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Monitoring 51 community wells in Araihazar, Bangladesh, for up to 5 years: Implications for arsenic mitigation

ALEXANDER VAN GEEN[1], ZHONGQI CHENG[1], QING JIA[1], ASHRAF ALI SEDDIQUE[2], MOHAMMAD WAHIDUR RAHMAN[2], MOHAMMAD MOSHIUR RAHMAN[2] and KAZI MATIN AHMED [2]

[1]*Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA*
[2]*Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh*

In order to reduce the exposure to As naturally occurring in shallow groundwater of the Bengal Basin, tens of thousands of tubewells tapping deeper aquifers of the Bengal Basin have been installed. We address here lingering concerns that As concentrations in deep tubewells might increase over time with monitoring data spanning a period of up to 5 years for 51 separate 115-545 (34–164 m) deep community wells installed in Araihazar upazila, Bangladesh. This exceptionally detailed data set shows that all but 4 of these community wells have consistently provided drinking water that meets the Bangladesh standard for As in drinking water of 50 $\mu g\ L^{-1}$; all but 10 community wells have also consistently met the World Health Organization (WHO) guideline for As of 10 $\mu g\ L^{-1}$. Groundwater pumped from one third of the community wells does not meet the current WHO guideline for Mn in drinking water of 0.4 mg L^{-1}, although Mn concentrations are lower than in most surrounding shallow wells. In addition to As and Mn, concentrations of 10 elements (Cr, Ni, Cu, Cd, Ba, Hg, Mo, Sb, Pb, and U) out of a total 19 inorganic constituents of potential health concern were monitored and found to be below their respective guideline values established by WHO. Further study is required to evaluate the health consequences of Mn exposure, but the increase in As concentrations in 4 community wells indicates that all deeper tubewells should be periodically re-tested.

Keywords: Arsenic, groundwater, Bangladesh, mitigation, hydrogeology, monitoring.

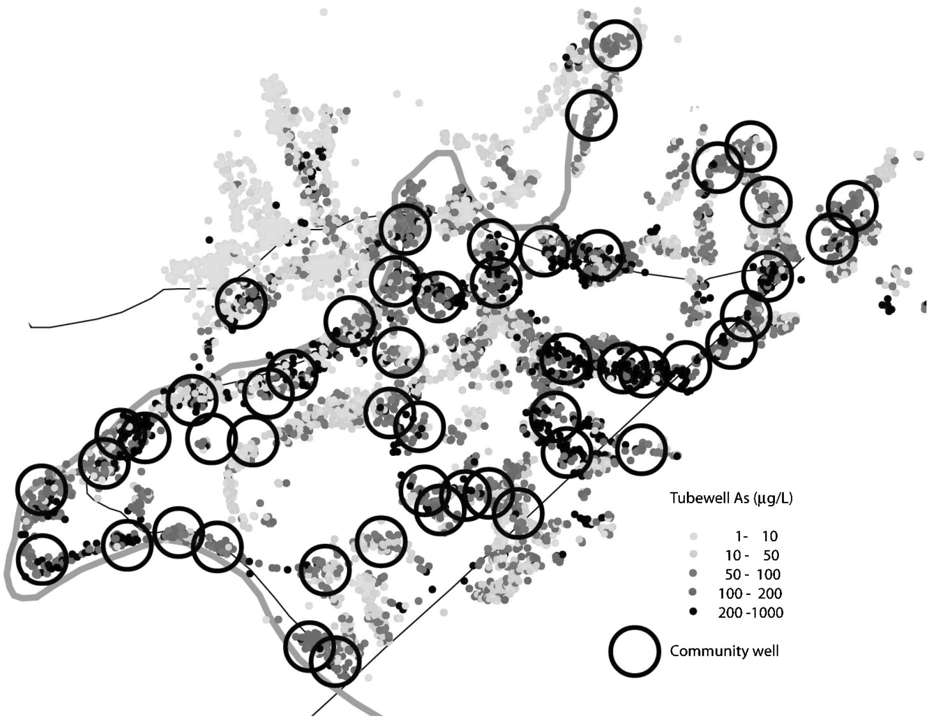
Introduction

Over the past two decades, tubewell surveys have shown that a growing number of Southeast Asian countries face the problem of natural groundwater contamination with arsenic.[1−7] In spite of these concerns, tubewells remain today the primary source of drinking water that is not heavily contaminated with human pathogens for millions of households throughout rural West Bengal (India) and Bangladesh, where elevated concentrations of As in groundwater were first reported. Although doubts have been raised about continued reliance on groundwater of any type, no realistic alternatives have to date been demonstrated to be effective at the necessary scale.[8,9] The implication is that the rural population of the Bengal Basin will probably continue to rely primarily on tubewells for at least another decade.

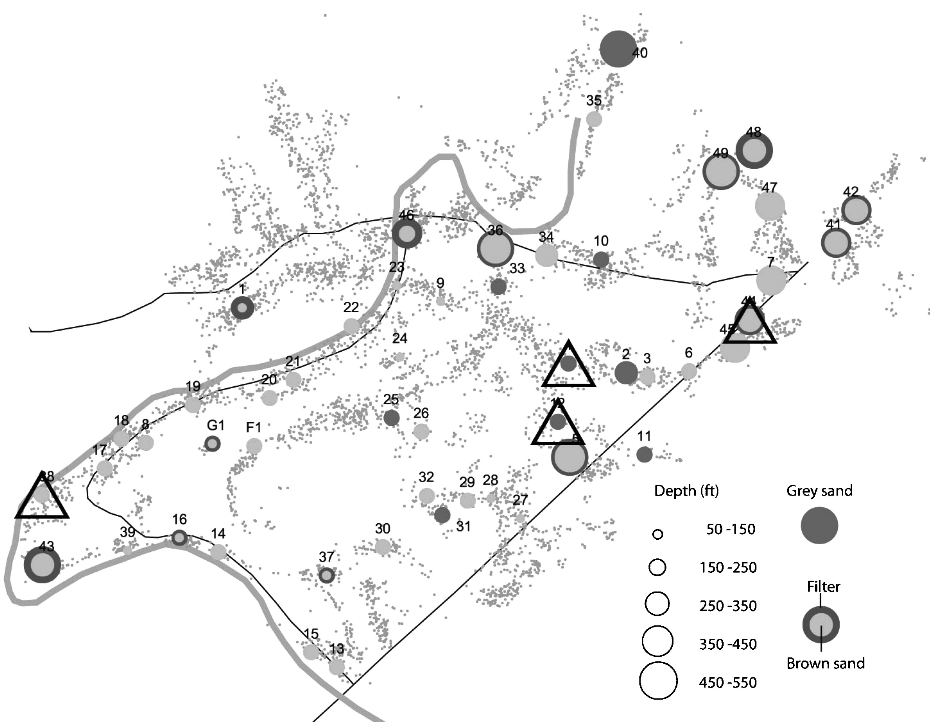
Thankfully, a significant proportion of the shallow tubewells that are elevated in As are no longer used as a source of drinking water because households have switched for drinking and cooking to tubewells that are low in As, either shallow or deep.[9,10] In the case of shallow aquifers, there is increasing evidence that the composition of groundwater is determined in large part by the local hydrogeology and therefore may not change drastically over time.[3,11,12] A highly scattered but significant increase of concentrations of As in groundwater with tubewell age has been reported on the basis of several independent data sets, however.[3,13,15] As stated in BGS/DPHE[3]: "It is tempting to deduce from this that the shallow wells become more contaminated with time. This may be true but these data do not themselves prove this to be the case. There could be other correlated variables that may account for the trends."

A somewhat different ongoing debate has focused on the viability of deeper aquifers as a source of safe drinking water. Unfortunately, these discussions have often been characterized by speculation rather than reporting of monitoring data that could help determine the reliability of deep tubewells as a source of drinking water (see technical comments by Sengupta *et al.*[16] Ravenscroft *et al.*[17] and a response by Cheng *et al.*[18] We present here monitoring data at an unprecedented combination of duration and temporal resolution for a set of 51 community wells installed between

Address correspondence to Alexander van Geen, Lamont Doherty Earth Observatory of Columbia University, 206 New Core Lab, Route 9W, Palisades, NY 10964; E-mail: avangeen@ldeo.columbia.edu



(a)



(b)

Fig. 1. Distribution and characteristics of private and community wells in Araihazar, Bangladesh. (a) Small colored dots indicate the location and As content of 6,500 private wells sampled in 2000–2001. Large black circles with a 400 m diameter indicate the location of 51 community wells. Also shown are the 2 main roads and the main river passing through the study area. (b) Circles positioned at the location of each community wells indicate the color of aquifer sands at the depth of the filter. The size of the circles corresponds to the 4 listed depth ranges of wells. The size of the inner orange circles indicate the upward extent of the brown sand deposits tapped by the community wells, using the same depth ranges. Triangles indicate the location of the 4 community wells that failed. The labels correspond to community well IDs listed in Table 1. The distribution of private wells shown in (a) is recalled with small grey circles in (b).

2001 and 2003 in Araihazar upazila, Bangladesh (Fig. 1). The depth of these wells ranges from 115 to 545 ft (34–164 m) and we refer to them as "deeper" wells to distinguish them from shallow wells that are often elevated in As. No attempt is made here to relate this expression to the various definitions of deep wells in the literature, all of which are somewhat arbitrary.

Previous work in Araihazar

Columbia University and partner institutions in Bangladesh launched in early 2000 a long-term study of the health effects of As exposure on a cohort of 12,000 people coupled to an investigation of the mechanism of As mobilization in groundwater.[13,19] The choice of a location for the study was dictated in part by the need for a wide range of exposure within a limited area. The medical work has and continues to document the significant impact of As exposure on health, including cognitive functions in children.[20] A recent study conducted in Araihazar concluded that the elevated Mn content of groundwater in many tubewells can also impair the mental development of children.[21]

Laboratory measurements have shown that approximately half of the 6500 tubewells sampled in Araihazar in 2000–2001 met the Bangladesh standard for As in drinking water of 50 μg L^{-1} and one quarter met the WHO guideline of 10 μg L^{-1}.[13] Exposure of the population of 70,000 living within the 25 km^2 area has been reduced in two principal ways. First, test results have induced over half the households with an unsafe well (we refer hereon to the Bangladesh standard for As unless the WHO guideline is specified) to seek another source of water, predominantly a nearby tubewell that was tested to be safe.[10,22] The sharing of existing, largely private, tubewells is not an option in villages with few or no safe wells, however. A total of 51 deeper community wells tapping aquifers that are low in As were installed throughout the study area to address this need between 2001 and 2003.[23] The community wells are popular. Each day, surrounding households pump more than 1000 L of water from many of them by hand. About one-tenth of the total population in the Araihazar study area that initially relied on unsafe wells have switched their consumption to one of the 51 community wells.[10]

Geological setting

Whereas no major river controls massive sediment deposition and erosion in the study area today, this probably was the case a few centuries ago, as suggested by the name of the Old Brahmaputra River meandering through the region today (Fig. 1a). The geological history of the area is also reflected in the distribution of wells across the area and delineates the location and shape of villages. Villages are often established on former sand bars and river banks because the slightly higher ground provides some protection against flooding.

Regional geology at the ∼10–100 km scale controls the sharp contrast in the almost uniformly low As content of tubewells in the northwestern corner of the study area compared to the rest of the region (Fig. 1a). A thick clay layer that extends to the surface to the northwest has constrained drillers to install wells to a depth of at least 100 ft (30 m), which in this particular area marks the top of what is likely to be the Dupi Tila formation, a >40,000 year-old deposit of orange-brown sands typically associated with low As concentrations in groundwater.[3,24] The cluster of low-As villages in the northwestern portion of the study area forms the boundary of a larger uplifted area centered around Dhaka where both shallow and deeper wells tap the Dupi Tila formation. The distribution of As for the remaining portion of the study area is highly variable and reflects predominantly the impact of local geology at the 0.1–1 km scale on groundwater recharge and therefore the composition of shallow groundwater.[12] Similarly complex distributions of As in groundwater have been reported on the basis of tubewell surveys elsewhere in the Bengal Basin.[3,14]

Methods

Community wells <300 ft (∼90 m) deep were installed by contracting local teams of drillers that use the entirely manual "hand-flapper" or sludger method. When an aquifer that is systematically low in As could not be reached, the partly mechanized "donkey pump" method was used instead.[25] All but a few of the wells were constructed with 2″ (∼5 cm) ID PVC pipe and a 10 ft (3 m) slotted PVC filter at the end. Local fine-grained material rather than pure clay or cement was used in an attempt to seal the area surrounding the PVC pipe above the filter.

Sand color was the principal criterion used to target low As aquifer for the installation of community wells in Araihazar because orange-brown deposits are typically associated with low groundwater As concentrations.[3,24] The 10 ft (3 m) filter at the bottom of a community well was in contact with orange-brown deposits for 43 out of the 51 community wells installed in Araihazar (Table 1). These 43 community wells range from 115 to 545 ft (34–164 m) in depth, with the depth of about half the wells within the 150–250 ft (45–75 m) range (Figs. 1b, 2). An additional 8 community wells ranging in depth from 180 to 520 ft (54–156 m) were installed within layers of grey or white sand because orange sands were not encountered during drilling. Most though not all of the deepest community wells are concentrated in the northeastern portion of the study area.

Groundwater samples were collected monthly without filtration from the cast-iron hand-pumps installed on the community wells, after pumping for about 5 minutes to flush the well pipe. Samples were collected into 60 mL acid-leached polyethylene sampling bottles and immediately

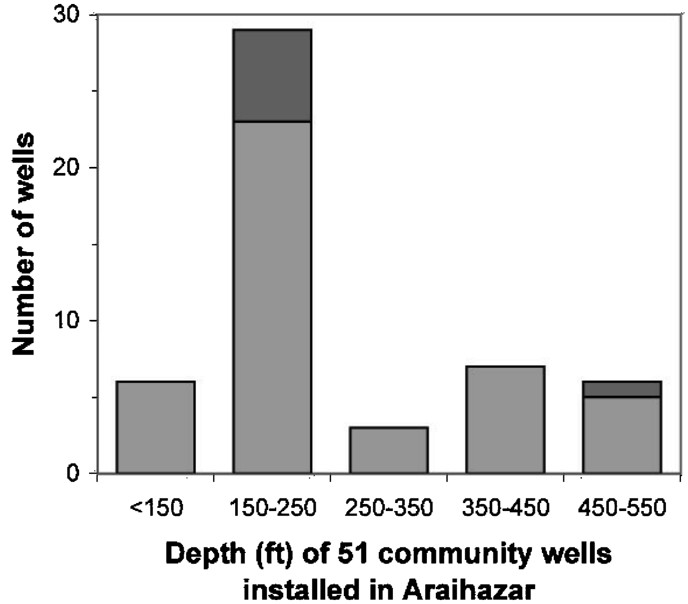


Fig. 2. Histogram of the depths of 51 community wells installed in Araihazar, distinguishing wells installed in sandy deposits that are orange-brown from wells installed in white or grey sands.

acidified to 1% HCl (Optima, Fisher) until December 2003, after which samples were collected into 25 mL acid leached HDPE scintillation vials with conical Polyseal* caps (Wheaton) and acidified at Columbia University when the samples were brought back for analysis, normally several months after collection. To demonstrate that delayed acidification doesn't affect the results, duplicate samples were collected in November 2005 from a set of 25 randomly selected wells of Araihazar. One sample from each well was acidified in the field and the other was acidified 24 hours prior to analysis of both sets in October 2006.

All groundwater samples were analyzed by high-resolution inductively-coupled plasma mass spectrometry (HR ICP-MS) on a single-collector VG Axiom for 24 major and trace elements that include As and Mn, as well as 10 elements (Cr, Ni, Cu, Se, Cd, Ba, Hg, Mo, Sb, Pb) of potential health concern using a procedure that requires only one single dilution.[26] The method allows rapid and precise measurements for As in aqueous samples because interferences by ArCl are eliminated. One annual sample from each of the 51 community wells was selected for initial screening. All monthly samples from four wells that exceeded the Bangladesh standard for As in drinking water of 50 μg L^{-1} were subsequently analyzed to investigate the nature of the failure. The effective detection limit of the method for As is $\sim$1 μg/L. The variability of As concentrations obtained for a consistency standard included with each run was 323 $\pm$ 9 μg/L, i.e., $\pm$3% (n = 11). Samples from the same well were analyzed within the same run to improve the precision of the time series data as much as possible. The precision of the method ranges from 1–3% for most other elements in the range of typical concentrations for groundwater.[26]

Results

The composition of groundwater samples acidified 11 months after collection was essentially identical to that of duplicates acidified immediately upon collection (Fig. 3). The finding holds not only for As, but also for P, Mn, and Fe as well as S, Ca, and K (Table 1). Two samples acidified at the later date contained somewhat lower concentrations of Mn and another (different) sample of Fe, but these differences could just as likely reflect entrainment of a few small aquifer particles in the duplicate acidified in the field as partial re-dissolution. Delayed acidification under controlled conditions in the laboratory therefore has no drawback that we can identify. In addition, there are two significant advantages: strong acid does not need to be transported to the field and the likelihood that a batch of samples is acidified with contaminated acid is reduced.

The installations of community wells in orange-brown sands were largely successful in the sense that the As content of the pumped water exceeded the WHO guideline of 10 μg L^{-1} for only 3 out of 43 of such community wells (Table 2, Fig. 4a). In one case (CW08), the As content declined to below 10 μg L^{-1} in subsequent years; but in the two other cases (CW38 and CW44) the installations clearly failed as concentrations of As eventually rose to well above 50 μg L^{-1}. The record is mixed for the additional 8 community wells that were installed within either white or grey sand deposits. The monitoring data show that 2 of these 8 wells eventually failed (CW04 and CW12), another 2 wells yielded water containing 10–20 μg L^{-1}. The 4 remaining wells installed white or grey sand deposits consistently met the WHO guideline of 10 μg L^{-1}, however.

Whereas the health effects of elevated Mn levels in drinking water are still poorly understood, a guideline value of 0.4 mg L^{-1} has been established by WHO. BGS/DPHE [3] and Cheng *et al.*[26] have pointed out that a large proportion of tubewells in Bangladesh do not meet this guideline. Groundwater Mn concentrations generally decline with depth but frequently not to levels that meet the WHO guideline. Out of a total of 51 community wells installed in Araihazar, the Mn contents of groundwater in 14 wells are greater than 0.4 mg L^{-1} (Table 2, Fig. 4b). Only 5 community wells exceed the WHO guideline by more than a factor of two, however (and all by less than a factor of 3). The proportion of wells exceeding the WHO guideline for Mn is approximately one third within the 100–250 ft as well as the 250–550 ft depth range (Fig. 4b). There is no systematic relationship between Mn and the color of aquifer sands either; concentrations in groundwater pumped from only 2 out of 8 community wells installed into white or grey sands exceeds 0.4 mg L^{-1}.

Q1

Table 1. Comparison of HR ICP-MS results for samples acidified in the field and 11 months later in the laboratory

	Acidified November 2005							Acidified October 2006						
Well ID	*P (mg/L)*	*S (mg/L)*	*K (mg/L)*	*Ca(mg/L)*	*Mn (mg/L)*	*Fe (mg/L)*	*As (mg/L)*	*P (mg/L)*	*S (mg/L)*	*K (mg/L)*	*Ca(mg/L)*	*Mn (mg/L)*	*Fe (mg/L)*	*As (mg/L)*
1338	0.11	4.9	2.6	37.1	2.22	0.53	33.4	0.07	5.1	2.6	37.3	1.27	0.45	25.3
1342	0.04	20.0	18.3	81.1	1.00	0.31	0.3	0.03	19.4	18.2	82.3	0.98	0.23	0.4
1359	0.16	12.5	3.7	66.2	2.81	2.05	31.7	0.16	12.6	3.8	67.2	2.46	1.96	28.4
1361	0.07	7.4	3.0	52.9	1.30	0.09	3.7	0.05	7.4	3.1	54.5	1.28	0.09	4.5
1373	0.58	18.3	4.5	55.7	1.57	3.59	25.1	0.54	17.6	4.6	55.1	1.55	3.56	26.2
1380	0.03	35.1	3.9	108.3	1.30	0.18	0.0	0.02	35.9	4.1	112.3	1.30	0.22	0.1
2160	0.27	3.5	4.6	52.9	1.98	2.85	109.7	0.26	3.4	4.7	53.5	2.02	2.88	112.2
2173	0.45	6.3	9.8	43.8	1.90	16.41	46.8	0.46	6.1	10.1	43.7	1.89	16.28	44.4
2221	1.21	0.5	9.8	114.3	5.17	26.89	220.5	1.29	0.5	9.7	117.0	5.08	26.36	211.7
2862	2.29	24.1	4.9	178.9	4.17	16.04	145.9	2.02	27.9	5.4	182.8	4.13	20.37	158.7
2877	0.38	0.5	7.9	32.8	1.73	1.13	63.8	0.35	0.5	7.8	31.1	1.41	1.17	60.3
4424	7.73	0.2	5.0	1.9	0.00	0.35	51.9	7.45	0.2	5.1	2.0	0.00	0.47	50.8
4427	6.23	0.2	6.4	3.1	0.00	0.41	61.5	6.50	0.2	6.8	3.1	0.00	0.44	64.7
4429	4.23	0.3	9.1	6.0	0.01	0.76	66.6	4.29	0.4	9.8	6.5	0.01	0.81	74.1
4431	4.15	0.4	10.2	8.0	0.04	3.34	83.2	4.16	0.4	10.1	7.7	0.03	2.49	86.5
4434	0.63	0.1	2.7	52.1	3.21	2.76	279.8	0.62	0.1	2.8	53.1	3.25	2.69	275.3
4444	0.47	0.2	2.5	54.7	2.47	5.76	271.5	0.55	0.3	2.6	57.2	2.51	5.80	275.5
4452	0.52	0.1	2.5	53.2	2.11	1.19	248.6	0.51	0.2	2.7	55.1	1.19	1.28	225.1
4475	0.31	3.9	3.3	100.3	2.37	2.92	105.3	0.37	4.0	3.7	103.5	2.30	2.97	109.6
4478	0.27	9.1	5.3	89.9	1.98	5.78	95.3	0.27	8.9	5.2	90.5	1.99	6.18	98.4
8156	0.51		2.6	45.7	3.36	2.91	295.3	0.51	0.4	2.5	46.9	3.32	2.87	288.9
8347	0.24	0.7	1.6	11.6	0.46	0.19	3.0	0.23	0.7	1.6	12.0	0.47	0.19	3.7
8353	1.33	0.1	4.9	36.1	0.04	3.34	152.6	1.40	0.1	4.8	36.0	0.04	3.62	158.0
8356	0.04	69.6	4.9	172.8	1.25	0.95	0.2	0.05	71.8	5.3	177.7	1.31	1.28	0.6
8442	0.09	4.7	2.4	32.4	0.64	1.20	29.7	0.08	5.3	2.5	34.8	0.49	1.35	30.8

Table 2. Characteristics of 51 community wells in Araihazar, Bangladesh. Red fonts indentify the four falled wells.

CW ID	Installation date	Status Sep of	Village name	Longitude	Latitude	Sand color at screen	Clay (ft)	Brown (ft)	Filter (ft)	Avg As (ug/L)	Stdev As	Avg Mn (mg/L)	Stdev Mn	n
1	January,2001	Abandoned	Darisatyabhandi	90.60322	23.78534	Orange-brown	95	95	275	1.3	0.0	0.11	0.06	21
2	January,2001		Bailar Kandi	90.63856	23.78036	Grey	150		295	0.3	0.0	0.88	0.01	23
3	August,2001		Bailar Kandi	90.64052	23.78005	Light brown	150	190	195	3.1	0.5	0.26	0.06	4
4	June,2004	Re-installed	Bailar Kandi	90.63325	23.78108	Brown-gray/yellowish brown	185		195	31.2	18.9	0.76	0.19	31
5	October,2001		Brahmandi	90.6335	23.7731	Yellowish brown	260	410	460	7.6	14.2	0.32	0.06	6
6	August,2001		Bailar Kandi	90.64434	23.7806	Yellowish brown	190	190	190	2.3	0.6	0.58	0.09	6
7	October,2001		Krishnapura	90.65173	23.78837	Yellowish brown	320	365	400	4.1	0.5	0.36	0.11	6
8	April,2003		Balia para	90.59457	23.77374	Yellowish brown	165	165	180	14.4	21.4	0.71	0.24	4
9	May,2003		Boro Monohordi Modhya Para	90.62142	23.78614	Yellowish brown	120	120	150	0.8	0.2	0.12	0.01	4
10	May,2003		Chotto Binairchar	90.63608	23.78994	Off-white	185		200	16.9	0.9	0.03	0.02	4
11	May,2003		Brahmondi	90.64037	23.77346	Brownish grey/yellowish gray	150		180	6.5	0.5	0.56	0.02	4
12	May,2003	Failed	Dhohor Maouroadi	90.63235	23.77612	Yellowish brown/yellowish gray	180		180	47.1	47.2	0.31	0.22	22
13	July,2003		Edbardi	90.61245	23.75499	Yellowish brown	160	165	205	0.7	0.2	0.06	0.03	4
14	July,2003		Uttrapur	90.6014	23.76459	Yellowish brown	165	165	175	1.4	0.2	0.02	0.03	4
15	July,2003		Edbardi	90.61007	23.75622	Yellowish brown	165	205	205	1.1	0.3	0.13	0.09	4
16	July,2003		Uttrapur	90.59781	23.76574	Yellowish brown	115	130	175	1.5	0.3	0.03	0.02	4
17	July,2003		Baliapara	90.59083	23.77152	Yellowish brown	175	175	210	1.3	0.4	0.75	1.01	3
18	July,2003		Baliapara	90.59233	23.77404	Yellowish brown	160	160	210	3.8	0.7	0.08	0.05	4
19	September,2003		Bati Gobindi	90.59884	23.77703	Yellowish brown	110	185	210	1.4	0.4	0.02	0.00	4
20	September,2003		Rishir Char	90.60586	23.77772	Yellowish brown	110	185	190	7.5	13.5	0.22	0.12	4
21	September,2003		Monohordi	90.60802	23.77931	Yellowish brown	100	190	200	1.2	0.5	0.17	0.06	4
22	September,2003		Monohordi	90.61327	23.78395	Yellowish brown	120	190	210	0.9	0.4	0.05	0.04	4
23	September,2003		Uzan Gobindi Pachim para	90.6174	23.78743	Reddish brown	110	140	150	1.7	1.6	0.35	0.04	4
24	September,2003		Chhoto Monohordi kanda para	90.6178	23.78139	Reddish brown	130	140	150	1.5	0.4	0.03	0.01	4
25	September,2003		Lashkardi	90.61708	23.77621	Yellowish gray	225		230	9.0	4.8	0.13	0.01	4
26	September,2003	Abandoned	Lashkardi Dokkin Para	90.61985	23.77508	Yellowish brown	210	215	220	2.5	1.8	0.27	0.10	2
27	September,2003		Maouradi	90.6291	23.76785	Reddish brown	130	140	150	0.7	0.3	0.70	0.06	4
28	September,2003		Maouradi Pachim Para	90.62634	23.76953	Yellowish brown	115	115	115	0.9	0.6	1.18	0.01	3
29	September,2003		Bara Fausa	90.62419	23.7693	Yellowish brown	145	180	185	1.6	0.9	0.31	0.03	4
30	September,2003		Shilmandi	90.6165	23.76525	Yellowish brown	150	175	195	1.3	0.8	0.63	0.13	4
31	September,2003		Bara Fausa	90.62189	23.76805	Yellowish gray	140		190	1.0	0.4	0.39	0.04	4
32	September,2003		Bara Fausa	90.62044	23.76966	Reddish brown	145	175	190	1.9	0.4	0.14	0.02	4
33	October,2003		Uzan Gobindi	90.6267	23.78748				230	2.3	0.3	0.08	0.03	4
34	October, 2003		Fakir Bari	90.63107	23.7902	Yelowish brown	325	340	340	1.9	0.4	0.14	0.01	3
35	September,2003		Chamer Kandi	90.635233	23.80183	Yellowish brown	170	180	190	0.6	0.2	1.04	0.01	3
36	September,2003		Uzan Gobindi	90.62637	23.79069	Yellowish brown	160	450	490	1.5	0.4	0.15	0.01	3
37	October,2003		Edbardi Kazi Para	90.61139	23.76275	Yellowish brown	130	130	160	1.2	0.6	0.27	0.04	3
38	March, 2005	Re-installed	Baliapara	90.58512	23.76919	Yellowish brown	150	175	175	120.3	142.0	0.65	0.16	25
39	October,2003		Bati Baliapara	90.5931	23.76458	Yellowish brown	120	130	135	1.0	0.3	1.11	0.27	3
40	October,2003	Abandoned	Panchgaon	90.63734	23.80779	Yellowish grey	240		520	1.5		0.18		1
41	October,2003		Araihazar	90.65764	23.79167	Yellowish brown	280	325	400	4.9	0.8	0.69	0.04	3
42	October,2003		Choto Baroibari	90.65943	23.79447	Yellowish brown	330	340	420	2.5	2.4	0.84	0.09	3
43	October,2003	Needs cleaninc	Bati Baliapara	90.585267	23.76325	Yellowish brown	260	345	530	0.8	0.2	0.24	0.08	2
44	October,2003	Failed	Noapara	90.64982	23.785	Yellowish brown	280	290	415	58.4	29.2	0.16	0.20	26
45	October,2003		Noapara primary school	90.6485	23.78262	Yellowish brown	260	380	425	5.7	0.6	0.42	0.02	3
46	October,2003		Bara Binairchar	90.61821	23.79184	Yellowish brown	220	220	420	2.7	1.5	0.04	0.01	3
47	October,2003		Mukundi	90.6515	23.79469	Yellowish brown	200	380	450	2.6	0.6	0.31	0.00	3
48	October,2003	Needs cleaninc	Mukundi Gazipura mosque	90.64996	23.79938	Yellowish brown	290	350	545	4.6	1.4	0.32	0.01	2
49	October,2003	Needs cleaninc	Kamrungirchar (Muza Kanda)	90.64696	23.79754			450	480	8.6		0.58		1
F1	January, 2002		Lashkardi mosque	90.60453	23.77364	Orange-brown	160	160	195	1.0	0.3	0.50	0.02	22
G1	January, 2002		Lashkardi Bilbari	90.60069	23.77376	Orange-brown	120	120	175	7.0	1.0	0.66	0.06	20

The 51 community wells installed in Araihazar all meet WHO guidelines for 10 additional elements of potential health that were tested (Cr, Ni, Cu, Cd, Ba, Hg, Mo, Sb, Pb, U). The only exceptions are a single sample from CW26 and three samples from CW04 which contain elevated concentrations of Pb (20 μg L^{-1}) and U (15 μg L^{-1}), respectively. The elevated levels were confirmed by re-analysis of the same samples; we attribute these few outliers to a sampling artifact. All other samples collected from the same community wells were consistently low in Pb and U.

The failure of CW04 in 2004 after 3 years of fluctuations in the composition of well water for As and other constituents has been discussed previously and was tentatively attributed to broken or disconnected PVC pipes at shallow depth.[11] Analysis of monthly samples provides here a detailed documentation of 3 new well failures. Between July 2003 and October 2004, concentrations of As in well water at CW12 remained generally below 10 μg L^{-1} (Fig. 5). Concentrations of As in CW12 sharply increased over the next 2 months to 230 μg L^{-1} then settled back to a remarkably constant level of ~60 μg L^{-1}. CW44 also failed around the same time and, again after a sharp transition, concentrations of As settled at a slightly higher level of ~80 μg L^{-1}. Whereas field-kit measurements indicated that the installation of CW38 was initially successful, concentrations of As rapidly rose to 350 μg L^{-1} during the following year. The re-installation of well CW38 at the same location to approximately the same depth in March 2005 subsequently yielded groundwater with an As content fluctuating between 10 and 20 μg L^{-1}.

The concentrations of Mn and many other elements also changed following the well failures (Fig. 5). In the case of CW04, Mn concentrations fluctuated around a mean of ~0.8 mg L^{-1} in concert with variations As until the well was re-installed. Concentrations of Mn remained remarkably constant at ~0.3 mg L^{-1} at CW12 throughout the sampling period, with the exception of two samples collected around the transition. Concentrations of Mn in CW38 also remained relatively constant and rose only slightly to ~0.7 mg L^{-1} after re-installation. Finally at CW44, the rise in As concentrations was accompanied by a drop to low Mn levels averaging ~0.1 mg L^{-1}.

Discussion

Our monitoring data show that a total of 39 community wells provided the residents of a 25 km^2 area of Araihazar

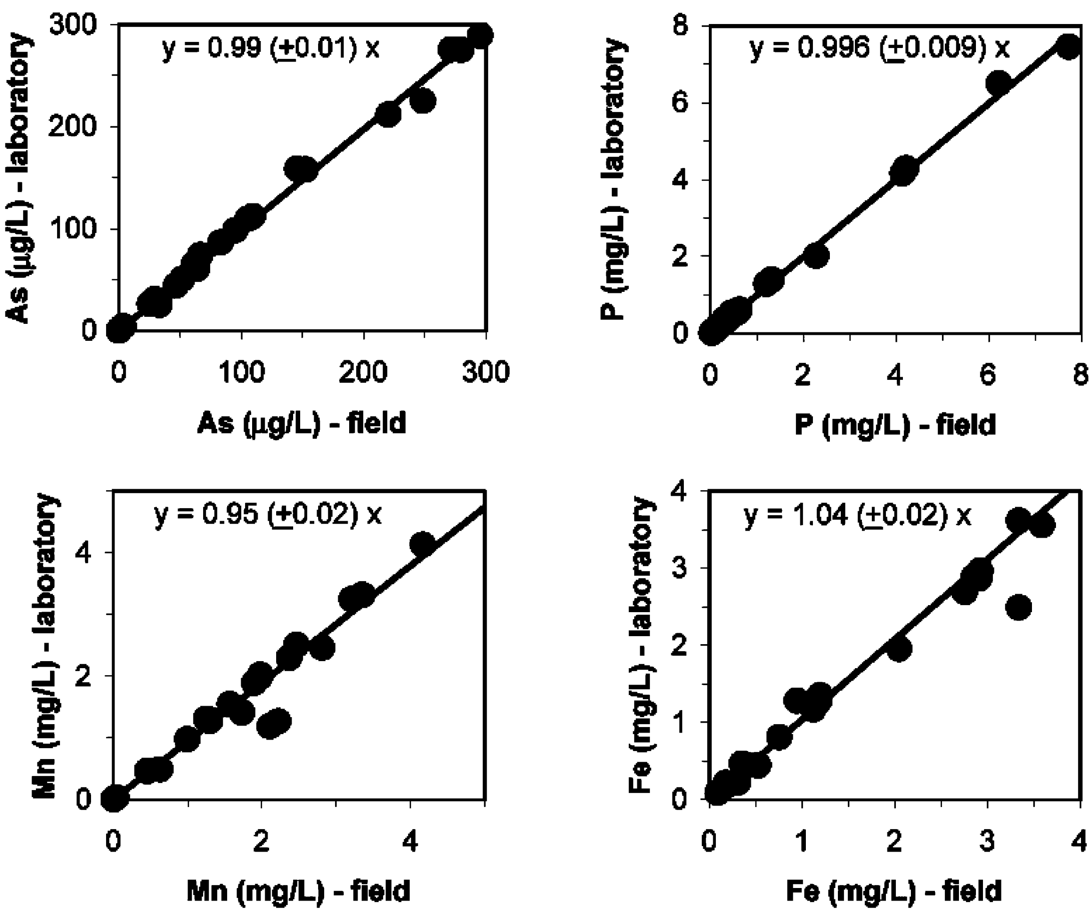
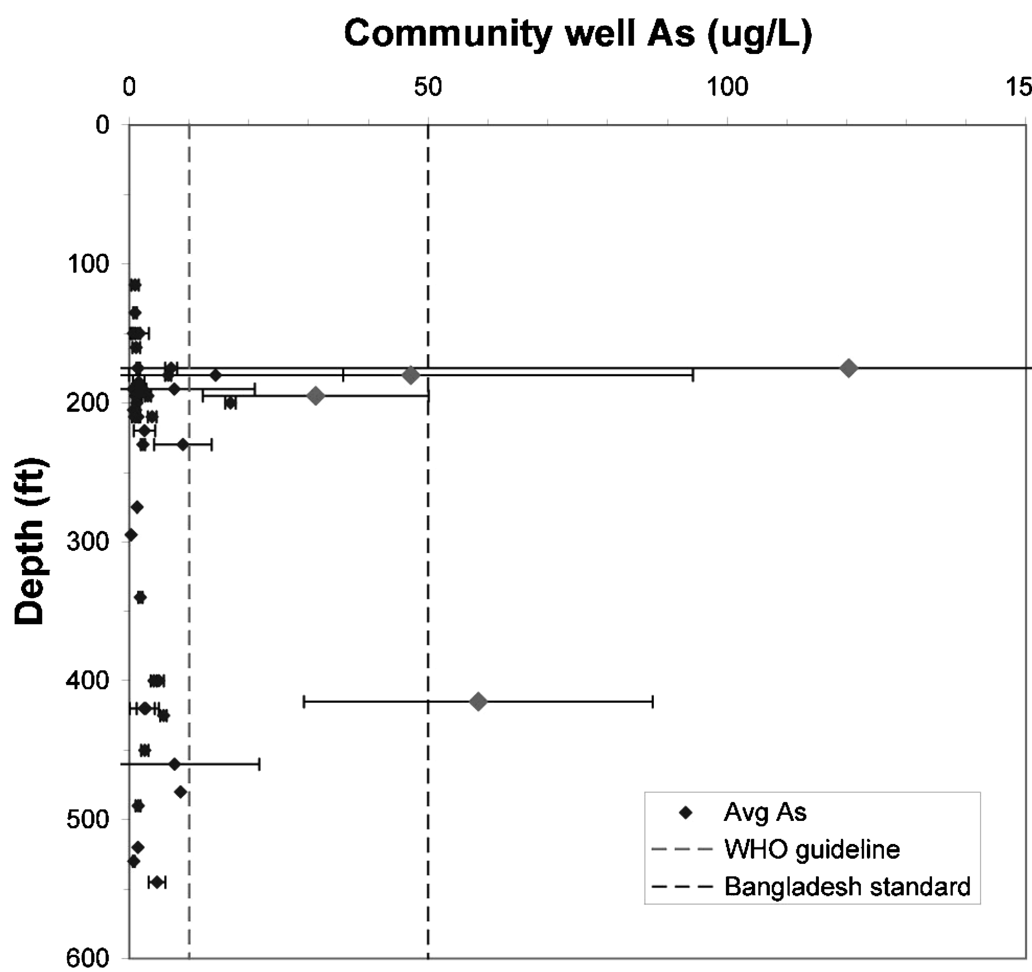


Fig. 3. Comparison of groundwater analyses for duplicate samples from tubewells of Araihazar, one of which was acidified immediately and the other 11 months later in the laboratory (Table 1).

with drinking water that consistently met the WHO guidelines for As and 10 other inorganic constituents of potential health concern over a period of at least 3 years. Informal surveys indicate that the average number of villagers relying on each community well is on the order of 200, with some wells serving 100 villagers and others well over 300.[10,23] Whereas most of the 39 wells draw their water from aquifers composed of orange-brown sands, three extended to deposits containing white or grey sands. The very wide depth range of the 39 community wells (Fig. 2) illustrates why, in our opinion, it is not helpful or geologically justified to define a minimum depth for those deep aquifers that are systematically low in As.[13] In a recent review of the deep aquifer system in Bangladesh, a similar approach that avoids assigning a particular depth to the definition of a deep aquifer was put forth.[27]

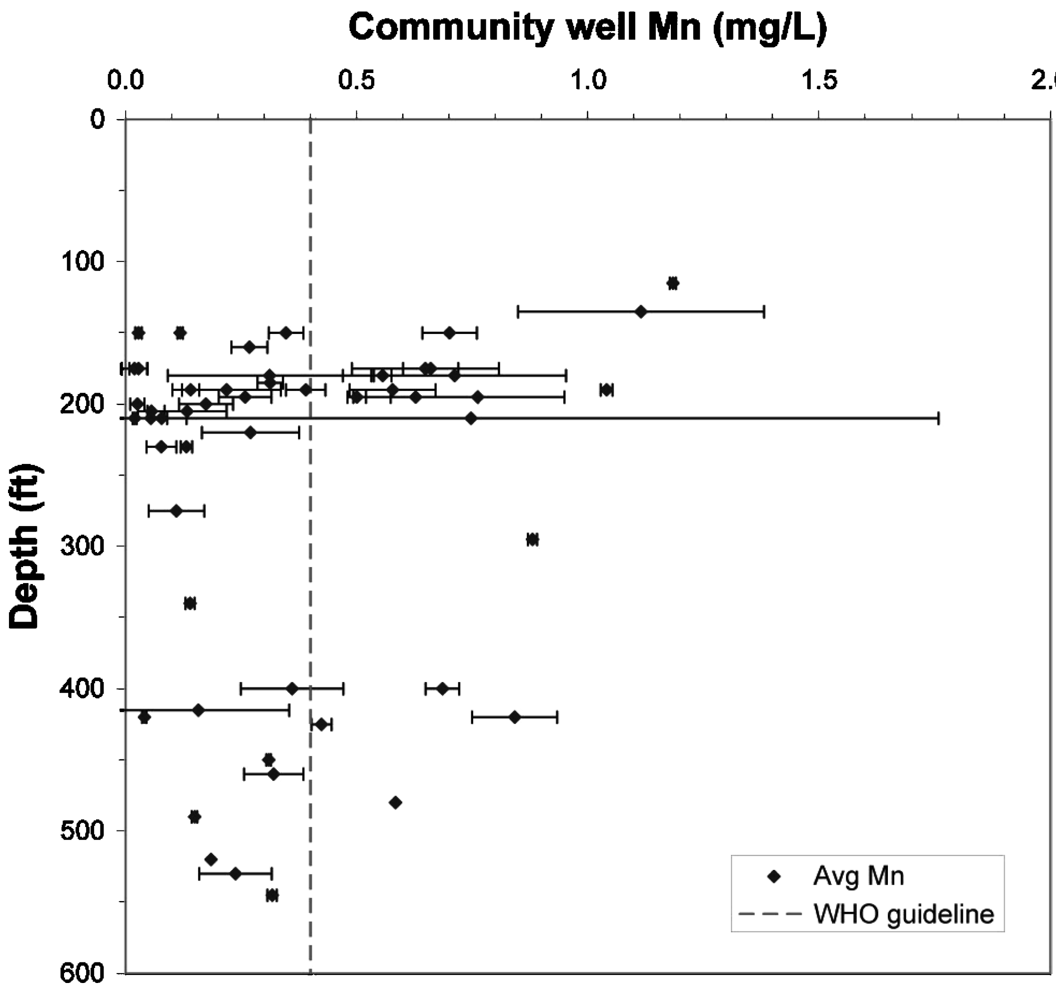
Whereas exposure to As has been drastically reduced for thousands of residents of Araihazar by the installation of community wells, the sharp rise in As concentrations observed in 4 community wells also provides a clear warning. It should not be assumed that a deeper well will continue to provide safe drinking water after being tested once soon after installation. We are currently investigating the origin of the failures, but no clear pattern has emerged to date. Two of the failures occurred in community wells drawing water from grey sands, but for the two other failed wells the sands surrounding the filter was orange-brown.

In the case of the three relatively shallow community wells that failed (CW04, CW12, CW38), a clay layer located within 0 to 25 ft (0–8 m) above the top of the filter should have limited drawdown of shallower groundwater elevated in As (Table 2). Grey sand layers ranging 5–25 ft (1.5–7.5 m) in thickness were recorded between the clay layer and the top of the filter during drilling at CW04 and CW38, however. Proximity of grey sands does not seem to be a primary factor determining well failure, however, because



(a)

Fig. 4. Average and standard deviation of (a) As and (b) Mn concentrations in 51 community wells shows as a function of depth. In all but 3 cases of community wells with maintenance problems (Table 1), the data extend over at least 3 years. The 4 community wells whose As content systematically exceeded the Bangladesh standard for As in drinking water of 50 μg L^{-1} are CW04 at 195 ft (58 m), CW 12 at 180 ft (54 m), CW38 at 175 ft (52 m), and CW44 at 415 ft (124 m). *(Continued)*



(b)

Fig. 4. (*Continued*)

grey sands were also encountered during drilling 10 ft (3 m) or less above the top of a filter for 11 out of the 36 successful community wells that extended to orange-brown sands (Table 2).

Preliminary results using a packer, an inflatable device that can isolate different sections of a well, suggests that contaminated water enters CW12 through the filter 180 ft (54 m) depth. Somehow, on a spatial scale that has yet to be defined, groundwater elevated in As appears to have reached the depth of the filter at this location. In the case of 415 ft (124 m)-deep well CW44, on the other hand, a recent packer test unambiguously indicated leakage of shallow groundwater elevated in As into the well between 150–200 ft (45–60 m) depth. In this case, therefore, the failure seems to have been caused by a mechanical failure of the PVC pipes or a pipe connection at a shallow depth, rather than drawdown of shallow groundwater elevated in As to the depth of the filter. Regardless of the mechanism(s) of failure, the clear implication is that any deeper well located in an area where shallow aquifers are elevated in As should be periodically re-tested. Several existing field kits are quite adequate for this purpose and their more widespread use should therefore be promoted. [9,28,29]

The elevated Mn content of groundwater pumped from a large proportion of the community wells installed in Araihazar is a vexing problem. Exposure to Mn via inhalation is known to be neurotoxic, but little is known about possible consequences of exposure via drinking water. A recent study conducted in Araihazar has shown a significant reduction in children's intellectual function at Mn concentrations >1.0 mg L^{-1} compared to children drinking groundwater with <0.2 mg L^{-1}.[21] Columbia University and its partners in Bangladesh intend to re-install those community wells that are <200 ft (60 m) deep and do not meet the WHO guideline of 0.4 mg L^{-1} for Mn to depths >400 ft (120 m) with the expectation that Mn concentration will meet the WHO guideline for about one third of these wells.

It is important, however, to keep the levels of Mn exposure caused by drinking water from the community wells in perspective. Re-analysis of water from a subset of 1300

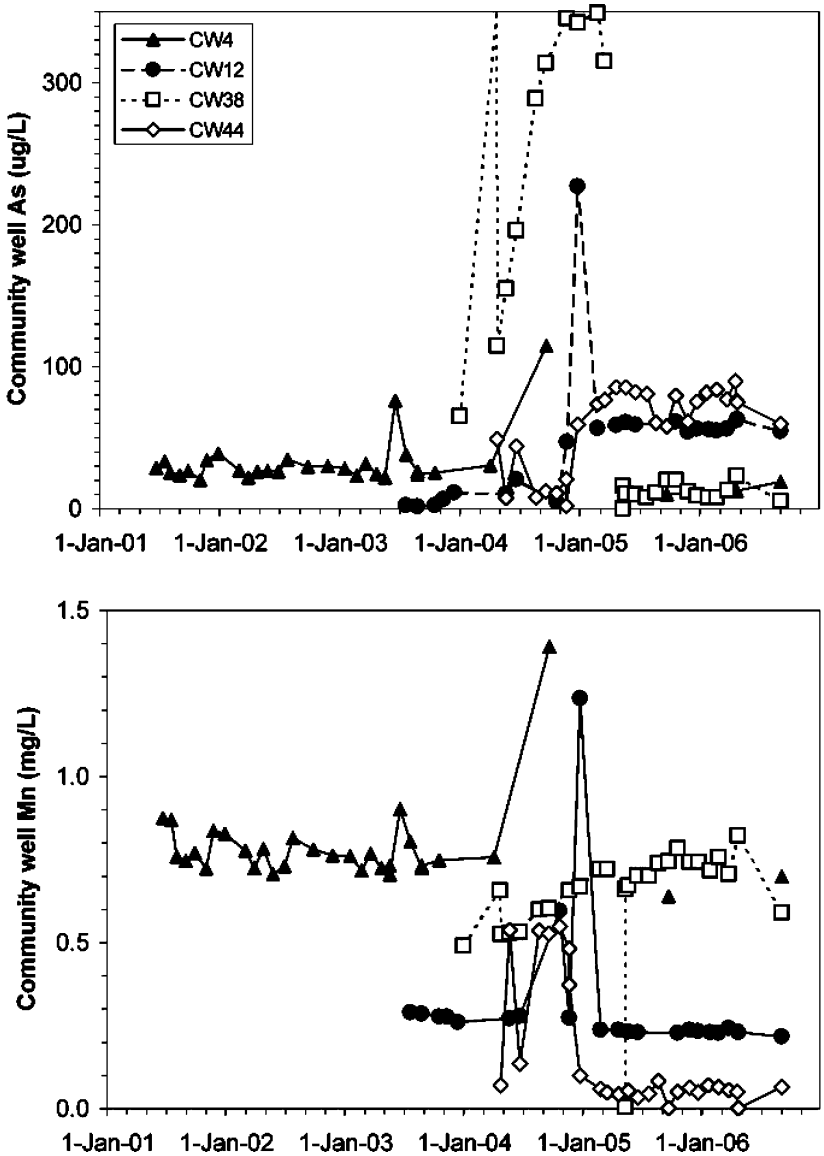


Fig. 5. Monthly variations in As and Mn content of groundwater pumped for wells CW04, CW12, CW38, and CW44. Wells CW04 and CW38 were re-installed to the same depth in June 2004 and March 2005, respectively.

wells from Araihazar containing >50 μg L^{-1} As by HR ICP-MS indicates an initial exposure averaging 1.6 mg L^{-1} for Mn (only 7% of these wells contained <0.4 mg L^{-1}). The potential health impacts of Mn need to be better understood and may provide another justification for, in the long-term, a water supply system for rural Bangladesh that does not rely on the use of untreated groundwater.

Conclusions

Extended monitoring of a considerable number of community wells in Araihazar has demonstrated that a single deeper community well can effectively reduce the exposure to As of a large number of households. The tens of thousands of deeper wells installed throughout the country by the government and the various aid organizations presumably have had a similarly beneficial impact.

The limited but significant number of well failures also provides a clear warning: concentrations of As will inevitably rise in a (hopefully small) fraction of deeper wells. The reason for these increases appears to be highly localized in the 4 cases that were documented in Araihazar. Further study is required to determine whether regional effects might play a role in other parts of the Bengal Basin with a very different geology or water pumping practices. For lack of realistic alternatives in the short to medium term, deeper community wells are likely to remain an important source of drinking water that meets health standards for many constituents including As, although not necessarily Mn.

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