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ORIGINAL ARTICLE

Arsenic-contaminated groundwater from parts of Damodar fan-delta and west of Bhagirathi River, West Bengal, India: influence of fluvial geomorphology and Quaternary morphostratigraphy

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Abstract Arsenic contamination in groundwater affecting West Bengal (India) and Bangladesh is a serious environmental problem. Contamination is extensive in the low-lying areas of Bhagirathi–Ganga delta, located mainly to the east of the Bhagirathi River. A few isolated As-contaminated areas occur west of the Bhagirathi River and over the lower parts of the Damodar river fan-delta. The Damodar being a Peninsular Indian river, the arsenic problem is not restricted to Himalayan rivers alone. Arsenic contamination in the Bengal Delta is confined to the Holocene Younger Delta Plain and the alluvium that was deposited around 10,000–7,000 years BP, under combined influence of the Holocene sea-level rise and rapid erosion in the Himalaya. Further, contaminated areas are often located close to distribution of abandoned or existing channels, swamps, which are areas of surface water and biomass accumulation. Extensive extraction of groundwater mainly from shallow aquifers cause recharge from nearby surface water bodies. Infiltration of recharge water enriched in dissolved organic matter derived either from recently accumulated biomass and/or from sediment organic matter enhanced reductive dissolution of hydrated iron oxide that are present mainly as sediment grain coatings in the aquifers enhancing release of sorbed arsenic to groundwater.

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Keywords Arsenic in groundwater · Damodar fan-delta · Quaternary morphostratigraphy · Source and release of arsenic · West Bengal (India)

Introduction

Extensive arsenic pollution in groundwater affect intensely populated and low-lying Bhagirathi–Ganga delta, southern West Bengal (India) and Bangladesh (Mandal et al. 1996; Nickson et al. 1998). The affected area, in contrast to many others (Smedley et al. 1996; Manning et al. 1998; Welch et al. 2000), is free of any mining, industrial and thermal water activities. Arsenic occurs naturally in flood- and delta-plain sediments (Kinnibugh and Smedley 2001; Acharyya et al. 1999, 2000; Acharyya and Shah 2005). The contaminated areas are located mainly to the east of the Bhagirathi River, West Bengal (Fig. 1; Mandal et al. 1996; Nickson et al. 1998). Contrary to earlier report (Mallick and Rajagopal 1996) some affected areas also occur over the Damodar fan-delta. The Damodar being a Peninsular Indian river, the arsenic contamination in this region is not confined to the Himalayan rivers alone as believed by some workers (Chakraborti et al. 2003; Mukhopadhyay et al. 2006). Arsenic contamination has been also recorded in river floodplains without major mountain ranges from United States (Saunders et al. 2005a). The role of geomorphology and Quaternary morphostratigraphy in controlling As contamination over the Damodar fan-delta and other areas west of the Bhagirathi River is the topic of present study. Studies in the West Bengal part of the Bengal Basin are mainly accounted in the present write-up.

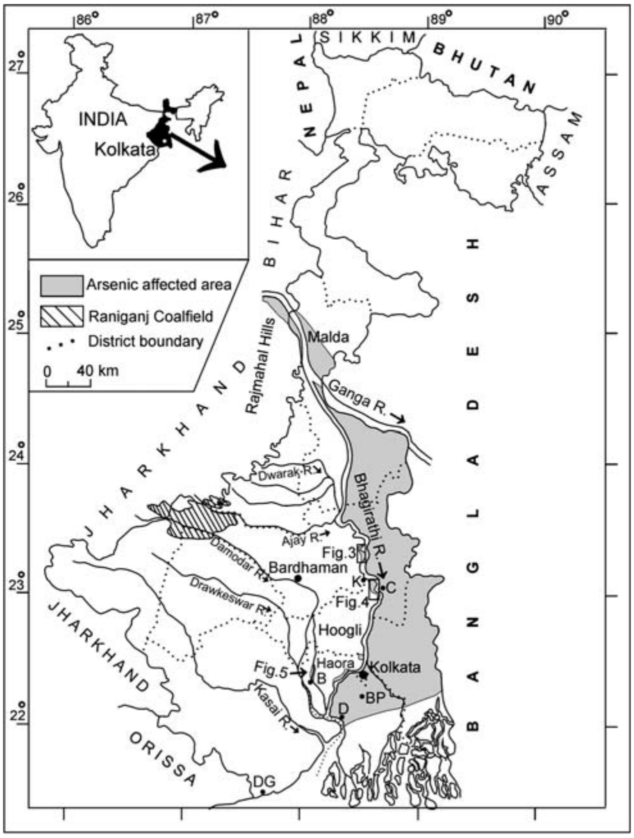

Fig. 1 Map showing arsenic-affected area in West Bengal, India

The upper permissible limit of arsenic in potable water is 50 µg/l in India, Bangladesh and some other countries. WHO (1993) recommended reduction of this limit to 10 µg/l, which has been endorsed by BIS (2003). Arsenic concentrations in tube-well water exceed 50 µg/l limit manifold in parts of affected area with wide variability in level in space and time, and numerous cases of arsenical diseases have been recorded (Mandal et al. 1996; Nickson et al. 1998).

Arsenic pollution in groundwater is known from many fluvio-deltaic tracts of the World like Hanoi City and the upper end of the Red River delta (Berg et al. 2001), as well as, from flood- and delta-plains of the Mekong River in Laos and Cambodia (Polya et al. 2005). Parts of Indus flood- and delta-plains in Pakistan are also strongly contaminated (Nickson et al. 2005; Ramay et al. 2004–2005). Thus, arsenic problem is common to several lower flood- and delta-plains in South and East Asia.

Materials and methods

Photogeomorphic mapping, of Bhagirathi–Ganga Delta Plain, west of the Bhagirathi River in southern West Bengal, was done through a detailed study of landforms and soils by air-photo interpretation supplemented by field studies. The methodology had established criteria to subdivide the unclassified Quaternary sediments into four well-defined morphostratigraphic units (Mallick and Niyogi 1972; Niyogi 1975). The map depicting parts of deltaic plains of the Bhagirathi River and fan-delta plains of the Damodar River is used as the base map for the present study (Fig. 2). The geomorphic features from the southern parts of the Damodar fan-delta have been mapped by us based on the study of IRS-1A imagery (November 1999) following same procedure, and it is integrated with the base map. The morphostratigraphic units have been correlated with the subsurface units further east. Stratigraphic levels of arsenic-contaminated aquifers are broadly determined based on local information from contaminated wells.

Arsenic concentrations in 424 tube-well water samples from the study area have been tested. EZ Hatch Arsenic Test Kit was used to determine As concentration at site by matching colouration by liberated arsine gas on mercuric bromide test strip. Kit data was used as a guide to delineate contaminated area. The minimum detection limit by Kit is 10 µg/l. Out of this 120 tube-well water samples from Balagarh Block (Fig. 4; Table 1) were analysed for As at the School of Environmental Studies (SOES) laboratory, Jadavpur University, Kolkata, following a flow injection HG-AAS system with minimum detection limit of 3 µg/l (Chatterjee et al. 1995) and 65 tube-well water samples from Haora district (Fig. 5; Table 2) were done at the Centre for Study of Man and Environment, Kolkata, laboratory using HG-AAS system following conventional method (IS-3025: part 37, 1988). It was observed that kit results vary from laboratory test by about ±20 µg/l. Dissolved Fe of water samples was analysed at laboratory by phenanthroline method by using UV spectro-photometer. Mineralogical analysis under petrological microscope, XRD on copper target, and SEM-EDX (at Geological Survey of India, Kolkata) was done on magnetic and weakly magnetic separates and handpicked grains from tube-well sandy sludge samples. As and Fe concentrations in leachets were estimated from washed sludge samples after digestion in 1 N HCl at CSME and GSI laboratories.

Results and discussion

As-contaminated areas in Damodar fan-delta and west of Bhagirathi River

Flanked by the Pleistocene terraces and older rocks to the west and north, the Bengal Delta covers eastern

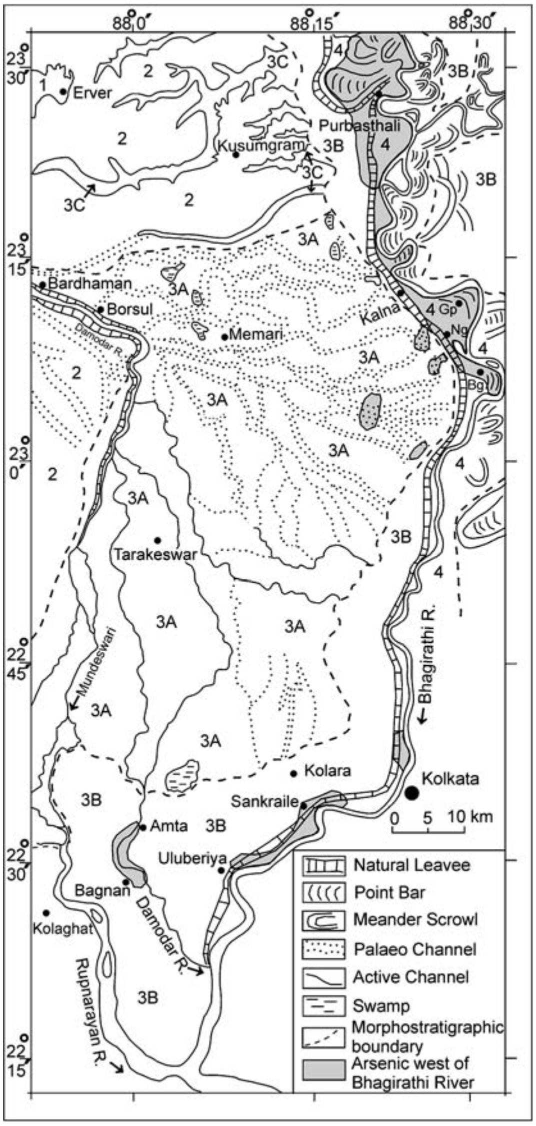

Fig. 2 Geomorphologic and Quaternary morphostratigraphic map west of Bhagirathi River, West Bengal, showing area of study. Morphostatigraphic units: *1* Laterite Plain (Pleistocene); *2* Kusumgram Plain (Older Delta Plain, Pleistocene–Holocene); *3* Kalna Plain (Younger Delta Plain, Holocene), *3A* Damodar fan-delta plain, *3B* Bhagirathi delta plain, *3C* valley cuts in *2*; *4* Recent Bhagirathi Plain. *Gp* Guptipara, *Ng* Natagarth, *Bg* Balagarh

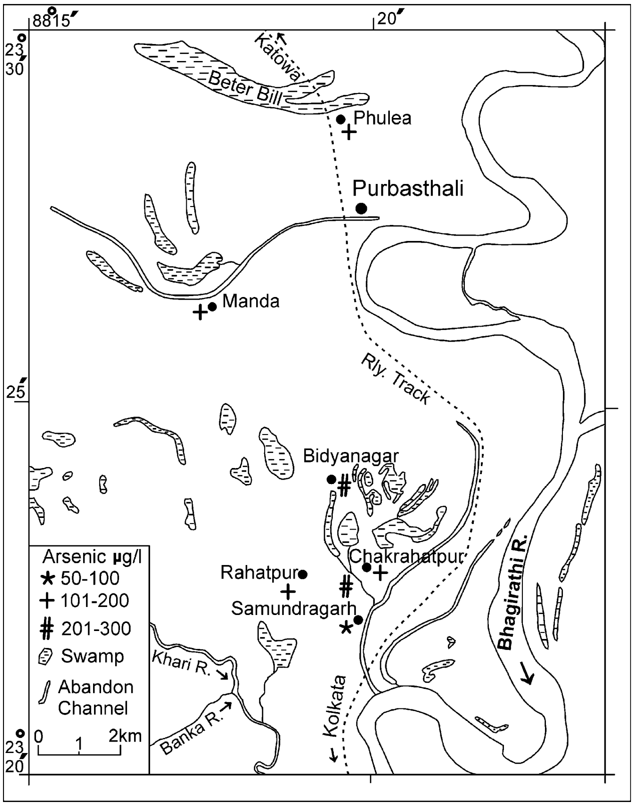

Fig. 3 Arsenic-affected area, Purbashali Block, District Bardhaman, West Bengal

parts of West Bengal (India) and most of Bangladesh. The Bengal Delta is fed by Himalayan and Peninsular Indian rivers and their distributaries. The stepped uplands in Jharkhand and West Bengal States, flanking the hills, consist of Laterite Plain and Older Alluvial Plain of Pleistocene and early Holocene ages, respectively (Acharyya et al. 2000). The Bhagirathi River has scoured its recent and immediately older deltaic basins, which have been progressively accreted by the ancient counterparts of the Ajoy, Damodar and Dwarkeswar rivers (Fig. 1) during the Quaternary sea level fluctuations as would be discussed later.

The western uplands of the Bengal Basin are divisible into three-stepped alluvial plains. A remnant of the Laterite Plain occurs near Erver (Fig. 2). The Kusumgram and Kalna Plains gradually come down in elevation in the east and southeast (Fig. 2). Recent fluvial features such as natural levees, point bars, cut-offs, back-swamps are vivid in air-photo, imagery and in Survey of India topographic sheets along the Bhagirathi River course.

The Damodar River had formed two alluvial fans: the Memari fan trending east and the Tarakeswar fan trending south (Fig. 2; Mallick and Niyogi 1972; Deshmukh et al. 1973; Niyogi 1975). These fan surfaces are broadly equivalent to the Kalna Plain or YDP. The Memari fan-delta plain is truncated by the YDP and Recent Plains of the Bhagirathi River system (Fig. 2). The Damodar river was flowing east to meet the Bhagirathi River during the middle of eighteenth century. But it has since rotated its course shifting its mouth 128 km to the south. The Ajoy river located further north, still flows east to meet the Bhagirathi river, which was the regional slope also followed by the

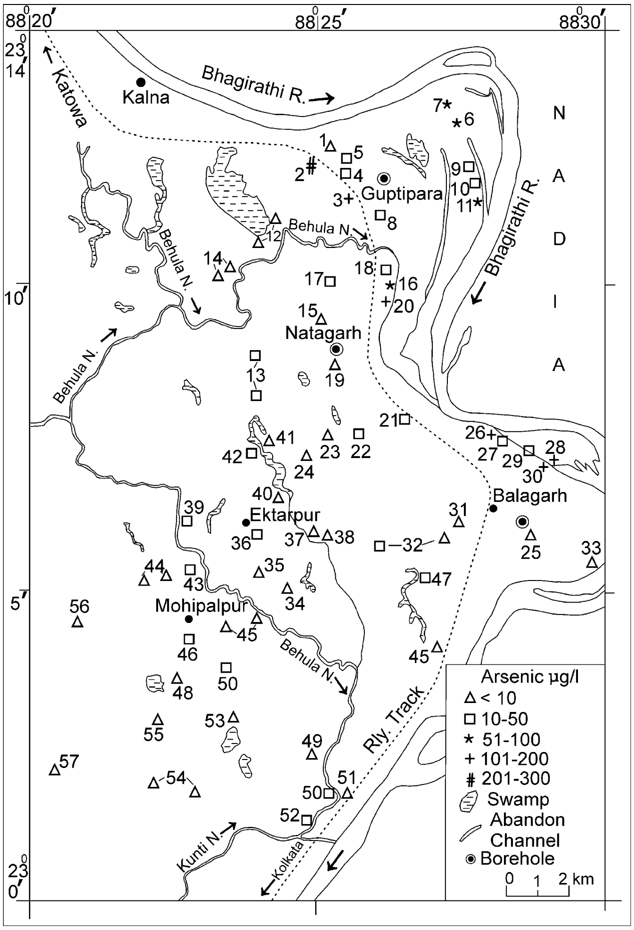

Fig. 4 Arsenic affected area, Balagarh Block, District Hoogli, West Bengal. Sample locations are shown in *numbers* and details given in Table 1

older proto-Damodar and other tributary rivers of the western upland (Fig. 1).

The fan-delta geomorphic features of the proto-Damodar river of YDP time is demonstrated by the presence of a system of eastward flowing abandoned channels, which bifurcate from Barsul area (Fig. 2). The present nala courses (Fig. 3) have taken variable southern swings since late eighteenth century. A deep tube-well, at Balagarh (Figs. 2, 3) located close to the truncated margin of the Memari fan-delta toe against the Recent Plains of the Bhagirathi River, records thick section of coarse and very coarse sand typical of fan facies (Fig. 6).

The geomorphic features of the Kusumgram Delta Plain, equivalent to ODP, are revealed by the presence of abandoned channels bifurcating from the Damodar river around Silla (located about 30 km upstream of Bardhaman and not shown in Fig. 2; Mallick and Niyogi 1972; Niyogi 1975), which was the apex of the Damodar fan-delta of ODP age. No fluvial landform could be deciphered on the still older Laterite Plain.

Areas covering ODP and older surfaces are free of arsenic contamination, which affects parts of YDP mainly to the east of the Bhagirathi River. However, several areas west of the Bhagirathi River are also arsenic affected (vide Figs. 3, 4, 5). The arsenic affected areas shown in Fig. 3 (Unpublished Report of PHE Govt. W.B.) are developed over a meander scroll of the Bhagirathi River, connecting Prubasthali–Manda–Betar Bill–Phulea (Figs. 2, 3) that had breached natural levee and spread over YDP.

Further south, YDP to the west of the Bhagirathi River channel merges with the truncated Damodar fan-delta (Memari fan-delta) plain close to Kalna (Fig. 2). The arsenic-affected aquifers around Guptipara and north of Balagarh railway station (Figs. 2, 4) are located beneath the Recent terraces and point bars of the Bhagirathi River. Several isolated arsenic-affected areas in the Balagarh Block are also located over the Damodar (Memari) fan-delta, where maximum As concentration of 85–90 µg/l have been recorded. The arsenic affected areas in Amta and Bagnan Blocks (Fig. 5) are located on either side of the present Damodar channel but south of the toe of the Damodar fan-delta. Amta and Bagnan areas record maximum As concentration of 50 and 90 µg/l, respectively.

Quaternary stratigraphy of As-affected area in the Bengal Delta

The sedimentation in the Bhagirathi–Ganga flood-delta plain was strongly influenced by sea-level changes during the Late Pleistocene and Holocene (Mallick and Niyogi 1972; Niyogi 1975; Banerjee and Sen 1987; Umitsu 1993; Acharyya et al. 2000; Goodbred and Kuehl 2000). In addition to stepped morphological character of the western uplands, the relative antiquity of their deposits have been worked out from the state of preservation of geomorphologic characters, erosion features and the nature and thickness of the developed soil profiles (Mallick and Niyogi 1972; Niyogi 1975).

The base of the Quaternary section is difficult to identify, but in many boreholes near the western upland a sequence of dominantly clay and sand having saline formation water and locally containing microfossils have been assigned Upper Pliocene age (Fig. 6; Bardhaman and Kalna wells; Sengupta 1966; Mallick and Niyogi 1972; Niyogi 1975). The presence of 75 Ka Toba-Ash-Bed marker has been recorded in the laterite-topped Quaternary profile (Acharyya and Basu 1993; Acharyya et al. 2000) from the Barakar river (a tributary of Damodar) from NW parts of the Raniganj Coalfield (Fig. 1). Thus the Laterite Plain morpho-

Table 1 Groundwater arsenic and iron analysis of Balagarh block, Hoogli district

S. No.	Village	No. of samples	Depth (m)	Arsenic (μg/l)			Iron (μg/l)
				Minimum	Maximum	Mode	
1	Sultanpur	6	21	14	110	<10	1,067–2,280
2	Bandhagachi	2	20	10	250		299–4,916
3	Fatepur	2	21	25	133		3,541
4	Mirdanga	4	20	10	50	25	4,321
5	Guptipara	5	15	25	72	25	4,541
6	Kishna Charbati	4	15	50	150	100	ND
7	Saktipur	5	36	50	127	75	3,021
8	Aida Kismat	5	21	15	25	15	ND
9	Phooltola	6	18	25	150	35	4,208
10	Saildanga	5	15	25	140	30	ND
11	Char Rampur	3	54	40	206	100	710–2,045
12	Ichapur	5	55	<10	17	<10	423–48,411
13	Inchura	2	55	15	17		986
14	Bakulia	2	55			<10	1,087
15	Tildanga	2	55			<10	1,368
16	Abdulpur	7	21	10	160	68	2,604
17	Bankipur	5	85	10	80	25	ND
18	Kamardingi	5	15	10	140	40	4,583
19	Natagarh	5	58	<10	28	<10	563
20	Paigachi	5	52	25	313	150	3,687–9,895
21	Korola	1	58		45		2,233
22	Belirgarh	1			17		15,735
23	Masda	1			<10		1,268
24	Raghunathpur	1	60		<10		342
25	Shripur-Balagarh	3	97		<10	<10	729
26	Babupara	7	21	25	250	125	958–2,687
27	Balagarh-Thakurpara	5	20	25	70	45	ND
28	Char Bhabanipur	6	20	25	250	125	1,229
29	M. Milangarh	3	15	<10	50	25	2,687
30	S. Milangarh	6	16	25	250	150	ND
31	Patuli	6	15		<10	<10	865
32	Jirat	5	21		<10	<10	402
33	Char Khairamari	6	15	<10	34	<10	3,021–4,208
34	Basna	2	68		<10	<10	443
35	Babla-Kangachi	1			<10		402
36	Musure	2	58	<10	22		4,346
37	Baleswar	1	93		<10		2,012
38	Dowapara	5	41		<10		362
39	Jagulia	2	41		<10	15	4,366
40	Ektarpur north	1	41		<10		402
41	Majdia	4	109		<10		2,978
42	Doha Tiorna	1	15		10		7,213
43	Mohipalpur	1	85		35		6,519
44	Kamarpara	3	91	<10	95	<10	1,267–13,038
45	Bhalki	3		<10	85	<10	17,606
46	Malancho	4	85	<10	76	25	503–3,018
47	Barayal	2	91	<10	12		2,596
48	Hamzanpur	1			<10		463
49	Malirber	1	40		<10		825
50	Simla	2	42	<10	23		382
51	Phoolpukur	1	109		<10		262
52	Nityanandapur	2		<10	48		6,056
53	Doharchaklai	1	76		<10		2,495
54	Digsui	1			<10		905
55	Pakri	1			<10		1,609
56	Chaptta	1			<10		644
57	Khanyan	1			<10		40

Detection limit of As 10 μg/l

ND not determined

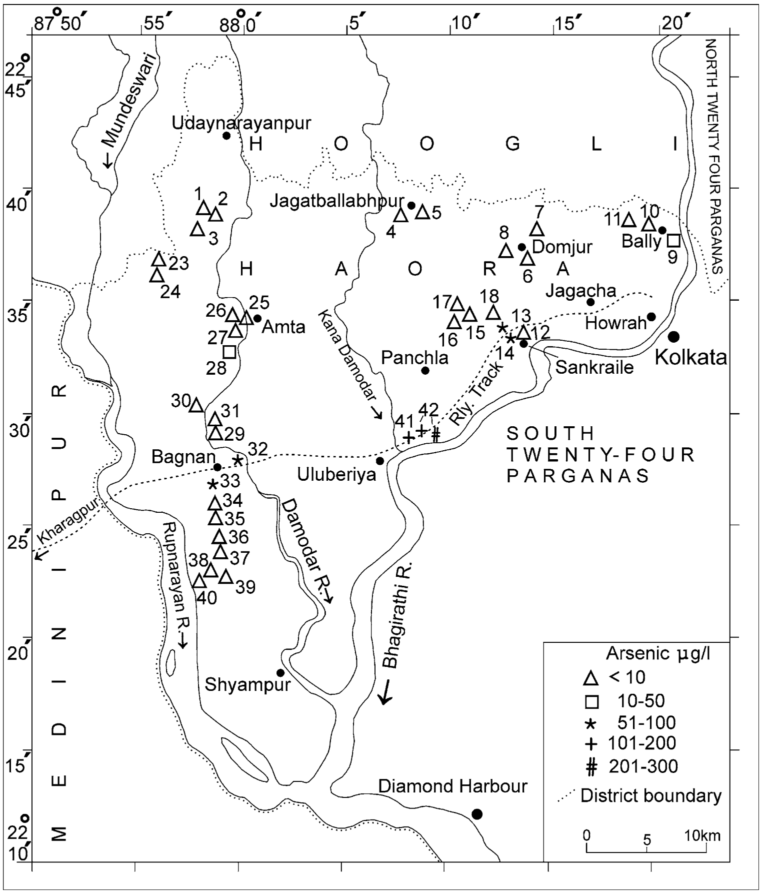

Fig. 5 Arsenic-affected area, Haora District, West Bengal. Sample locations are shown in *numbers* and details given in Table 2

stratigraphic unit is dated Pleistocene, whereas the OAP developed to its east is early Holocene in age (Acharyya et al. 2000). The laterite- or red-mottled soil profile-capped sedimentary unit is also well recognized in subsurface and represents basal unit of the Quaternary column (Fig. 6; Bardhaman and Kalna wells; Mallick and Niyogi 1972; Niyogi 1975). The immediately overlying unoxidized calcrete-bearing unit is dominantly made up of relatively finer and fining upward alluvium, which have been correlated to the Kusumgram Formation or the ODP morphostratigraphic unit (Fig. 6). In turn, it is disconformably followed by the Kalna Formation or the YDP morphostratigraphic unit.

The Holocene sediments beneath YDP in West Bengal and Bangladesh have been tentatively classified into three broad stratigraphic units based on limited subsurface data (Umitsu 1993; Acharyya et al. 2000; Goodbred and Kuehl 2000). The near surface Unit 3 consists of mud, silt, fine sand and locally present peat beds; Unit 2 is dominantly composed of fine, often dirty sand with clay intercalations, whereas, the Unit 1 is coarser, cleaner and sandy. Most arseniferous tubewells generally tap aquifers in Unit 2. Correlation of these units with the morphostratigraphic units recognized from the western uplands is shown in Fig. 6.

C^{14} ages from organic matter from various levels of Unit 1 from eastern and southern parts of Bangladesh (Kinnibugh and Smedley 2001; Umitsu 1993); and clay beds inter-bedded with gravel and overlying a +6 m medium grained sand bed from Digha area and similar sand bed from Diamond Harbour area (Fig. 1; Hait et al.1996), range from 28,300 to 12,300 years BP. The Unit 1 with basal sand and gravel was thus deposited as entrenched valley fills during Late Pleistocene and earliest Holocene under low-stand setting.

Sea level gradually decreased and reached their lowest level of ~135 m during the Late Pleistocene optimum (~18,000 years BP), when the Pleistocene and Late Tertiary sediments located in the present delta and shelf areas were exposed to erosion and oxidation. Parts of the Pleistocene cover around the present delta region remained as incised upland terraces in the west, north and southeast, dissected by the proto-Bhagirathi–Ganga–Brahmaputra river system. These sediments were oxidized and were also well flushed by groundwater under a higher hydraulic head because of their initial low-stand setting and later upland terraced position.

Table 2 Groundwater arsenic and iron analysis of Haora district

S. No.	Village	Block	No. of samples	Depth (m)	Arsenic (µg/l)			Iron (µg/l)
					Minimum	Maximum	Mode	
1	Bhabanipur	Udaynarayanpur	5	79		<10	<10	
2	Sonatola	Udaynarayanpur	4	76		<10	<10	ND
3	Gumagarh	Udaynarayanpur	4	76		<10	<10	
4	Panchyet-2	Jagatballavpur	5	40		<10	<10	
5	Baragachia	Jagatballavpur	5	58		<10	<10	ND
6	Natun Pally	Domjur	5	58	<10	20	<10	
7	Uttar jahapardaha	Domjur	6	61	<10	15	<10	ND
8	Khantora	Domjur	5	61	<10	18	<10	
9	Makaltola	Bally-Jagacha	15	30	10	300	40	
10	Belanagar	Bally-Jagacha	2	30		<10	<10	680–2,580
11	Raghunathpur	Bally-Jagacha	2	30		<10	<10	
12	Station para	Sankraile	5	41	<10	25	<10	
13	Hobapota	Sankraile	6	36	<10	200	50	
14	Middapara	Sankraile	5	30	50	200	75	
15	Dhulagarh pubpara	Sankraile	4	46		10	<10	380–5,820
16	Dhulagarh sibtola	Sankraile	5	43		<10	<10	
17	Dhulagarh bazar	Sankraile	5	46		<10	<10	
18	Chaturbhujkati	Sankraile	5	40	<10	50	<10	
19	Panchala bazar	Panchala	5	41		10	<10	
20	Moktarpara	Panchala	3	41		10	<10	ND
21	Dharmatala	Panchala	3	46		10	<10	
22	Sepahipara	Panchala	4	41		10	<10	
23	Jhikra	Amta-2	4	70		<10	<10	
24	Durgapur	Amta-2	3	73		<10	<10	
25	Betai	Amta-2	4	36	<10	25	<10	
26	Jagal garia	Amta-2	3	182		<10	<10	310–490
27	Gajipur	Amta-2	4	36	<10	50	<10	
28	Gajipur ashipur	Amta-2	5	36	10	50	25	
29	Bangalpur	Bagnan-1	4	106	<10	24	10	
30	Harap	Bagnan-1	5	91	<10	40	<10	
31	Bhuiara	Bagnan-1	4	18	<10	50	15	
32	Muralibar	Bagnan-1	5	18	10	75	60	2,430–7,530
33	Khalore	Bagnan-1	5	18	15	90	70	
34	Nunthiya	Bagnan-2	5	18	<10	80	<10	
35	Mubkalyan	Bagnan-2	5	18	<10	40	<10	
36	Sahra	Bagnan-2	5	18	<10	35	<10	
37	Salukpara	Shyampur-2	2	218		<10	<10	
38	Jagdishpur	Shyampur-2	2	212		<10	<10	
39	Naul	Shyampur-2	3	197		<10	<10	ND
40	Nakulyar	Shyampur-2	3	200		<10	<10	
41	Baidya colony	Uluberia-2	15	12	50	300	150	ND
42	Shyamsundarchak	Uluberia-2	20	12	25	500	100	

Detection limit of As 10 µg/l

ND not determined

Based on C^{14} ages from various levels of Unit 2 and base of Unit 3, the age of Unit 2 has been broadly inferred to be 10,000–7,000 years BP (Umitsu 1993; Hait et al. 1996; Acharyya et al. 2000). Based on the presence of molluscs, planktonic diatoms and plynological remains, the coastline of Bhagirathi–Ganga delta was located to the north of Kolkata during the deposition of Unit 2. Under the combined influence of tectonism and eustasy, the growth of the Ganga delta began around 10,000 years BP, when the Early Holocene transgression led to back-flooding of its low-stand alluviated valleys and laterite surfaces (Acharyya et al. 2000; Goodbred and Kuehl 2000). The Ganga delta as different from the other well-studied delta systems of the world (Stanley and Warne 1994) had immense sediment discharge from the Himalayas, which allowed deltaic deposition to keep pace with the very rapid rates of sea level rise during the early-mid Holocene transgression (Acharyya et al. 2000).

Sea level again began to rise rapidly between 7,000 and 5,500 years BP, reaching higher than the present level and southern parts of the Ganga–Bhagirathi delta were invaded further by tidal mangrove and encroached by the Bay of Bengal. The sea level subse-

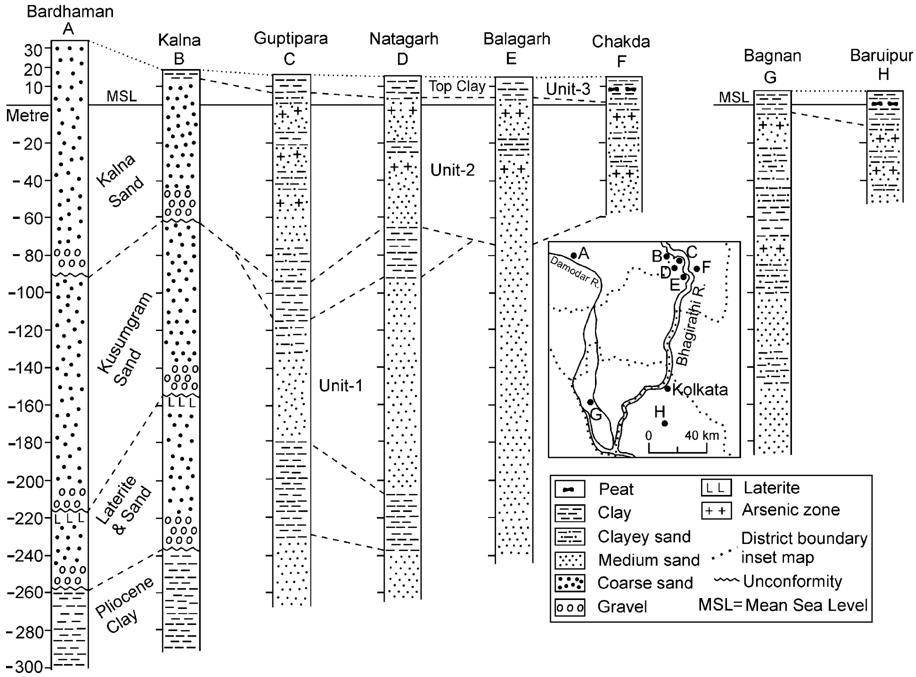

Fig. 6 Lithological column of boreholes showing broad correlation. Borehole locations shown in *inset* map

quently dropped initiating a phase of subdued marine regression. The Unit 3 in the Bhagirathi–Ganga delta from West Bengal and Bangladesh is ~7,000 years BP, and younger in age. Typical estuarine brackish to fresh water environment have been described from clay-rich sediment (Banerjee and Sen 1987) in and around Kolkata and close to the western bank of the Bhagirathi River and south of the Damodar fan-delta, southern West Bengal. These sediments occur at 7–2 m beneath m.s.l. and are located in areas 80–120 km inward from present seashore. There was widespread development of marine and fresh water peat layers around Kolkata and about 60 km further north during 7,000–2,000 years BP (Banerjee and Sen 1987).

The arsenic-contaminated aquifers occur at several places flanking the west bank of the Bhagirathi River, west of Kolkata and those from Bagnan and Amta Blocks, occurring close to and on either side of the Damodar river channel (Figs. 2, 5). The contaminated aquifers occur at depths 10–40 m corresponding to Unit 2, and are located significantly below the clayey carbonaceous zone bearing Unit 3 recorded in several tube-wells (Fig. 5). Similar lithology is also recorded from the uppermost sections of boreholes at Chakdah and Baruipur (Figs. 1, 6), at much higher level than the arsenic-bearing aquifers. The top clay zone recorded from arsenic-affected Guptipara, Natagarh and Bagnan wells also possibly has similar lithological character and may be correlated to the Unit 3. However, lithological details are not available from the Central Goundwater Board.

Source and release of arsenic in groundwater

No specific sources of arsenic in groundwater could be identified for the Bhagirathi–Ganga delta. Several potential sources occur in the Ganga River catchment in the Himalayas (north of West Bengal and other sections) and also in the Peninsular India (Acharyya et al. 1999; Acharyya 2001). Natural arsenic in Holocene alluvial aquifer has been linked to tectonic, weathering and microbial process, which often cause contaminated groundwater to occur at long distance from their ultimate source (Saunders et al. 2005b). The Damodar River, confined to the Peninsular India flows through several Gondwana coalfields and many coal seams from the Raniganj (Fig. 1) and Jharia basins (located immediately west), have As concentration varying from 65–360 ppm (Geological Survey of India, unpublished data). Minor sulphide occurrences are also known from adjacently exposed basement rocks from the Damodar catchment area. These might account for mild arsenic contaminations recorded over the Damodar fan-delta plain. The Mahanadi and Pranhita–Godavary valleys, in the Peninsular India having several Gondwana coalfields (Acharyya 2000), and sulphide occurrences, some of the latter being arsenic bearing, might also have arsenic-contaminated areas in their flood- and delta-plains.

Contrary to claim otherwise, our mineralogical studies on sediment cores and tube-well sludges indicate that arsenic-rich pyrite or any other arsenic minerals are rare or absent in the aquifers from affected areas in West Bengal. However, rare presence of biogenic pyrite is recorded in reducing environment often in association of degraded plant remains (Fig. 7; Acharyya 2001; Pal et al. 2002; Acharyya and Shah 2005). The presence of biogenic pyrite is also recorded along magnetite grain boundary (Fig. 8). The As-bearing nature of biogenic pyrite indicates co-precipitation and sorbing of arsenic in pyrite, which thus have acted as sinks for and not sources of arsenic. Studies on cores of aquifer sediments from arsenic-contaminated and adjacent safe zones from Chakdah and Baruipur areas, West Bengal (Fig. 1), reveal following sediment fractions to be arsenic bearing: iron-oxide-coated quartz and clay (illite) grains, iron–manganese–siderite, magnetite and biotite/chlorite. These fractions are relatively more in the aquifers from contaminated zone (Acharyya 2001; Pal et al. 2002). Sediment samples from parts of Balagarh block and over the Damodar fan-delta also reveal similar mineralogical assemblage. Quartz and clay grains in tube-well sludge are often coated by hydrated iron oxide. XRD studies on iron-coated blackened mineral and sediment grains reveal the presence of chlorite, illite, amphibole, etc. (Fig. 9). These mineral grains also show enrichment in arsenic (Table 3).

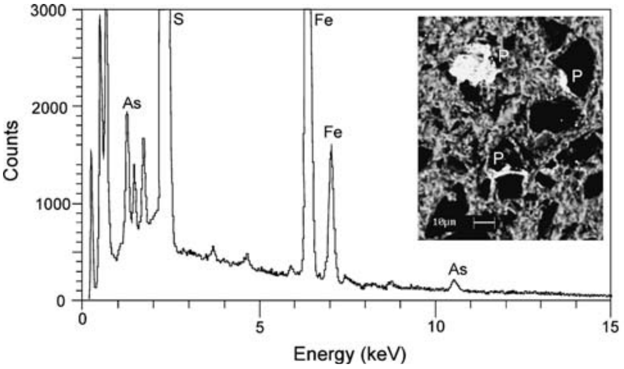

Fig. 7 SEM micrograph and EDX scan of carbonaceous clay grain, 136 m below ground level (b.g.l.) Balagarh borehole. Biogenic pyrite (*P*) often arsenic (*As*) bearing follow grain boundary

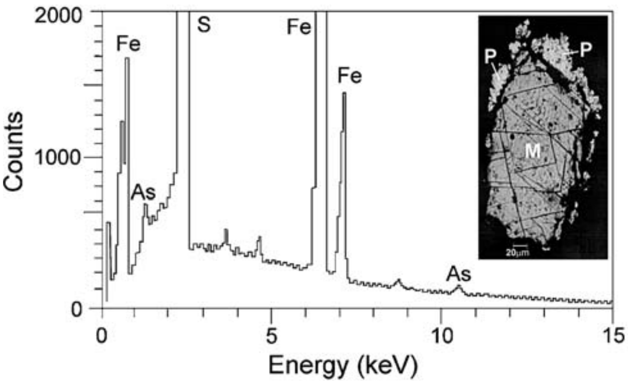

Fig. 8 Rim of biogenic pyrite (*P*) on magnetite grain (*M*). SEM-EDX scan shows arsenic-bearing nature of pyrite. Nicargachi well (GSI) in Chakda area (approximate depth 32 m b.g.l.)

Arsenic release by the once-popular oxidation of pyrite (Roy Chowdhury et al. 1999), which is still favoured by some workers from West Bengal, has been disapproved in general, because pyrite is nearly absent in the affected aquifer sediments and sulphate concentrations are very low in affected groundwater (mean value generally ≤1 mg/l; Kinnibugh and Smedley 2001) even when arsenic concentration is high. Biomediated reductive dissolution of hydrated iron oxide (HFO) that occurs mainly as coatings on sediment grains and corresponding oxidation of sedimentary organic matter is regarded as the main mechanism, which mobilizes arsenic to groundwater from aquifer sediments (Nickson et al. 1998; Kinnibugh and Smedley 2001). Arsenic sorbed in discrete phases of hydrated Fe–Mn oxide was preferentially entrapped in argillaceous and organic-rich Holocene floodplain and deltaic sediments. The Damodar fan-delta facies, being relatively coarser, are unlikely to be enriched significantly in HFO and organic matter; however, the setting can account for minor occurrences of As-affected areas.

Recent studies has established that iron-rich groundwater is produced by the activities of anaerobic heterotropic Fe^{3+}-reducing bacteria (IRB), which preferentially reduce and dissolve least crystalline discrete phases of HFO, with consequent release of its sorbed arsenic and other trace elements to groundwater (Lovley and Chapelle 1995; Saunders et al. 1997). Ferrous ion released to groundwater on reduction from sediment coatings of HFO or other Fe-bearing mineral phases present in the alluvium possibly reacted with abundantly present bicarbonate in groundwater to precipitate siderite concretions. These concretions grew around sediment grains and/or centres of IRB colony (Acharyya and Shah 2005). Colony like aggregates of Fe–Mn–siderite concretions and frambroidal pyrite has been recorded from aquifer sediments from Balagarh and Chakdah area, respectively (Pal et al. 2002; Acharyya and Shah 2005). The presence of biogenic objects few microns in length and less than a micron width has been reported inside some of these concretions, which have recorded presence of bacteria (Sengupta et al. 2004). That reduction of HFO is common and intense in affected aquifer in the Bhagirathi–Ganga flood-delta

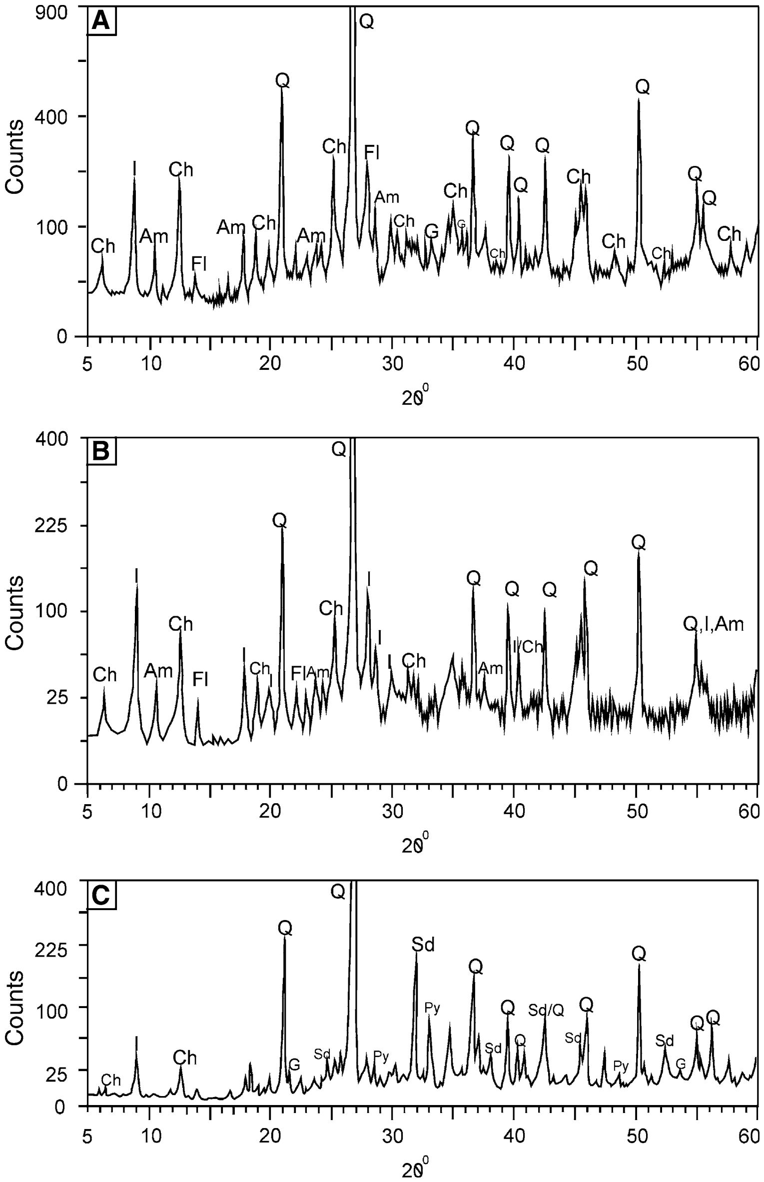

Fig. 9 XRD graph on selected iron-stained black grains in sandy samples. a Char Rampur (110 m b.g.l.), b Paigachhi (103 m b.g.l.), c Balagarh (136 m b.g.l.). *Am* Amphibole, *Ch* Chlorite, *Fl* Feldspar, *G* Goethite, *I* Illite, *Py* Pyrite, *Q* Quartz, *Sd* Siderite

Table 3 Chemical analysis of washed tube-well sludge samples, Balagarh block, Hoogli district

S. No.	Location	Depth zone (m)	Acid leachable		Total	
			As (ppm)	Fe (%)	As (ppm)	Fe (%)
1	Char Rampur, magnetic fractions	97–121	55	7.1	185	54.20
2[a]	Char Rampur, non-magnetic fractions	97–121	13	4.76	103	6.10
3	Char Rampur, magnetic fractions	73–91	NA	NA	280	5.2
4	Char Rampur, non-magmetic fractions	73–91	NA	NA	620	3.3
5[a]	Balagarh, non-magnetic fractions	136	355	9.58	985	10.58
6	Hasimpur, non-magnetic fractions	115	110	NA	112	NA
7	Sarenda, non-magnetic fractions	125	220	NA	635	NA

[a] XRD analysis Fig. 9

NA not available

plain is indicated by high maximum concentration of dissolved Fe (≤9–36 mg/l) in arsenic-contaminated groundwater (Nickson et al. 1998; Acharyya et al. 1999; Acharyya and Shah 2005). In the Damodar fan-delta area (in Balagrh Block) maximum dissolved Fe is 13–10 mg/l.

Even within arsenic-affected areas, dug-wells are found to be arsenic safe. Dissolved Fe concentration in dug-well water is also low indicating their oxidizing nature. In the study area, it has been frequently observed that often arsenic contaminated tube-wells are being used for drinking water, whereas well-constructed dug-wells with arsenic-safe water are poorly maintained and used unhygenically for other purposes.

The chemistry of arsenic-affected tube-well water in West Bengal and Bangladesh is invariably based on study of mixed water samples from different depth of aquifers. An inflatable packer–straddle–pump assembly was used by some of us (Guha et al. 2005), to test chemical and microbiological characteristics of aquifer water from specific depth from a tube-well in Chakdah area (Fig. 1). Interpretation of sediment and water analysis indicates that iron-reducing condition has developed at several levels together with the presence of iron-reducing bacterial activity where reduction of hydrated ferric oxide was able to mobilize arsenic from sediment to groundwater. Although arsenic is present in the sediment throughout the depth of the borehole, it did not have any relation to release of arsenic to groundwater. Nitrate- and sulphate-reducing conditions were not capable of releasing arsenic. Clayey lenses in the aquifer created low permeability zones preventing fresh nutrients like nitrate and sulphate to reach these levels where iron-reducing conditions prevailed and released arsenic.

The arsenic-affected areas investigated during the present study (Figs. 3, 4, 5) are all preferentially located close to the present distribution of abandoned or channel meanders. Recent studies from other arsenic-affected areas in West Bengal have also shown that arsenic-contaminated wells have a spatial association with abandoned channels, swamps (Mukhopadhyay et al. 2006). Most of abandoned channels, swamps and present channels are perennially or seasonally water filled and are also sites of biomass accumulation. In a typical aquifer in Bangladesh, based on chemical data, it was interpreted that As mobilization was associated with reduction process driven by inflow of carbon released by recent biogeochemical process (Harvey et al. 2002). Excessive pumping of groundwater cause recharge of aquifer mainly from such surface water bodies transporting dissolved organic carbon released either by recent biogeochemical process and/or those derived from sediment column of floodplain and delta setting and bring them in contact with HFO that is present mainly as sediment grain coatings. The process promotes reductive dissolution of HFO, releasing sorbed arsenic to groundwater. The depth reached by reducing recharge water depends on the hydrological conditions of aquifer.

Conclusion

Arsenic contamination in groundwater is pervasive in low-lying areas of the Bengal delta located mainly to the east of the Bhagirathi River. A few isolated areas over the Damodar fan-delta that drain into the Bengal delta from the west are also contaminated. The source of arsenic is dispersed in the Ganga River catchment. Gondwana coal seams and other Peninsular Indian rocks were possible sources of arsenic that contaminated parts of the Damodar fan-delta. The sedimentation in the Bhagirathi–Ganga delta was strongly influenced by sea-level changes during Late Pleistocene–Holocene. Arsenic contamination is confined to parts of the Younger Delta Plain (Holocene), whereas, the Older Delta Plains are unaffected. The Holocene subsurface sediments beneath the Younger Delta Plain in West Bengal and Bangladesh have been tentatively classified into three broad units. The near surface Unit 3 consists of mud and fine sediments with locally present peat beds; Unit 2 is dominantly composed of fine, often dirty sand with clay intercalations; whereas, the Unit 1 is coarser, cleaner and sandy. Most arseneous tube-wells generally tap aquifers in Unit 2, which were deposited around 10,000–7,000 years BP, and under combined influence of the Holocene sea-level rise and rapid erosion in the Himalaya. As-bearing pyrite or any other As minerals is nearly absent in the alluvial aquifer from the Bengal flood-delta and arsenic occurs adsorbed on HFO, which were preferentially trapped in finer fluvial sediments and occur as coating on quartz, clay, ferromagnesian mineral and sediment grains. Arsenic-contaminated groundwater under study is uniformly reducing in nature and often enriched in dissolved iron. Arsenic is released to groundwater along with Fe^{2+}, by biomediated reductive dissolution of HFO with corresponding oxidation of organic matter. The latter were either derived from aquifer sediment and/or from recent biomass in surface water bodies, which mainly provided recharge water. Arsenic is released to groundwater under iron-reducing condition and generally in the presence of iron-reducing bacteria. Thus, even in areas with strong arsenic-contaminated tube-wells, dug-well water—because of its oxidizing nature—is generally arsenic safe.

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