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ORIGINAL ARTICLE

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Delineation of arsenic-contaminated zones in Bengal Delta, India: a geographic information system and fractal approach

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Abstract Groundwater extracted from shallow aquifers in the Bengal Delta is contaminated with arsenic. The fluviodeltaic process that creates aquifers, ironically, extends its role to also contaminating them with arsenic. The arsenic distribution maps show a spatial association of arsenic-contaminated wells with palaeo/cut-off/abandoned channels. Weight-on-evidences analysis indicates that the zones of contamination occur around palaeo-channels within a corridor of 500–700 m that contains most of the contaminated wells. These corridors are interpreted to be the zone of channel shifting. Contaminated wells represent point fractal geometry that can be separated into isolated points and clusters. Clusters occur within the zone of channel shifting as obtained by weight-on-evidences analysis. Isolated points occur within floodplain or back swamp areas. Clusters and isolated point fractals are interpreted to reflect the process of arsenic release into groundwater. The migration of biomass within the permeable sandy domain of channel deposits is proposed to be the predominant process in generating clusters. The isolated points represent restricted biomass spreading in less permeable clay-silt dominated floodplains.

Keywords Arsenic · Palaeochannel Weight-on-evidences analysis Fractal · Bengal Delta · India

Introduction

The population of the West Bengal delta are supplied their drinking- and irrigation water from a few million tube-wells. A vast majority of these wells have been installed privately with locally available expertise, without any check of the quality and yield of the water that originates from them. All of the tube-wells tap water from sandy aquifers constituted of Holocene fluvial material, and it has become apparent that a large number of these wells now yield water with an arsenic content that is more than one order of magnitude above the Indian drinking water standard. This arsenic occurs as a natural contaminant, and its concentration in the drinking- and irrigation water can be taken as a measure of arsenic exposure of the population using it (Ahsan et al. 2000). Accurate information on the number of the tube-wells yielding unsafe water, their distribution or the number of people being exposed to arsenic is not available. To date, no survey has been planned to identify unsafe tube-wells – unlike the survey being carried out in neighbouring Bangladesh – although attempts may be made to identify safe wells area-wise/village-wise and motivate people to switch to safer wells. This strategy is being promoted as part of a wider mitigation plan in certain locations of Bangladesh (Gelman et al. 2004).

In West Bengal, wells seemingly yield water containing low or high levels of arsenic more-or-less randomly, without a simple spatial pattern. Consequently, it has not been possible to obtain a reliable arsenic content without actually measuring the water of a specific well. In the investigation reported here, measurements taken in contiguous villages in a particular region were found to show a systematic pattern with respect to the occurrence

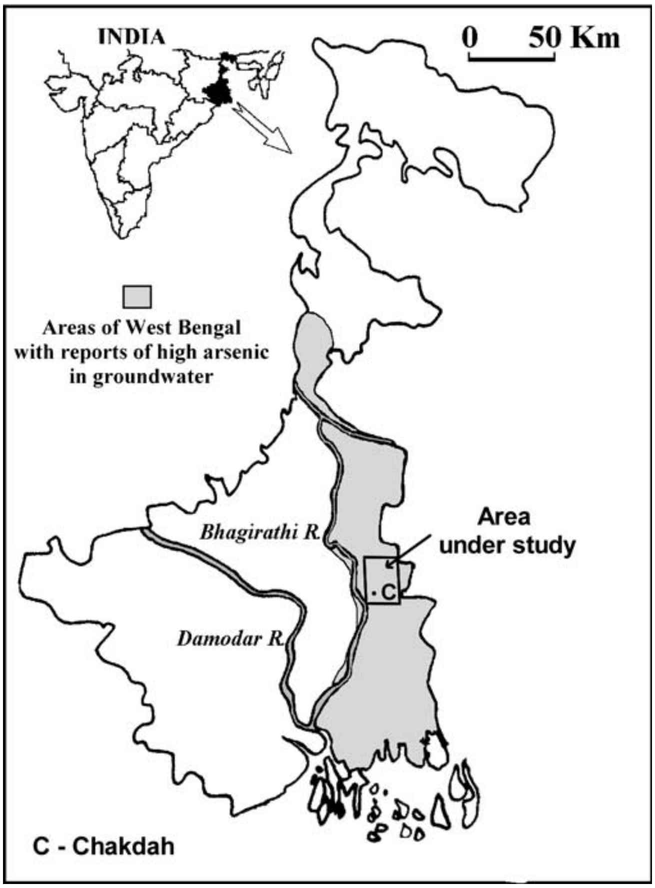


Fig. 1 Location map of the study area

of arsenic in the well water. Water was measured from 1,070 wells, varying in depth from 10 to 150 m, situated in parts of the 24-Parganas (N) and Nadia districts (Fig. 1) in order to investigate whether there is a pattern of distribution of high-arsenic levels in the water from the wells. The correlation of arsenic levels with the present drainage pattern is illustrated along with suggestions regarding the cause of such patterns. Once the pattern is identified, arsenic-free well water may be predicted without actually making measurements, thus making the switch to safer wells easier and immediate. This process would also allow new community wells to be planned in the safe water zones and the subsequent supply of water through PVC pipelines to villages located in the unsafe zones.

Geological and geomorphological framework

Flanked to west, north and east by Pleistocene terraces and older rocks, the Bengal Delta encompasses most of Bangladesh and the adjoining state of Indian West Bengal. Considered to be among the best examples of a modern delta with respect to sediment debauchment, the Bengal Delta is fed by Himalayan rivers – the Ganga, Brahamputra, Meghna and their distributaries – flowing down to the Bay of Bengal. The Bengal Delta evolved in three stages; a Wisconsin sea-level lowering, Flandrian transgression and a regressive third stage with eastward delta progradation. Gradual migration of the Ganga to the east has also occurred. Geomorphologically, the delta can be divided into four major units: palaeo-delta, sub-aerial delta, transitional unit and marine unit, each with different landforms. In general, the delta presents a complex sequence of sedimentary deposits ranging from coarse to fine clastics, peaty and carbonaceous materials and calcareous sediments, with rapid facies variation both vertically and laterally.

This study is restricted to the West Bengal area east of the Bhagirathi river. In the West Bengal part of the Bengal Delta, the Holocene sequence is classified into the Older Alluvium Plain (OAP), overlain by the Young Delta Plain (YDP). Both are incised by the present channel and delta plain of the Bhagirathi river (Acharyya et al. 2000). The study area is a portion of the Bhagirathi-Ichamati-Jamuna distributary system, which formed during the last 10,000 years. It is a monotonous alluvial plain with relief in the range of 8–11 m.a.s.l. Various levees, active/abandoned channels, cut-off meander loops, ox-bow lakes, back swamps and inter-levee depressions/flood basins – mostly aggraded – are common. The active channels are the rivers Hoogly and Ichamati, which skirt the western and eastern side, respectively, and flow south. The master slope is to the south and southeast. The present landscape evolved from the shifting of channels, which align primarily north to south, with convexity towards the east. Arsenic-contaminated groundwater is restricted to the YDP part of the delta.

The Krishnanagar-Ranaghat area of West Bengal is completely blanketed by Holocene unconsolidated sediments that fall within the late Holocene Bhagirathi morphostratigraphy. The landscape is a large fine sand/silt-dominated tract with medium-to-coarse sand-bearing sediments of disjointed palaeo-channel courses and patchy lens of clay-rich marshes. In the subsurface, a continuous fine-to-medium sand/silt fluvial sequence along with thin (centimetre to metre scale) clay bands predominates. Moderately thick subsurface lenses of clay are also encountered, and at various places a thick clay cap tops the sequence. The resulting aquifers represent relatively coarser sand lenses of varying depth and thickness. In short, the subsurface sediment distribution is typical of a fluvio-deltaic depositional system in which channel fill, channel bar and inter-fluve sediments are vertically stacked. There appears to be a correlation between the distribution of these palaeo-channels and clay lenses with arsenic-contaminated groundwater.

Table 1 The frequency distribution of arsenic values in domestic tube-wells located in the Krishnanagar and Ranaghat areas, Nadia District, West Bengal, India

As range (mg/l)	Tube-wells in the Krishnanagar area			Tube-wells in the Ranaghat area		
	Frequency	Frequency (expressed as a percentage)	Cumulative frequency (expressed as a percentage)	Frequency	Frequency (expressed as a percentage)	Cumulative frequency (expressed as a percentage)
0–0.01	11	2	2	155	28	28
0.01–0.03	240	46	48	133	24	52
0.03–0.05	12	2	50	72	13	65
0.05–0.07	77	15	65	56	10	75
0.07–0.09	63	13	78	87	16	91
0.09–0.2	93	18	96	38	7	98
0.2–1	21	4	100	12	2	100
Total	517	100		553	100	

Geographic information system (GIS) data

Arsenic levels in aquifer sediments can be viewed on scales ranging from a delta scale (10^4 km^2) with a system of rivers to a cadastral scale (only a few square kilometres) through an intermediate scale involving hundreds of square kilometres. Depending on the scale, high arsenic levels may be confined to a single geomorphic unit or to a assemblage of morphometric units typical of a river sub-basin. The Geological Survey of India (GSI) has generated arsenic content data on different scales. Scale 1:50,000 is an optimum balance for studies of landform and arsenic distribution. The geomorphological elements generated by an active channel are best studied at the same scale. Typically, arsenic determination is done with E-Merck field test kit with a range of 0.01–0.5 mg/l. The data has been transferred to a 1:50,000 scale topographical base map correlated with palaeo- and present-day geomorphological units.

Geographic information system tools have been used in this study for building a spatial database and to create a probabilistic model for predicting spatial relationship. Tube-well arsenic data and imagery have been correlated with palaeo-channel distribution. The tube-well locations as point and arsenic values as class were entered into the spatial database. The digitally processed IRS-1D satellite data (2003) were used to generate a palaeo channel distribution map. The composite image generated through combining spectral bands 2, 3 and 4 were georeferenced by registering with selected ground control points that are predominantly identifiable from the digital data and topographic maps (1:50,000 scale). The resultant false colour composite image shows dense vegetation in deep red and scattered vegetation in light red. The water bodies are black and dark grey in colour, and palaeo-channels exhibit a curvi-linear grey tone. Interpreted palaeo-channels have been picked out and incorporated in GIS (ArcGIS 9.0 of ESRI) as line coverage.

Arsenic distribution map – GIS and fractal analysis

The tube-well data include arsenic analysis of 517 and 553 samples from the Krishnanagar and Ranaghat areas of Nadia district, West Bengal (Table 1). The frequency distribution of the number of tube-wells with different ranges of arsenic content is presented in Fig. 2a, b. Both

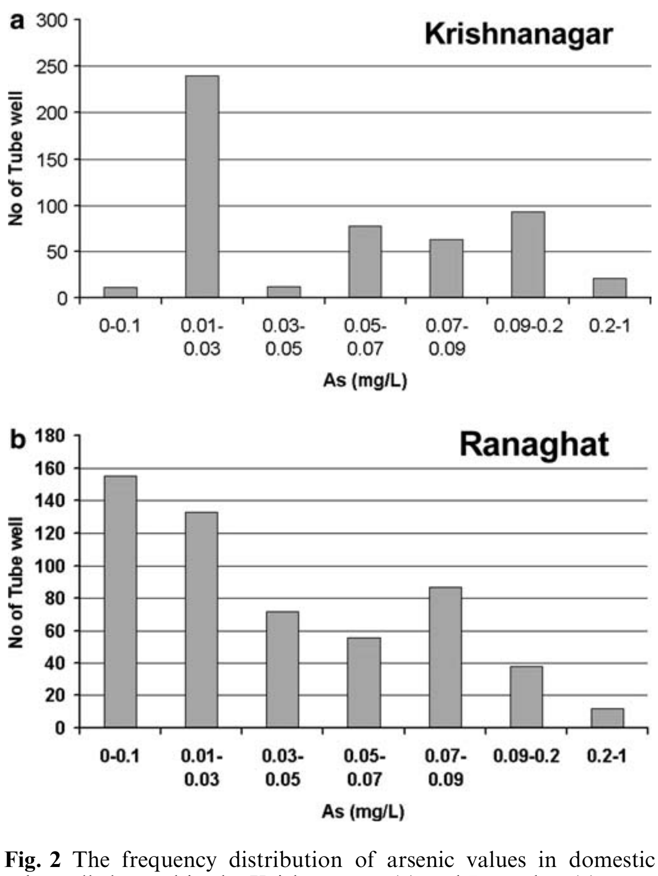


Fig. 2 The frequency distribution of arsenic values in domestic tube-wells located in the Krishnanagar (**a**) and Ranaghat (**b**) areas

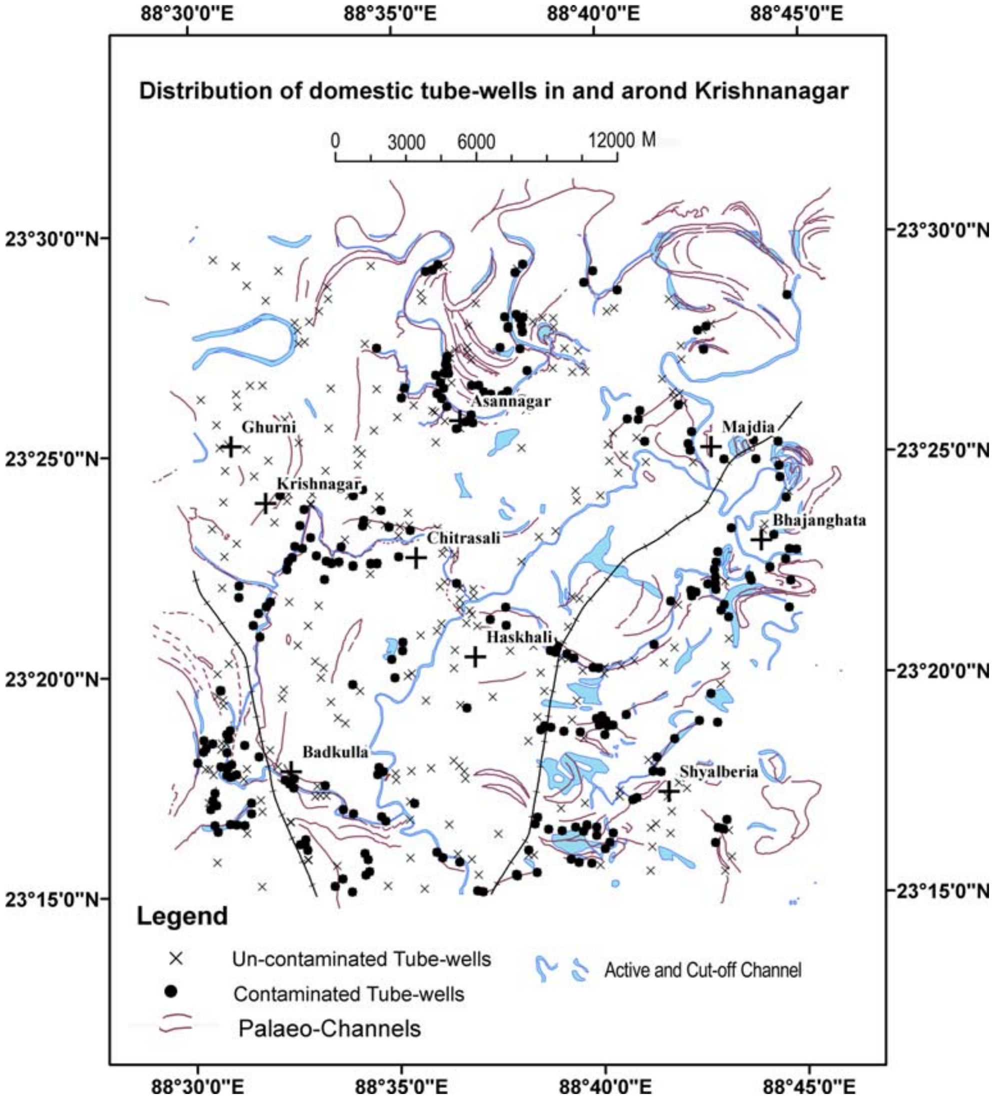


Fig. 3 Arsenic distribution map of the Krishnanagar (**a**) and Ranaghat (**b**) areas, Nadia district, West Bengal, India

areas have positively skewed distribution as observed with a maximum frequency below 0.03 mg/l of arsenic. If 0.05 mg/l arsenic is considered the acceptable cut-off level (Indian drinking water standard), 50% of the wells in the Krishnanagar area and 35% of the wells in the Ranaghat area are above the permissible limit. At Krishnanagar, the lower frequency was at 0.03–0.05. Succeeding values tend to make the distribution bimodal to some extent. In the Ranaghat area, values show gradually decreasing frequencies with a minor peak at 0.07–0.09 mg/l.

Arsenic distribution in shallow aquifers was plotted on a 1:50,000 scale topographic base map. The palaeo-channel dispositions along with contaminated wells are shown in Fig. 3a, b for Krishnanagar and Ranaghat areas, respectively. Two significant observations emerge from the pattern. Firstly, contamination is not uniformly present in the entire area and arsenic-free areas predominate. Secondly, the arsenious wells (As≥0.05 mg/l) occur as clusters primarily concentrated around palaeo/abandoned/cut-off channels. GIS analysis using known data on the locations of contaminated tube-wells and the palaeo-channels was performed to verify the spatial relationships and controls of arsenic distribution.

Weight-on-evidences analysis (Bonham-Carter 1994) using Bayesian statistics was employed to estimate the dependence of arsenic contamination on palaeo-channels. On the basis of the map pattern, this spatial analysis calculates the conditional probability of the occurrence of one event – i.e. contaminated wells – provided another event – i.e. palaeo-channel – is present. An iterative method using corridors of different width around the palaeo-channels was utilised to calculate the weights $W+$ and $W-$ (Table 2). $W+$ indicates the probability of the occurrence of a contaminated well if a palaeo-channel is present within the corridor of a given width. $W-$ indicates the probability of non-occurrence of a contaminated well even if a palaeo-channel corridor contains the well site.

Fig. 3 (contd.)

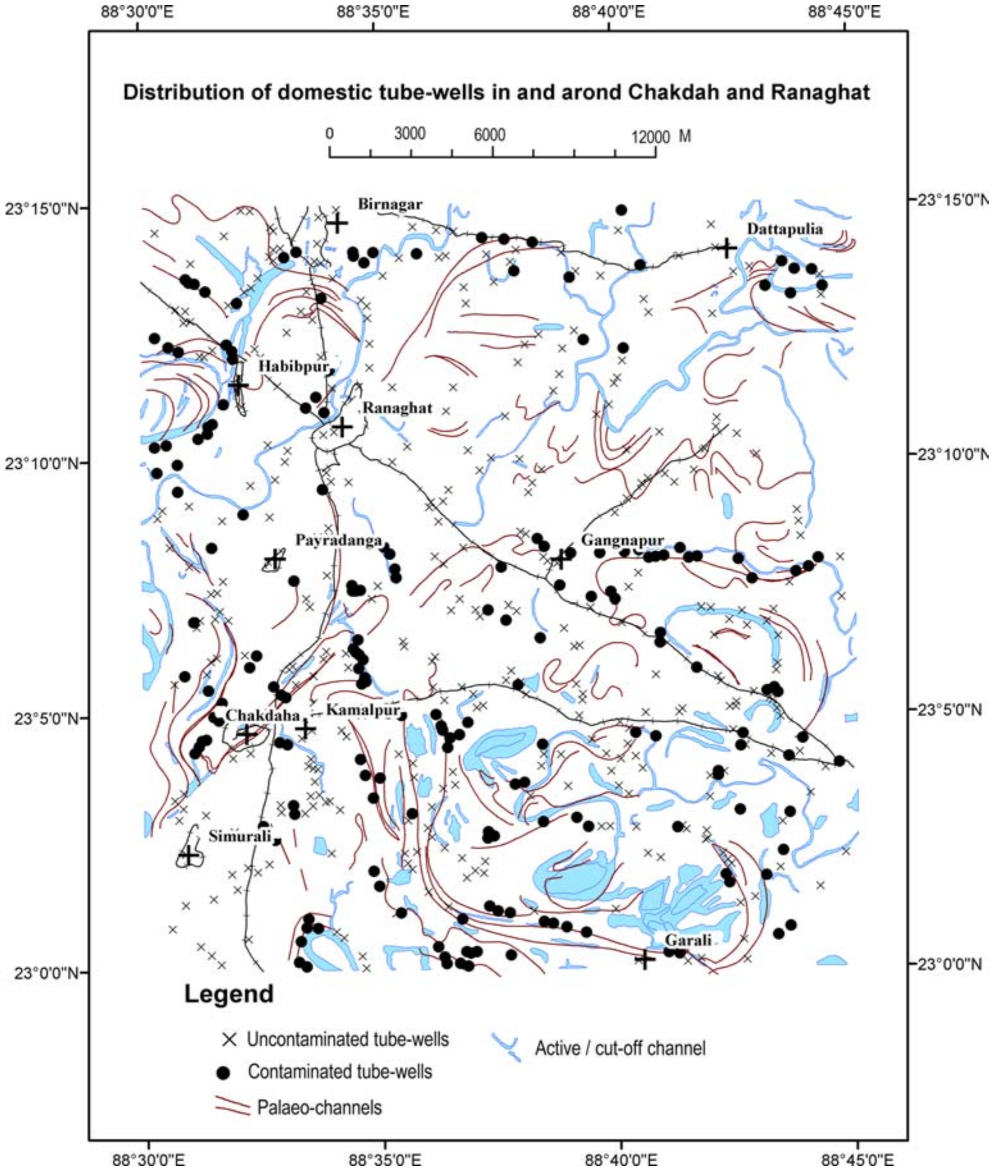


Table 2 Bayesian weights ($W+$ and $W-$) and contrast (C) calculated for variable buffer distances (in metres) from palaeo-channels of the Krishnanagar and Ranaghat area

Distance (m)	Number of tube-wells under pattern	$W+$	$W-$	Contrast (C)
Krishnanagar area Total area under evaluation: 716.02 km^2 Total no. of contaminated tube-wells:254				
250	130	0.9390	−0.4938	1.4328
500	219	0.7674	−1.4707	2.2381
750	240	0.2605	−0.8899	1.1504
1000	252	0.0686	−1.2355	1.3041
Ranaghat area Total area under evaluation: 714.64 km^2 Total no. of contaminated tube-wells: 193				
150	50	0.6216	−0.1500	0.7716
250	82	0.6942	−0.3146	1.0088
500	121	0.4390	−0.4682	0.9072
750	149	0.3196	−0.6557	0.9753
1000	160	0.1510	−0.5185	0.6695

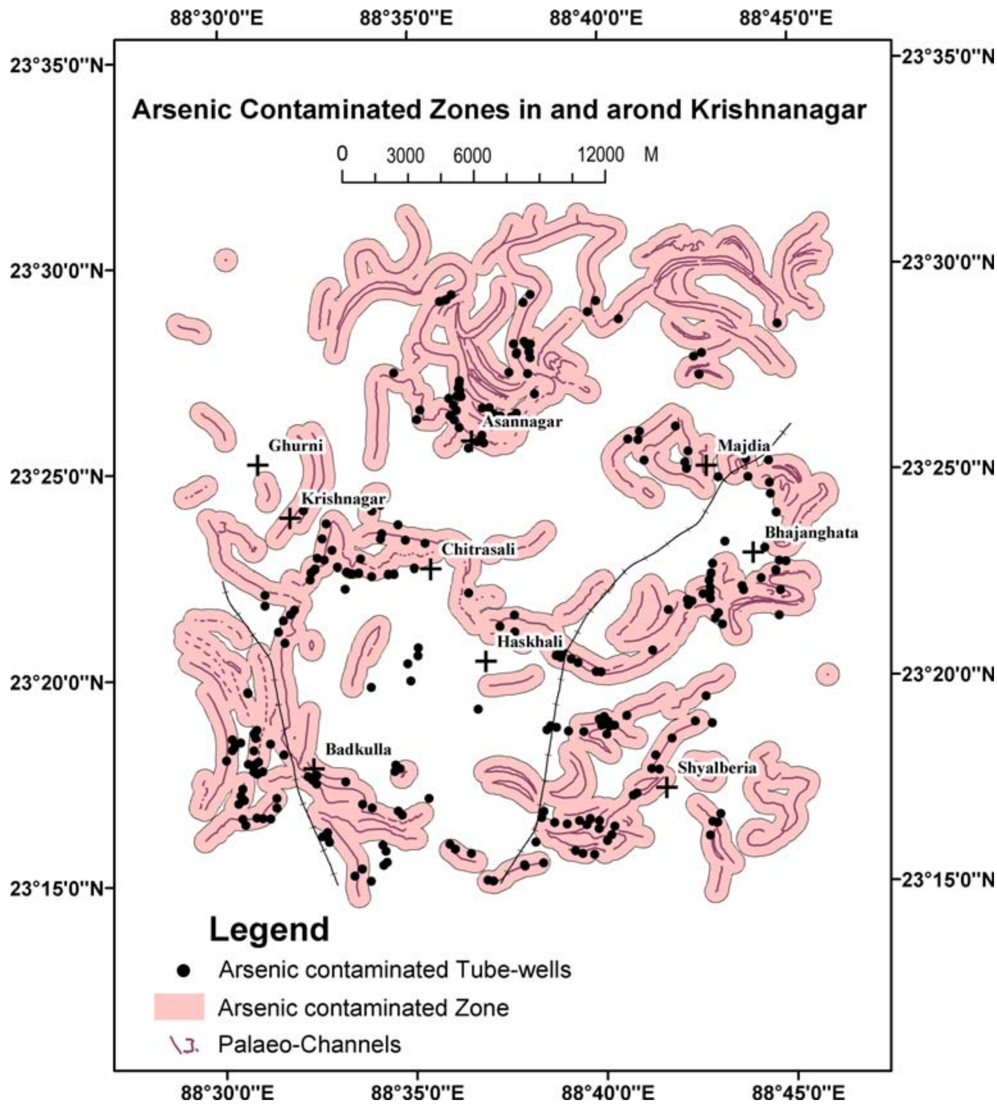
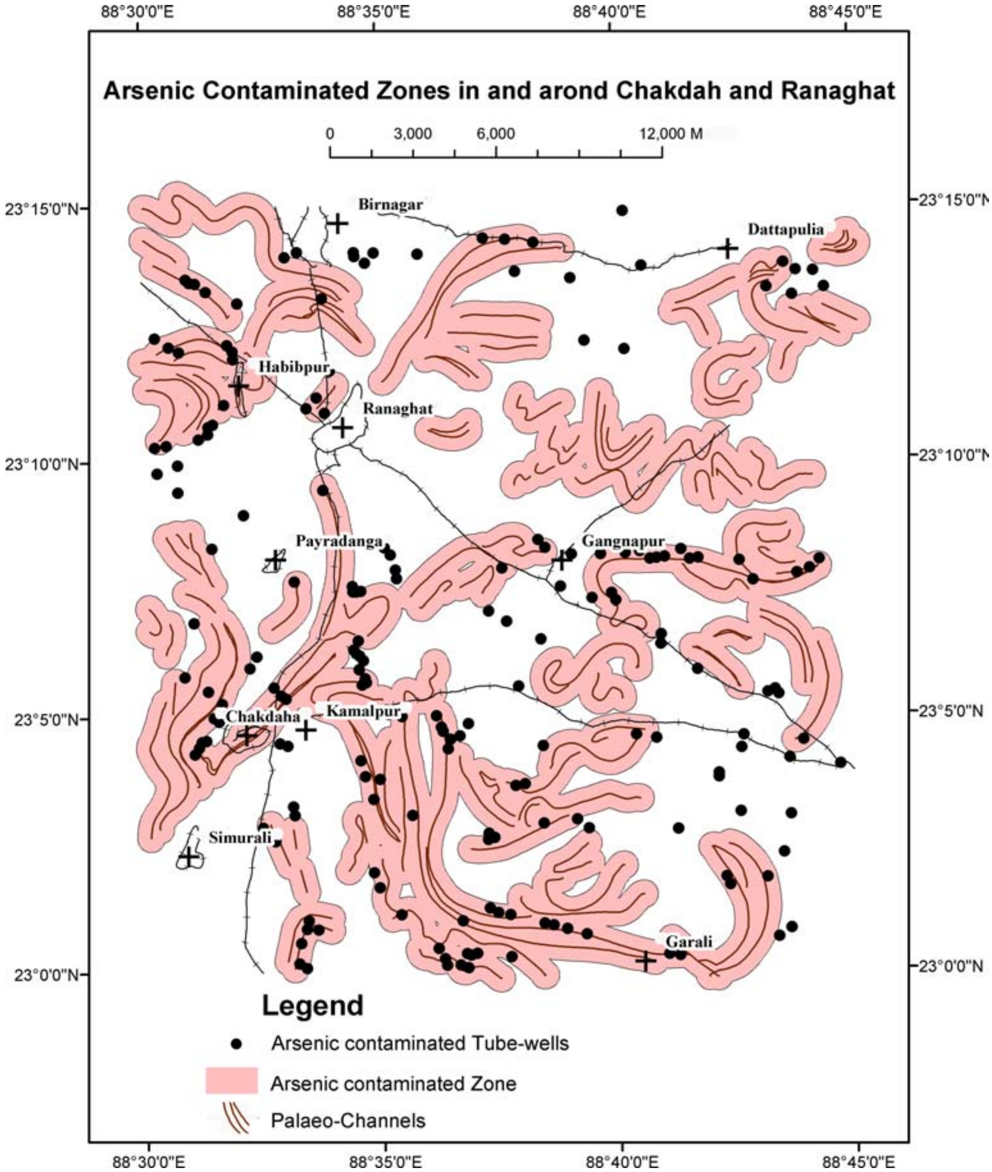


Fig. 4 Distribution of arsenic-contaminated wells within palaeo-channel corridors found in the, Krishnanagar (**a**) and Ranaghat (**b**) areas, Nadia district, West Bengal, India

Corridors of different widths around the palaeo-channels were generated and converted to binary predictor evidence maps with assignment of '1' for within the corridor and '0' for outside of the corridor. The numbers of contaminated wells falling within the corridors were then calculated. The mathematical treatment of the entire process is given in detail by Bonham-Carter (1994) for further reference. Table 2 shows the weights of different buffers as well as the number of contaminated wells within the buffers. The difference in weights, called contrast (*C*), is a useful parameter by which to judge the spatial association of contaminated wells in relation to palaeo-channels. Higher positive values of *C* indicate a greater positive association. A zone of influence can be thought of as the corridor with the highest *C* and usually indicates the optimum cut-off distance at which the predictive power of the binary pattern is maximised (Bonham-Carter et al. 1988). In the case of the Krishnanagar area, the 500-m corridor was found to have the maximum value of *C* (2.2381), and 86% of contaminated wells were found within the corridor. This buffer zone can be interpreted to be the average area of shifting stream courses and taken as the characteristic contaminated zone beyond which the chance of finding contaminated tube-wells will be less (Fig. 4a). In Ranaghat area, *C* values for 250, 500 and 750 m are 1.0088, 0.9072 and 0.9753, respectively (Table 2b). Whereas 250-m corridors were found to contain 42% of the contaminated wells, the 500- and 750-m corridors cover 63 and 77% of the contaminated wells, respectively. Thus, for Ranaghat area, a 750-m influence zone can be considered to be optimum (Fig. 4b).

Spatial association is merely an indication that there is an underlying causative process. The explanation for the spatial association in terms of a common factor is obtained from geometric analysis. Fractal analysis was

Fig. 4 (contd.)



used in this case. Fractal objects with 'self-similar' symmetry were used to characterise apparently disordered geometric systems. Fractal analysis can also be used to analyse non-geometrical objects; for example the spatial distribution of various measurable natural quantities, of which the geochemical distribution of an element is a specific example (Bolviken et al. 1992). Once the fractal nature of palaeo-channels and arsenic-contaminated wells is established, it can be argued that there is a causative relationship between the two.

The Box-counting method (Feeder 1988) was used to calculate fractal dimensions. The palaeo-channel lines or contaminated tube-wells were overlaid with a grid of square boxes (pixels) which progressed from the smallest to successively larger boxes by combining the pixels in an up-scale manner (Cheng 1999). The numbers of boxes (N_n) of size r_n required to cover data were then plotted in a log-log scale as a function of r_n. To denote the distribution as fractal, N_n with a characteristic linear dimension greater than r_n must satisfy the relation $N_n = C1/N_n^D$, where $C1$ is the proportionality constant and D is the fractal dimension, calculated as factor $\log(N_{n+1}/N_n)/\log(r_n/r_{n+1})$ (Turcotte 1997).

For the palaeo-channel data, the plots of $\log(N_n)$ versus $\log(1/r_n)$ gave a perfect straight line (Fig. 5a, b). These plots indicate that palaeo-channel data obey scale invariant curvilinear fractal geometry with the fractal dimension varying from 1.1481 to 1.1583. Box-counting measurements for contaminated tube-well data of the two areas generated non-linear plots (Fig. 6a, b). There is a change in geometry depending on scale (Quillon et al. 1995; Quillon and Sornetto 1996; Lei and

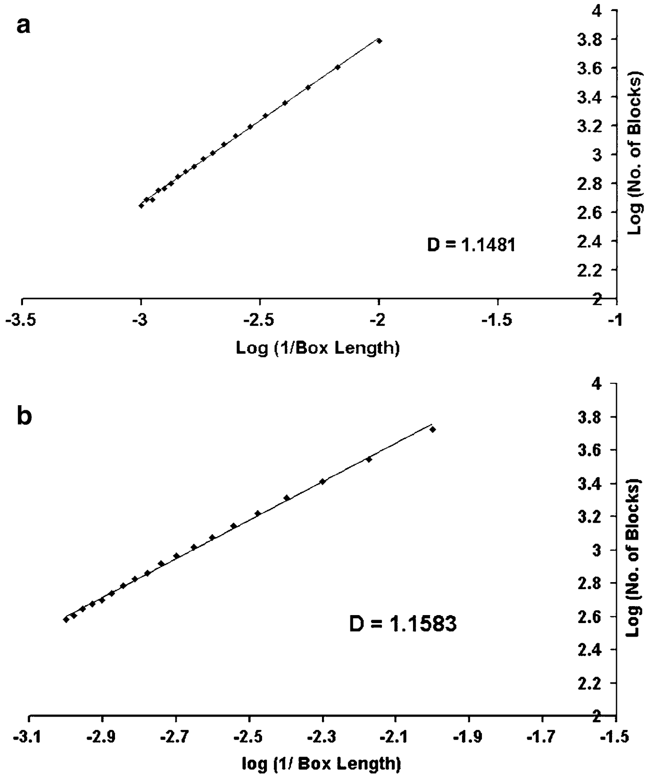


Fig. 5 Statistics using the box-counting algorithm on the interpreted palaeo-channel data on the Krishnanagar area (**a**) [correlation is used to obtain the fractal dimension ($D = 1.1481$)] and on the Ranaghat area (**b**) [correlation is used to obtain the fractal dimension ($D = 1.1583$)]

Kusunose 1999). Lei and Kusunose (1999) pointed out that geological systems have a common characteristic scale (in terms of length) which breaks the spatial dimension into two bands (one higher than the characteristic length and other below it). Thus, $\log(N)-\log(1/r)$ is linear in each of these bands, and two capacity dimensions (D_0) corresponding to two bands can be obtained respectively; the intersection point of these two lines is the characteristic length where geometry changes. For Krishnanagar, the geometry was split into two bands, one with a capacity fractal dimension of 0.1174 and the other with 0.4084, with the characteristic length being 350 m where two bands intersected. For Ranaghat, the data was also separated into two capacity bands at 250 m where the fractal dimension of 0.1049 was separated from 0.3557. The significance of the fractal analysis is discussed below.

Discussion

We report here on arsenic contamination in groundwater from the low-lying part of the Bengal Delta consisting of Holocene to Recent alluvial deposits of the Himalayan rivers. Fluvial depositional processes produce different landforms, including channel bar, point bar, levee, back swamps and others, each with its typical sediment character. In a prograding delta environment with southward migrating shoreline, bottom clay (Upper Tertiary) underlies a predominant sand-silt sequence punctuated by discontinuous clay lenses. The present study of shallow aquifers of the Krishnanagar-Ranaghat area may be viewed within this framework.

The shallow aquifers are mostly unconfined or semi-confined, and are recharged from the top as well as flushed horizontally. It has been established that arsenic comes to this delta as a natural contaminant carried in the sediments by the Himalayan rivers. The element is deposited together with the sediments, becoming fixed in the mineral constituents of the aquifer (Sengupta et al. 2004; Oremland and Stolz 2005). It can, therefore, be presumed that arsenic distribution in the aquifer sediments is a product of the same process that created the fluvial landscape. The current question is whether the pattern of arsenic concentration in the groundwater has any relation with the arsenic distribution in the host aquifer sediments and, consequently, be inferred to have been also generated by the fluvial process. It is generally accepted that arsenic is released from the sediments and enters the groundwater. However, the mechanism of release from solid to aqueous phase and the factors controlling the release are not yet thoroughly understood.

The present work attempts to establish connections between the geomorphic elements that the fluvial process has created and the pattern of arsenic distributions in groundwater and to identify the type of influence the geomorphic components wield on the aqueous arsenic distribution. As stated, arsenic levels in groundwater in the area are not uniform. Tube-wells yielding water with arsenic levels greater than the Indian standard for drinking water (>0.05 mg/l) are confined to zones showing a systematic pattern (Sengupta et al. 2003, 2004). These zones in which there is a high level of arsenic in the groundwater constitute only a fraction of the total area and also demonstrate a close spatial association with geomorphic elements – that is to say, palaeo/abandoned and cut-off meander channels. GIS-based weight-on-evidences modelling indicates an optimum 500- and 750-m corridor of influence on either side of the palaeo-channels in the Krishnanagar and Ranaghat areas, respectively. Most of the contaminated wells are located in this zone. The 500- and 700-m buffer zones statistically represent the size of the sand bodies that are the products of coalescing channel bars. The width of the corridor corresponds to the span of the valley in which channel shifting was confined during the formation of the sand bars. On either side beyond the width of the corridor, the sand bodies grade into sediments of

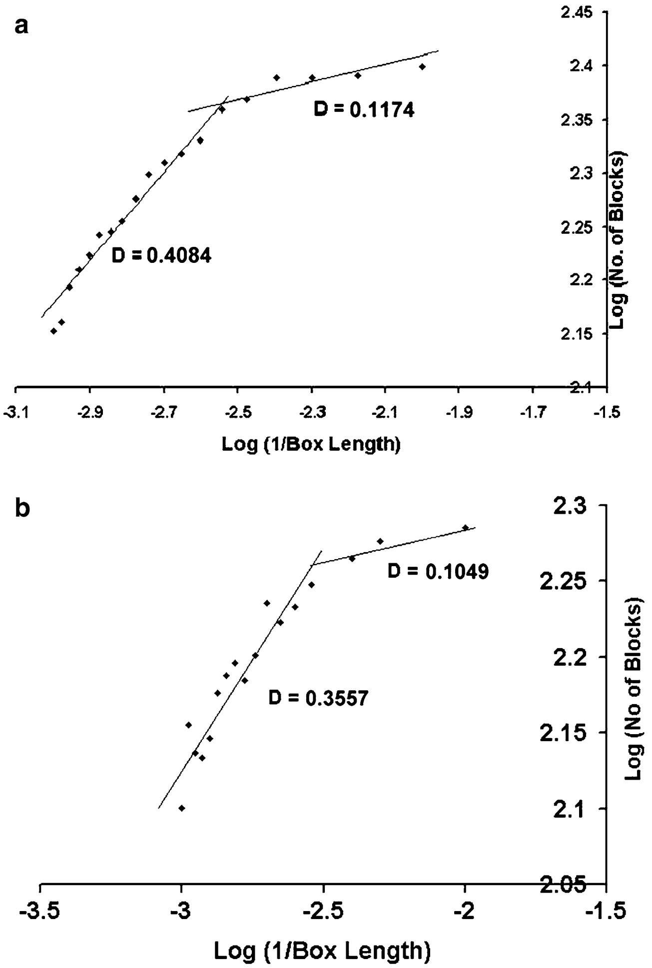


Fig. 6 Statistics using the box-counting algorithm on the contaminated tube-well data on the Krishnanagar area (**a**) [correlation is used to obtain two capacity dimensions, $D = 0.1175$ (up to 350 m) and $D = 0.4084$ (beyond 350 m)] and on the Ranaghat area (**b**) [correlation is used to obtain two capacity dimensions, $D = 0.1049$ (up to 250 m) and $D = 0.3557$ (beyond 250 m)]

floodplain facies, with corresponding changes in the character of the sediments.

There is a lack of any pattern in the arsenic content and aquifer sand across the area; additionally, the presence of arsenic in sediments does not show any spatial correlation with the geomorphic elements. Arsenic values from sediments belonging to the sandy facies are restricted to a small range of 1–3 mg/kg, with only a few rare outliers (Pal et al. 2002). Analyses of samples from clay lenses and layers reveal consistently higher arsenic levels than those found in samples from sandy soils.

Sediment profiles associated with the different geomorphologic elements differ in character; however, the levels of sediment arsenic are not significantly different in the different profiles. There does appears to be some pattern with respect to arsenic content in the groundwater. For demonstrating the relation, the alluvial landscape may be divided into three domains: (1) areas of channel deposits (predominantly sand); (2) areas of floodplain deposits (predominantly clay); (3) a mixed domain where constituents of these two interfinger.

The first domain includes the palaeo-channels as well as the statistically estimated corridor on either side of the channels; the sediment profile is presented in profile'B' of Fig. 7. Here a sand sequence underlies the top soil, and it is this domain that the majority of contaminated tube-wells are located. There is, however, no systematic pattern of depth-wise variation in the levels of aqueous arsenic. The second domain includes floodplains, and its sediment profile is profile 'A' of Fig. 7. Here a thick, impervious sticky clay cap (>25 m) overlies sand and silt. Groundwater extracted in this sequence is invariably arsenic-free irrespective of the depth of withdrawal. The mixed domain (Profile 'C' of Fig. 7) contains an impervious clay horizon belonging to floodplain facies at a depth of 25–30 m, which separates one relatively older channel facies from a younger one. Areas in the mixed domain contain both safe and contaminated tube-wells, and no pattern of arsenic distribution has been observed. The water quality in terms of arsenic content is solely depth-dependent in this domain: groundwater from the lower aquifer is invariably arsenic free, while that from the shallower of the two aquifers overlying the clay is contaminated.

There is a close spatial association between contaminated tube-wells and specific domains in the fluvial landscape, irrespective of a lack of any pattern in sediment arsenic. This observed contrast can be explained if the amount of arsenic release from the solid phase in different domains is variable. The presence or absence of impervious clay in profiles 'A' and 'B' may have created a difference in the physical and chemical environment of the aquifer in the two domains. In profile 'A', the physico-chemical condition prevents the release of sediment arsenic to the aqueous phase, while the opposite occurs in profile 'B'. In a situation such as profile 'C', the clay separating the two aquifers creates an identical difference between the upper and lower aquifer, thus causing a contrast in the arsenic content of the groundwater. The separating layer of clay in the mixed domain has yet another role. Being impervious yet able to adsorb arsenic, the clay prevents contaminated groundwater of the shallow aquifer from percolating below.

Thus, the specific physical and chemical environment at a specific location will favour – or not – the release of arsenic from the solid to the aqueous phase; if it favours the release,arsenic hotspots will be created. The character of the aquifer sediments, which is domain-specific, enforces the spatial association of the hotspots with particular geomorphic elements of the fluvial landscape. Various taxonomically diverse organisms obtain energy for growth from arsenic (Oremland and Stolz 2003). These act in different ways, either oxidizing arsenite or

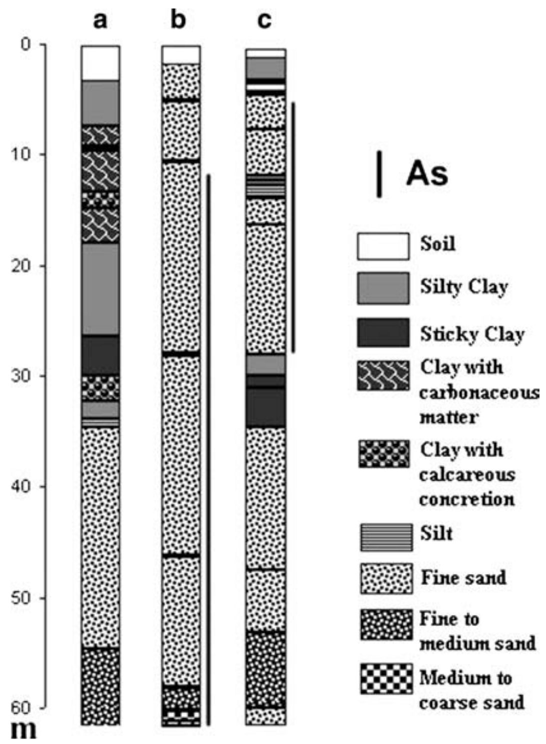


Fig. 7 Schematic diagram representing different sediment pack, Krishnanagar and Ranaghat areas, Nadia district, West Bengal, India. *A* Flood plain area, *B* palaeo-channel area, *C* channel deposits separated by intervening flood plain clay

reducing arsenate with or without organic carbon as source of energy and cell material. The net result of the activity of these organisms is either the contaminant is added to the aqueous system or it is removed from it. Consequently, the difference in the physical and chemical environment, in addition to influencing the release of arsenic, may also control the type of microbes surviving in that particular environment. Ultimately, the activity of these organisms – release or removal – will be domain-specific and further amplify the spatial association of hot spots and safe zones.

According to one hypothesis developed in Bangladesh, the availability of organic matter controls the release of arsenic. Most of the palaeo/abandoned/cut-off channels in the area are perennially or seasonally water filled so that the volumes of water change at different times of the year. These water bodies are also sites of biomass accumulation. During the recharging of aquifers from these surface water bodies, organic carbon contributed by the biomass is carried into the aquifer up to a certain depth depending on the hydrological conditions. The shallow aquifer becomes susceptible to arsenic release upon the introduction of labile organic matter which presumably stimulates microbial respiration and the subsequent reductive dissolution of Fe^{3+} solids with which the released arsenic is associated (Swartz et al. 2004). In Bangladesh, the depth profile of dissolved arsenic in groundwater shows a prominent peak (Harvey et al. 2002; Van Geen et al. 2004). This arsenic peak is accompanied by a peak of dissolved ammonia. Similarly, in the present study area, the groundwater contents of dissolved arsenic and ammonia showed maximum values at a depth of 20–35 m (Fig. 8). This arsenic and ammonia release can be explained as the consequence of biomass introduction into the aquifers during recharge from surface water bodies. Depending upon pressure gradient and permeability, the biomass is distributed into the coalescing sand body until the impervious floodplain clay is reached. The ammonia generated by decomposition of the biomass creates reducing conditions that trigger the release of arsenic from aquifer sediments. This process operates within the zone of influence of the channels – i.e. the 500- and 750-m corridors in the Krishnanagar and Ranaghat areas, respectively – as established by the weight-of-evidences analysis.

The fractal geometry of the contaminated tube-wells also reflects the process of arsenic release triggered by the migration of biomass as elaborated above. Contaminated tube-wells show fractal geometry within two different capacity bands separated by a characteristic length of 250–350 m. This could imply that the distribution pattern of contaminated wells changes as the frame of reference is changed. At a scale ranging from 100 to nearly 250–350 m, the contaminated wells are represented as scattered points. Over a scale range from 250–350 to at least 1000 m, the contaminated wells exhibit a clustered pattern. This characteristic length represents the average distance between adjacent pair of contaminated tube-wells in Krishnanagar-Ranaghat area. The occurrence of the clusters as well as of isolated contaminated tube-wells is interpreted to reflect the process of arsenic release into aqueous phase. The map of Fig. 4 shows that the clusters of contaminated tube-wells fall within the corridor of channel shifting, whereas the isolated hotspots predominantly occur outside the corridor. The nature of sedimentary deposition indirectly determines the occurrence of clusters or points by controlling the migration of biomass along with groundwater movement. As such, the occurrence of clusters over channel deposits could be explained as being indicative of the greater spread of biomass within more permeable sandy domains. In areas that fall outside of this corridor, the restricted migration of biomass inhibits the formation of clusters, and contaminated tube-wells occur as isolated points.

Conclusion

In the Krishnanagar-Ranaghat area arsenic contamination in groundwater is determined by the distribution of palaeo/abandoned/cut-off channels. The contaminated wells are restricted to a corridor of 500–750 m around the

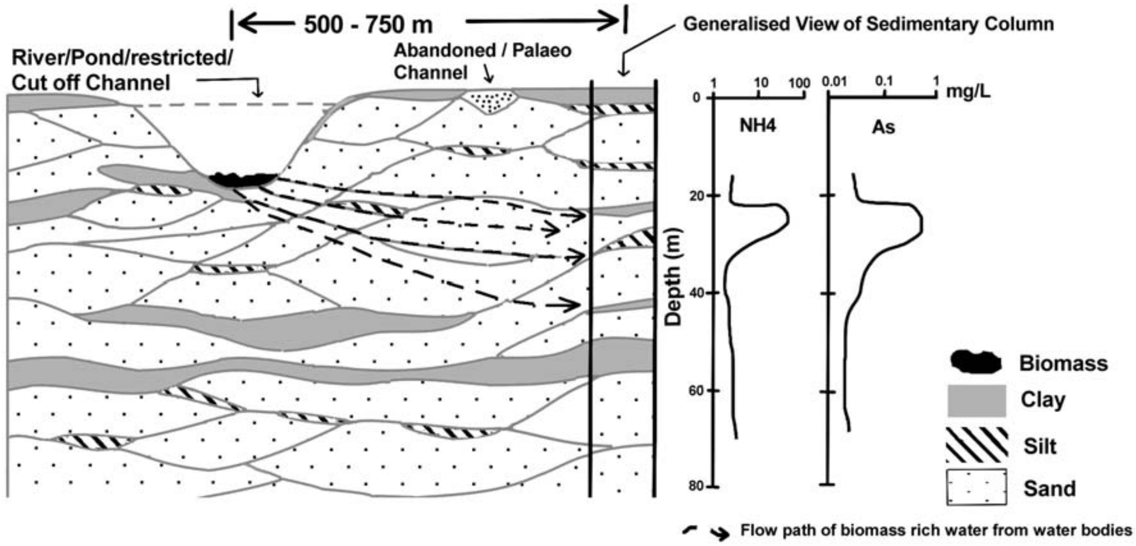


Fig. 8 Model showing arsenic release under reducing conditions due to the effect of biomass migration

palaeo-channels. Arsenic content of the aquifer sediments does not show any spatial correlation with the geomorphic elements. Thus, it can be inferred that prevalent physicochemical and microbial conditions in the areas of the channel deposits where the majority of contaminated tube-wells are located are conducive to the release of arsenic into thegroundwater. These are the areas where the introduction of biomass through groundwater recharge from surface water bodies creates environments that favour the release of arsenic from aquifer sediments by reductive dissolution or desorption.

Contaminated tube-wells occur either as isolated points or clusters. The clusters are aligned along the palaeo-channels and restricted to the area lying within the corridor of shifting channels. On the other hand, the isolated points fall outside of the corridor generated by the shifting channels.

This study endorses a predictability regarding the occurrence of arsenic-contaminated tube-wells based on geomorphic units. This information can be applied to other areas of the Bengal Delta for optimising both sampling for future surveys as well as a mitigation programme. The results also demonstrate with confidence that with the identification of geomorphic units, safer wells may be reliably predicted without actual physical measurement.

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