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Numerical modelling of groundwater flow to understand the impacts of pumping on arsenic migration in the aquifer of North Bengal Plain

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In this paper, numerical simulations of regional-scale groundwater flow of North Bengal Plain have been carried out with special emphasis on the arsenic (As)-rich alluvium filled gap between the Rajmahal hills on the west and the Garo hills on the east. The proposed concern of this modelling arose from development that has led to large water table declines in the urban area of English Bazar block, Malda district, West Bengal and possible transport of As in the near future from the adjacent As-polluted aquifer. Groundwater occurs under unconfined condition in a thick zone of saturation within the Quaternary alluvial sediments. Modelling indicates that current pumping has significantly changed the groundwater flowpaths from pre-development condition. At the present pumping rate, the pumping wells of the urban area may remain uncontaminated till the next 25 yrs, considering only pure advection of water but some water from the As-polluted zone may enter wells by 50 yrs. But geochemical and other processes such as adsorption, precipitation, redox reaction and microbial activity may significantly retard the predicted rate by advective transport. In the rural areas, majority of the water pumped from the aquifer is for irrigation, which is continuously re-applied on the surface. The near-vertical nature of the flowpaths indicates that, where As is present or released at shallow depths, it will continue to occur in pumping wells. Modelling also indicates that placing all the pumping wells at depths below 100 m may not provide As-free water permanently.

1. Introduction

Elevated level of arsenic (As) in drinking water is a current menacing problem of West Bengal (India) and Bangladesh which form an integral part of Bengal Basin. Thousands of people are suffering from an incurable disease of As contamination and more thousands may be affected with this disease in the near future. With the onset of Green Revolution in India during the sixties and outbreak of epidemics of cholera, millions of tube wells were sunk to tap the plentiful and apparently clean water in the sands and silt of the Ganga flood plain to provide for drinking and irrigation purposes (Sikdar and Banerjee 2003). At least 85% of the combined population of 240 million use groundwater for domestic water supply, including drinking, majorityfrom depths <100 m, which is widely polluted with As (PHED 1991; DPHE 1999, 2001; vanGeen *et al.* 2003; McArthur *et al.* 2004, 2008, 2011, 2012a, b, 2016; Jakariya *et al.* 2007; Nickson *et al.* 2007; Sikdar and Chakraborty 2008; Fendorf *et al.* 2010; Hoque *et al.* 2012, 2014; Ghosal *et al.* 2015). The long term consumption of As-contaminated water has resulted in chronic As-toxicity (arsenicosis) in human body (Dhar *et al.* 1997;

Smith *et al.* 2000; Argos *et al.* 2010; Guha Mazumdar 2012). This calamity has triggered many studies on the geochemical processes of release of As from the aquifer sediments and the mitigation technologies. Studies on migration of As within the aquifer system of the Bengal Basin are very few. Michael and Voss (2009a) carried out a quantitative, large-scale hydrogeologic analysis and numerical simulation of the entire Bengal Basin, looking at the benefits of water wells that pump from depths where the water is less contaminated as an alternative to other solutions such as filters. Another groundwater flow model has been developed by Mukherjee *et al.* (2007, 2011) for the southern part of West Bengal stretching from Murshidabad in the north to the Bay of Bengal in the south, approximately 21,000 km^2 in area, designed to better understand shallow and deep large-scale flow patterns in the region. McArthur *et al.* (2008) have constructed an outline of a 5-layer steady state mathematical model of groundwater flow in Barasat (West Bengal) with a constant recharge of 100 mm per year to underpin the conceptual model of flow of groundwater in the area. In this modelling effort, MODPATH module (Pollock 1994) was used to track the paths of non-reactive particles entering at the water table. Sikdar *et al.* (2013) have developed a heterogeneous anisotropic steady-state groundwater flow model for the multi-aquifer system of a part of southern Bengal Basin which shows that human intervention has changed the natural groundwater flow system. They calculated that the As migration rates range between 0.21 and 6.3 m/yr and 1.39×10^{-2} and 0.4 m/yr in horizontal and vertical directions, respectively. Till date, no comprehensive modelling study has been done for the North Bengal Plain.

The proposed concern of this modelling arose from groundwater development that has led to large water table declines near the pumping centres in the municipal or urban area of English Bazar block of Malda district. In the municipal area, groundwater contains <10 µg/L of As and is used for domestic purposes. In the adjacent rural area, groundwater contains >10 µg/L of As and is used mostly for agricultural purposes. Heavy pumping in the municipal area may allow groundwater to flow from the adjacent As-polluted aquifer. The $\delta^{18}O$ and tritium values of groundwater are within the range of monsoon precipitation composition which indicates that groundwater is probably recharged primarily from precipitation. The plots of $\delta^{18}O$ and δD show slight deviation from the Local Mean Water Lines suggesting that some evaporation of rainfall occurs prior to or during infiltration. Depletion or enrichment of $\delta^{18}O$ and δD with depth is also not observed and tritium content is also similar at various depths (Chakraborty

and Sikdar 2009). Therefore, modern groundwater has invaded into the deeper part of the aquifer. As a result, there is a possibility of downward movement of As-rich shallow groundwater into the deep part of the aquifer due to pumping for domestic and irrigation purposes (Chakraborty and Sikdar 2009). Therefore, the objectives of the study are to better understand the groundwater flow system in regional and local scales of a large, complex sedimentary aquifer system and the potential for sustainable supply of As-free groundwater from wells from a highly stressed aquifer adjacent to an As-polluted aquifer.

2. Study area

This study was undertaken for the entire North Bengal Plain with special emphasis on English Bazar block of Malda district, West Bengal, located in the As-polluted alluvium filled gap between the Rajmahal hills on the west and the Garo hills on the east. English Bazar block is bounded by latitude 24°50′−25°05′N and longitude 88°−88°10′E with a total area of 265 km^2. The area can be divided into two parts: the municipal or urban area covering an area of about 14 km^2 in the east-central part and the non-municipal or rural area covering about 252 km^2 (figure 1). The topographic elevation ranges between 22.4 and 25 m and gently slopes towards the southern edge of the River Mahanada. The area is covered by Quaternary sediments of two different ages: the Older Alluvium of Pleistocene age and the Younger Alluvium of Holocene age (figure 1). Gravels, pebbles, sand, and clay mixed with silt are the main components of Quaternary sediments (figure 2). A detailed discussion of the surface and subsurface geological setup of the study area is given in Chakraborty and Sikdar (2009). Groundwater occurs under unconfined condition within the Quaternary alluvial sediments.

3. Topography and hydrology of the North Bengal Plain

The North Bengal Plain is characterized by gentle rolling topography. The northern and western boundaries, however, are areas of very rapidly rising topography and transition from the deltaic sediments to hard rock. The northern boundary, i.e., the southern Himalayas, receives a very large amount of yearly rainfall, which likely sustains a water table near the surface in the foothills of these formations. The thickness of the aquifer increases and the hydraulic gradient decreases towards southern part of the basin. Monsoonal precipitation enters the aquifer in the foothills, flows
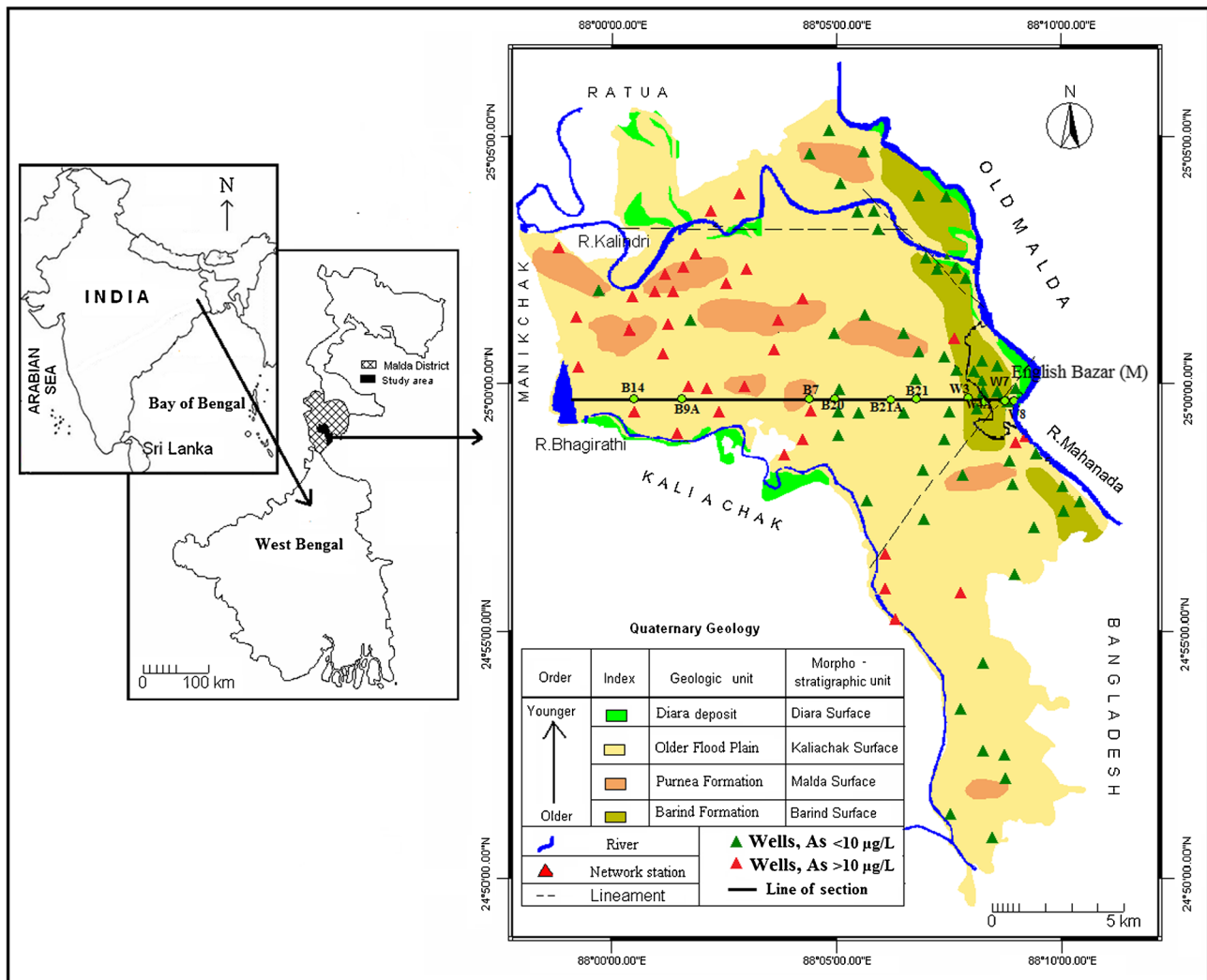
Figure 1. Location of the study area in English Bazar block of Malda district, West Bengal of sampled wells and spatial distribution of surface geology. Black solid line is the line of cross-section shown in figure 2.

swiftly through the thin aquifer and then spreads to greater depths with rapid fall in the velocity towards south. Some water is also recharged from the western boundary, the Rajmahal Hills (Michael and Voss 2009a). Hence, regional and local groundwater flow systems develop, being manifested at depth and near the surface, respectively. The local flow system is dependent on the local gradients with relatively shorter flowpaths (Toth 1970).

The hydrology of the North Bengal Plain is controlled by the southwest monsoon. Monsoonal rainfall occurs from June to October. The 10-year average rainfall during monsoon is 1116 mm and during non-monsoon, it is 337 mm. The average number of rainy days is 67 (CGWB 2001). Precipitation during monsoon months contributes 78% of the total annual rainfall. The monsoon rains are sufficient to fill the aquifer almost to the ground surface each year nearly everywhere in the basin (Burgess *et al.* 2002) resulting in extensive flooding and surface water bodies running together. But during dry season, huge rivers, lakes and ponds dominate the surface hydrology. Similarity of tritium value range in rainwater with that of groundwater points to the fact that the aquifer is directly recharged from monsoonal precipitation (Chakraborty and Sikdar 2009). In Malda district, measurement of water level data in 32 network stations by the Central Ground Water Board in 2000 shows a rise in water level in the range of 0.07–5.78 m due to recharge of groundwater during monsoon season (CGWB 2001). But at places covering a very small area, fall in water level of 0.14–0.79 m has been recorded, which might be attributed to the combined effect of localized temporal heavy withdrawal of groundwater and less precipitation in those areas during the year (CGWB 2001).
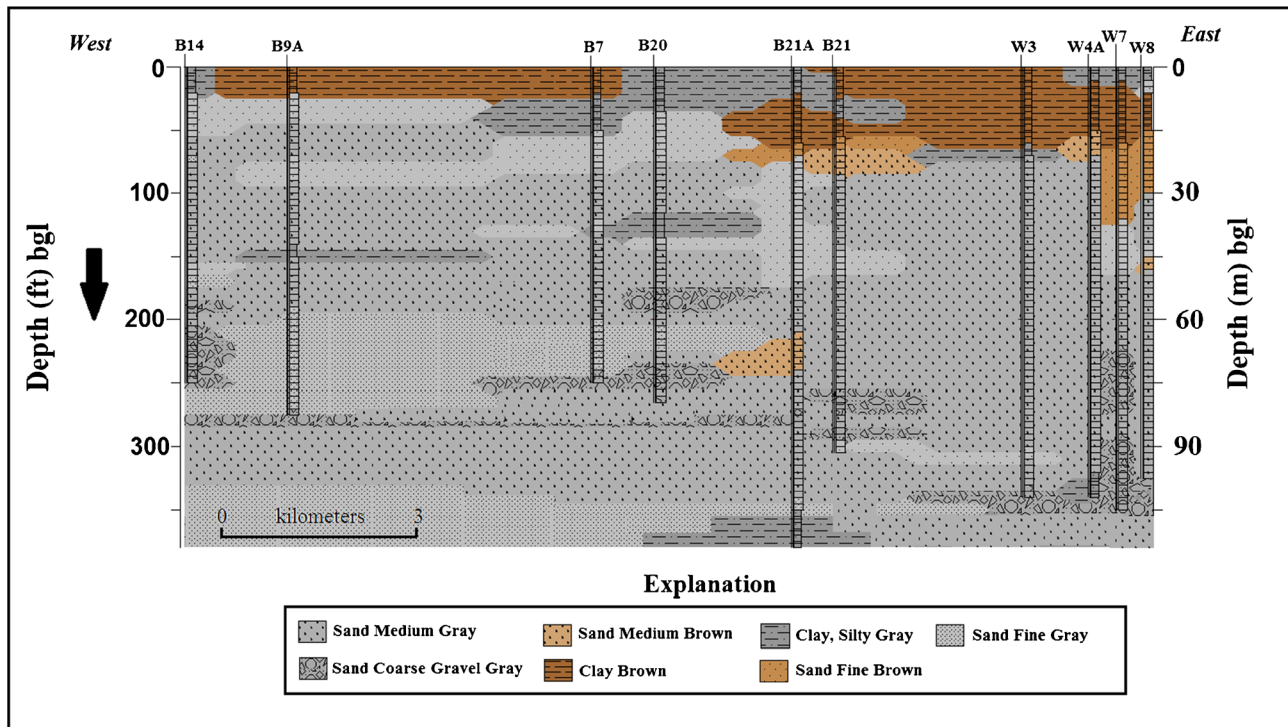
Figure 2. Subsurface geological profile along the line of section shown in figure 1.

4. Materials and methods

4.1 *Water table*

Water-table measurement was carried out in 2005 in 93 network stations (observation wells) in English Bazar block. The depths of these wells vary between 10 and 121 m. Latitude and longitude of each well were recorded in the field with a hand-held GPS using WGS 84 as the reference datum. The ground level was created from the Shuttle Radar Topography Mission (SRTM) elevation data (EROS 2002) with a spatial resolution of 90 m.

4.2 *Groundwater flow model development*

A homogeneous anisotropic steady-state groundwater flow model has been developed using MOD-FLOW (McDonald *et al.* 2000) to comprehend the groundwater flow system under three development scenarios: pre-development, current pumping and possible future pumping (figure 3). The models were developed using MODFLOW-GUI pre-processor (Winston 2000) based on ArgusONE^TM commercial software. After model development, sensitivity analyses of the model under both pre-development and current-development conditions were carried out to evaluate the impacts of parameter uncertainty and spatial variability on the model behaviour and model predictions. To trace the advective flowpaths of groundwater, MODPATH

(Pollock 1994) particles are placed at various depths and tracked backward in different simulations to understand the recharge area of the well water under different pumping conditions.

4.3 *Conceptual aquifer model*

The conceptual model is based on the observed hydrostratigraphy from lithological logs. Seventy-four liological logs ranging in depth from 10 to 308 m have been analysed. These include 62 lithologs collected from the municipal and panchayat offices of English Bazar block, four lithologs from south and north Dinajpur districts (Deshmukh *et al.* 1973) and eight from Malda district (Deshmukh *et al.* 1973; CGWB 2001).

From a hydrogeologic point of view, the sediments in the study area have been categorized as aquifer (fine to coarse sand) and aquitard (clay mixed with silt). The aquitard occurs at the top of the sedimentary sequence down to a depth of 10 m from ground level and again at a depth of 140 m continuing down to the basement. The upper 30 m of the aquifer is made of fine sand followed at depth by 30 m of medium sand and 70 m of coarse sand. Layers of clay and silt are always present even in units conceptually classified as aquifers. However, these units are often thin and spatial extent of such layers or lenses is often limited, and hence cannot be correlated among boreholes. The aquitard at the top is also not persistent and grades
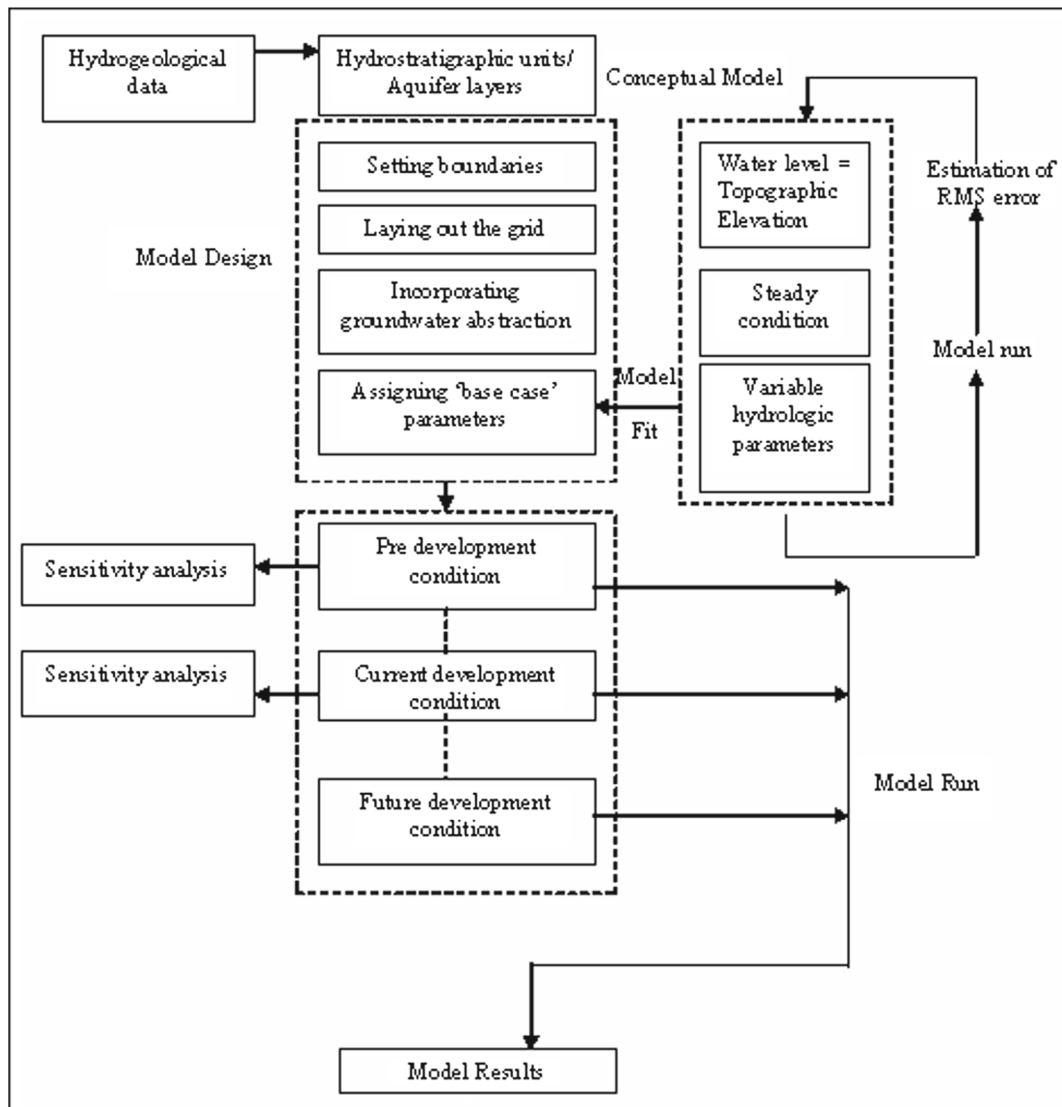
Figure 3. Flow chart for groundwater flow modelling.

Table 1. *Hydraulic conductivity values of different lithologies.*

	Hydraulic conductivity (m s^{-1})	
Type of sediment	Rahman and Ravenscroft (2003)	Hussain and Abdullah (2001)
Clay, silty	–	4.6×10^{-7}
Fine sand	3.0×10^{-4}	–
Medium sand	5.8×10^{-4}	–
Coarse sand	1.1×10^{-3}	–

into fine to medium sands. The Holocene aquifer system in western Bangladesh is also layered, but highly transmissive, with a trend of increasing permeability with depth and no significant confining unit (Burgess *et al.* 2002). The English Bazar block is located adjacent to the River Ganga near the border with Bangladesh. The northeastern part of the area lies on the Barind tract, where a 30-m thick unit of silt and clay overlies the sand and

gravel. This fine grain sediment continues laterally to a distance of 5–7 km and then grades into sand towards the west (Chakraborty and Sikdar 2009).

The horizontal hydraulic conductivity (Kh) for different layers of the conceptual aquifer system was chosen based on the literature values (table 1). No estimation of vertical hydraulic conductivity of the present study area is available in the literature, but according to Ravenscroft *et al.* (2005),

the value could be of lower order magnitude. The conductivity also varies with the age of the sediments. The Pleistocene sediments have lower conductivity as compared to the similar Holocene sediments because of *in-situ* weathering (Rahman and Ravenscroft 2003). Therefore, hydraulic conductivity could change rapidly, spatially and with depth.

4.4 *Model boundaries*

It is not easy to understand the groundwater flow system in English Bazar block with only a local area model, because groundwater flowpaths may span a regional scale. Therefore, the model area should be a hydrologically closed system with major hydrologic boundaries on all four sides. Due to layered but connected nature of the aquifer of the study area and the absence of local hydrological boundaries, the model area is very large, extending from the River Ganga in the south to the consolidated rocks of Himalayan foothills in the north, and from the outcrop of Precambrian crystalline bedrock in the Rajmahal Hills in the west, to

the River Brahmaputra in the east in Bangladesh (figure 4).

The bottom of the model is a no-flow boundary, represented either by Precambrian basement (granite) or by a very low permeability lithounit (shale). In the present model domain, Miocene Shale was not explicitly identified. Shale (Boka Bil or Upper Marine Shale) was identified in only three deep boreholes in Bangladesh (Khan 1991). Granite was identified in another two boreholes in West Bengal, with depth ranging between 213 and 305 m (Deshmukh *et al.* 1973). The top of the shale was chosen as the model bottom where it exists. In areas where shale is absent or could not be identified, top of the granite has been chosen as the model bottom. Where information on the depth of the shale or Precambrian basement was unavailable from boreholes, the depth to the Precambrian basement was estimated based on a contour map published in the MPO (1985) and used as the bottom model boundary. The elevations were input to the model as points and interpolated to form the bottom surface, the depth varying between 10 and 1000 m below ground surface. In the eastern part
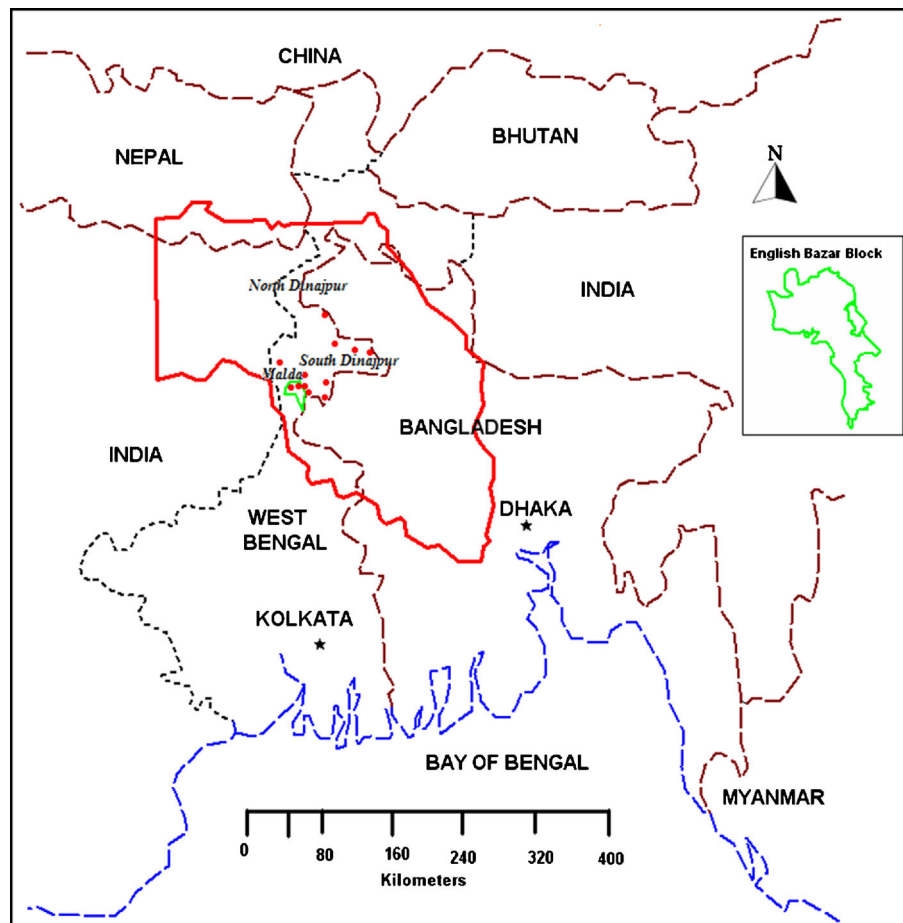

Figure 4. Location of the model area. Red line indicates model boundary, green line indicates English Bazar block boundary, blue line indicates coastline, brown line indicates international boundary, black line indicates state boundary and red dots indicate boreholes.

of the model area, the basement is shallow and is <100 m below the land surface. Therefore, model grid cells in the bottom two geological units of this area are designated as inactive.

The top of the model represents the topography. The Shuttle RADAR Topography Mission (SRTM) elevation data (EROS 2002) with a spatial and altitude resolution of 90 and 1 m, respectively was sub-sampled onto the model grid by averaging the data points in each cell. The top boundary of the model, most realistically, is in a transient condition with water level varying with seasons and water requirement for crops (Michael and Voss 2008). The computation of the total recharge is difficult to estimate for such a huge area. Water level measurements taken by the State Water Investigation Directorate (SWID), Government of West Bengal, from 1984 to 2005, at four locations throughout the English Bazar block, indicate that the water table falls a couple of meters each year. In the dry season of the year 2005, the average drop of water level in 93 wells is 1.07 m, with a standard deviation of 0.67 m (Chakraborty and Sikdar 2011). The water level then rises to a wet-season high due to monsoonal recharge, which in many cases is the land surface or slightly above it. Since the aquifer is fully recharged after each monsoon, the present study has been carried out considering the system at steady-state with a prescribed head everywhere at the top surface.

The northern and western edges of the model boundary, where the hard rocks are exposed, are drawn arbitrarily along the approximate 100 m topographic contour. This is done based on the assumption that the 100 m topographic contour represents the water table elevation in the foothills which provides the necessary driving force for the water to flow through the aquifer (Michael and Voss 2009a). These two sides of the model are closed to groundwater flow and have vertical no-flow boundary because of the presence of crystalline rock through which lateral recharge to the adjacent aquifer cannot take place.

The eastern and the southern model boundaries truncate the River Ganga in West Bengal and the River Brahmaputra in Bangladesh. There are two ways to represent the river boundary. First, by closing the side of the model below the two rivers with a vertical no-flow boundary, assuming water does not flow laterally under the river. Second, is to set a prescribed head along the river down to the bottom of the model and thereby allowing groundwater to flow in or out of the model beneath the rivers. In the absence of definite knowledge of the groundwater flow system near these rivers, modelling was carried out using both types of model boundary. The 'base case' model has been set up by closing the model sides below the two rivers.

4.5 *Discretization*

The entire model area has been divided laterally into 144 (x) × 127 (y). The grid has 10 times finer discretization in the study area than the surrounding areas, with cell widths that vary from 500 to 5000 m (figure 5). Fine discretization allows detailed representation of the groundwater flow in the study area, while coarse discretization in the larger area allows efficient modelling of the entire regional system. Vertically, the area has been divided into six units with varying thickness and vertical discretization (table 2). The thickness of the bottom unit (Unit 6) is variable depending on the basement topography.

4.6 *Groundwater abstraction*

In most areas within North Bengal Plain, particularly in rural communities' water supply for domestic and agricultural use is met from groundwater (Kinniburgh *et al.* 2003). Drinking water tubewells fitted with handpump in the rural area are generally installed in shallow depths ($\sim$10–50 m) with an abstraction rate of 0.68 m^3/hr. In urban areas, water is often supplied by deeper ($\sim$70–135 m) high-capacity pumping wells, which have high abstraction rates (50–100 m^3/hr) and is distributed by pipes.

In India, the total requirement of water for domestic and industrial use in rural areas is 60 liters per capita per day (GEC 1997; SWID 2003). In Bangladesh, the same is approximately 50 liters per capita per day (WARPO 2000). But the demands are less in rural areas and more in urban areas. Since industrial use of water is very low in the model area, a conservative value of 50 liters per capita per day has been used. Using this value, the rate of groundwater withdrawal for domestic and industrial use by the 37 million people living in the model area (except English Bazar block) works out to be 21 m^3/s. Out of this total abstraction, it is assumed that 50% is abstracted from a depth of 10–40 m, 20% from a depth of 40–70 m and 30% from 70–120 m below ground level (bgl). This assumption is based on limited field investigation of the depth distribution of wells in the model area. Domestic pumping rates have been calculated based on population estimates. Population data for the districts of West Bengal were obtained for 2001 (Census 2001) and calculated for 2005 (the reference year for this model) based on the decadal growth rate of the district during 1991–2001. Population data for the districts of Bangladesh for 1991 were used to calculate the population of 2005 by using the yearly growth rate of 2.09% (CIA 2006). The amount of domestic, industrial and irrigation water abstraction for
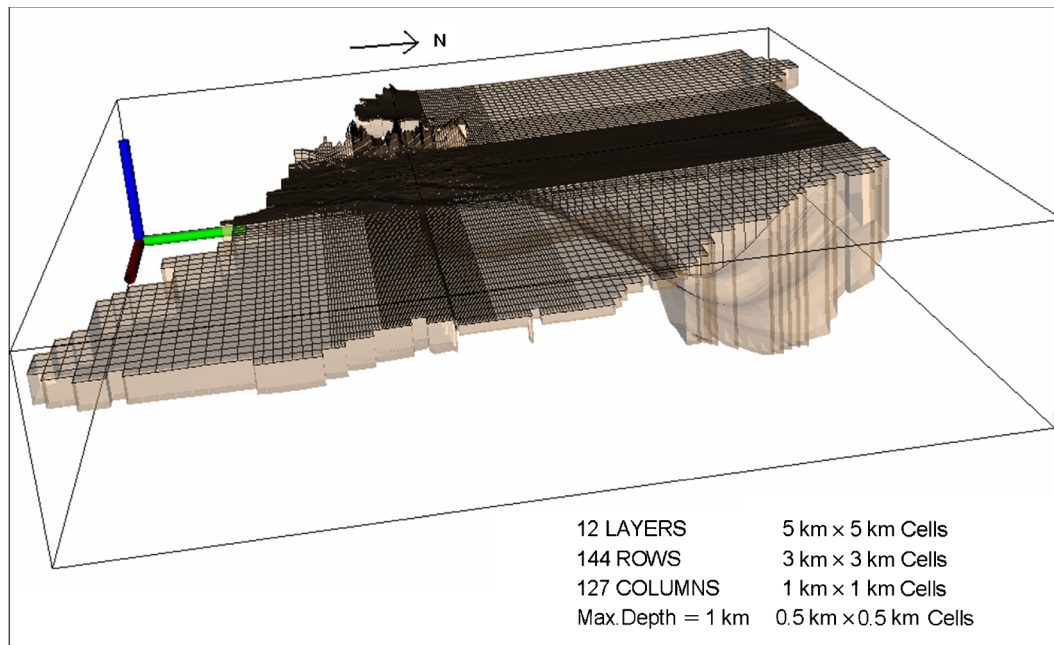
Figure 5. Horizontal discretization of the model area.

Table 2. *Vertical discretisation and unit thickness.*

Unit no.	Thickness (m)	Number of vertical cells
1	1	1
2	9	1
3	30	3
4	30	3
5	70	3
6	840	1

the English Bazar block, as calculated from GEC-97 norms is 57 million cubic meters (MCM) per year (Chakraborty and Sikdar 2011) and has been incorporated separately into the model since this area has been given special emphasis in the present study.

Irrigation pumping was estimated from the proportion of the surface area irrigated in each district of West Bengal and Bangladesh (WARPO 2000; SWID 2003) and a yearly application depth. Boro (winter) rice is by far the most common crop, requiring about 1 m (Harvey *et al.* 2005) to 3 m (AIP/PHED 1995) of annual irrigation, whereas kharif rice requires only about 0.3 m, and summer paddy about 1.2 m (Sahu *et al.* 2013). A representative value of 1 m per year of pumping was used in the model. The rates of abstraction (both domestic and irrigation) for the modelled area not included in Bangladesh or West Bengal are extrapolated from values estimated in adjacent districts.

Innumerable tube wells in the very large model area make it very difficult to simulate pumping by representing individual wells. Therefore, it has been assumed that in the entire model area, pumping takes place over the depth interval where the strainers of the wells are placed and is represented as area wells, i.e., withdrawal per area based on estimates made for each district in North Bengal and Bangladesh except English Bazar municipal area.

Domestic and irrigation tube wells are screened at all depth zones of the aquifer. In the rural area, most of the domestic wells are screened at a shallower level compared to the irrigation wells. In the municipal area, drinking water wells abstract groundwater from the deeper part of the aquifer. Presently in English Bazar Municipality, 33 wells abstract groundwater from a depth of 100 m with a discharge of 65 m^3/hr and is represented as point wells in the model. Domestic, industrial and irrigation drafts calculated for English Bazar block as per Groundwater Estimation Committee (GEC) 1997 norm are 12, 3 and 42 MCM/yr, respectively (Chakraborty and Sikdar 2011).

4.7 *'Base case' hydrogeologic parameters*

As mentioned earlier, within the sandy aquifer the fine grain sediments occur as lenses and pinch out over short distances. Hence these lenses are important in reducing the ease of vertical groundwater flow but do not separate the sediments into different aquifers. Pumping tests carried out by

different agencies in India and Bangladesh indicate that the top 200 m of sediments behave as a single hydraulically connected layered aquifer system (Deshmukh *et al.* 1973; MPO 1985; CGWB 1997). There is no depletion or enrichment of $\delta^{18}O$ and δD with depth and tritium concentration is also similar at various depths indicating a single aquifer system (Chakraborty and Sikdar 2009). Therefore, in the present study, the north Bengal sediments are considered to be a single large, anisotropic aquifer system down to a consistent low-permeability unit, perhaps the Upper Miocene shale or Precambrian granite. For ease and simplicity, groundwater flow modelling in the present study is based on the concept of the equivalent homogenous porous medium with a porosity of 0.2 (Harvey 2002; JICA 2002; Michael and Voss 2009a) by which it is assumed that the real heterogeneous aquifer can be simulated as single homogeneous porous media.

To estimate the equivalent horizontal and vertical hydraulic conductivity values of the anisotropic aquifer system, driller log analysis has been used in the present study. Hydraulic conductivity values were assigned to four categories of lithology obtained from borehole log descriptions (table 1). The equivalent conductivities for layers of infinite extent in the horizontal (arithmetic mean of the conductivity of the geological layers) and vertical (harmonic mean of the conductivity of the geological layers) directions were determined using the method presented in the paper by Michael and Voss (2009b).

4.8 *Model calibration*

Model calibration was done by evaluating the residual and root mean square errors between the simulated head and the measured field head under current-development conditions to estimate the 'base case' hydrogeologic parameters for model runs by varying the anisotropy and by varying Kh for a fixed anisotropy. Residual error is computed by dividing the sum of residuals by the number of residuals. Because both positive and negative residuals are used in calculation, these values should be close to zero for a good calibration. The RMS error is the square root of the sum of the squared differences between the observed field data and the computed one under current-development condition.

4.9 *Model sensitivity*

Sensitivity analysis of the model under both pre-development and current-development conditions has been carried out to evaluate the impact of uncertainty in values of important hydrogeologic parameters including bulk anisotropy, boundary conditions and vertical discretization on the modelled head and horizontal flow paths (hpl). The sensitivity of the model was tested by varying the parameter values from that of the 'base case' for pre-development and current-development conditions and measuring the horizontal path length (hpl), i.e., the lateral distance from recharge point to discharge point and the travel time.

4.10 *Groundwater flow simulation*

In order to understand the present stress on the aquifer, it is imperative to understand the flow system, which prevailed during the pre-development or unstressed condition. The flow system could have been local (vertical flow systems with short horizontal path lengths; closely spaced recharge and discharge areas) or regional (horizontal flow systems with long horizontal path lengths; widely spaced recharge and discharge areas).

The groundwater flow model was run in steady-state condition using 'base case' parameter values with a prescribed head layer everywhere at the elevation of the land surface. MODPATH (Pollock 1994) particles were placed in the municipal well screens at a depth, 100 m below ground surface: one in every 8th cell and at depths of 40 m outside the municipal area. The particles follow advective flowpaths, i.e., movement of the contaminants at the same speed as the average groundwater flow as predicted by MODPATH, and are tracked backward towards recharge locations. For each model run, an attempt was made to understand the distribution of head and nature of path lines. The generated path lines give an idea of the part of the aquifer from where the water would have come into the region of current municipal well screens under no pumping condition (unstressed aquifer).

5. Results and discussion

5.1 *'Base case' hydrogeologic parameters*

Twelve driller log (Deshmukh *et al.* 1973; CGWB 2001; figure 4) analysis resulted in Kh values ranging from 1.25×10^{-4} to 7.98×10^{-4} m s^{-1} with a mean value of 3.29×10^{-4} m s^{-1}. The vertical hydraulic conductivity (Kv) values range from 1.28×10^{-8} to 1.29×10^{-6} m s^{-1} with a mean value of 3.73×10^{-7} m s^{-1}. The Kh/Kv values range from 350 to 12,000 with a mean value of 3225 (table 3). The 'base case' model Kh and Kv values have been ascertained by model calibration discussed in the next section.

5.2 *Model calibration*

For model calibration the simulated head data and field head data of post-monsoon 2005 for each

Table 3. *Estimated equivalent horizontal and vertical hydraulic conductivity and anisotropy from borehole log. The location of the boreholes are shown in figure 4.*

Borehole no.	Kh (m s^{-1})	Kv (m s^{-1})	Kh/Kv
1	1.53×10^{-4}	1.28×10^{-8}	12000
2	1.94×10^{-4}	3.88×10^{-8}	5000
3	1.25×10^{-4}	7.81×10^{-8}	1600
4	1.83×10^{-4}	2.03×10^{-7}	900
5	2.85×10^{-4}	7.13×10^{-8}	4000
6	7.98×10^{-4}	2.00×10^{-7}	4000
7	1.25×10^{-4}	3.13×10^{-8}	4000
8	3.90×10^{-4}	7.80×10^{-8}	5000
9	3.50×10^{-4}	3.50×10^{-7}	1000
10	4.95×10^{-4}	9.90×10^{-7}	500
11	3.96×10^{-4}	1.13×10^{-6}	350
12	4.53×10^{-4}	1.29×10^{-6}	350
Mean	3.29×10^{-4}	3.73×10^{-7}	3225

Table 4. *Calculated errors between simulated head and observed head with varying anisotropy.*

Anisotropy	Residual error	Root mean square error
350	−2.41	8.40
2000	−1.10	1.45
3000	−0.36	1.25
4000	−0.88	1.36
5000	1.07	3.47
12000	5.96	20.12

Table 5. *Calculated errors between simulated head and observed head for varying Kh and anisotropy of 3000.*

Kh (m s^{-1})	Residual error	Root mean square error
3×10^{-4}	−0.36	1.25
3.5×10^{-4}	−0.62	1.29
4×10^{-4}	−1.00	1.32

justifies the concept of simulating the real heterogeneous, anisotropic porous medium of the area as homogenous anisotropic porous media for the purpose of groundwater modelling.

5.3 *Sensitivity analysis*

5.3.1 *Effects of anisotropy*

Under pre-development conditions, the sensitivity of the model to anisotropy was tested by varying the anisotropy by different orders of magnitude from the 'base case' (table 6). Decreasing the anisotropy the hpl decreases, while increasing the anisotropy, the mean hpl increases sharply. The mean travel time sharply increases or decreases with changing anisotropy. Therefore, the flow system with a lower anisotropy is more local, while the system with a higher anisotropy is more regional. Under current-development conditions, change in anisotropy by one order of magnitude from the 'base case' changes the mean hpl and the mean travel time quite significantly. Similar to pre-development case, in the current-development, the flow system with a lower anisotropy is more local, while the system with a higher anisotropy is more regional. Therefore, it can be concluded that under pre-development and current-development conditions, the hpl and travel time are very sensitive to change in anisotropy.
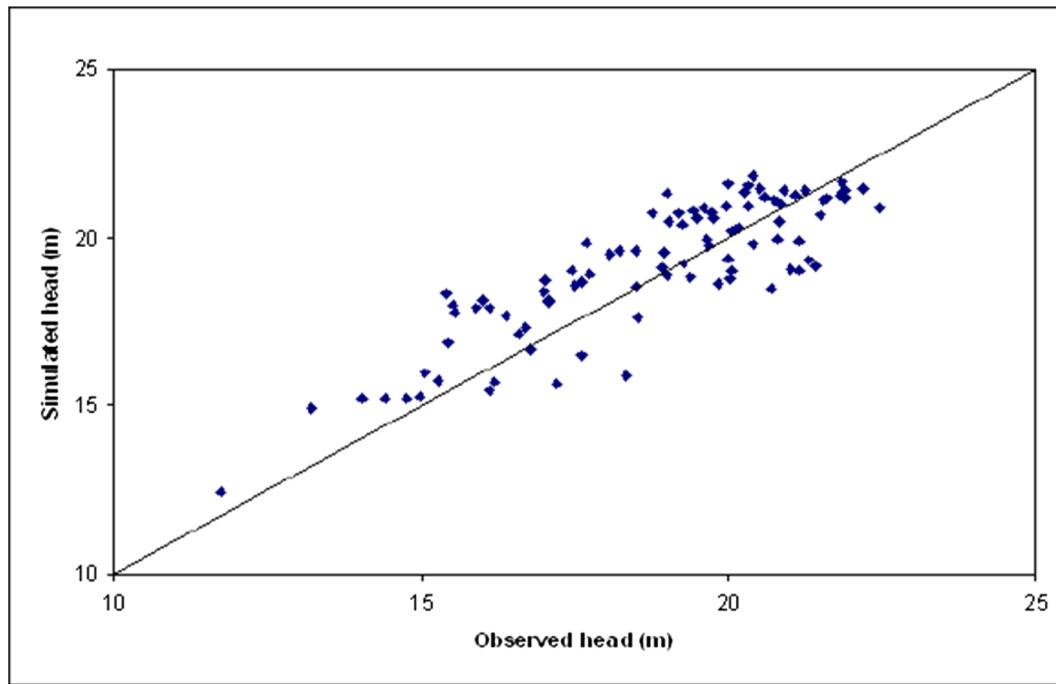
network station were plotted for various runs by varying the anisotropy from 350 to 12,000 and by varying Kh for a fixed anisotropy of 3000. The residual and root mean square errors between the simulated head and the observed head for each of the cases were calculated (tables 4 and 5). The differences between the observed and simulated values are probably a cumulative manifestation of some errors in the specified head boundaries, discrepancies in topographic elevations of the water table, and uncertain aquifer parameters. The minimum residual error and root mean square error is observed for anisotropy of 3000, Kh = 3×10^{-4} m s^{-1} and Kv = 1×10^{-7} m s^{-1} which is –0.36 and 1.25, respectively. Therefore, these values have been chosen as the large-scale bulk properties of the aquifer system. The plots of 'base case' simulation are fairly close to the 1:1 line and therefore, there is a good agreement between the calculated head and the observed head (figure 6). This gives a strong support for the chosen 'base case' model hydrologic parameters. The spatial distribution pattern of the residuals for the 'base case' model hydrogeologic parameters is more or less random (figure 7). This indicates that zoning of K values may not be required for this model and perhaps

Figure 6. Scatter plot showing the simulated head *vs.* observed head of post-monsoon, 2005 of English Bazar block.

5.3.2 *Effects of boundary conditions*

In steady-state simulation, the boundary conditions largely determine the flow pattern. Hence, correct selection of boundary condition is a critical step in model design. The boundary conditions with greatest uncertainty are at and below the rivers along the eastern and southern sides. The 'base case' simulation has been carried out by closing the side of the two rivers assuming that water does not flow laterally under the river. The uncertainty of the model analysis to the chosen boundary conditions was investigated by setting a prescribed head along the sides below the rivers down to the bottom of the model and thereby allowing groundwater to flow beneath the rivers having the same 'base case' anisotropy.

Under pre-development conditions, by opening the sides below the two rivers, the mean hpl is identical with the base case with slight increase in mean travel time (table 6). Therefore, by opening the sides below the two rivers, there is no significant change in the flow system. Thus, uncertainty of boundary conditions does not impact the results. Under current-development, the mean hpl and mean travel time have slightly increased from the 'base case' (table 6). Simulations have indicated that the change in boundary condition may impact the flow paths in terms of thousands of years, but in terms of tens or even hundreds of tears the flow paths are similar to the 'base case'. Hence the effect of boundary condition is insignificant considering maximum simulation time of 200 yrs.

5.3.3 *Effects of vertical discretization*

Under pre-development and current-development conditions, doubling the vertical discretization produced results similar to the 'base case' (table 6). Therefore, the model is adequately discretized in vertical direction to provide a good numerical solution.

5.3.4 *Pre-development groundwater flow simulation*

Simulations using the base case parameters under pre-development conditions indicate that the regional flow is towards the south. The head distribution for the depth of 100 m for the entire model domain is shown in figure 8. The flowpaths of particles tracked backward from the area of municipal wells at a depth of 100 m to their point of recharge in the north considering only the process of advection is shown in figure 9. The groundwater flows into the area of municipal wells mostly from Gajol in the north. Some water flows from the adjacent area in the west from Uttar Nazipur (figure 9). Colours represent travel time, increasing towards the point of recharge. The length of each pathline indicates the scale of the system, i.e., the greater the distance that porewater in the deep part of the aquifer has travelled from its recharge point, the more regional the system is. This can be quantified by calculating the straight-line distance, or horizontal path length (hpl), from recharge point to endpoint. For the base case parameters, the mean
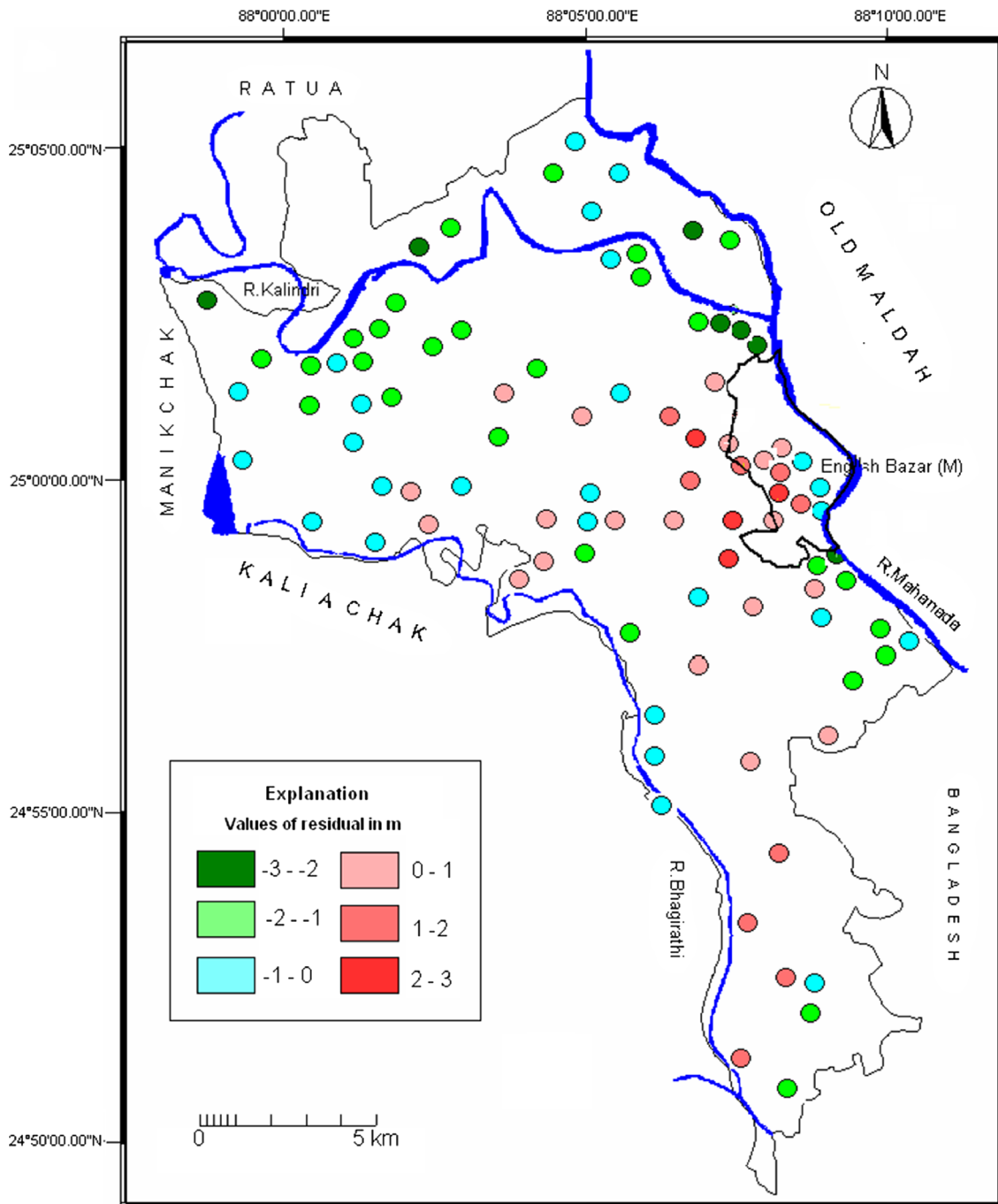
Figure 7. Distribution of residuals (observed head – simulated head).

hpl of particles tracked backward from the area of municipal wells at a depth of 100 m to their point of recharge is 13 km and the mean travel time is ∼1000 yrs (table 6).

5.3.5 *Current-development groundwater flow simulation*

Simulations under current-development conditions indicate that a groundwater trough has formed under the municipal area due to heavy groundwater abstraction for drinking and domestic purposes (figure 10). The drawdown is significant in the municipal area of English Bazar block and also in a large area just south of the inactive area (figure 11). The drawdown due to pumping in the municipal area extends far beyond the municipal boundary and therefore, wells in the rural area interfere with those of the municipality. The result is that the drawdowns of interfering wells are increased with a corresponding lowering of water table.

Ninety-nine paths ending at the bottom of the domestic pumping zone in the municipality at a depth of 100 m and beginning at recharge locations,

Table 6. *Results of sensitivity analysis for pre-development and current-development simulations with different anisotropy, boundary condition and vertical discretization for particles tracked backward from the area of municipal wells at a depth of 100 m to their point of recharge.*

|	Kh/Kv	Kh	Max. hpl (km)	Min. hpl (km)	Mean hpl (km)	Mean travel time (year)
Pre-development						
Low anisotropy	300	3.0×10^{-4}	6	0.07	1	61
Base case	3000	3.0×10^{-4}	19	2	13	1078
High anisotropy	30,000	3.0×10^{-4}	179	173	176	28,749
Prescribed head all along the river up to bottom of the model (river boundary-open)	3000	3.0×10^{-4}	18	4	13	1144
Increased Vertical discretization	3000	3.0×10^{-4}	20	3	13	1067
Current development						
Low anisotropy	300	3.0×10^{-4}	19	0.03	4	233
Base case	3000	3.0×10^{-4}	21	0.04	10	853
High anisotropy	30,000	3.0×10^{-4}	216	0.44	75	8928
Prescribed head all along the river up to bottom of the model (river boundary-open)	3000	3.0×10^{-4}	29	0.04	12	1056
Increased vertical discretization	3000	3.0×10^{-4}	21	0.04	10	908
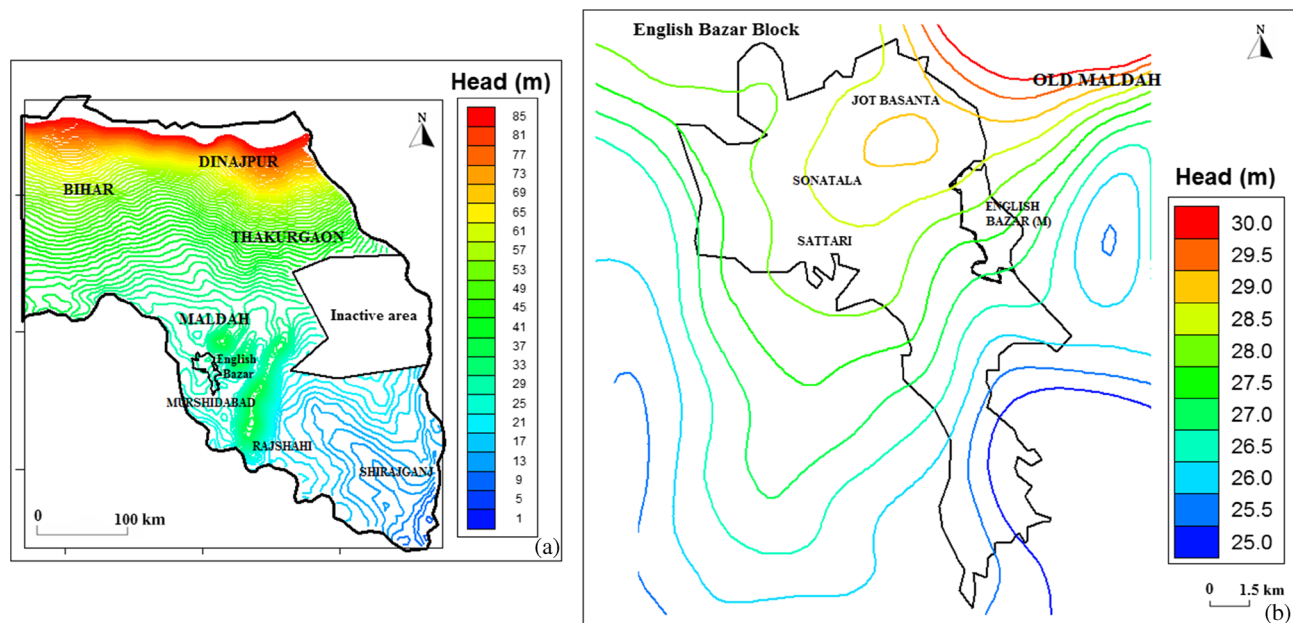
Figure 8. Spatial distribution of head under pre-development conditions in (**a**) North Bengal Plain and (**b**) English Bazar block at a depth of 70–100 m. The area where the basement depth is <100 m has been indicated as 'inactive area'.

were determined by backward tracking, considering only the process of advection, and using base case parameter values for a few pumping scenarios. With current abstraction, the modelled pattern of the pathlines of groundwater flow from the recharge area to English Bazar municipality is quite different from the pre-development case. In the pre-development condition, the water flows from a restricted recharge area (figure 9); however, with the introduction of groundwater abstraction, the flow field spreads over a wider region in the west and east of the municipality (figure 12). There are two groups of pathlines: (i) very short and near vertical and groundwater flows directly into the
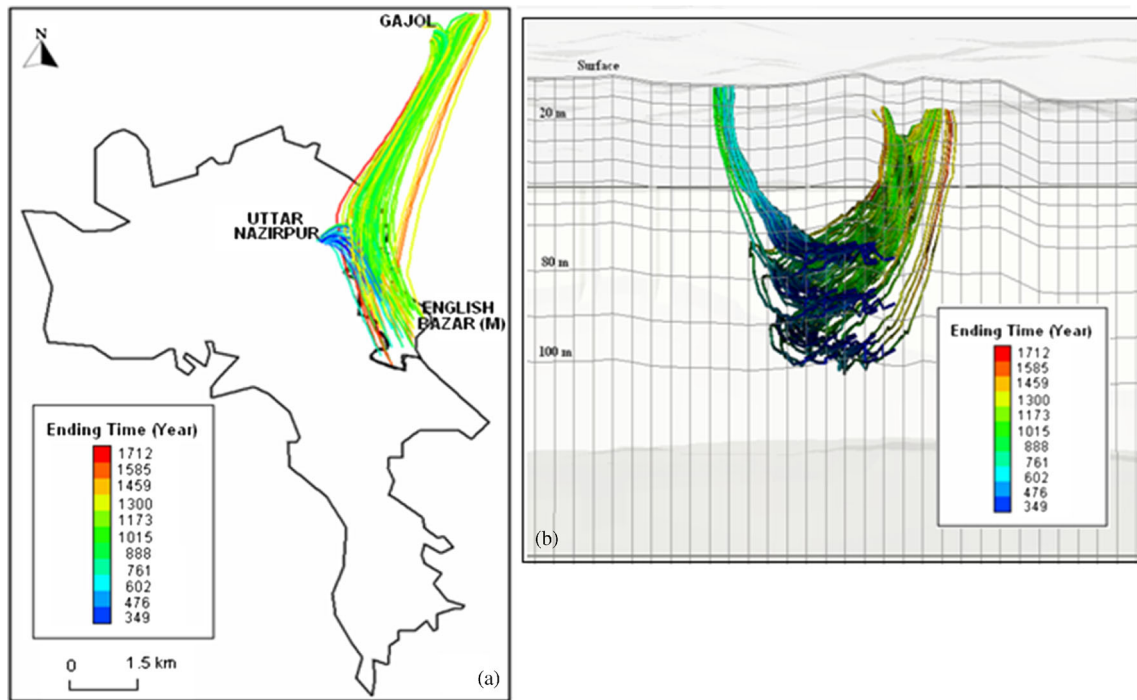
Figure 9. (**a**) Recharge areas of groundwater of English Bazar Municipality at 100 m depth under pre-development conditions. In (**b**), the view is from the south with vertical exaggeration of 50×.
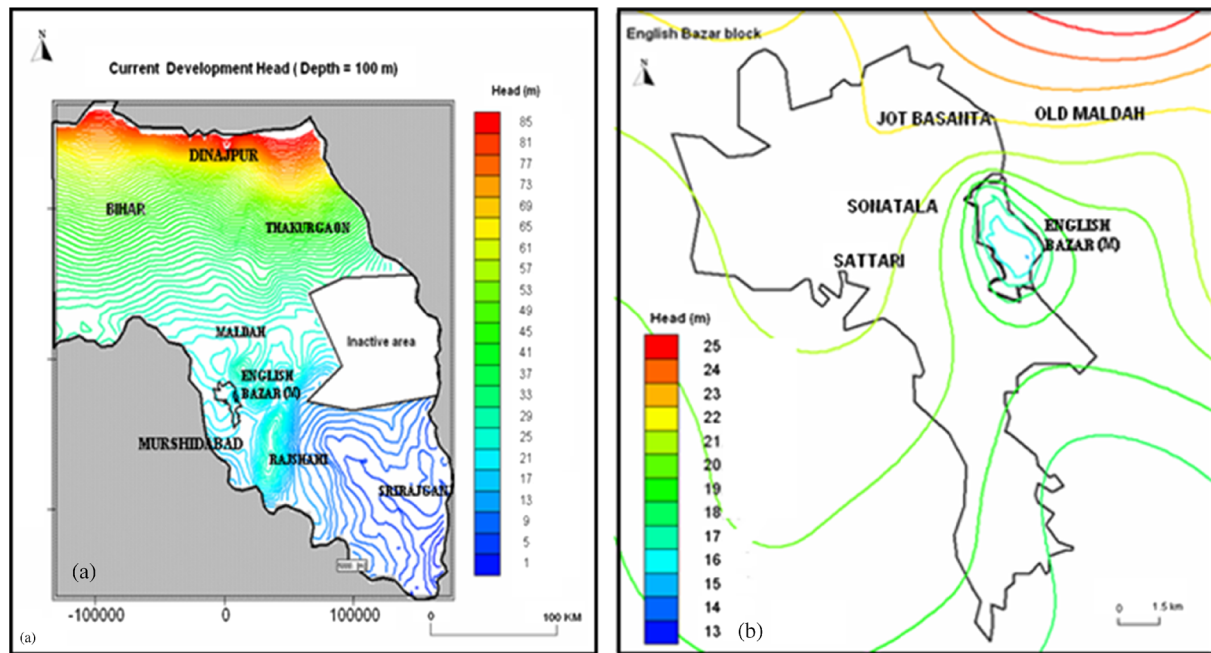

Figure 10. Spatial distribution of head under current-development of (**a**) North Bengal Plain and (**b**) English Bazar block. In (**a**), the area where the basement depth is <100 m has been marked as 'inactive area'.

wells from the surface, and (ii) long; hpl up to a maximum of 21 km flowing from NNE (figure 12). The two pathlines may have been caused due to pumping at different depths of the aquifer. For the present pumping rate, the mean hpl is 10 km and the mean travel time is 853 yrs (table 6).

5.4 *Advective transport of arsenic*

5.4.1 *Current-development*

The model was run with 'base case' values for specified simulation time of 25, 50 and 100 yrs
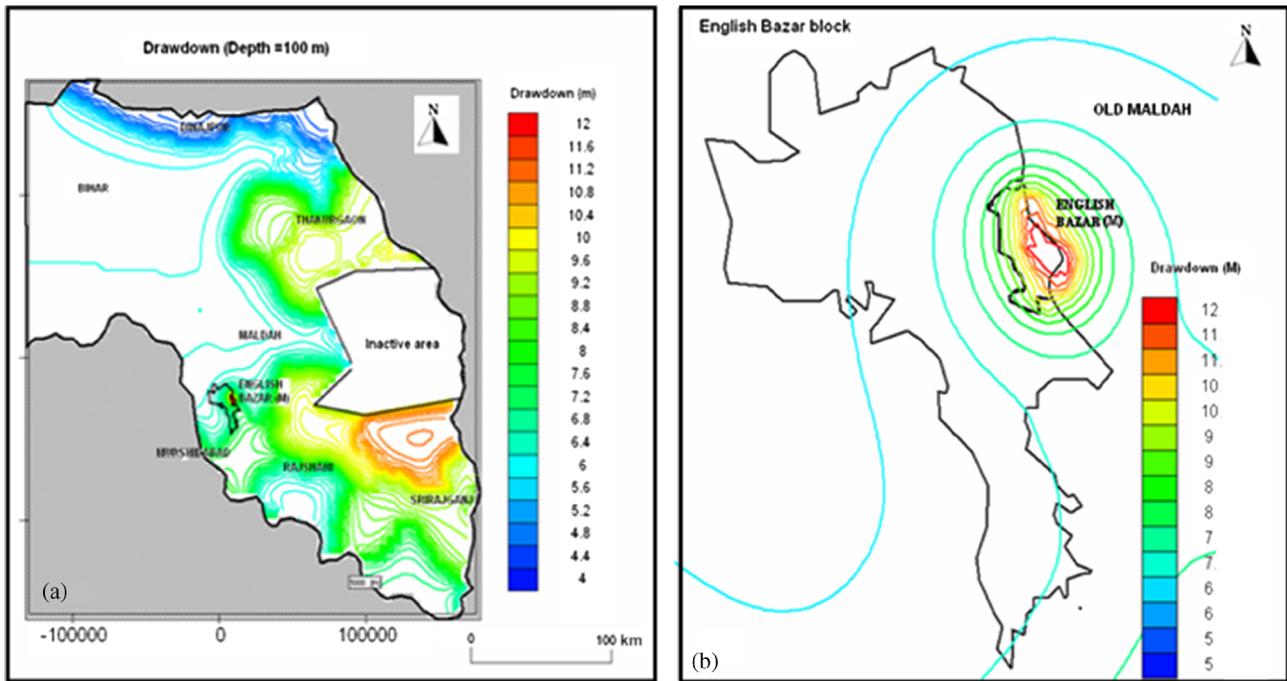
Figure 11. Spatial distribution of drawdown under current-development in the depth range of 70–100 m of (**a**) North Bengal Plain and (**b**) English bazaar block. In (**a**), the area where the basement depth is <100 m has been indicated as 'inactive area'.
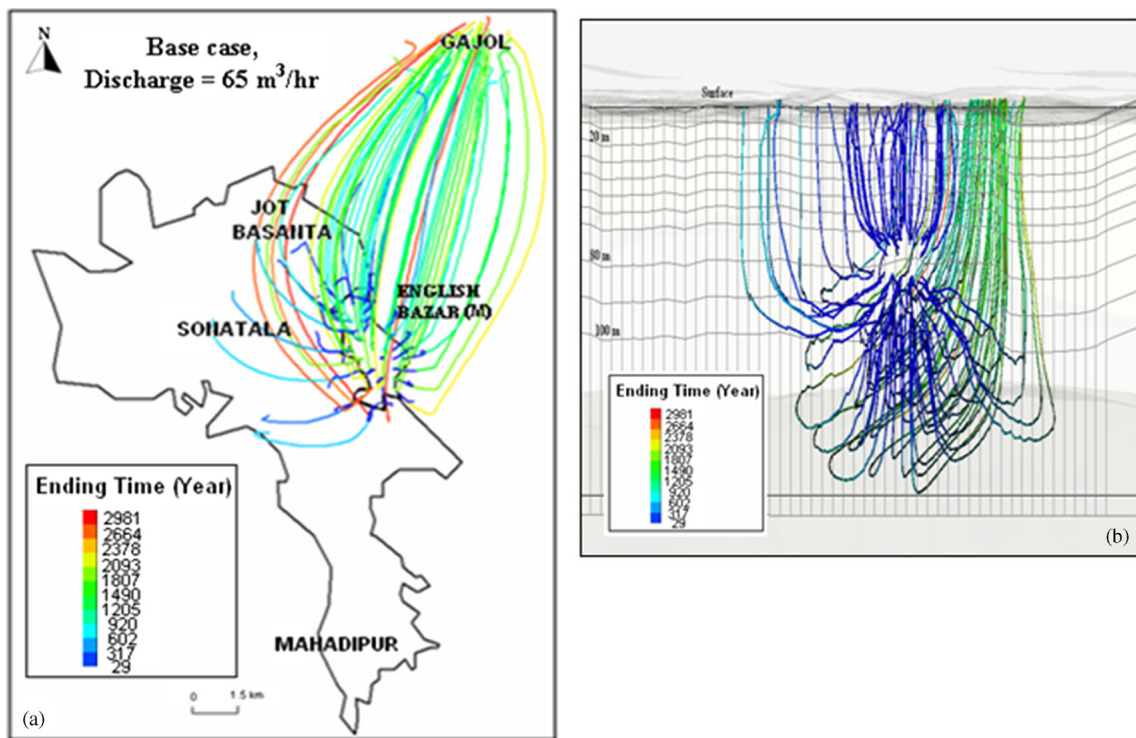

Figure 12. Recharge areas of groundwater of English Bazar Municipality at 100 m depth under current-development conditions. In (**b**), the view is from the south with vertical exaggeration of 50×.

at 65 m³/hr discharge per well in the municipal areas of English Bazar block to estimate the percentage of paths that will enter into the area of municipal wells from the areas where the As concentration is >10 µg/l and <10 µg/l (figure 1) during the indicated period of time (figure 13). The
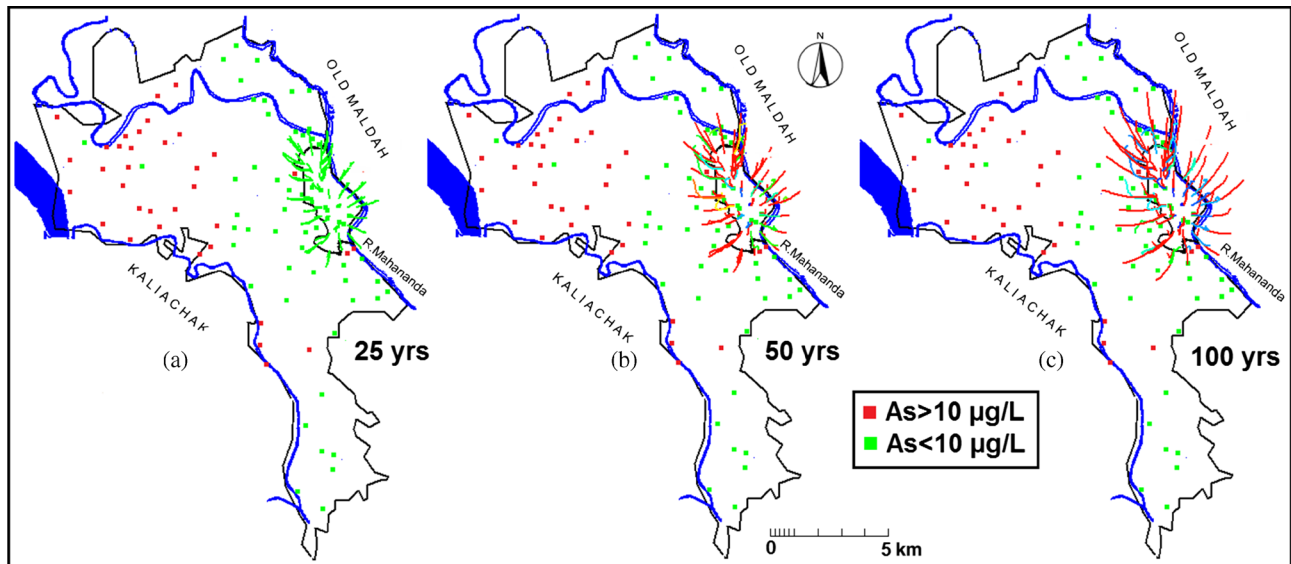
Figure 13. Current-development pathlines to locations at 100 m depth for different simulation times at 65 m³/hr discharge per well with base case anisotropy: (**a**) 25, (**b**) 50 and (**c**) 100 yrs. These times represent three different times of travel to the wells, showing which water will reach the wells after pumping for the indicated amount of time.

paths are controlled by the distributions of head and drawdown in the wells of the municipal area (figures 10 and 11). After 25 yrs of pumping at the present abstraction rate, no particles will come from the As-polluted zone, but after 50 yrs 1% of the particles will come from As-polluted zone, which will increase to 3% after 100 yrs (table 8). Hence, in most probability the municipal aquifer will remain As-free for the next 25 yrs at the current pumping rate based on advective groundwater flow. But true transport rates of dissolved As could be faster or slower depending on the spatial distribution of effective porosity values and on the heterogeneity of the aquifer's hydraulic conductivity distribution. Furthermore, As may be sorbed or be otherwise retarded in its movement by geochemical and other processes, causing its rate of migration to be slower than that of the water itself. These processes include adsorption, precipitation, redox reaction, microbial activity, colloidal transport and dissolution and transformation of naturally occurring minerals (Ravenscroft *et al.* 2001). Thus, the municipal wells may continue to yield As-free water for even longer period of time as predicted by MODPATH.

Outside the municipal area, the paths are selected to end at shallow depth (40 m) where most of the irrigation wells are screened. Under current pumping conditions, the flowpaths are near-vertical with very short horizontal path lengths. This indicates that, where As is present or released at shallow depths, it will reach the well depths within few tens of years and will continue to occur in pumping wells (figure 14). Therefore, a cycling of As between the surface and the shallow pumping zone

is taking place. The concentration of As in such a process can be reduced by dilution and/or sorption. Chances of dilution are less since the flow is near vertical. Therefore, most of the discharge of water from the aquifer takes place due to evaporation in the dry period. Some water is also discharged laterally into the river. The net result of evaporation is concentration of As. Monsoonal rain recharges the aquifer completely which tends to dilute the concentration of As. So there is a fluctuation in the concentration of As with seasons. But most of the water (with high As) applied for irrigation is after the monsoon. Thus, As will infiltrate into the aquifer rather than being washed away by monsoonal flooding. So, net dilution of As is unlikely to take place. Again As may not be removed by sorption since the Holocene sediments are in a reducing condition. Therefore, under the present pumping condition, natural flushing of As from the shallow aquifer may not take place. Hence, domestic wells of the English Bazar block tapping the aquifer at a depth of 15–57 m outside the municipality will continue to pump out As-polluted water. If all domestic wells are screened below 100 m, then the pathlines continue to remain near vertical and may start receiving water from the As-rich zone of the aquifer by 10 yrs due to advective transport. Therefore, lowering of the domestic wells in the As-free zone may not ensure As-free drinking water permanently. This corroborates with the findings of Mukherjee *et al.* (2011) local-scale study site in Nadia district where they showed that deep groundwater abstraction can draw As-rich water from 50 m below land surface to 150 m depth within a few decade.
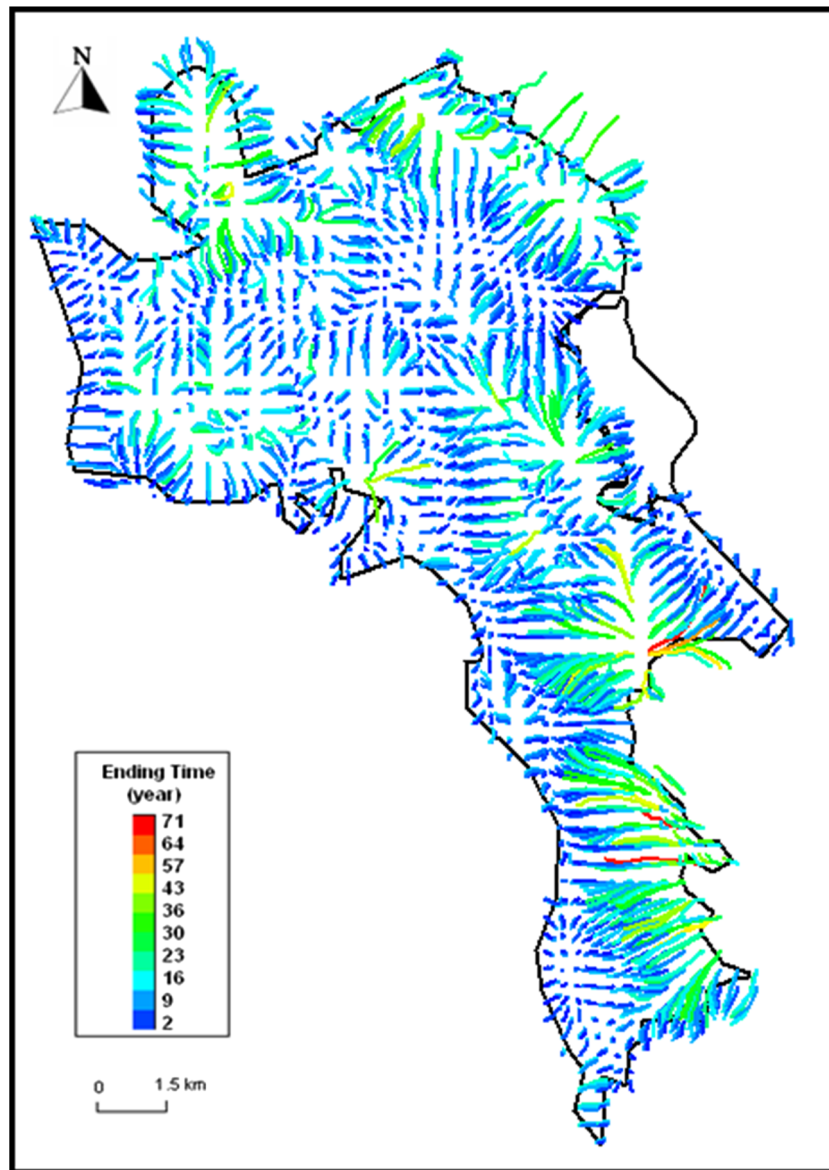
Figure 14. Current-development pathlines to locations at 40 m depth for 65 m^3/hr discharge per well with base case anisotropy.

Table 7. *Results of simulation with variable discharge rate of municipal well with 'base case' hydrogeologic parameters.*

Discharge rate per well (m^3/hr)	Max. hpl (km)	Min. hpl (km)	Mean hpl (km)	Mean travel time (year)
30	21	0.02	9	743
65	21	0.04	10	853
100	21	0.08	11	982

One way of managing the situation is allowing all the abstraction (domestic and irrigation) from the As-free zone by placing the screens of the wells below a depth of 100 m. Running the new model with the 'base case' hydrogeologic parameters, it is observed that the pathlines continue to remain near vertical and may start receiving water from the As-polluted zone of the aquifer by 10 yrs due to advective transport. There is no change in the percentage of pathlines from the As-free zone for a time frame of 25, 50 and 100 yrs. Hence, lowering of the domestic wells in the As-free zone may not ensure As-free water permanently. Therefore, our findings in English Bazaar of the North Bengal
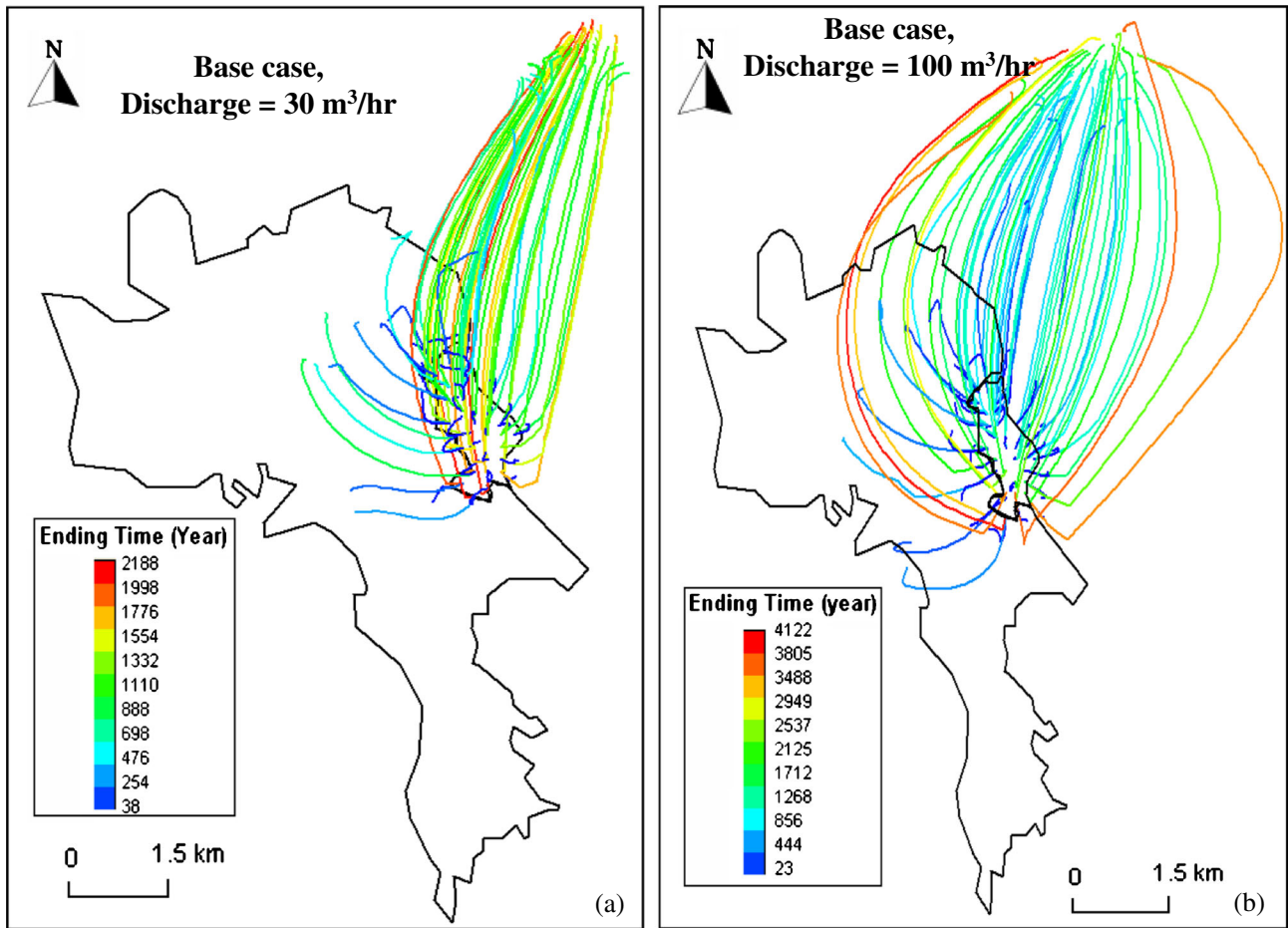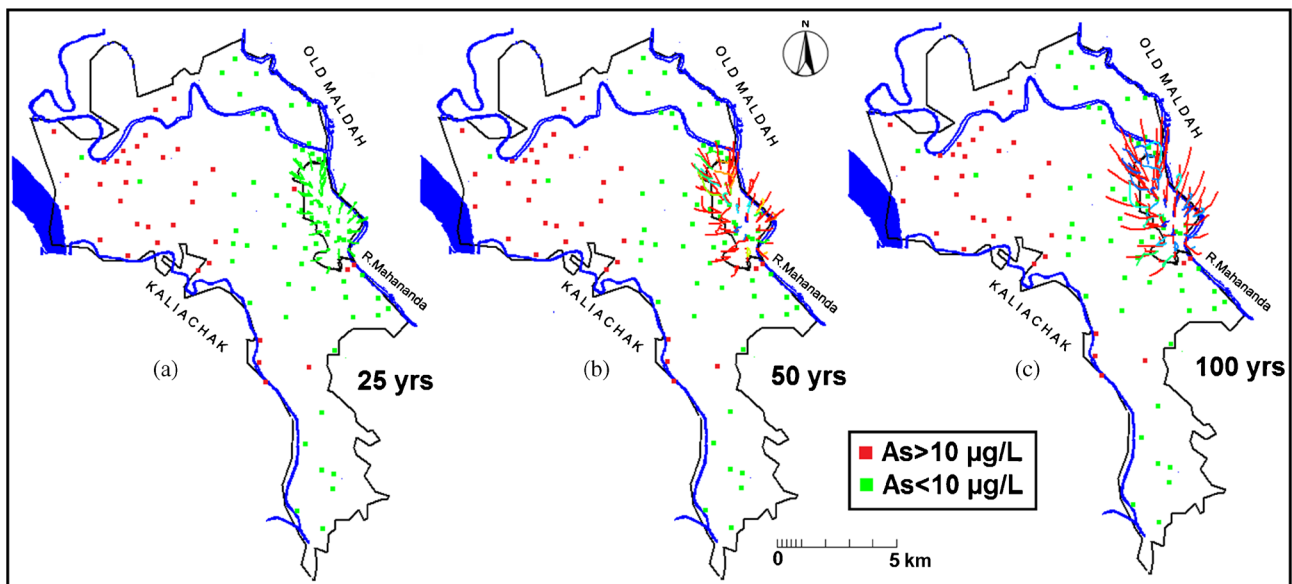
Figure 15. Recharge areas of groundwater at 100 m depth of English Bazar Municipality for base case hydrologic parameters under assumed future-development conditions of (**a**) 30 m^3/hr discharge per well and (**b**) 100 m^3/hr discharge per well.

Figure 16. Recharge areas of groundwater at 100 m depth of English Bazar Municipality for base case hydrologic parameters under assumed future-development conditions for different simulation times at 30 m^3/hr discharge per well: (**a**) 25, (**b**) 50 and (**c**) 100 yrs. These times represent three different times of travel to the wells, showing which water will reach the wells after pumping for the indicated amount of time.
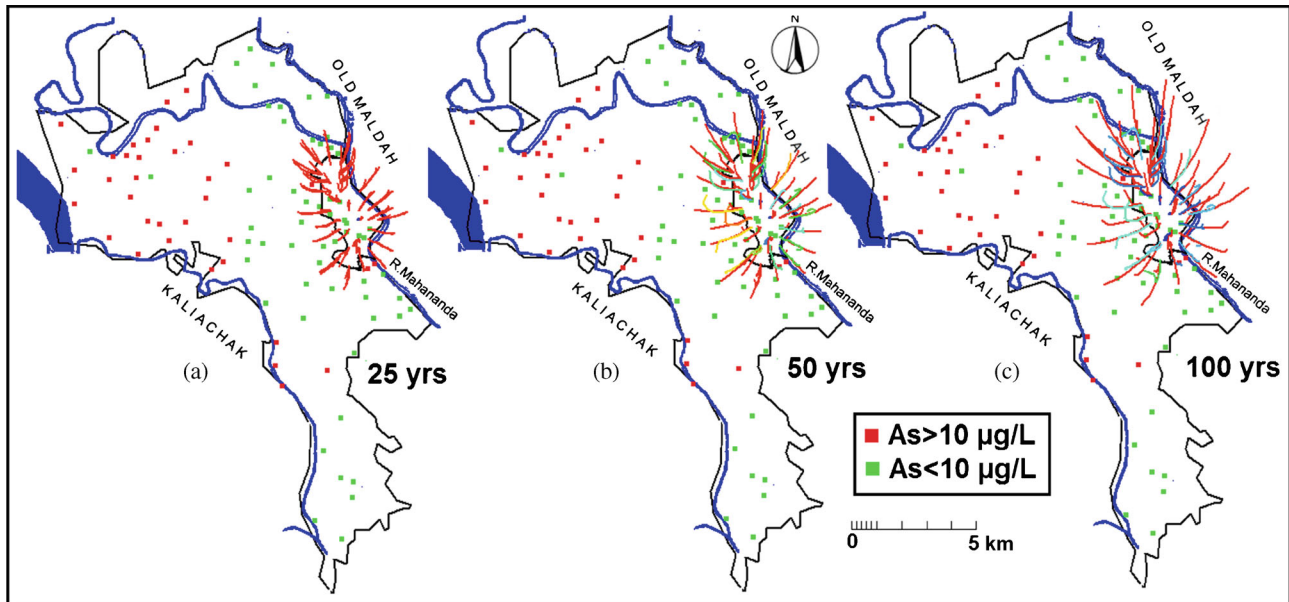
Figure 17. Recharge areas of groundwater at 100 m depth of English Bazar Municipality for base case hydrologic parameters under assumed future-development conditions for different simulation time at 100 m^3/hr discharge per well: (**a**) 25, (**b**) 50 and (**c**) 100 yrs. These times represent three different times of travel to the wells, showing which water will reach the wells after pumping for the indicated amount of time.

Table 8. *Results of simulation of current and future abstraction for different time frame.*

Year	Percentage of flow paths from areas with <10 µg/L As	Mean hpl (km)	Percentage of flow paths from areas with >10 µg/L As	Mean hpl (km)
Base case anisotropy with 65 m^3/hr discharge per well				
25	100	0.90	0	0
50	99	1.18	1	2.25
100	97	1.57	3	3.22
Base case anisotropy with 30 m^3/hr discharge per well				
25	100	0.57	0	0
50	100	0.87	0	0
100	98	1.29	1	2.37
Base case anisotropy with 100 m^3/hr discharge per well				
25	100	1.12	0	0
50	98	1.42	2	2.34
100	96	1.83	4	3.41

Plain differs from that of Michael and Voss (2008) based on regional scale modelling of the entire Bengal Basin where they inferred that with shallow high irrigation pumping and low scale deep pumping for domestic purpose, the deeper part of the aquifer system may provide a sustainable source of As-safe water. This may be due to the limited thickness of the aquifer in English Bazar block.

5.4.2 *Future development*

The model was run assuming future discharge rates of the municipal wells to be 30 and 100 m^3/hr per well. The mean hpl and travel time are shown in table 7. Figure 15 shows the recharge area of the

wells and is self-explanatory. The results for the simulation time of 25, 50 and 100 yrs are shown in figures 16–17 and table 8. At 30 m^3/hr pumping, no particles will come from As-polluted zone for 50 yrs, but after 100 yrs of pumping, 1% of the particles may flow from the As-polluted zone. But if the pumping rate is increased to 100 m^3/hr, then by 50 yrs 2% of the paths will enter the municipal aquifer from the As-polluted zone which may increase to 4% by the next 50 yrs (table 8).

6. Conclusion

The vulnerability of deep wells to contamination by As is governed by the geometry of induced

groundwater flow paths, and the lithological and geochemical conditions encountered between the shallow and deep regions of the aquifer system. This study indicates that the groundwater of the urban area of English Bazar Block will continue to be As-free for the foreseeable future at the current pumping rate which has resulted in >10 m drawdown. Outside the municipal area, irrigation pumping is predominant, the groundwater is As-rich and the flow paths are near-vertical. Hence, As-rich water applied on the irrigated land will be transported downward within 10 yrs. Therefore, flushing of As from the shallow aquifer may not take place and there will be recycling of As-rich water within the shallow aquifer. Similar conditions may be prevalent in other basins around the world. Therefore, fine-scale hydrogeologic analysis based on numerical simulation of shallow and deep groundwater flow should be applied to evaluate the complex three-dimensional flow field, incorporating spatial heterogeneity, to investigate the security of deep municipal abstraction for drinking purpose in other As-affected areas of Bengal Basin and in other As-polluted basins worldwide. This would minimize the risk of both deep and shallow aquifers that are currently unpolluted and identify safe drinking water well-field areas in As-polluted regions of the world.

Acknowledgements

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