions of 1,000 m (x)×1,000 m (y). Maximum thickness of the model was 330 m. The SRTM DEM was used to define the surface elevation. The model was vertically discretized in 22 layers (total of 810,700 3-D grid cells). Except for the top layer, which had variable thickness as a result of topographic features, and the 4th layer, which had a thickness of 5 m in order to accommodate shallow irrigation wells, all layers were defined as 15 m thick. The aquifer-aquitard relationship of the model was based on the hydrostratigraphic model (1,000 m×1,000 m× 15 m) developed in RockWorks. The 22nd layer (285–300 m below MSL) was defined as the basal no-flow boundary, consistent with the extensive clay layer at about 300 m below MSL. Transmissivity (T) values of sediments were calculated iteratively, using the method of Mace (2001), from 132 specific capacity tests in the study area (35 from Murshidabad, 15 from Nadia, 56 from North 24 Parganas and 26 from South 24 Parganas):

$$T_f = \frac{S_c}{4\pi} \ln\left(\frac{2.25 \times T_i \times t_p}{r_w^2 S}\right) \quad (1)$$

In this method, T_i is the initially assumed and T_f is the final T value, respectively, S_c is specific capacity, t_p is duration of pumping, r_w is the well radius, and S is storativity (set to an average of 0.03; SWID 1998). The average hydraulic conductivity (K) was calculated from the T and modeled aquifer thickness for the four districts, and was found to range between 19.8 m/day and 65.0 m/day, with an mean of 42.1 m/day. Hence 42 m/day was used as the initial horizontal K (K_x=K_y) value for sand, with K_z assumed equal to 1/10 K_x (within the range given by Deming 2002). An initial $K_{x\text{-}y}$ value of 4 m/day was assigned for sandy clay according to BGS/DPHE/MML (2001) and 0.01 m/day was selected for clay according to JICA (2002). Porosity was assigned as 0.2 (Harvey 2002). The final values of the aquifer parameters were ascertained by inverse modeling and model response to sensitivity analyses (mentioned later). The layers were allowed to have seepage from the top and leakage through the base, making them hydraulically connected. The top-most layer was defined as unconfined and the second layer as unconfined (T varying). The rest of the layers were defined as confined, as the water table was not expected to fall >30 m.

The rivers shown in Fig. 1b were used as the specified head boundaries (Fig. 6a). The rivers were divided into 11 reaches and were assigned attributes like channel width (W) and length (L), stream stage, channel bed elevation and thickness (h), and sediment type based on data collected from the field or from various sources. Due to unavailability of measured conductance (C) data of river beds for the study area, C values were calculated as (in m^2/day):

$$C = \left(\frac{K \times W \times L}{h}\right) \quad (2)$$

where K is the hydraulic conductivity (range: 25 to 15 m/d) of the bed sediments (assumed from the calculated K values for similar sediment type of the adjoining aquifers). Below the boundaries, the layers were assigned with conductivity according to the modeled lithology. The Bay of Bengal was set as a constant-head (0 m) boundary, which was assigned to the southernmost rows at the edge of the study area along the coastline (low tide line) and to the top four layers of the model (Fig. 6a). The depth of the boundary was based on the bathymetric data from Survey of India (1971).

Recharge

The total recharge inflow in the study area can be conceptualized as having several sources (after Ravenscroft 2003): 1) precipitation, 2) irrigation return flow, and 3) seepage beneath standing surface water bodies (e.g., lakes, ponds) and losing reaches of streams. No detailed previous data on total recharge were available for the study area and hence it was one of the least certain input parameters.

SWID (1998) estimated that meteoric recharge is up to 15% of total precipitation. The average annual precipitation in the study area, which was calculated from 25 locations in and near the study area (Fig. 6b) based on multiple years' data (mostly 1901 to 1970, maximum range 1811 to 2005) obtained from the National Climatic Data Center (2005) is 1,484 mm. BGS/DPHE/MML (2001) estimated meteoric recharge in the range of 0.3–5.5 mm/d (i.e. ~100 to 2,000 mm annually) for different areas of Bangladesh. However, due to distinct wet (monsoon) and dry (pre-monsoon and post-monsoon) seasons, annual recharge needs to be considered in a seasonal perspective.

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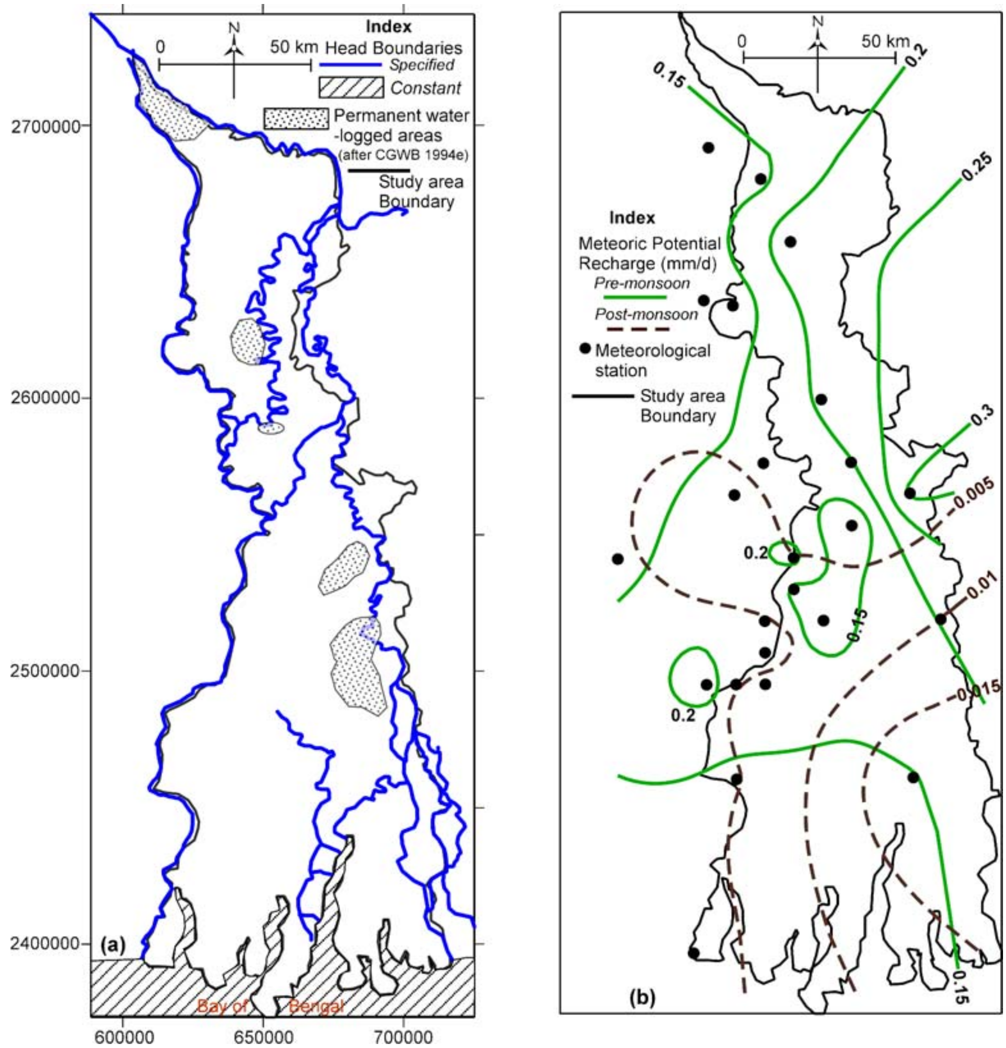

Fig. 6 Maps of the study area showing: **a** the boundary conditions used in the models along with the permanent water-logged areas (redrawn after CGWB 1994e); **b** the 25 meteorological stations in and around the study area whose data were used in contouring the zonal (developed by kriging) meteoric potential recharge (PR) used in the models

On average (1901 to 1970), the seasonal rainfall can be considered as pre-monsoon (January–May, 16.23% of annual rainfall), monsoon (June–October, 82.21%) and post-monsoon (November–December, 1.57%). This indicates that the bulk of the precipitation takes place during the wet season, and suggests that meteoric groundwater recharge also disproportionally takes place during this time. The total rain water that is available for recharge can be termed as potential recharge (PR):

$$R - ET = PR = AR + SF \tag{3}$$

where R is total precipitation, ET is evapotranspiration, SF is the surface overflow and AR is the amount of meteoric water that actually recharges the aquifer. During dry seasons, PR ≈ AR because SF is extremely low (available PR is likely to infiltrate). However, during the wet season, after a period when the aquifers become completely replenished (aquifer-full conditions), any further PR is rejected (also sometimes termed as rejected recharge). This contributes to extensive flooding (as noted in BGS/DPHE/MML 2001; Ravenscroft 2003), and SF >> AR. Accurate quantification of AR and SF requires long-term hydraulic head data and surface water stage measurements from multiple locations in the study area. Because such data were not available, AR was estimated indirectly by approximation of seasonal PR from meteoric data (years 1901 to 1970 in most locations, 1811 to 2005 in Calcutta). As discussed earlier, during the pre- and post-monsoon seasons, the estimated PR was used as the AR in the model. However, for the monsoon, inverse modeling with expected hydraulic head data was used to estimate the AR for aquifer-full conditions. The recharge was applied to the top layer of the model.

The PR was estimated as a difference of the total precipitation and the ET in a specific area. ET was calculated by the method of Pike (1964) as

$$ET(mm/month) = \frac{P}{\left[1 + \left(\frac{P}{PET}\right)^2\right]^{1/2}} \tag{4}$$

where P is average precipitation (mm/month) and PET is potential evapotranspiration (mm/month). Values of PET

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were approximated from the method of Malmstrom (1969):

$$PET(mm/month) = 40.9 \times e^*(\tau) \quad (5)$$

where $e^* = 0.611 \times exp\left(\frac{17.3 \times \tau}{\tau + 237.3}\right)$, and τ is average monthly temperature (°C).

The values obtained from these simplistic meteorological methods, which are enhanced versions of the methods of Penman (1948) and Thornthwaite (1948), are certainly not as accurate as would have been obtained by using sophisticated models (e.g., Penman-Monteith; FAO 1990). However, the simpler methods were preferred for this study because they do not require approximation of a large number of parameters for which data were not available. The mean PR calculated for the study area, 587 mm/year or 1.61 mm/day (range: 384–767 mm/year), is 39% of the mean annual rainfall. This mean PR is very close to the empirical estimate of average recharge (600 mm/year or 1.64 mm/day) by Basu et al. (2001) and Dowling et al. (2003) for the entire Bengal basin. The calculated PR values also fall in the range of annual PR estimated from adjoining areas of Bangladesh by systematic multiyear studies of MPO (1987) and BGS/DPHE/MML (1999), and by field experimentation of JICA (2002) in Jessore, southwest Bangladesh (709 mm). The monthly PR data for each of the 25 locations were further grouped according to the previously defined seasons: pre-monsoon (mean: 0.18 mm/day, range 0.15–0.25 mm/day), monsoon (mean: 3.67 mm/day, range 2.41–4.86 mm/day), and post-monsoon (mean: 0.06 mm/day, range 0.05–0.08 mm/d). These calculated PR data from the 25 meteorological stations (as mentioned before) were used to develop zonal recharge values by kriging in the seasonal flow models (Fig. 6b).

JICA (2002) noted that, in areas of Bangladesh adjoining the present study area, hydraulic heads in observation wells (n=300) fall by 1–3 m during the pre-monsoon because of extensive pumping. These withdrawals are replenished annually, leading to similar groundwater levels at the beginning of each irrigation season (BGS/DPHE/MML 2001). This indicates that the total annual recharge is equal to the difference in groundwater levels between the wet and dry seasons. During the pre-monsoon in the study area, hydraulic heads fall to a mean of 5.35 m bgl in observation wells (range: 0.8–16.3 m, SD 2.8, n=97). Hence, assuming aquifer-full conditions (as indicated by extensive flooding during each monsoon) in most parts of the study area, the total average inflow is ~2–4 m (excluding the upper <1–3.5 m of soil). Mass-balance calculations thus suggest that a majority of recharge is non-meteoric inflow (NMI), most probably return flow from flood irrigation along with percolation from surface water bodies (as advocated by Harvey et al. 2005, 2006 and Ashfaque and Harvey 2006). As there were no previous estimates available for these inflow amounts, the observed heads in the study area (n=118) were used in inverse simulations with the present-day models, and the NMI input was estimated.

Groundwater abstraction

In the study area, four types of wells are typically used for abstraction of groundwater: private or government-owned, shallow (generally 10–50 m depth), low-yield, hand-pump tubewells (HTW); government-owned, electric-motor-driven, high-yield (50–100 m^3/h), public-water-supply deep tubewells (PDTW); private, relatively shallow (generally 10–70 m depth), low to medium yield (10–20 m^3/h), shallow irrigation tubewells (STW), operated by diesel-powered [4.5 horse power (h.p.)] centrifugal or submersible pumps; and government-owned, relatively deep (60–180 m; CGWB 1994e), high-yield (up to 200 m^3/h), deep irrigation tubewells (DTW), operated by electric (18–20 h.p.) turbine or submersible pumps.

The HTWs are discontinuously used throughout the day for domestic purposes and would have very limited effect on regional groundwater flow. The PDTWs are typically used for 6 h/day for water supply through piped schemes and, because of their limited numbers and restricted hours of operation, they were not considered in this modeling exercise, except in and around Calcutta, where the main abstraction takes place by a dense network of PDTWs (Table 1). The STWs and DTWs are suspected to have maximum effect on the groundwater flow systems

Table 1 Details of deep irrigation wells (DTWs) for each district and public-water-supply deep tubewells (PDTWs) for Calcutta that were used in groundwater models

District	Pump details		Pre-monsoon		Monsoon		Post-monsoon	
	Number[a]	Rate (m^3/h)[b]	Operation hours(/day)[b]	Pumping (m^3/m^2/day)	Operation hours(/day)[b]	Pumping (m^3/m^2/day)	Operation hours(/day)[b]	Pumping (m^3/m^2/day)
Murshidabad	445	150	15	3.32E–04	4	8.84E–05	6	1.33E–04
Nadia	757	150	15	4.67E–04	4	1.25E–04	6	1.87E–04
North 24 Parganas	324	100	15	1.23E–04	4	3.29E–05	6	4.94E–05
South 24 Parganas	29	75	15	3.23E–06	4	8.62E–07	6	1.29E–06
Calcutta	500[c]	100	6	1.41E–03	6	1.41E–03	6	1.41E–03

[a] MID (2001)

[b] M.K. Sinha, State Water Investigation Directorate, Government of West Bengal, personal communication, 2004

[c] Number of PDTWs estimated from The Statesman, Calcutta, 6 June 2004, local section, page 6

and hence were used in the model as pumping nodes. Their current estimated number for each district within the study area (according to the last census; MID 2001) and generalized estimates of hours of operation, depth, and pumping rate (local information and M.K. Sinha, SWID, Government of West Bengal, personal communication, 2004) (Tables 1 and 2) were used to determine the pumpage for each grid cell following the equation:

$$Q = \left(\frac{N \times r \times t}{A}\right) \times a \quad (6)$$

Here, Q=the assigned total pumpage (outflow) value to each grid cell for a specified time [L^3]; A=area of each district within the model boundary [L^2]; N=number of pumps; r=pumpage rate [L^3/T]; t=hours of operation per day [T]; a=area of each grid cell.

In the study area, rice is cultivated by flood irrigation during the pre-monsoon, requiring at least 1 m of groundwater abstraction, followed by mainly rainwater-fed cultivation during the monsoon, and groundwater-fed post-monsoon cultivation. Based on the cultivation seasons and distribution of recharge, three sets of models were developed for this study:

i) with pumping: monsoon (M-p), post-monsoon (POSTM-p), pre-monsoon (PREM-p), based on numbers of DTWs and PDTWs in 2001;
ii) without pumping: monsoon (M), post-monsoon (POSTM), pre-monsoon (PREM), assuming no DTWs or PDTWs (pre-1970s conditions);
iii) projected pumping: average population growth of West Bengal for 1991–2001 was 18.15%; rates by district are tabulated in Table 3 (Census 2001). Assuming the same rate of population growth in the next two decades, projected number of pumps and pumping rates for 2011 (2011-p) and 2021 (2021-p) for each district were calculated according to the following equation:

$$N = \eta \times p \quad (7)$$

where N=projected number of pumps; η=number of pumps per capita in 2001; p=projected population in the year of interest. Based on these estimated data, two pre-monsoon models (assuming same pumping rates, hours of operation and tapped depths as at present) were simulated.

The modeling was started with the M models, suggesting conditions at the end of monsoon season. The top of the uppermost layer was assigned as the initial head for these models, simulating the aquifer-full condition. Subsequently, the post- and pre-monsoon models were developed with starting head conditions forwarded from the end of the preceding model.

Inverse modeling and sensitivity analyses

Some of the parameters used for modeling were better known (e.g., surface elevation, PR, pumping) than others (e.g., hydraulic properties, NMI). Hence, inverse modeling was performed for parameter estimation for K of sand and clay, porosity, and NMI using recent hydraulic-head values (sources: field measurements; CGWB 1994d, e; SWID 1998; Public Health Engineering Department, Government of West Bengal, unpublished data, 2005). These were measured in different locations and seasons (n=97 for pre-monsoon and n=21 for post-monsoon), mostly from deep wells in the main aquifer within the study area. Due to the larger number of data points available (mostly measured during April and May) for the PREM-p model, it was used as the base model for estimation of aquifer parameters and pre-monsoon NMI, while the POSTM-p model was used only for the post-monsoon NMI. In the inverse mode, initial values of aquifer parameters were based on the values obtained from previous studies or field measurements (as described above) and the total inflow (meteoric recharge+NMI). The values obtained at the end of the analyses were used for forward simulations and determining the calibration statistics for PREM-p. Sensitivity of hydraulic heads in target wells to model parameters was also analyzed in the PREM-p model by sequentially varying the $K_{x\text{-}y}$ of sand and clay, NMI, stream bed conductance, stages of major streams, and groundwater abstraction.

Results and discussion

Inverse modeling, sensitivity, and calibration

Inverse modeling predicted an average value of 37.5 m/day (K_x) and 25 m/day (K_y) for the aquifer and 0.1 m/day

Table 2 Details of shallow irrigation wells (STWs) for each district that were used in groundwater models

District	Pump details		Pre-monsoon		Monsoon		Post-monsoon	
	Number[a]	Rate (m^3/h)[b]	Operation hours(/day)[b]	Pumping ($m^3/m^2/day$)	Operation hours(/day)[b]	Pumping ($m^3/m^2/day$)	Operation hours(/day)[b]	Pumping ($m^3/m^2/day$)
Murshidabad	66,664	10	12	2.65E–03	4	8.83E–04	6	1.32E–03
Nadia	94,789	10	12	3.12E–03	4	1.04E–03	6	1.56E–03
North 24 Parganas	63,202	10	12	1.93E–03	4	6.42E–04	6	9.63E–04
South 24 Parganas	9,452	10	12	1.12E–04	4	3.75E–05	6	5.62E–05

[a] MID (2001)

[b] Estimated from CGWB (1994e), SWID (1998), MID (2001) and field information

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Table 3 Projected details of irrigation wells (DTWs and STWs) for each district and PDTWs for Calcutta used in the groundwater models

District	Human population[a]		Pre-monsoon 2011				Pre-monsoon 2021		
	Growth rate (1991–2001) (%)	No. of DTWs[a]	Pumping (m3/m2/day)	No. of STWs[a]	Pumping (m3/m2/day)	No. of DTWs[a]	Pumping (m3/m2/day)	No. of STWs[a]	Pumping (m3/m2/day)
Murshidabad	23.76	551	4.92E–04	82,503	4.92E–02	682	6.09E–04	102,106	6.09E–02
Nadia	19.54	905	6.70E–04	113,311	5.59E–02	1,082	8.01E–04	135,452	6.69E–02
North 24 Parganas	22.69	398	1.82E–04	77,543	2.36E–02	488	2.23E–04	95,137	2.90E–02
South 24 Parganas	20.85	35	4.69E–06	11,423	1.02E–03	42	5.67E–06	13,804	1.23E–03
Calcutta	3.93	520	1.46E–03	–	–	540	1.52E–03	–	–

[a] Calculated based on Census (2001)

(K_{x-z}) for aquitards. These values are within the range of sand and clay K values reported by BGS/DPHE/MML (2001) and JICA (2002), as noted above. The values also agree well with Michael and Voss (unpublished) who calculated a mean K_{x-y} value of 43.2 m/day (range: 0.5–259 m/day) for the whole Bengal basin based on drillers' log analyses and on inverse simulations using hydraulic heads and groundwater ages. The inverse model converged with its initially assigned porosity value of 0.2.

The results of the sensitivity analyses showed that the model was most sensitive to changes in net inflow (and thus groundwater abstraction), followed by K of the aquifer. The model was found to be insensitive to porosity and stream-bed conductance. Moving the constant-head boundary (Bay of Bengal) 10 km landward from the originally designated position had a negligible effect on the nearby calibration targets (<5% change in the computed heads). Stream stages (specified heads) controlled heads in adjacent cells, but no discernable effect was observed for targets that were ~5 km away.

Figure 7 shows the posted residuals (difference between observed and computed head) from the forward model calibration of PREM-p and POSTM-p with the best-fit parameter values obtained from the inverse simulations. The simulations yielded mean residuals of −1.2 m (range: −8.34–7.52 m, SD 3.10 m) and 0.52 m (range: −3.70 to 5.60 m, SD 2.17 m), respectively, and showed r^2 values of 0.81 and 0.93, respectively, for bivariate plots of computed head versus observed head. The residual (i.e., the error range) of the computed head at any individual calibration target point was probably a cumulative manifestation of the assumption of basin-wide uniform values for each aquifer parameter, discrepancy of topographic elevation of the target point (~±2 m), and local flows (including effects of micro-topography and small surface water bodies, such as paleochannels and ponds). The residual subsumes the uncertainties associated with the simplification of seasonality, estimated recharge rate, stream stage estimation, difference between attributed and actual land use (e.g., pumping rate, number of hours of pumping), and local-scale variations in lithology. Some areas have larger positive residuals (observed>computed; e.g., in and around Calcutta) or negative residuals (observed<computed; e.g., northern parts of Murshidabad and south-central North 24 Parganas). These indicate that zonal (local to intermediate-scale) refinement of the model input parameters is required for better simulation results in those areas (which is beyond the scope of the present study).

Net inflow and mass balance

Since the 1970s, pumping has lowered the water table in the dry seasons. To balance groundwater abstraction while still attaining aquifer-full conditions at the end of the monsoon, recharge must have increased. Figure 8 shows the comparison of mass balance between the various model scenarios. The mean meteoric recharge calculated is 183 mm/year (range: 148–211 mm/year) (Table 4). According to SWID (1998), recharge would be ≤~223 mm/year (15% of mean annual precipitation). Rangarajan and Athvale (2000) determined a mean natural recharge rate of 198 mm/year (13.6% of annual precipitation) from their study area in North 24 Parganas in 1995 using a tritium injection method. The adjoining areas of Bangladesh were identified to have usable potential recharge of<250 mm/year (MPO 1987) to<300 mm/year (BGS/DPHE/MML 1999). The estimated total groundwater abstraction from the study area is 8.7×10^9 m^3/year, of which 89% is contributed by shallow pumping and 11% by deep pumping. Consequently, 274 mm/year of NMI is required to attain the observed heads (Table 4). The mass balance error ranges between 0.005% (PREM-p) and −0.0003% (2021-p). Using the estimated volume of the aquifer in the lithologic model and assuming a porosity of 0.2 (Harvey 2002), the volume of groundwater under aquifer-full conditions would be ~4.5×10^{11} m^3. The estimated total recharge for the study area is between 9.4×10^9 and 1.3×10^{10} m^3, which is ~2% of the total groundwater resource.

Groundwater flow

Prior to extensive pumping (pre-1970s)

The sequence of the modeling for the study area starts with the monsoon model (M). However, hydraulic heads

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Fig. 7 **a** Plot of observed versus computed heads during pre-monsoon and post-monsoon and **b** map of residuals (observed-computed heads) calculated at each of the calibration targets during pre- and post-monsoon with pumping models

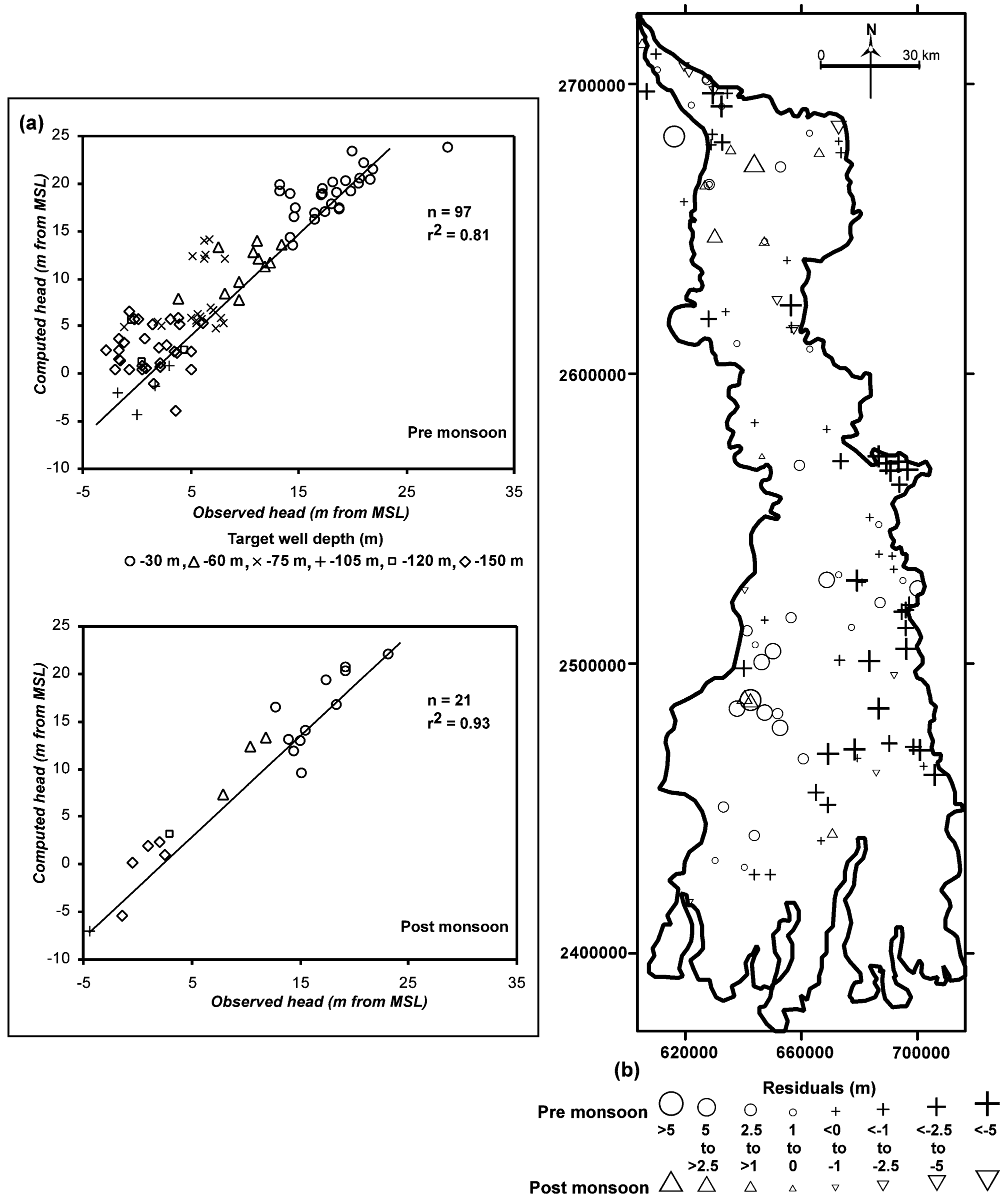

Fig. 8 Plot of mass balance of the eight flow scenarios

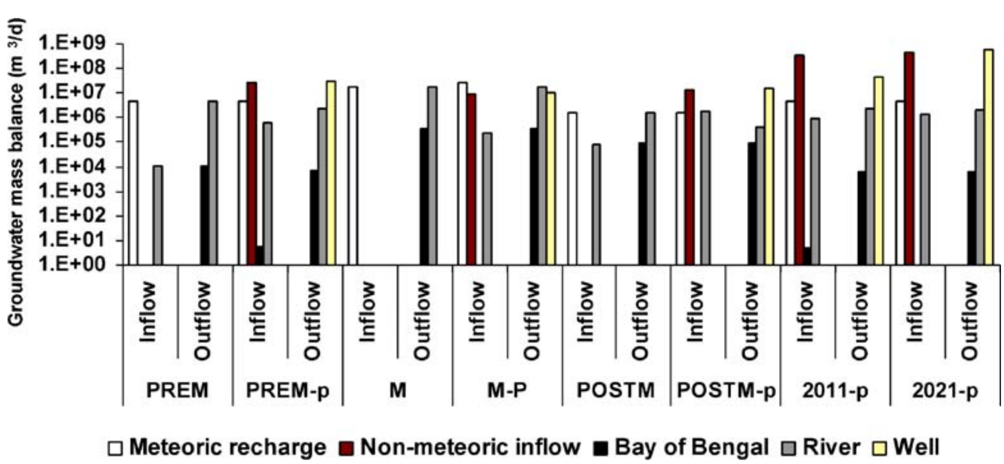

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Table 4 Calculated present-day net inflow (meteoric recharge and non-meteoric inflow) and total abstraction in the study area (per m^2)

Parameter	Pre-monsoon	Monsoon	Post-monsoon	Annual mean
Meteoric recharge (mm/d)	1.8×10^{-1} range 2.5 to 1.5×10^{-1}	1.0×10^{0} range 1.1×10^{0} to 8.0×10^{-1}	6.0×10^{-2} range 8.0×10^{-2} to 2.0×10^{-2}	5.0×10^{-1} range 5.8×10^{-1} to 4.1×10^{-1}
Mean non-meteoric inflow (mm/day)	1.4×10^{0}	4.5×10^{-1}	6.8×10^{-1}	7.5×10^{-1}
Total abstraction (mm/day)	1.5×10^{0}	5.1×10^{-1}	7.6×10^{-1}	1.2×10^{0}

for M are not mapped because groundwater flow essentially ceases during aquifer-full conditions. Figure 9a,b shows the final simulation results of the dry-season models as contour maps of hydraulic heads in the area. The dry-season models without pumping (POSTM and PREM) suggest that there was topographically-controlled, regional groundwater flow from the northern boundary of the study area to the south-southeast toward the Bay of Bengal. This regional flow began during the post monsoon (model POSTM). The flow pattern consists of widely-spaced water level contours suggesting groundwater flow along a low hydraulic gradient. The pattern is marked by a groundwater mound in central North 24 Parganas. The pre-monsoon season (PREM) follows the post-monsoon with groundwater flow along a steeper gradient. Groundwater mounds are more numerous and larger in PREM, indicating areas with aquifer saturation (in Lalgola and Bhagwangola areas of northern Murshidabad, Palashi and Kaliganj areas of northern Nadia, and Haroa and Arsula areas of east-central North 24 Parganas). Such aquifer saturation should be manifested by the presence of wetlands. CGWB (1994e) published a map of permanent water-logged areas of the study area (Fig. 6a). Most of these areas show a good visual fit with the simulated groundwater mounds of PREM. The reason for this water-logging is probably a conjunctive effect of the presence of a near-surface aquitard (Fig. 3a–c) and very flat topography. The result is flow stagnation and groundwater discharge to adjoining areas with lower hydraulic heads. Near the active delta front, contours are convex towards the south and broadly spaced, consistent with tidal fluctuations and submarine groundwater discharge (SGD) to the Bay of Bengal.

Present-day and projected

The M-p model exhibits aquifer-full conditions like those of model M. Similarly, Harvey et al. (2005) reported cessation of groundwater flow during the monsoon in flooded parts of their study area in Bangladesh. BGS/DPHE/MML (2001) reported that up to 56.9% of the total area of Bangladesh flooded annually between 1954 and 1988 (based on Miah 1988 and Brammer 1990). Although no such historical data were available for the current study area, Sanyal and Lu (2003) reported that 75% of the area has medium to very high flood hazard potential. Field observations indicated that floodwater reached ~2 m above ground surface in northern Nadia (Jumpukur, 46) during the year 2000 flood.

The present dry-season models with pumping (POSTM-p and PREM-p) indicate that in all of the districts within the study area, except the southern half of South 24 Parganas, the regional flow paths have been eliminated by the formation of cones of depression (from ~1 km to several km in diameter) due to pumping. Vertical, local-scale convective flow cells are found to have developed corresponding to these depressions. In southern North 24 Parganas and South 24 Parganas, flow reversal with concave contours toward the Bay of Bengal has developed, indicating increased inflow from the Bay of Bengal. This observation is supported by reports of salt-water intrusion in these areas (CGWB 1994d, e; SWID 1998, Mukherjee 2006, Mukherjee et al. 2007; Mukherjee and Fryar 2007). The POSTM-p model shows the initiation of shallow cones of depression. The most prominent groundwater low is in central North 24 Parganas around Calcutta. The cones of depression expand during the pre-monsoon with the formation of prominent groundwater lows in central Murshidabad [Murshidabad-Jiaganj (e.g., location 81, 82 in Fig. 2), Behrampur (e.g., 83, 84), Hariharpara (e.g., 141, 142) and Domkal blocks (e.g., 91), see ESM Table 1 for locations], northern Nadia [Kaliganj (e.g., 44, 45, 46, 57) and Nakashipara blocks (e.g., 47, 48)], south-central Nadia [Shantipur (e.g., 53), KrishnaNagar-I (e.g., 54, 55) and Ranaghat-I blocks (e.g., 51)], southern Nadia [Chakdah (e.g., 56), Haringhata (close to 56), Habra-II (e.g., 5) and Amdanga blocks (e.g., 8)], and northern North 24 Parganas and Calcutta. The depression in and around Calcutta (CGWB 1994e; Sikdar et al. 2001) is most acute, corresponding to the aggregate urban pumping by the PDTWs. The abstraction supersedes any recharge in the area. However, the aquifers near Calcutta have not completely dried up, and there is a cluster of higher positive residuals (Fig. 7b) in this region (including the blocks of Rajarhat in North 24 Parganas and Sonarpur and Baruipur in South 24 Parganas). This suggests that more inflow is available than estimated, probably from northern North 24 Parganas and southern Nadia, plus enhanced

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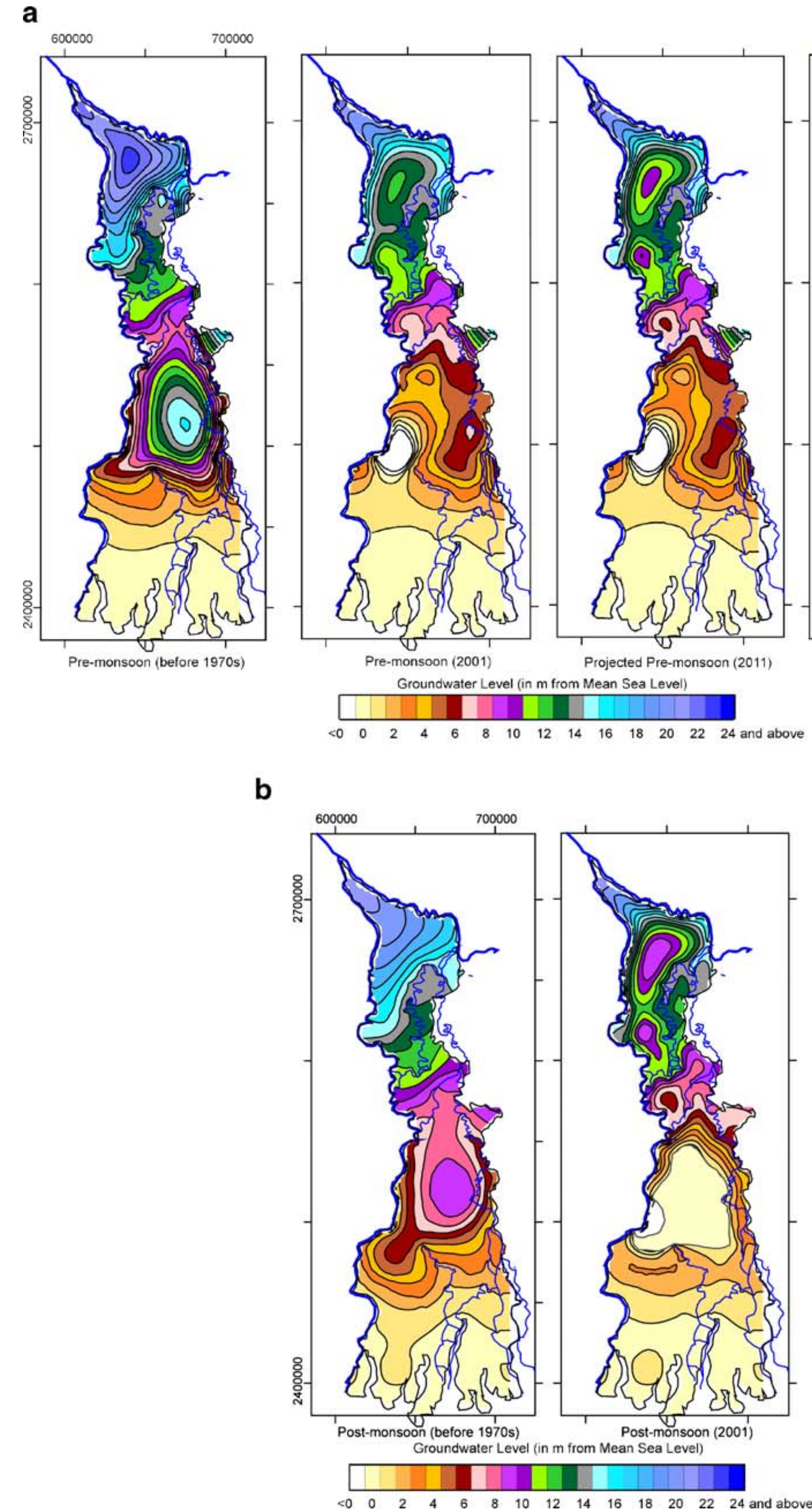

Fig. 9 **a** Modeled groundwater level maps obtained from Pre-monsoon (before 1970s i.e. the PREM model), Pre-monsoon (2001 i.e. PREM-p model), Projected Pre-monsoon (2011 i.e.2001-p model), and Projected Pre-monsoon (2021 i.e.2021-p model). The *bold blue lines* indicate the major rivers in the area. **b** Modeled groundwater level maps obtained from Post-monsoon (before 1970s i.e. the POSTM model) and Post-monsoon (2001 i.e. POSTM-p model). The *bold blue lines* indicate the major rivers in the area

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inflow from the River Bhagirathi-Hoogly, as suggested by Mukherjee et al. (2007). The groundwater mounds in northern Murshidabad [near Jangipur (e.g., 74, 75) and Bhagwangola (e.g., 76, 77, 78)] and south-central North 24 Parganas have been substantially reduced in extent. The cluster of high negative residuals in these areas suggests that the model is overestimating inflow (which probably comes from the River Ganges in Murshidabad and meteoric recharge in North 24 Parganas).

In the pre-monsoon models of 2011 and 2021 (2011-p and 2021-p), the cones of depression are projected to become more intense. For 2021, groundwater lows beneath the bottom of the first layer are simulated for central Murshidabad, northern North 24 Parganas, and south-southeast of Calcutta. These lows imply severe overdraft (abstraction >> recharge). The modeled groundwater highs in Murshidabad and North 24 Parganas are barely discernable. However, it should be noted that the goodness of the prediction of the future groundwater flow will largely depend on the real increase in abstraction rate in comparison to the projected increase, and also to some extent on the future climatic conditions like sea-level rise and seasonal distribution of rainfall.

Interaction of shallow and deep flow

The layer-by-layer mass-balance calculation of the undisturbed groundwater flow (PREM) model (Fig. 10) suggests that the majority of groundwater flow occurs between layers 2 and 9 (approximately MSL to 105 m below MSL). This indicates that the local flow systems predominate, which agrees well with the conclusion of Harvey et al. (2005) for their study area in Bangladesh. The volume of medium to regional-scale flow up to a depth of ~200 m (layer 15) is less but still significant. However, below that depth to the base of the model (in the deeper parts of the Sonar Bangla aquifer and the isolated aquifers), there is minimal recharge or outflow, which indicates relatively long residence times (negligible flushing). This deep groundwater has been identified as geochemically distinct by Mukherjee (2006).

Interaction with rivers and Bay of Bengal

The most important interaction of groundwater with surface water bodies takes place as SGD through the delta front in South and North 24 Parganas. The present-day total annual SGD has been estimated (Table 5) to be ~5.9×10^7 m^3, which decreased by about 4% from an annual SGD of 6.1×10^7 m^3 since the onset of pumping. Dowling et al. (2003) estimated annual SGD as about $1.5\pm0.5\times10^{11}$ m^3 of water for the entire delta front (~500 km wide). Considering that the delta front in the present study area is 110 km (i.e., ~1/5th of the total delta front), the present estimates for SGD are negligible. The probable reason for the difference is that Dowling et al. (2003) considered that all the recharge water reaching below 30 m (first 2 layers of the present model) is discharged to the Bay of Bengal. However, the present study suggests that a large amount of the recharge water is withdrawn through pumping and a considerable amount of water also upwells from the aquifer deeper than 30 m to the rivers. The present day annual sea water intrusion is estimated to be only 8.8×10^2 m^3 (it seems that the modeled intrusion has been underestimated), which is still ~100% more than prior to the 1970s. Although the estimated present seawater intrusion is several orders of magnitude lower than the SGD, intrusion causes significant modification of groundwater chemistry by mixing in southern South and North 24 Parganas (CGWB 1994d; Mukherjee 2006; Mukherjee et al. 2007; Mukherjee and Fryar 2007).

The inflow of river water into the subsurface has increased by ~97% in the last three decades, but the annual total outflow to rivers is still an order of magnitude greater than the inflow (Table 3). Comparison of water-level contours between the PREM and PREM-p models suggests that during summers prior to 1970 the River Ganges and some reaches of the rivers Bhagirathi-Hoogly, Jalangi, and Ichamati were mostly gaining (primarily in northern Murshidabad and southern Nadia southward to Calcutta). At present, western portions of the River Ganges remain gaining, although the reach east of Bhagwangola (77 and 78 in Fig. 2) to the Bangladesh border has become losing. The River Bhagirathi-Hoogly

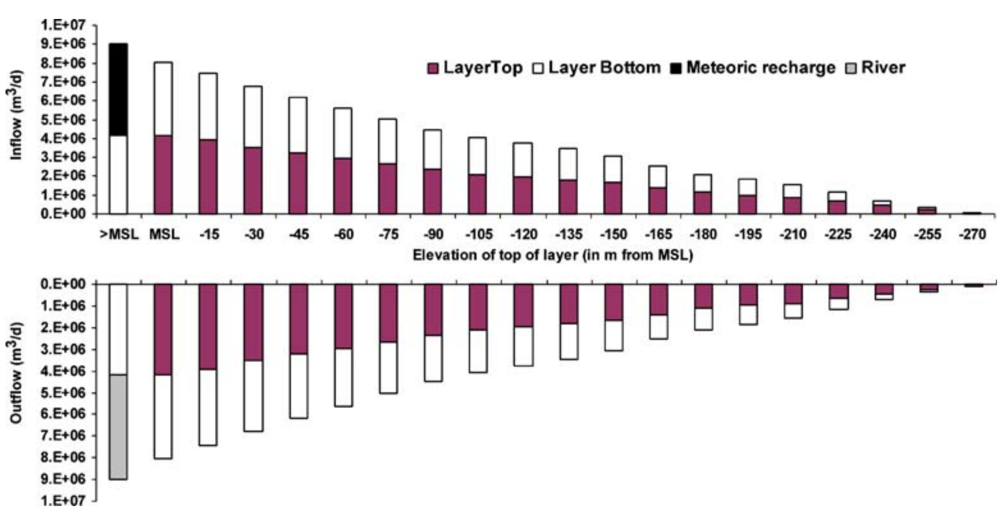

Fig. 10 Plot of mass balance for each layer for the undisturbed groundwater flow in the study area, pre-monsoon without pumping (pre-1970s)

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Table 5 Comparison of surface water-groundwater interaction between present-day (2001) and pre-1970s. SGD=submarine groundwater discharge

	Pre-monsoon (present)	Monsoon (present)	Post-monsoon (present)	Annual (present)	Pre-monsoon (pre-1970s)	Monsoon (pre-1970s)	Post-monsoon (pre-1970s)	Annual (pre-1970s)	Annual change (to present from pre-1970s)	
									Volume (m^3)	%
SGD to Bay of Bengal (m^3)	1.0E+06	5.2E+07	5.5E+06	5.9E+07	1.6E+06	5.4E+07	5.5E+06	6.1E+07	−2.2E+06	−3.7
Inflow from Bay of Bengal (m3)	8.8E+02	0.0E+00	3.0E+00	8.8E+02	0.0E+00	0.0E+00	3.0E+00	3.0E+00	8.8E+02	99.7
Outflow to rivers (m^3)	3.7E+08	2.8E+09	2.4E+07	3.2E+09	7.3E+08	2.6E+09	9.6E+07	3.4E+09	−2.5E+08	−7.7
Inflow from rivers (m^3)	9.5E+07	3.7E+07	1.1E+08	2.5E+08	1.6E+06	0.0E+00	4.9E+06	6.5E+06	2.4E+08	97.4

has become losing from south of Behrampur to Beldanga (86), near Kaliganj and Nakashipara (44, 45, 46, 47, 48), in central Nadia, in northern North 24 Parganas and around Calcutta. The stable-isotope composition of Calcutta groundwater was found to be similar to that of the River Bhagirathi-Hoogly (Mukherjee et al. 2007), supporting this last observation. Excluding the northernmost reach, the River Jalangi and most parts of the River Ichamati remain gaining.

Conclusions and implications for As-contaminated groundwater flow

The present study provides the first published interpretation of the regional-scale hydrostratigraphic architecture and regional groundwater flow in the western Bengal basin of India. The importance of the study rests on the fact that the investigated area is part of one of the worst naturally-contaminated regions in the world. One of the main objectives of this study was to understand how hydrostratigraphy and pumping affect the movement of the potentially As-affected groundwater at the regional scale. Although previous studies in Bangladesh (varying from local to catchment scale) have tried to evaluate these effects (e.g., JICA 2002; Cuthbert et al. 2002; Harvey et al. 2005; Burgess and Ahmed 2006), no such published work exists for the western Bengal basin.

Lithostratigraphic modeling indicates that the study area has a major single-aquifer system, which lacks (except in the southern parts) any continuous confining layer except at the local scale (one to a few km). However, the southernmost areas exhibit a multilayer system where the aquifers are separated from each other by thick aquitards. Hence, the absence of confining layers may facilitate vertical and horizontal groundwater flow and mixing.

Groundwater modeling in the present study suggests that prior to the onset of extensive pumping in the 1970s, regional-scale flow occurred within the major aquifer system during the dry season. This implies that As present in the up-gradient region would be transported down-gradient (toward the south) and diluted unless other As sources were present along the flow path. However, because of the low topographic gradient (~0.1 m/km), the regional flow rate, and thus the rates of contaminant transport and flushing, were probably very slow.

With the initiation of pumping, several local to intermediate-scale flow systems replaced the dominant regional flow system. The hydraulic gradients were dictated by the pumping centers and aquifer architecture. Because of the absence of continuous confining layers in much of the study area, pumping induced mixing between relatively shallow and deeper groundwater, which may have led As-enriched water to spread downward (Mukherjee 2006). Anthropogenically-altered groundwater dynamics have also increased recharge rates during the last three decades. Consequently, downward fluxes of dissolved oxygen (Das et al. 1995) and organic carbon (Harvey et al. 2002) may have drastically increased, thereby perturbing redox- dependent biogeochemical processes in the subsurface (Harvey et al. 2002, 2005; Mukherjee 2006). Moreover, much of the As that is being pumped to the land surface is distributed on agricultural fields, and the As that does not accumulate in crops could re-circulate into the subsurface via enhanced recharge. This scenario may worsen if pumping increases in the future. The smaller rivers in the area were found to be mostly gaining, although groundwater discharge to rivers has decreased because of pumping. As a consequence, the outflow from the shallow aquifers may impact the chemistry of smaller rivers, as indicated by recent detections of As (Mukherjee 2006). In summary, in light of the hydrostratigraphic framework of the basin, the present land-use patterns have made the regional aquifer system more vulnerable to contamination.

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References

Acharyya SK, Lahiri S, Raymahashay BC, Bhowmik A (2000) Arsenic toxicity of groundwater in parts of the Bengal basin in India and Bangladesh: the role of Quaternary stratigraphy and Holocene sea-level fluctuation. Environ Geol 39(10):1127–1137

AIP/PHED (1991) National drinking water mission submission project on arsenic pollution in groundwater in West Bengal. Final report of Steering Committee, Arsenic Investigation Project (AIP) and Public Health Engineering Directorate (PHED), Government of West Bengal, India 58 pp

AIP/PHED (1995) Perspective plan for arsenic affected districts of West Bengal. Arsenic Investigation Project (AIP) and Public Health Engineering Directorate (PHED), Government of West Bengal, India

Alam M, Alam MM, Curray JR, Chowdhury MLR, Gani MR (2003) An overview of the sedimentary geology of the Bengal basin in relation to the regional tectonic framework and basin-fill history. Sediment Geol 155:179–208

Allison MA (1998) Geologic framework and environmental status of the Ganges-Brahmaputra Delta. J Coast Res 14(3):826–836

Allison MA, Khan SR, Goodbred SL, Kuehl SA (2003) Stratigraphic evolution of the late Holocene Ganges-Brahmaputra lower delta plain. Sediment Geol 155(3–4):317–342

Ashfaque KN, Harvey CF (2006) Groundwater flow dynamics and arsenic mobilization in Mushiganj, Bangladesh. Geological Society of America, Abstracts with Programs 38(7):242

Basu AR, Jacobsen SB, Poreda RJ, Dowling CB, Aggrawal PK (2001) Large groundwater strontium flux to the oceans from the Bengal Basin and marine strontium isotope record. Science 293:1470−1473

BGS/DPHE/MML (1999) Groundwater studies for arsenic contamination in Bangladesh, Phase I: Rapid investigation phase. Department of Public Health Engineering, Govt. of Bangladesh, British Geological Survey and Mott MacDonald Ltd., UK

BGS/DPHE/MML (2001) Arsenic contamination of groundwater in Bangladesh, vol. 2: final report, Kinniburgh, D.G., Smedley, P. L. (Eds.). British Geological Survey (BGS) Technical Report WC/00/19, Keyworth

Bhattacharya P, Chatterjee D, Jacks G (1997) Occurrence of arsenic-contaminated groundwater in alluvial aquifers from the delta plain, eastern India: options for a safe drinking water supply. Water Res Develop 13:79–92

Biswas B (1963) Results of exploration for petroleum in the western part of Bengal basin, India. Proceedings of Symposium on Development of Petrology. Mineral Resource Division Service, no. 18(1):241–250

Brammer H (1990) Floods in Bangladesh II: Flood mitigation and environmental aspects. Geogr J 156:158–165

Burgess WG, Burren M, Perrin J, Ahmed KM (2002) Constraints on sustainable development of arsenic-bearing aquifers in southern Bangladesh. Part 1: A conceptual model of arsenic in the aquifer. In: Hiscock KM, Rivett MO, Davison RM (eds.) Sustainable Groundwater Development. Geological Society, London, Special Publications 193, 145–163

Burgess WG, Ahmed KM (2006) Arsenic in aquifers of the Bengal Basin - from sediment source to tubewells for domestic water supply and irrigation. In: Naidu R, Smith E, Owens G, Bhattacharya P, Nadebaum P (Eds.) Managing Arsenic in the Environment: From Soil to Human Health. CSIRO Publishing, Adelaide

Census (2001) Provisional population totals. Census of India, chapter 3, series 1. Government of India

CGWB (1994a) Hydrogeology and groundwater resource of Murshidabad district, West Bengal. Technical Report, series D, Central Ground Water Board (CGWB), Eastern Region, Government of India

CGWB (1994b) Hydrogeology and groundwater resource of Nadia district, West Bengal. Technical Report, series D, Central Ground Water Board (CGWB), Eastern Region, Government of India

CGWB (1994c) Hydrogeology and groundwater resource of North 24 Parganas district, West Bengal. Technical Report, series D, Central Ground Water Board (CGWB), Eastern Region, Government of India

CGWB (1994d) Hydrogeology and groundwater resource of South 24 Parganas district, West Bengal. Technical Report, series D, Central Ground Water Board (CGWB), Eastern Region, Government of India

CGWB (1994e) Hydrogeological atlas of West Bengal, scale 1: 2,000,000. Central Ground Water Board (CGWB), Eastern Region, Government of India

CGWB (1997) High arsenic groundwater in West Bengal. Technical Report, series D, Central Ground Water Board (CGWB), Eastern Region, Government of India

Coleman JM (1969) Brahmaputra River: channel processes and sedimentation. Sediment Geol 3:129–239

Coleman JM (1981) Deltas: processes of deposition and models of exploration, 2nd edition. Burgess, Minneapolis

Cuthbert MO, Burgess WG, Connell L, (2002) Constraints on sustainable development of arsenic-bearing aquifers in southern Bangladesh. Part 2: Preliminary models of arsenic variability in pumped groundwater. Part 1: A conceptual model of arsenic in the aquifer. In: Hiscock KM, Rivett MO, Davison RM (eds.) Sustainable Groundwater Development. Geological Society, London, Special Publications 193, 165–179

Das D, Chatterjee A, Mandal BK, Samanta G, Chakraborti D, Chanda B (1995) Arsenic in groundwater in six districts of West Bengal, India: the biggest arsenic calamity in the world. Part 2: Arsenic concentration in drinking water, hair, nails, urine, skin-scale and liver tissue (biopsy) of the affected people. Analyst 120:917–924

Davies J (1995) The hydrochemistry of alluvial aquifers in central Bangladesh. In: Nash H, McCall GJH (eds.) Groundwater Quality. Chapman & Hall, London, 9–18

Deming D (2002) Introduction to hydrogeology. McGraw-Hill, New York

Dowling CB, Poreda RJ, Basu AR (2003) The groundwater geochemistry of the Bengal basin: weathering, chemsorption, and trace metal flux to the oceans. Geochim Cosmochim Acta 67(12):2117–2136

DPHE/BGS/MML (1999) Groundwater studies for arsenic contamination in Bangladesh, Phase I: Rapid investigation phase. British Geological Survey and Mott MacDonald Ltd., UK

Evans P (1964) The tectonic framework of Assam. J Geol Soc India 5:80–96

Fairbanks RG (1989) A 17,000 glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. Nature 342:637–642

 DOI 10.1007/s10040-007-0208-7

FAO (1990) Penman-Monteith equation. Food and Agriculture Organization (FAO) method 56 (FAO–56)
Ghosh AR, Mukherjee A (2002) Arsenic contamination of groundwater and human health impacts in Burdwan District, West Bengal, India. Geological Society of America, Abstracts with Programs 34(2):107
Ghosh NC, Chakraborty B, Mazumder PK (1999) Groundwater flow model. Proceedings of Workshop on Groundwater and Its Protection with Special Reference to Arsenic Contamination, Calcutta, CGWB, India
Goodbred SL, Kuehl SA (2000) The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta. Sediment Geol 133:227–248
Goodbred SL, Kuehl SA, Steckler MS, Sarkar MH (2003) Controls on facies distribution and stratigraphic preservation in the Ganges-Brahmaputra delta sequence. Sediment Geol 155(3–4):301–316
Harvey CF (2002) Groundwater flow in the Ganges delta. Science 296:1563
Harvey CF, Swartz CH, Badruzzaman ABM, Keon-Blute N, Yu W, Ali MA, Jay J, Beckie R, Niedan V, Brabander D, Oates PM, Ashfaque KN, Islam S, Hemond HF, Ahmed MF (2002) Arsenic mobility and groundwater extraction in Bangladesh. Science 298:1602–1606
Harvey CF, Swartz CH, Badruzzaman ABM, Keon-Blute N, Yu W, Ali MA, Jay J, Beckie R, Niedan V, Brabander D, Oates PM, Ashfaque KN, Islam S, Hemond HF, Ahmed MF (2005) Groundwater arsenic contamination on the Ganges delta: biogeochemistry, hydrology, human perturbations, and human suffering on a large scale. Cs R Geosci 337(1–2):285–296
Harvey CF, Ashfaque KN, Yu W, Badruzzaman ABM, Ali MA, Oates PM, Michael HA, Neumann RB, Beckie R, Islam S, Ahmed MF (2006) Groundwater dynamics and arsenic contamination in Bangladesh. Chem Geol 228:112–136
Hassan MQ (1992) Saline Water Intrusion and Hydrogeological Modelling in Southwest Bangladesh. Schezky & Jeep, Germany
Horneman A, VanGeen A, Kent DV, Mathe PE, Zheng Y, Dhar RK, O'Connel S, Hoque MA, Aziz Z, Shamsudduha M (2004) Decoupling of As and Fe release to Bangladesh groundwater under reducing conditions. Part I: Evidence from sediment profiles. Geochim Cosmochim Acta 68(17):3459–3473
Hossain AFMA, Siddiqui S, Khan ZH, Hassan M, Sadek S (2003) Development of groundwater modeling at SWMC. In: Rahman AA, Ravenscroft P (eds.) Groundwater resources development in Bangladesh. The University Press, Dhaka, 141–159
Imam MB, Shaw HF (1985) The diagenesis of Neogene clastic sediments from Bengal basin, Bangladesh. J Sediment Petrol 55:665–671
Islam MS, Tooley MJ (1999) Coastal and sea level changes during the Holocene in Bangladesh. Quat Int 55:61–75
Islam MN, Uddin MN (2002) Country paper on hydrogeology section. Proceedings of International Workshop on Arsenic Issue in Bangladesh, 23 pp
JICA (2002) The study on the ground water development of deep aquifers for safe drinking water supply to arsenic affected areas in western Bangladesh. Draft final report, book 1–3. Japan International Cooperation Agency, Kokusai Kogyo Co. Ltd. and Mitsui Mineral Development Engineering Co. Ltd
Lindsay JF, Holiday DW, Hulbert AG (1991) Sequence stratigraphy and the evolution of the Ganges-Brahmaputra complex. AAPG Bull 75:1233–1254
Mace RE (2001) Estimating transmissivity using specific-capacity data. Geological Circular 0102, Bureau of Economic Geology, University of Texas at Austin
Malmstrom VH (1969) A new approach to classification of climate. J Geogr 68:351–357
Maxey GB (1964) Hydrostratigraphic units. J Hydrol 2:124–129
McArthur JM, Ravenscroft P, Safiullah S, Thirlwall MF (2001) Arsenic in groundwater: testing pollution mechanisms for aquifers in Bangladesh. Water Resource Res 37:109–117
McArthur JM, Banerjee DM, Hudson-Edwards KA, Mishra R, Purohit R, Ravenscroft P, Cronin A, Howarth RJ, Chatterjee A, Talukder T, Lowry D, Houghton S, Chadha D (2004) Natural organic matter in sedimentary basins and its relation to arsenic in anoxic groundwater: the example of West Bengal and its worldwide implications. Appl Geochem 19:1255–1293
McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference ground-water flow model. U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, A1
Miah MM (1988) Flood in Bangladesh: A hydromorphological study of the 1987 flood. Academic Publishers, Dhaka
MID (2001) Report of 3rd Minor Irrigation Census in West Bengal 2000–2001. Minor Irrigation Department, Government of West Bengal, India
MMP (1982) Northwest Bangladesh Groundwater Model. Sir M MacDonald & Partners, UK and Bangladesh Agricultural Development Corporation, Government of Bangladesh
Morgan JP, McIntire WG (1959) Quaternary geology of Bengal Basin, East Pakistan and India. Geol Soc Am Bull 70:319–342
MPO (1987) Groundwater Resources of Bangladesh. Technical Report 5, Master Plan Organization (MPO), Dhaka, Harza Engineering, USA, Sir M MacDonald & Partners, UK, Meta Consultants, USA and EPC Ltd, Dhaka
MPO (1990) Description of Groundwater Model Programs. National Water Plan Project Phase II, Master Plan Organization (MPO), Dhaka, Harza Engineering, USA, Sir M MacDonald & Partners, UK, Meta Consultants, USA and EPC Ltd, Dhaka
Mukherjee S (2004) Prerequisite studies for numerical flow modeling to locate safe drinking water wells in the zone of arsenic polluted groundwater in the Yamuna sub-basin, West Bengal, India. Proceedings of 32nd International Geologic Congress, Florence, Italy
Mukherjee A (2006) Deeper groundwater chemistry and flow in the arsenic affected western Bengal basin, West Bengal, India. Unpublished Ph.D. dissertation, University of Kentucky, Lexington
Mukherjee A, Fryar AE (2007) Deeper groundwater chemistry and geochemical evolution modeling of the arsenic affected western Bengal basin, West Bengal, India. Applied Geochemistry (in press)
Mukherjee A, Fryar AE, Rowe HD (2007) Regional scale stable isotopic signature and recharge of the deep water of the arsenic affected areas of West Bengal, India. J Hydrol 334(1–2):151–161
National Climatic Data Center (http://www.ncdc.noaa.gov/oa/pub/data/ghcn/v2/ghcnftp.html), accessed June, 2005
Nickson R, McArthur JM, Ravenscroft P, Burgess WG, Rahman M (1998) Arsenic poisoning of groundwater in Bangladesh. Nature 395:338
Nishat A, Bhuiyan, MA, Saleh FM (2003) Assessment of the groundwater resources of Bangladesh. In: Rahman AA, Ravenscroft P (eds.) Groundwater resources development in Bangladesh. The University Press, Dhaka, 87–114
Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc Royal Soc London A 193:120–145
PHED (2003a) Tubewell particulars of water supply schemes, district Murshidabad. Public Health Engineering Directorate, Government of West Bengal, Calcutta, India
PHED (2003b) Tubewell particulars of water supply schemes, district Nadia. Public Health Engineering Directorate, Government of West Bengal, Calcutta, India
PHED (2003c) Tubewell particulars of water supply schemes, district North 24 Parganas. Public Health Engineering Directorate, Government of West Bengal, Calcutta, India
PHED (2003d) Tubewell particulars of water supply schemes, district South 24 Parganas. Public Health Engineering Directorate, Government of West Bengal, Calcutta, India
PHED (2004) Map showing arsenic affected blocks in West Bengal. Public Health Engineering Directorate, Government of West Bengal, Calcutta, India
Pike JG (1964) The estimation of annual runoff from meteorological data in a tropical climate. J Hydrol 2:116–123

 DOI 10.1007/s10040-007-0208-7

Rangarajan R, Athvale RN (2000) Annual replenishable ground water potential of India – an estimate based on injected tritium studies. J Hydrol 234:38–53

Ravenscroft P (2003) Overview of the hydrogeology of Bangladesh. In: Rahman AA, Ravenscroft P (eds.) Groundwater resources development in Bangladesh. The University Press, Dhaka, 43–86

Ravenscroft P, McArthur JM, Hoque B (2001) Geochemical and palaeohydrological controls on pollution of groundwater by arsenic. In: Chappell WR, Abernathy CO, Calderon R (eds.) Arsenic exposure and health effects IV. Elsevier, Oxford, pp 53–77

Ravenscroft P, Burgess WG, Ahmed KM, Burren M, Perrin J (2005) Arsenic in groundwater of the Bengal basin, Bangladesh: Distribution, field relations, and hydrogeologic setting. Hydrogeol J 13:727–751

Saha AK (1991) Genesis of arsenic in groundwater in parts of West Bengal. Annual volume, Center for Studies on Man and Environment, Calcutta, India

Sanyal J, Lu XX (2003) Application of GIS in flood hazard mapping: a case study of Gangetic West Bengal, India. Proceedings of Map Asia Conference, GISdevelopment.net

Seaber PR (1988) Hydrostratigraphic units. In: Back W, Rosenshein JS, Seaber PR (eds) The Geology of North America, vol. O–2, Hydrogeology. Geological Society of America pp 9−14

Sengupta S (1966) Geological and geophysical studies in the western part of the Bengal Basin, India. AAPG Bull 50:1001–1017

Sikdar PK, Sarkar SS, Palchoudhury S (2001) Geochemical evolution of groundwater in the Quaternary aquifer of Calcutta and Howrah, India. J Asian Earth Sci 19(5):579–594

Smith AH, Lingas EO, Rahman M (2000) Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. Bull World Health Org 78(9):1093–1103

Survey of India (1971) Map of West Bengal, scale 1: 1000,000. Publishing group of Survey of India, Government of India, Calcutta, India

SWID (1998) A comprehensive hydrogeological information of Murshidabad district. Geologic Division No. III, State Water Investigation Directorate (SWID), Government of West Bengal, Calcutta, India

Tagore R (1905) Amar Sonar Bangla (My Golden Bengal). Baul (Folk Singer), Visva-Bharati Publications, Calcutta, India

Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38:85–94

Tóth J (1963) A theoretical analysis of groundwater flow in small drainage basins. J Geophys Res 68:4795–4812

Uddin MN, Abdullah SKM (2003) Quaternary geology and aquifer systems in the Ganges-Brahmaputra-Meghna delta complex, Bangladesh. Proceedings of South Asian Geological Congress

Umitsu M (1987) Late Quaternary sedimentary environment and landform evolution in the Bengal Lowland. Geogr Rev Japan, Series B, 60:164–178

Umitsu M (1993) Late Quaternary sedimentary environments and landforms in the Ganges Delta. Sediment Geol 83:177–186

UNDP (1982) Groundwater survey: The hydrogeological conditions of Bangladesh. UNDP Technical Report DP/UN/BGD–74–009/1

van Geen A, Ahmed KM, Seddique AA, Shamsudduha M (2003) Community wells to mitigate the current arsenic crisis in Bangladesh. Bull World Health Org 82:632–638

van Wonderen JJ (2003) The use of groundwater models for resource assessment in Bangladesh. In: Rahman AA, Ravenscroft P (eds.) Groundwater resources development in Bangladesh. The University Press, Dhaka, 127–140

von Brömssen M, Jakariya M, Bhattacharya P, Ahmed KM, Hassan MA, Sracek O, Jonsson L, Jacks G (2007) Targeting low-arsenic aquifers in Matlab Upazila, Southeastern Bangladesh. Sci Tot Environ 379(2–3):121–132

WHO (1993) Guidelines for drinking-water quality. Vol. 1 recommendations, 2nd edn. World Health Organization (WHO), Geneva

 DOI 10.1007/s10040-007-0208-7