Ineffectiveness and Poor Reliability of Arsenic Removal Plants in West Bengal, India

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In the recent past, arsenic contamination in groundwater has emerged as an epidemic in different Asian countries, such as Bangladesh, India, and China. Arsenic removal plants (ARP) are one possible option to provide arsenic-safe drinking water. This paper evaluates the efficiency of ARP projects in removing arsenic and iron from raw groundwater, on the basis of our 2-year-long study covering 18 ARPs from 11 manufacturers, both from home and abroad, installed in an arsenic affected area of West Bengal, India, known as the Technology Park Project (TP project). Immediately after installation of ARPs on August 29, 2001, the villagers began using filtered water for drinking and cooking, even though our first analysis on September 13, 2001 found that 10 of 13 ARPs failed to remove arsenic below the WHO provisional guideline value (10 μg/L), while six plants could not achieve the Indian Standard value (50 μg/L). The highest concentration of arsenic in filtered water was observed to be 364 μg/L. Our 2-year study showed that none of the ARPs could maintain arsenic in filtered water below the WHO provisional guideline value and only two could meet the Indian standard value (50 μg/L) throughout. Standard statistical techniques showed that ARPs from the same manufacturers were not equally efficient. Efficiency of the ARPs was evaluated on the basis of point and interval estimates of the proportion of failure. During the study period almost all the ARPs have undergone minor or major modifications to improve their performance, and after our study, 15 (78%) out of 18 ARPs were no longer in use. In this study, we also analyzed urine samples from villagers in the TP project area and found that 82% of the samples contained arsenic above the normal limit.

Introduction

Before 2000 there were five major incidents of groundwater arsenic contamination in Asian countries: Bangladesh (*1–4*), West Bengal, India (*5–7*), and three sites in China (*8*). By 2004 new instances emerged from different Asiatic countries (*9*) with reports of arsenic contamination in the Kurdistan province of western Iran (*10*) and in Vietnam (*11*). Our preliminary studies point to further arsenic contamination in India and Bangladesh involving a significant portion of the Ganga–Meghna–Brahmaputra (GMB) plain, an area of 569 749 km^2 with a population of over 500 million (*9, 12*).

Since 1997, the governments of Bangladesh and West Bengal, the World Bank, UNICEF, WHO, and other international aid agencies along with national nongovernmental organizations (NGOs) have initiated a two-phase program to combat the arsenic crisis. The first phase was identification of the contaminated tube wells and the second the provision of safe drinking water. Tube wells were painted green or red corresponding to arsenic concentrations below and above 50 μg/L, respectively, utilizing field kits for arsenic testing. The poor reliability and validity of these field kits seriously disrupted the national programs (*13, 14*). UNICEF stopped using these kits in West Bengal, India, after evaluating them independently, and the South East Asia Regional director of WHO urged the development of a standardized laboratory testing of arsenic (*15*), but the debate persists (*16*).

The plan to use arsenic removal plants (ARP) posed a scenario of controversy like that of field kit testing, fueled by the keen interest of many national and international companies to supply ARPs and other water treatments. The installation of ARPs based on adsorption, coprecipitation, and ion-exchange techniques began at the end of 1998 in West Bengal. Over 1900 ARPs have been set up, at an average price of US$1500/unit, in nine arsenic affected districts of West Bengal with comparable installations in Bangladesh.

Our preliminary investigations of the efficiency of ARPs in West Bengal also began in late 1998, resulting in the submission of five reports evaluating the efficiency of 513 ARPs in the districts of Nadia, Murshidabad, and North 24-Parganas of West Bengal to the Government of West-Bengal, ARP manufacturers, and other concerned NGOs for their information and follow-up action. Our study findings from July 1999 to July 2004 are shown in Table 1 of the Supporting Information.

Description of Evaluation Procedures. While our initial studies on ARP effectiveness were underway, the Technology Park Project (TP project) was implemented at Baruipur in the arsenic-affected district of South 24-Parganas (Figure 1) by the All India Institute of Hygiene and Public Health (AIIH&PH), Kolkata, in partnership with a number of NGOs and with the financial support of the India–Canada Environment Facility (ICEF), New Delhi, to demonstrate, monitor and evaluate the currently available technologies for arsenic removal (*17*).

In the TP project, 19 ARPs from 11 different national and international manufacturers were installed. Figure 2 shows a schematic diagram of a typical ARP. Table 1 is a detailed description of the ARPs (*17, 18*) installed in the TP projects, defining the mechanism of activity, media, price, and the manufacturer's stated achievement target for arsenic and iron removal. All of the ARPs, except plants 3 and 17, were installed on August 28, 2001, with the filtered water from each made available to the villagers for drinking and cooking as of August 29, 2001. Plants 3 and 17 were installed on August 7, 2002 and May 22, 2002, respectively. Plant 19 was not

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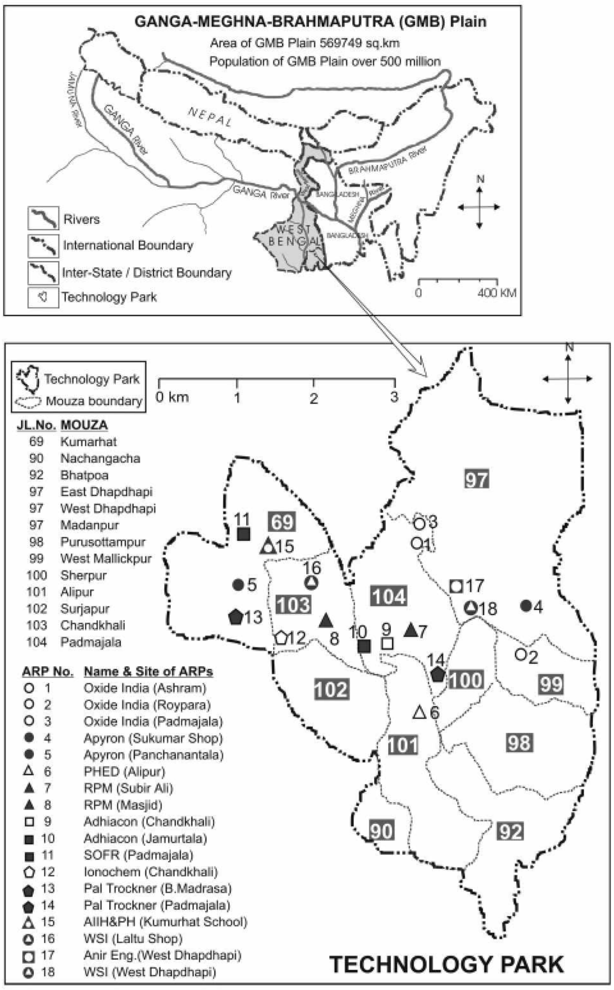

FIGURE 1. Map of the study area indicating the location of the arsenic removal plants installed therein.

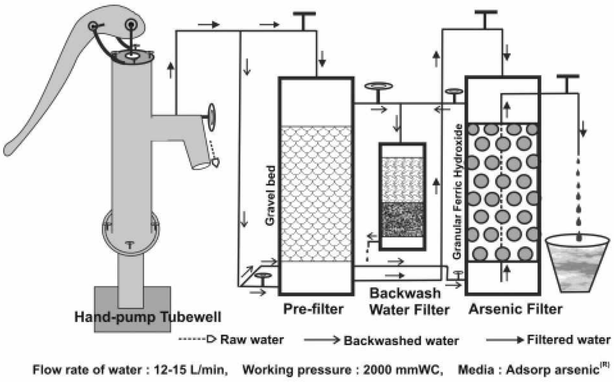

FIGURE 2. Schematic diagram of a typical arsenic removal plant (Pal-Trockner).

installed until the last months of the project and is excluded from our evaluation. Table 2 of the Supporting Information lists the number of samples received for analysis from each ARP and the reasons for missing samples.

The stated achievement targets for the ARPs varied widely: Oxide-India (plants 1–3) and Pal-Trockner (plants 13, 14) cited arsenic free water, an impracticable target; RPM marketing (plants 7, 8) claimed an arsenic removal target of below detection limit (BDL), which obviously varies with the analytic method. For these cases, the WHO target for arsenic, $\leq 10\ \mu g/L$, was assumed (*19*).

The target levels for iron also varied. Oxide India and Adhiacon cited the WHO permissible limit, while Pal-Trockner and Ionochem listed 300 $\mu g/L$ as the limiting concentration for iron. No health-based guideline value for drinking water iron is proposed by WHO (*19*), but taste is usually unacceptable at iron concentrations above 300 $\mu g/L$, and this is used as the target for our evaluation.

During our 2-year study period (September 13, 2001 to September 8, 2003), most of the ARPs underwent some major or minor changes, including media, design, or site change, resinking, etc. Only three ARPs (plants 4, 5, 15) were consistently in operation. Four ARPs (plants 1, 10, 11, 18) were officially abandoned by the project authority due to poor performance and failure to cope with the problem of silvery colloidal sand rising along with the water and choking the tube well and the filter media of the ARPs, known as sand gushing.

Experimental Methods

Study Area. The study area, Technology Park, has an area and population of 8 km^2 and 23 963, respectively, and is located in the Baruipur block of the South 24-Parganas district, one of the nine arsenic-affected districts of West Bengal (Figure 1). Of the 4720 families residing in the project area, approximately 45% were below the poverty level. The primary sources of drinking water were, and continue to be, shallow tube wells. We had previously analyzed 856 tube well water samples from the 15 villages in the project area and observed that 46% and 38% of them had arsenic concentrations >10 and $>50\ \mu g/L$ respectively, while 16% of the analyzed tube-wells showed arsenic concentrations above 300 $\mu g/L$, the concentration predicting overt arsenical skin lesions (*6*). Our medical team registered 107 patients with arsenical skin lesions from 92 affected families in the area.

We performed the chemical analysis of both raw and filtered water samples from each of the ARPs in operation through the 2-year study period with weekly samples from September 2001 until August 2002 and biweekly samples from September 2002 until September 2003. Water was initially analyzed for five parameters: arsenic, iron, conductivity, hardness, and pH; when stability was evident, the later samples were analyzed only for arsenic and iron and occasionally for other parameters.

Instrumentation. A flow injection hydride generation atomic absorption spectrometer (FI-HG-AAS) and a UV spectrophotometer were used for the arsenic and iron analyses as described in earlier publications (*20*, *21*).

TP Project Authority Protocol. The terms of agreement between the TP project authority and our laboratory regarding the collection and analysis of water samples were as follows.

(1) Water samples for chemical analysis were collected from each ARP before and after filtration by the project authority according to our prescribed procedure as described in previous publications (*12*, *22*).

(2) The TP project authority sent both raw and filtered water as coded (blinded) samples from all ARPs on Wednesday afternoon; analyses were to be carried out on the same day and a report submitted to the TP authority the following day.

(3) The TP project authority would independently analyze duplicate aliquots at their laboratory and one or more outside laboratories. The project authority would inform our laboratory immediately of any significant differences.

Interlaboratory Comparison. In addition to the TP project protocols, we carried out interlaboratory comparisons for both arsenic and iron on our own. Aliquots of raw water samples from 16 tube wells from the study area were sent to the Intronics Technology Centre (ITC), Dhaka, Bangladesh, and Central Food Laboratory (CFL), Kolkata, India, after analyses for arsenic in our laboratory by the FI-HG-AAS method. Both outside laboratories conducted arsenic analyses by FI-HG-AAS after reduction. No significant differences

TABLE 1. Description of the ARPs Installed in Technology Park

no.	manufacturer	no. of plants	mechanism of activity	media	media capacity	price (US$)	manufacturers' claim for efficacy of removal	
							As	Fe
1	Oxide India (Catalysts) Pvt. Ltd., Durgapur, representing B. E. College model	3	adsorbant	activated alumina AS-37	based on 2 years base performance with 600 L/h capacity, 4000 L/ day for 0.5 ppm raw water	1070 + 326 per charge + 4% sales tax	arsenic-free water	permissible limit
2	Apyron Technologies India (P) Ltd., representing Apyron Technologies Inc. USA	2	adsorbant	Aqua Bind (activated alumina mostly in combination with metal oxide) patented	based on 1 ppm, 1000 L/day with periodic media replacement at 6–8 months	1810 + 340 per charge	<10 ppb	NA[a]
3	Public Health Engineering Dept (PHED), Govt. of West Bengal	1	adsorption	red hematite (Fe_2O_3) lumps + quartz + sand + activated alumina	600–1000 L/h (requires periodic sludge removal and/or backwash/ cleaning)	611 as per 1997 estimate	below permissible limit of 0.05 mg/L	NA
4	RPM marketing Pvt. Ltd., New Delhi, representing Alcan Chemicals USA	2	adsorbant	activated alumina + AAFS-50, patented	based on 200 000 L/year with 0.5 ppm per liter intake	1000 + 453 per media charge	below detection level	NA
5	School of Fundamental Research (SOFR), Kolkata	1	adsorption	aluminum silicate + ferric hydroxide	based on 0.5 ppm, 2000 L/day media recharging at 4–6 months	181 + 27 per recharge	<50 ppb	NA
6	Adhiacon, Kolkata	2	catalytic precipitation/ electron exchange	AFDWS-2000 (patent pending)	based on 1 ppm, up to 10 000 L (requires periodical sludge removal or backwash)	1698	as prescribed by WHO	as prescribed by WHO
7	Ionocem, Kolkata	1	ion exchange	ferric hydroxide	based on 0.5 ppm, 1 440 000 L with 600 L/h	883	<0.01 ppm	0.33 ppm
8	Pal Trockner (P) Ltd. Kolkata (German origin)	2	adsorbant	AdsorpAs (patented)	900 000 L based on 1 ppm (requires periodic backwash)	1675 + 566 per recharge	arsenic-free water	<0.3 mg/L
9	All India Institute of Hygiene & Public Health (AIIH&PH), Kolkata	1	oxidation + coagulation + flocculation/ precipitation/ filtration	clorinating agent (BP) + ferric alum (calcd dose)	1000 L/h (requires periodical sludge removal and/or cleaning)	792 + periodic chemical charges	remove 95%	remove 90%
10	W. S. I., USA, represented by Harmonite Impex (Pvt.) Ltd., Kolkata	2	ion exchange	bucket of resins (BOR) mostly in combination with metal oxide (patented)	300 000 L based on 1 ppm	2088 + 883 per recharge + 4% sales tax	<0.05 mg/ L	NA
11	Anir Engineering, collaboration with ITP Gmbh, Germany	1	adsorption	slurry/granular ferric hydroxide (S/GFH)	600–900 L/h (requires periodic backwashing twice/thrice per week)	815 + 192 per recharge + maintenance of 27 per year	NA	NA

[a] NA, information is not available.

TABLE 2. Descriptive Statistics (minimum, maximum, mean, and standard deviation in μg/L) of Each of the ARPs Installed in Technology Park (September 13, 2001 to September 8, 2003)

		arsenic in filtered water					iron in filtered water				
ARP ID	name and site of the ARP	no. of observations	min.	max.	mean	SD	no. of observations	min.	max.	mean	SD
1	Oxide India (Ashram)	52	<3	401	40	10	52	<40	3791	450	1064
2	Oxide India (Roy Para)	71	<3	36	8	7	67	<40	1512	101	191
3	Oxide India (Padmajala)	27	<3	25	5	5	23	<40	1521	251	400
4	Apyron (Sukumar Shop)	74	<3	279	24	49	70	<40	937	71	113
5	Apyron (Panchanan tala)	74	<3	139	26	32	70	<40	210	55	38
6	PHED (Alipur)	60	<3	150	27	32	58	<40	1958	131	262
7	RPM (Subir Ali)	60	<3	169	45	37	52	<40	2439	272	416
8	RPM (Masjid)	53	<3	97	19	22	69	<40	356	57	49
9	SFR (Padmajala)	73	<3	480	37	75	69	<40	5250	613	1120
10	Adhiacon (Chadkhali)	27	22	282	94	65	27	52	4312	1366	1182
11	Adhiacon (Jamurtala)	38	<3	157	43	43	38	<40	8104	929	1373
12	Ionochem (Chandkhali)	70	<3	99	15	15	66	<40	4723	267	726
13	Pal Trockner (B Madrasa)	72	<3	107	8	17	68	<40	1521	99	214
14	Pal Trockner (Padmajala)	67	<3	195	13	30	63	<40	2291	734	595
15	AIIH & PH (K. School)	74	<3	45	21	8	70	<40	420	110	98
16	WSI (Laltub Shop)	64	<3	115	33	33	60	<40	2083	378	529
17	Anir Engineering (West Dhapdhapi)	37	<3	105	27	22	33	<40	1294	286	388
18	WSI (West Dhapdhapi)	19	<3	173	45	54	19	<40	895	153	225
all plants together			<3	480	26	45		<40	8104	306	672

could be observed in arsenic and iron concentration level among the various laboratories as shown in Figures 1 and 2 of the Supporting Information.

Urine Analysis. In the four revisits in the four months, we collected urine samples for arsenic analysis from a convenience sample of 150 villagers who had lived in the TP project area throughout the project. For controls, urine samples were collected from 78 residents of the Midnapore district of West Bengal, an arsenic-safe area. Inorganic arsenic and its metabolites in urine samples were measured with no chemical treatment. The method of collecting urine samples, the analytical procedure, and analysis of the NIST urine standard have been discussed elsewhere (*12*).

Statistical Analysis. Standard statistical techniques were applied to analyze and present the data. An ANOVA was applied to test the homogeneity of the performance level of the ARPs. Paired *t*-test and independent *t*-test were used to test the efficiency of the ARPs as well as to test the difference between two ARPs of same manufacturer. Point and interval estimates of the proportion of "failure" were used to assess the efficiency of the ARPs.

Results

Arsenic Concentration in the Filtered Water of ARPs: September 13, 2001 to September 8, 2003. The first set of water samples were received and analyzed by our laboratory on September 13, 2001. Filtered water samples were available for 13 of the 16 ARPs that began operating on August 29, 2001. The initial analyses of arsenic and iron, shown in Table 3 of the Supporting Information, showed that out of 13 ARPs, nine (69%) failed to remove arsenic in filtered water to the target set by manufacturers; 10 (77%) and six (46%) of the ARPs failed to reduce arsenic concentrations in filtered water to 10 and 50 μg/L, respectively; and six (46%) ARPs failed to reduce iron below 300 μg/L. The highest concentrations of arsenic and iron in filtered water were 364 and 5250 μg/L, respectively.

The minimum, maximum, mean, and standard deviation of arsenic concentrations in filtered water, as found in our 2-year study, for each ARP are given in Table 2. The overall mean arsenic concentration in filtered water was 26 μg/L with a standard deviation of 45 μg/L. The highest mean arsenic concentration, 94 μg/L, was observed in plant 10 and the lowest, 5 μg/L, in plant 3; plant 9 had the largest standard deviation.

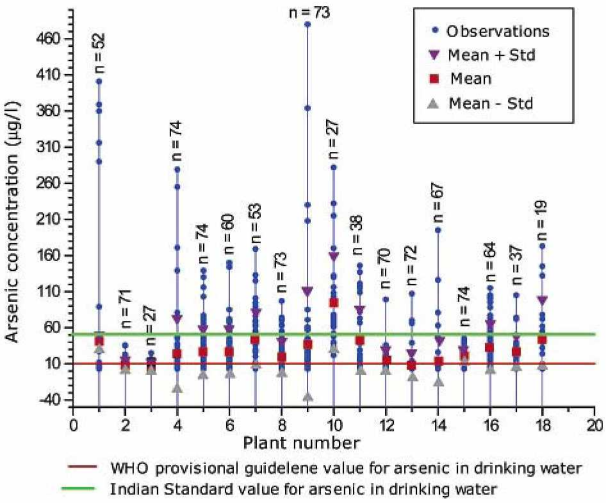

FIGURE 3. Scatter plot of arsenic concentration in filtered water along with mean and standard deviation for each ARP.

Only two of 18 ARPs (plants 2, 15) achieved 100% control of arsenic, ≤50 μg/L, throughout the study period. Though plant 3 could maintain the level below 50 μg/L, it was installed midway in the project. However, plant 15 could not meet the manufacturer's claim of 95% arsenic removal (average arsenic concentration in raw water was 215 μg/L and that in the filtered water was 21 μg/L). The filtered water concentration could have crossed 50 μg/L, if the raw water arsenic concentration were higher.

The efficiency of the ARPs was compared by ANOVA. A high *F* value (9.044) indicates a significant difference between ARP performance levels. A paired *t*-test indicated that ARPs can reduce arsenic from raw water. Unfortunately, none of the ARPs (Figure 3) could reduce the levels of arsenic to meet WHO provisional guideline value (*19*).

Iron Concentration in the Filtered Water from ARPs. The overall mean iron concentration in filtered water was found to be 306 μg/L with a standard deviation of 663 μg/L (Table 2). The maximum iron in filtered water was 8104 μg/L in plant 11. Only one ARP (plant 5) achieved iron ≤300 μg/L throughout the study period. A scatter plot of iron concentrations showing the mean and standard deviation in filtered water from each ARP is shown in Figure 3 of the Supporting Information**.** ANOVA (F = 14.091) found the ARPs to be nonhomogeneous in terms of iron removal.

Evaluation of the ARPs on the Basis of the Proportion (*p*) of Failure. Defining arsenic and iron concentrations above established safe levels as "failure" and the remainder as "success" we determined the point estimates as well as the 95% confidence intervals for the proportion of failure, p, from 0 to 1, for each of the ARPs for both arsenic and iron concentrations (Table 4 of the Supporting Information). The lower the value of p, the more efficient the ARP. If the 95% confidence interval contains zero, the performance of the corresponding ARP is regarded as satisfactory; if not, the ARP is considered inefficient. Only one ARP (plant 3, installed midway in the project) maintained arsenic concentrations within the target set by the manufacturer as well as the WHO guideline value, on the basis of the confidence interval. Five ARPs (plants 2, 3, 12, 15, 17) maintained arsenic $\leq$50 μg/L on the basis of the confidence interval, but only two ARPs (plants 2, 15) maintained the arsenic in filtered water $\leq$50 μg/L throughout the project period. In terms of iron removal, six ARPs (plants 2, 4, 5, 8, 13, 18) performed satisfactorily on the basis of the confidence interval; only plant 5 maintained the iron in filtered water $\leq$300 μg/L throughout the study period.

Intermanufacturer Comparison. The filter efficiency of ARPs from the same manufacturer was compared. The three ARPs from Oxide India (plants 1–3) differed significantly in the reduction of arsenic and iron from raw water (F = 5.17 and 3.89) at the 5% level of significance, with adequate control of arsenic by plants 2 and 3 and adequate control of iron by plant 2. Significant differences in both arsenic and iron removal were found between each of the two ARPs from WSI (plants 16, 18), RPM (plants 7, 8), Adhiacon (plants 10, 11), and Pal-Trockner (plants 13, 14). The two ARPs from Apyron differed only in the removal of iron. Figure 4 shows the scatter plot of the arsenic concentrations in filtered water of the individual ARPs and Figure 4 of the Supporting Information shows those for iron concentrations.

Effect of Backwash on Performance. Since the villagers were allowed to use the filtered water for drinking and cooking purposes immediately after scheduled backwashing, we evaluated, in May 2003, the effects of backwashing and forward washing on the arsenic content of treated water from the 13 ARPs in operation. Figure 5 shows the arsenic concentration in filtered water before backwashing and at different time intervals after backwashing. Four ARPs (plants 3, 5, 13, 16) had arsenic concentrations <10 μg/L and another three (plants 4, 9, 17) had concentrations of 282, 286, and 60 μg/L, respectively, in filtered water before backwashing. The remaining six ARPs had arsenic concentration between 10 and 50 μg/L. All of the ARPs, except plants 8 and 16, produced higher concentrations of arsenic at the initial stage of forward washing; all but three ARPs (plants 4, 6, 17) achieved arsenic $\leq$50 μg/L within 3 h of forward washing. Two ARPs (plants 3, 17) delivered arsenic >50 μg/L both before backwashing and after forward washing during the entire day. An irregular pattern of arsenic concentration was observed for plant 6.

Some of the ARPs produced safe water after a minimum forward washing (10 L) but others failed to produce safe water even after a whole day of forward washing (839 L). More data are required to determine the optimum volume and duration of forward washing required for arsenic-safe water after back washing.

Arsenic Content of Backwashed Water. We analyzed the backwashed water three times (twice for both arsenic and iron and once for only arsenic) in December 2002, March 2003, and on May 2003 during the 2-year study period. The mean and maximum arsenic concentrations were found to be 2923, 12 307; 1336, 1392; and 668, 1436 μg/L, respectively.

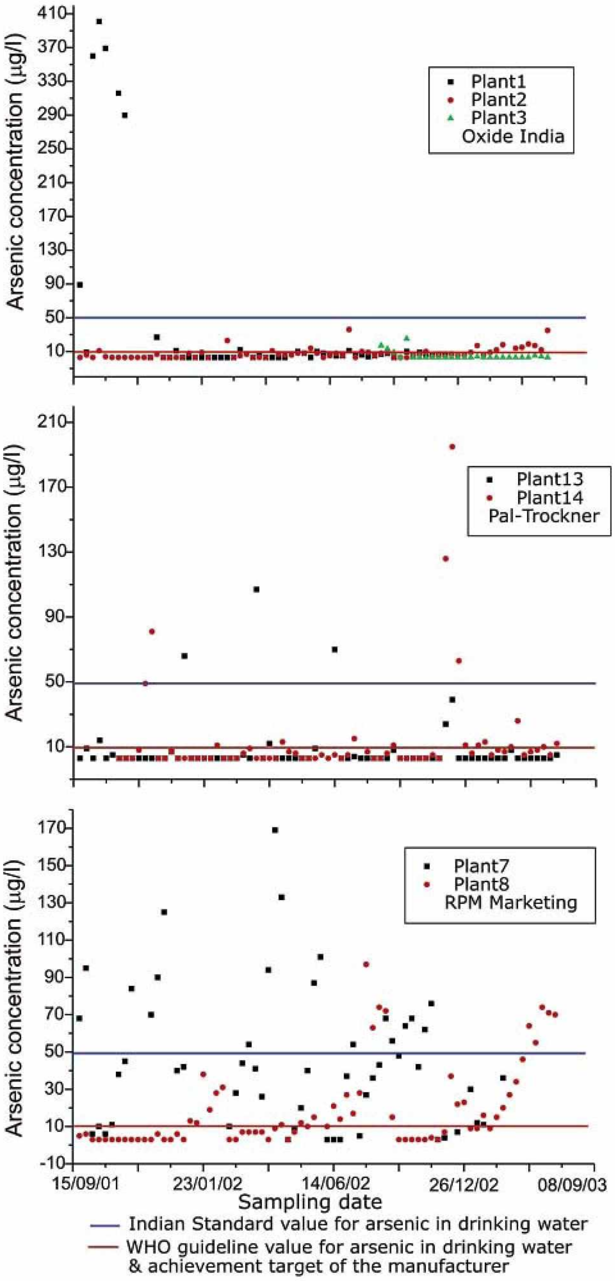

FIGURE 4. Scatter plot of arsenic concentration in filtered water of different ARPs from the same manufacturer.

Postevaluation Status of the ARPs. The TP project area was revisited three times in 2004 and once in 2005 to assess the condition of the ARPs. On our last visit, January 26, 2005, only three of 18 ARPs were still in operation and used by the villagers, five were defunct, three had been removed by the villagers or manufacturers, four had been closed down by the TP project authority, and three were not used by the villagers (one for an unhygienic condition and the other two for not being user-friendly).

Analysis of the urine samples from 150 villagers of the TP project area who had used the ARP water for 2 years showed 82% of the samples to contain arsenic above the normal limit (*23*, *24*), significantly higher than that of urine from 78 villagers from an unaffected area (Figure 6). The minimum, maximum, and mean arsenic concentrations in urine were found to be 10, 870, and 104 μg/1.5 L, respectively, with a standard deviation of 116 μg/1.5 L.

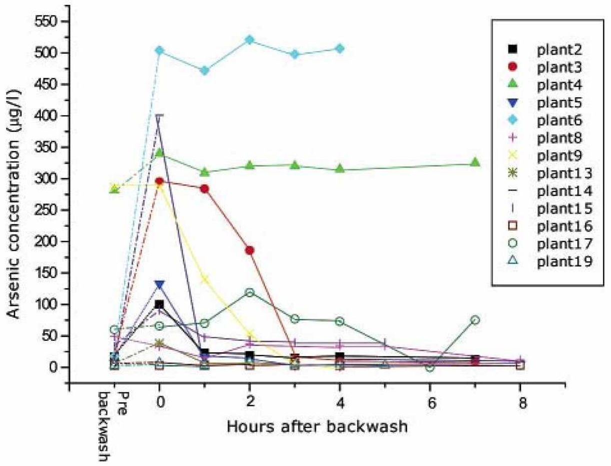

FIGURE 5. Arsenic concentration in filtered water from different ARPs before backwash and at different time intervals after backwash.

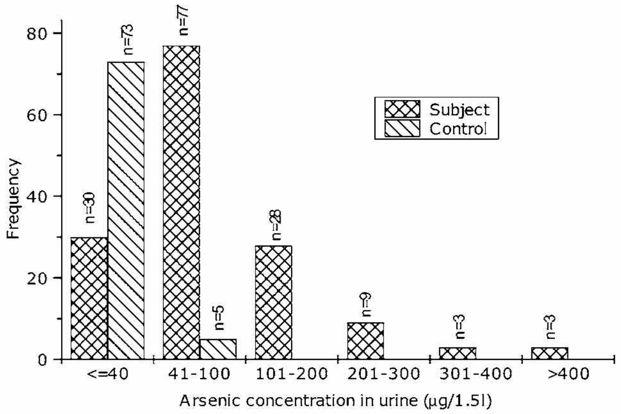

FIGURE 6. Comparative bar diagram of urinary arsenic concentration of TP project area population and control population.

Discussion

Poor Performance of the ARPs and the Impact on Villagers. The primary goal of the ARP project was to provide drinking water with arsenic $\leq$50 μg/L, the current standard for India. The Bureau of Indian Standard (BIS) recommended, in September 2003, a reduction in drinking water arsenic to no greater than 10 μg/L (*25*), consistent with the WHO standard and that of most developed countries, but this has not yet been implemented. This study defines the inability of the current generation of ARPs to reliably reduce arsenic and iron to acceptable levels.

Causes Behind Poor Performance of the ARPs. Our 2-year study identified some of the technical problems contributing to the poor performance of the ARPs.

Maintenance. Backwashing of the ARPs is critical for consistent and efficient performance with respect to arsenic and iron removal from contaminated raw water (*18*), but the standards for the frequency, volume, and duration of the subsequent forward washing were not defined by the manufacturers or the project authority. We did find (Figure 5) that for 10 of 13 ARPs, the arsenic level in filtered water was $\leq$50 μg/L after 3 h of forward wash.

Clogging. Seven of the 18 ARPs required a change of the media well before the maturity of the media capacity predicted by the manufacturers. The media composition of several ARPs was changed in an effort to enhance performance (Table 2 of the Supporting Information). Sand gushing was an unavoidable but incompletely anticipated problem of the pressure pump ARPs, since the arsenic affected areas of West Bengal are in recent alluvial depositional areas. Plants 7 and 14 suffered from this problem on the second day of operation. All but three ARPs (plants 5,12,15) faced this problem (Table 2 of the Supporting Information) and some became inoperable even after resinking of the tube wells. Plant 1 had to be closed down despite four efforts to resolve sand gushing by resinking the tube well. The TP authority in association with the manufacturers subsequently implemented resinking at a different site and introduced a new type of filter strainer intended to prevent the fine silvery colloidal sand from gushing into the pipes.

Lack of User Friendliness. The attachment of the ARPs to existing tube wells involves some changes in the mouth and head of the tube well (Figure 2). When the mouth valve is in the closed position, arsenic-safe water can be obtained through the ARP; the open position yields arsenic-contaminated raw water, appropriate only for domestic purposes other than drinking and cooking. If the mouth valves are jammed, the villagers use arsenic-free water for all purposes, including bathing; when the valve attached to the ARP is jammed, they receive contaminated water. The packing at the head of the tube wells to facilitate the flow of water into the ARP from the tubewell is often inadequate. On pumping, water erupts from the head of the tubewell and drenches the user. The pressure is often so high that the pump handle rebounds, injuring the user (*26*). ARPs increase the collection time. Washer damage is more frequent when ARPs are attached to the tube wells. Users often complain that the treated water is malodorous and red/yellow in color.

In addition to, or because of, the technological limitations of the ARPs, the villagers' lack of awareness of the problem, coupled with poverty and educational deficits, limits the users' participation in the project. We observed in our earlier field study (*27*) that the performance of the ARPs is improved by appropriate maintenance with regular backwashing and ARPs are utilized by residents concerned with the success of the project.

Poor Management of Backwashed Sludge from ARPs. The high arsenic back washings are typically discarded on a nearby open field, pond, road or other area near the ARPs, evoking the possibility of a future environmental hazard. The TP authority set no rules for sludge management and only one manufacturer offered a separate device for disposal of the high-arsenic sludge.

Alternate Safe Water Options. With no known effective medical treatment for those suffering from arsenic toxicity, the provision of safe water and nutritious food are considered the only effective management of early and mild skin lesion cases, and all sources of safe water merit consideration. The per capita available surface water in arsenic affected areas of West Bengal is about 7000 cubic meters. During the monsoons, the average annual rainfall in this region is about 1600 mm. In addition, West Bengal is richly endowed with other available surface water resources such as wetlands, flooded river basins, lagoons, ponds, and ox-bow lakes. This available surface water can be tapped as an important source of drinking water, provided proper purification measures are undertaken. Alternative safe water options such as dug wells and rainwater harvesting may also be explored if bacterial and other chemical contaminants are controlled.

Tube wells free from arsenic and other water-borne contaminants are important sources of safe water that can still be used. The mitigation strategies may also focus on informing people of the level of arsenic in their tube well water, labeling the wells and promoting the sharing of safe tube wells. Deep, arsenic-safe, community wells may also be installed, particularly in those areas with little opportunity for well switching (*1*, *28*). All well water should be repetitively tested for different contaminants including arsenic and fluoride, since 62.5 million people in India suffer from fluorosis due to fluoride-contaminated tube well water (*29*).

Most importantly, educating the villagers in the affected areas about the existence, magnitude, danger, and symptoms of the arsenic problem and the importance of cheap nutritious food in preventing toxicity; training them on issues of water management; and involving the whole community in the maintenance of their water source can alleviate the problem to a large extent.

This 2-year study of the TP project has helped define some of the on-site problems of ARPs, such as the need to define the frequency and intensity of backwashing and to dispose of the high-arsenic backwash properly, the high concentrations of arsenic in the early phases of forward flushing, the capacity of the filter media, and the need for the units to be user-friendly. It is hoped that this information will contribute to the ability of the next generation of arsenic removal systems to provide consistently safe water, ultimately achieving arsenic $\leq 10\ \mu g/L$.

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Supporting Information Available

Additional information relating to both arsenic and iron removal performance of the ARPs. This material is available free of charge via the Internet at http://pubs.acs.org.

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