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Assessment of performance of community iron removal plants in selected rural areas of Bangladesh

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Abstract

The most widely reported groundwater quality problems in Bangladesh include excessive concentrations of As and Fe. However, available data suggest that excessive concentration of Mn is also a significant problem in many areas. Although many community-based iron removal plants (IRPs) have been developed that are also utilized for As removal, there is little data available on the performance of these plants with regard to Mn removal. This study made a rapid assessment of the chemical and microbiological water quality in community IRPs, developed by different NGOs. With few exceptions, the community IRPs appears to be very effective in removing Fe from groundwater, with an average 2-log reduction.

The plants also effectively removed Mn from water (mean: 1-log reduction) but there was significant variation which appears to depend on a number of factors, e.g., provision for aeration, depth of filter bed, filtration rate, and manganese level in raw water. The plants are moderately effective in reducing As, with an average 0.5-log removal. As removal was related more to raw water iron levels than other design factors. The treated water from all units showed low to moderate fecal coliform contamination, highlighting the importance of promoting improved operation, maintenance, and hygiene practices, and development of suitable disinfection process for such community units. It is very important to develop specific criteria for designing community groundwater treatment plants that would simultaneously remove Fe, As and Mn from groundwater to safe levels.

Keywords: Iron Removal, manganese removal, arsenic removal, groundwater, aeration, sand filtration, removal efficiency.

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1. Introduction

The discovery of widespread arsenic (As) contamination of groundwater in Bangladesh has led to a re-assessment of water quality in general. While bacteriological contamination still represents a major threat to public health, it is now recognized that drinking water may also be contaminated with chemicals, which either have direct health impacts or indirect impacts by making the water unpalatable to the consumer. The National Hydro-geochemical Survey conducted by the British Geological Survey (BGS and DPHE 2001) and the National Drinking Water Quality Survey (NDWQS) (BBS and UNICEF 2009) showed that in Bangladesh, large numbers of wells exceed permissible limits for iron (Fe) and manganese (Mn). This is true for shallow tubewells, and also to some extent for deep tubewells and ring-wells, which are common water supply options in As-affected areas. The National Hydro-geochemical Survey found that half of the 3,534 wells surveyed in 61 out of 64 districts exceeded the Bangladesh drinking water standard (1 mg/l) foriron (Fe), and three quarters exceeded the permissible limit (0.1 mg/l) for manganese (Mn). Both of these limits are based on aesthetic concerns; above these levels, people may be unwilling to drink the water, and turn instead to a better-tasting, but microbiologically less safe water sources. Some of the reported Fe and Mn concentrations (BGS and DPHE 2001) are very high, over ten times the permissible limit. Iron and manganese concentrations as high as 25 mg/l and 10 mg/l, respectively have been reported. Average Fe concentration in the surveyed wells has been reported to be 3 mg/l (median 1 mg/l) and average Mn concentration 0.5 mg/l (median 0.3 mg/l) (BGS and Water Aid 2001). Manganese also has adverse health impacts, and WHO recommends a guideline value of 0.4 mg/l (WHO 2004) to protect against neurological damage. About 40% of wells sampled in the BGS-DPHE survey exceeded this limit for Mn as well (Hasan and Ali 2010). It should be noted that (WHO 2011**)** eliminated the health-based guideline value for Mn citing that this value (i.e. 0.4 mg/l) is well above concentrations of Mn normally found in drinking water. Obviously this logic is not valid for Bangladesh, since well water Mn concentration in many regions of Bangladesh exceeds 0.4 mg/l by a large margin.

Unlike As, which has a distinct regional distribution pattern with highest contamination in the south, south-west, and north-eastern regions of Bangladesh, high concentrations of Mn can be found in most areas, but relatively high concentrations are seen in the current Brahmaputra and Ganges flood plains. The distribution generally does not correspond to that of As (BGS and Water Aid 2001), and elevated Mn is found in both shallow and deep aquifers. In a recent study, groundwater from a deeper aquifer (190-240m) in Munshiganj district has been found to contain low concentrations of As (< 10 mg/l), but very high (2 to 5 mg/l) concentrations of Mn (Hug et al. 2011).This means that groundwater with acceptable concentration of As may not have acceptable concentration of Mn. The Fe problem has long been recognized in Bangladesh, and a number of technologies were developed for Fe removal at municipal, community and household levels in the 1980s (Ahmed 1981; Ahmed and Smith 1987). Community-level Fe removal units, mostly attached to hand tubewells, were first installed in Bangladesh in the early 1980s. However, these community-level iron removal plants (IRPs) did not enjoy wide public acceptance and were mostly abandoned shortly after commissioning, primarily because of certain design problems (e.g. the perforated channel used for aeration too short and narrow, inadequate detention time in the sedimentation basin) and difficulties in operation and maintenance (e.g. breakage and non-availability of spare parts, lack of motivation for cleaning of the units).

During 1983-85, a total of 250 IRPs were constructed throughout Bangladesh, but the plants faced an unacceptable level of failure due to construction problems, inappropriate technology in certain aspects, poor maintenance, lack of continued support and advice to solve technical problems, and lack of beneficiary participation (DPHE and UNICEF 1990). A total of 50

IRPs were constructed in the western region of the country under a crash program in 1985-86, but these units were eventually abandoned, primarily due to operation and maintenance problems (Azim 1991). With the discovery of widespread As contamination of groundwater in the 1990s, community- and household-level groundwater treatment units generated renewed attention (Ahmed 2003). When water is treated for Fe removal following conventional methods (involving oxidation of dissolved ferrous iron into ferric iron and its subsequent precipitation as ferric hydroxides), some of the As, if present in water, will also be removed as a result of adsorption onto ferric hydroxide flocs and co-precipitation. Since many As-affected areas also suffer from high Fe concentration, many NGOs are now installing different types of such IRPs for arsenic mitigation purposes.

The Mn issue however has attracted relatively less attention, partly because ground waters high in Mn are often found to be high in Fe as well, and both result in a similar metallic taste. There is widespread awareness about iron in groundwater but relatively little regarding presence of Mn. Manganese can be removed using the same processes of oxidation, precipitation and filtration as in Fe removal, but at circum neutral pH, oxygenation of Mn(II) is much slower than that of Fe(II). Conventionally, a strong oxidant such as chlorine or potassium permanganate is used for oxidation of Mn(II) rather than oxygen alone (Hartmann, 2002). Mn(II) oxidation can lead to precipitation of Mn(III,IV) oxides, which are good adsorbants and oxidants (Hem, 1978). Microorganisms can catalyze oxidation of both Fe(II) and Mn(II) (Mouchet 1992; Vandenabeele et al. 1992; Tyrrel and Howsam 1997; Tyrrel et al. 1998; Tekerlekopoulou and Vayenas 2007), though the relative contribution of chemical and biological mechanisms to Mn removal remains unclear (Olańczuk-Neyman and Bray 2000).

One major concern with IRPs is the risk of contamination of treated water with fecal coliforms, which pose a new health risk to the consumers. However, data on bacteriological quality of water treated in community-based IRPs are limited. There is also little information available about the removal of As in these plants, and less still about Mn. The current study was designed to fill these knowledge gaps by investigating chemical and microbiological water quality in a number of community groundwater treatment plants being used in rural areas of Bangladesh.

2. Methodology

2.1 Design details of community IRPs/AIRPs

The performance of four different sand filter designs was assessed in this study. The community groundwater treatment plants based on these designs are supported by different non-governmental organizations (NGOs). All four designs are similar in principle and involve aeration followed by filtration. Table 1 shows the important features of each type of plant.

Table 1
Important features of community iron and arsenic-iron removal plants

Design Type	Installation cost (US$)	Population served (No.)	Approximate per capita cost (US$)	Filter bed depth (cm)	Filter x-sectional area (cm^2)	Flow rate of water (l/min)	Cleaning frequency (months)
Design-I	135	100-150	\$0.90-\$1.35	76 x 2	3,350 x 2	1-1.25	0.5
Design-IIA	25	18-30	\$0.83-\$1.38	65	4,536	1.5	2-3
Design-IIB	25	20-30	\$0.83-\$1.25	23-43	4,536	1.0	2-3
Design-III	80	100-120	\$0.67-\$0.80	31	2,806	--	2-3
Design-IV	200	40-50	\$4.00-\$5.00	53	8,495	--	3

For each selected design, multiple units (Table 2) currently in operation were assessed; a total of fifteen different IRPs were visited. The following section provides brief description of the plants assessed. Additional details of each plant assessed are reported in (Hoque 2006) and (BUET 2005).

Design-I

The tubewell-attached treatment units based on Design I consist of an aeration chamber, one up-flow filter unit consisting of brick chips and local sand, and one down-flow sand filter; all chambers are made of brick and mortar. From tubewell, water is pumped into the aeration chamber. From the bottom of the aeration chamber, water enters the up-flow filter bed (filter unit 1) consisting of brick chips and sand. From this filter water enters a down-flow sand filter (filter unit 2). Each filter bed, about 67cm x 50 cm in cross-section, is about 76 cm deep. Treated water is collected from a tap located at the bottom of this sand filter unit.

Each Design-I unit generally serves about 15 to 20 families, with a total population of approximately 100 to 150. Cleaning is required approximately every 15 days: the chamber is drained; filtration media is completely removed and placed on polythene sheets. The media is then washed manually in a water bucket before being replaced in the filtration chamber. The cleaning process is quite rigorous and takes half a day if 2 to 3 persons are engaged for this process.

Design-IIA and Design-IIB

A local NGO working in Manikganj (near Dhaka) developed two types of treatment units of similar design (consisting one cylindrical filter chamber), one working in up-flow mode (Design-IIA) and the other in down-flow mode (Design-IIB). The filter bed in both types of units consists of brick chips (≤ 2 cm), charcoal and Sylhet sand (a type of coarse local sand with fineness modulus > 2, available in the northeastern region of the country), contained in a cylindrical reinforced cement concrete (RCC) chamber. The filter bed rests on a filter plate fitted with a plastic net. In Design-IIA, the cylindrical chamber is around 102 cm in height and around 76 cm in diameter; the depth of the filter bed is about 65 cm. Water from a hand tubewells pumped into a PVC pipe and water drips into the filter bed (thereby facilitating aeration) through perforations in the pipe, and finally treated water is collected in the chamber located below the filter chamber. Water is collected by users from this chamber through taps.

In Design-IIB, water coming from a tubewell enters the cylindrical chamber at its bottom through a water-tight PVC pipe. Water passes through the filter media consisting of brick chips, charcoal and *Sylhet* sand, placed sequentially. The chamber is around 70 cm in height and 76 cm in diameter. The depths of the filter beds in the two units tested were 23 cm (IIB-1 in Table 2) and 43 cm (IIB-2 in Table 2). Treated water is collected by the users through a tap attached at the top chamber. It is important to note that unlike in Design-IIA, there is no provision for aeration in Design-IIB unit. Maintenance operations of the Design-II units are similar to those of the Design-I units. The units are cleaned once every 2-3 months.

Design-III

The Design-III units are primarily designed for removal of excess Fe from dug well water. Water from dug well is pumped by a hand-tubewell into a down-flow filter chamber (about 46 cm x 61 cm in cross-section) consisting of a layer of local sand on top, underlain by a layer of *Sylhet* sand and a layer of brick chips at the bottom. After passing through the filter bed, water is stored in the reservoir located at the bottom, from which water is collected by a tap. It should be noted that in the filter bed, water first passes through a finer media (sand), followed by a coarser media (brick chips); this is contrary to the conventional wisdom and is likely to result in quicker clogging of the sand bed with precipitated iron flocs. Each Design-III dug-well-IRP serves about 20-25 families covering about 100-120 people. Bleaching powder (approximately 100 gm) is added to the filter unit of the IRPs once every 2 to 3 months for disinfection. Bleaching powder (approximately 250 gm) is also added to the dug well itself once a year. After addition of bleaching power, water is passed through the IRP until the treated water does not smell of chlorine any more.

Design IV

The Design-IV treatment units are being used in many As affected areas of Bangladesh for removal of both Fe and As. The units consist of three chambers made of RCC, namely an aeration chamber, a filter chamber, and a storage chamber. The aeration chamber is about 104 cm in diameter and 122 cm in height. At the top of the chamber, there is a perforated channel through which water drips into the chamber. The filter chamber is about 104 cm diameter and 91 cm in height. The filter media, about 53 cm in height, consists of different sizes brick chips, charcoal and *Sylhet* sand. The unit is cleaned every 2-3 months, following the procedure described above for the Design I unit.

2.2 Assessment of performance

Performance of each treatment plant was assessed in terms of its effectiveness in removing dissolved Fe, As and Mn from raw water. A rapid assessment was made by measuring concentrations of these constituents in the raw and treated water at each plant. In addition, fecal coliform concentration of raw and treated water samples was also assessed at each plant. At each community treatment plant site, a sanitary inspection was carried out by filling out a "sanitary inspection form", in order to assess overall sanitary condition in and around the treatment unit and its possible impact of the water quality (e.g. possible bacterial contamination from a pit latrine).

During field visits to the treatment plants, caretakers were surveyed to find out schedules of operation and maintenance and the most recent date of maintenance. However, in all cases there were no written records; caretakers quoted maintenance date from memory and in many cases they were not sure themselves. As a result, these data were considered unreliable and the effect of operation and maintenance practices on filter performance could not be assessed in this study. No major qualitative differences in operation and maintenance between the different filter designs were noted. Two Design-I plants were assessed twice.

The pH, temperature, conductivity, turbidity and Mn concentrations of the water samples were measured in the field. Manganese concentration was determined by the PAN method using a Spectrophotometer (Hach DR/2000). The pH was measured with a pH meter (Geotech) attached with a pH electrode (WTW, SenTix41), conductivity was measured by a conductivity meter (Hach), and turbidity by a turbidimeter (Hach 2100P).

Raw and treated water samples were collected in two pre-washed 500 ml polyethylene bottles; one bottle was preserved with 1 ml concentrated hydrochloric acid, and was later used for analysis of dissolved As and Fe in the laboratory. Arsenic concentrations were determined with an AAS (Shimadzu Japan AA6800) attached with a graphite furnace. Iron concentrations were determined with flame emission atomic absorption spectrophotometry, using an AAS (Shimadzu Japan AA6800). Detection limits of As and Fe were 1 μg/L and 0.02 mg/L, respectively. Alkalinity and hardness of the collected samples (non-acidified) were measured in the laboratory following Standard Methods. These laboratory tests were completed within

24 hours of sample collection. Samples for analysis of fecal coliform (FC) were collected in special sample bags (Nasco-Whirl) and immediately put in ice box for transportation to the laboratory. Tests for FC were made using the membrane filtration technique and in all cases commenced within 8 hours (maximum) of sample collection.

3. Results and discussion

Figure 1, 2 and 3 shows Fe, Mn, As concentrations of raw and treated water from the treatment plants assessed in this study. Table 2 shows the raw and filtered water quality data. It shows median reduction of Fe was nearly 2-log (99%), while Mn and As were reduced by about 1-log (91%) and 0.5-log (72%), respectively. In all but a few cases the Bangladesh drinking water standards for Fe and As were met by the plants, but some plants exceeded both the Bangladesh standard and the WHO Guideline value for Mn. The two Design-I filters which were visited twice, showed similar performance at both times.

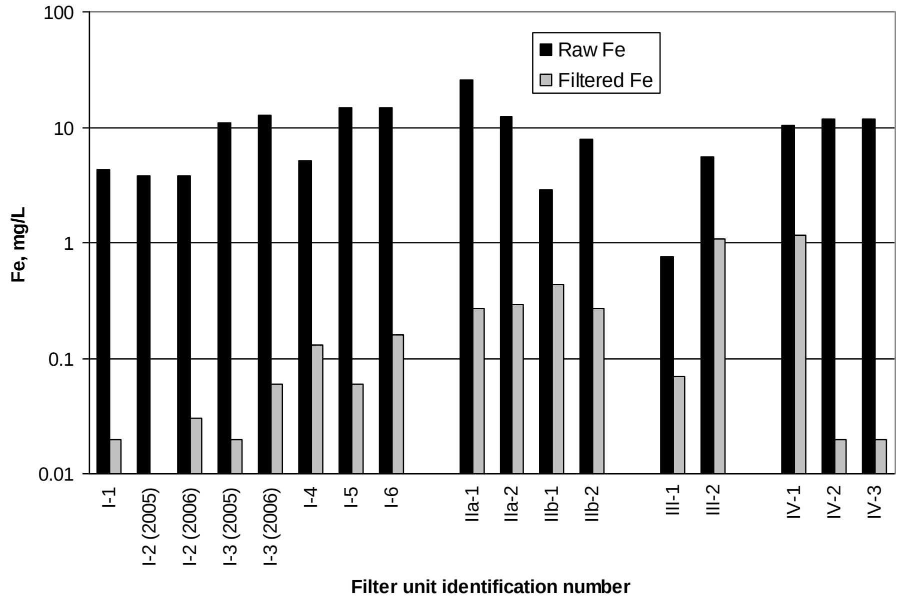

Fig. 1. Iron concentrations of raw and treated water in different filter designs

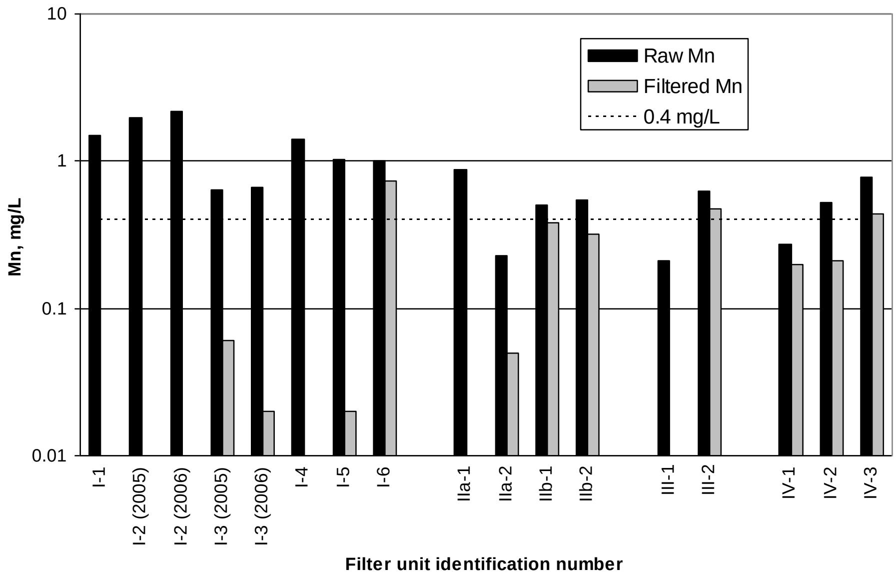

Fig. 2. Manganese concentrations of raw and treated water in different filter designs

The Design I treatment plants showed the best Fe removal, followed by the Design IV plants. Design-I plants have a two-bed design, with a relatively large cross-sectional area and provision for aeration. Design-IIA plants were superior to the Design-IIB plants in terms of iron removal, and the Design-III plants the least efficient. Fe removal capability was found to be relatively insensitive to raw water characteristics, and probably reflects design parameters such as cross-sectional area and provision for aeration. A similar relative ranking holds for Mn removal, with the Design-I plants giving the best results (except for one unit). Design-IIA plants gave nearly 90% Mn removal, but the Design-IIB and Design-IV plants showed little ability to remove Mn.

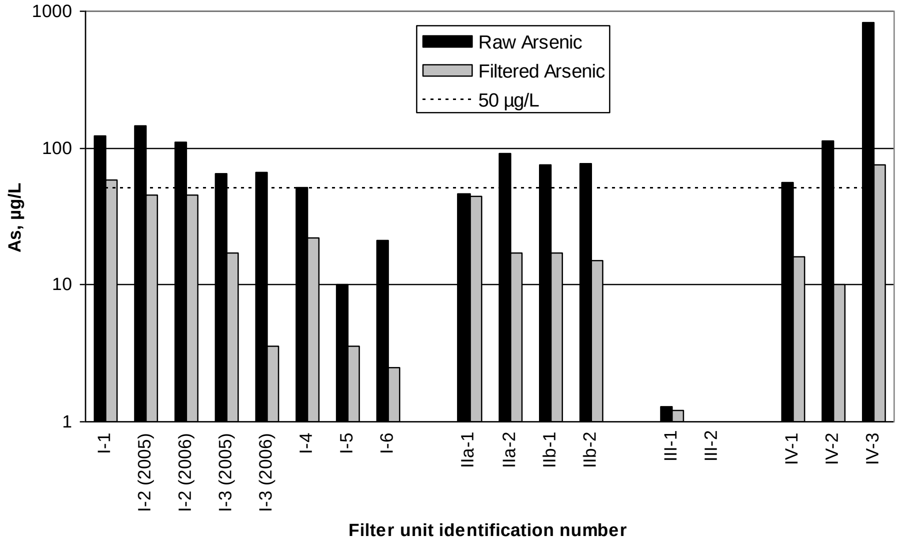

Fig. 3. Arsenic concentrations of raw and treated water in different filter designs

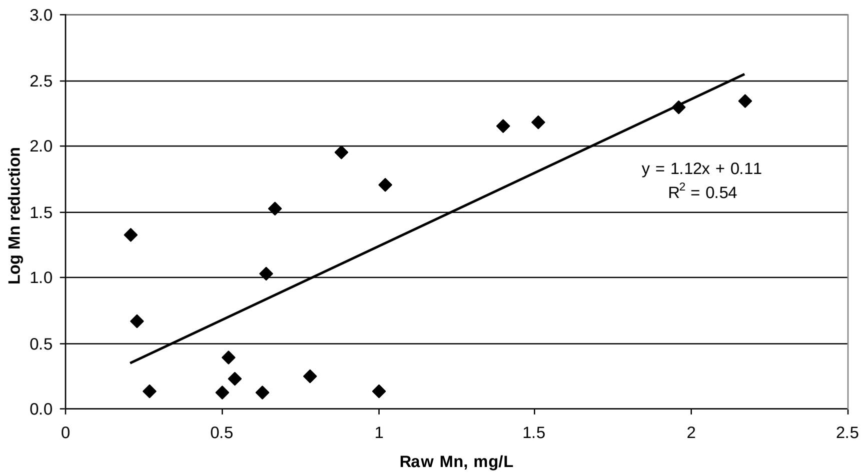

Fig. 4. Relationship between Mn concentration in raw water and Mn removal efficiency

Comparison of different filter designs provides some insight into the Mn removal mechanism in these plants. While Design-IIA and IIB are similar in many ways, the much lower Mn removal in the up flow Design-IIB plants may be attributed to lack of aeration and lower filter media depths. The filters showing best Mn removal (Design-I) have large aeration chambers, larger cross-sectional area, and deeper bed depths (Table 1). While there was no significant relationship between raw Fe levels and Mn reduction, or between Fe removal and Mn removal, filters having high levels of Mn in raw water showed higher reductions in Mn (Figure 4).This could be explained by the progressive development of Mn(IV) oxide coatings on filter media resulting from Mn(II) oxidation and precipitation. These Mn(IV) oxides can themselves oxidize additional Mn(II), creating an autocatalytic cycle (Hem, 1979). It was noted that in some of the Design-I filters which were most effective in removing Mn, filter grains were darkened, most likely due to deposition of Mn oxide coatings. Plant caretakers were unaware that these coatings might present an autocatalytic benefit, and proposed to replace the filter media with fresh media. The beneficial effect of these coatings should be made part of standard caretaker training where Mn levels are high.

Arsenic removal was best in the Design-IV filters, in spite of the fact that one of these plants had by far the highest influent As level at 872 ppb. However, as removal follows no clear pattern by design; rather, the influent Fe concentration seems to be the key factor. As raw iron levels increase, arsenic removal increases (Table 2).

Table 2
Chemical and microbiological quality of raw and treated water samples collected from community groundwater treatment plants

Sl. No.	Treatment Plant	Iron (mg/L)		Manganese (mg/L)		Arsenic (mg/L)		Fecal Coliform (#/100mL)	
		Raw	Treated	Raw	Treated	Raw	Treated	Raw	Treated
1	Design I-1	4.32	< 0.02	1.51	< 0.01	123	59	--	--
2	Design I-2	11.00	< 0.02	0.64	0.06	65	17	Nil	6
3	Design I-2	12.80	0.06	0.67	0.02	66	4	Nil	80
4	Design I-3	3.77	< 0.02	1.96	< 0.01	144	45	Nil	80
5	Design I-3	3.77	0.03	2.17	< 0.01	110	45	Nil	80
6	Design I-4	14.60	0.06	1.02	0.02	10	4	Nil	20
7	Design I-5	14.70	0.16	1.00	0.73	21	3	Nil	76
8	Design I-6	5.18	0.13	1.40	< 0.01	51	22	Nil	80
	Design-I Average	8.77	0.06	1.30	0.11	74	25	Nil	60
9	Design IIA-1	12.50	0.29	0.23	0.05	92	17	Nil	55
10	Design IIA-2	25.60	0.27	0.88	< 0.01	46	44	66	20
	Design-IIA Average	19.05	0.28	0.56	0.03	69	31	33	38
11	Design IIB-1	2.85	0.44	0.50	0.38	75	17	Nil	148
12	Design IIB-2	7.78	0.27	0.54	0.32	77	15	60	22
	Design II-B Average	5.32	0.36	0.52	0.35	76	16	30	85
13	Design III-1	0.75	0.07	0.21	0.01	1.3	1.2	200	68
14	Design III-2	5.49	1.09	0.63	0.47	< 1.0	< 1.0	100	TNTC
	Design III Average	3.12	0.58	0.42	0.24	1	1	150	> 68
15	Design IV-1	10.40	1.16	0.27	0.20	56	16	8	13
16	Design IV-2	11.70	< 0.02	0.52	0.21	113	10	Nil	4
17	Design IV-3	11.70	< 0.02	0.78	0.44	824	75	Nil	23
Design IV Average		11.27	0.40	0.52	0.28	331	34	3	13
Total Average (n=17)		9.35	0.24	0.88	0.17	110	23	27	52
Total Median(n=17)		9.87	0.10	0.73	0.06	71	17	Nil	53

In the filters assessed in this study, As removal was most likely achieved by adsorption onto iron oxy-hydroxide solids formed from dissolved iron during aeration, co-precipitation (and subsequent retention of iron solids by filter media), and direct adsorption onto the filter media. Given the median arsenic reduction of 72%, filters could effectively treat raw water containing up to approximately 200μg/l and still meet the Bangladesh drinking water standard. However, the influent iron concentration also plays a critical factor. Only two filters in this study produced filtered water containing more than 50 μg/l As. One of these (#17 Table 2) had very high raw water As and in spite of more than 1-log reduction still exceeded the Bangladesh limit. The reason for poor arsenic removal in the other plant (#1 Table 2) is not clear.

Other raw water quality parameters measured in this study (pH, turbidity, electrical conductivity, alkalinity and hardness; reported in Table 3) were not found to have any influence on the performance of the filter units in removing Fe, As and Mn (Hoque 2006). Table 3 shows that in general the treatment processes in the filter units result in slight increase in pH (average about 0.40 unit), significant reduction in turbidity, slight reduction in conductivity, alkalinity and hardness (with few exceptions in case of hardness). Design-I units appear to be the most efficient in reducing turbidity from raw water.

Table 3
Concentrations of selected water quality parameters in raw and treated water samples collected from community groundwater treatment plants

Sl. No.	Treatment Plant	pH		Turbidity (NTU)		Conductivity (□ S/cm)		Alkalinity (mg/L as $CaCO_3$)		Hardness (mg/L as $CaCO_3$)	
		Raw	Treated	Raw	Treated	Raw	Treated	Raw	Treated	Raw	Treated
1	Design I-1	--	--	--	--	--	--	--	--	--	--
2	Design I-2	6.75	7.02	9.71	0.63	1069	1051	491	482	350	330
3	Design I-2	7.12	7.43	2.81	0.43	948	914	504	468	366	370
4	Design I-3	6.87	7.21	2.81	0.43	948	914	407	402	574	382
5	Design I-3	6.87	7.21	2.81	0.43	--	--	396	402	374	418
6	Design I-4	6.88	7.76	95.1	0.32	--	--	342	318	310	258
7	Design I-5	6.71	7.26	116	0.31	--	--	402	360	322	264
8	Design I-6	6.92	7.25	36.9	0.27	--	--	402	380	362	332
9	Design IIA-1	6.85	7.25	17.0	2.61	920	885	465	421	364	352
10	Design IIA-2	7.03	7.77	132	1.34	--	--	396	290	276	238
11	Design IIB-1	6.90	6.91	69.4	2.5	--	--	384	312	328	252
12	Design IIB-2	7.05	7.18	74.3	3.36	--	--	358	312	310	260
13	Design III-1	7.12	7.65	3.16	2.86	2050	1954	580	550	--	--
14	Design III-2	7.05	7.19	25.8	13.0	5730	5430	800	760	--	--
15	Design IV-1	6.84	7.26	32.8	12.5	1026	1005	510	450	349	387
16	Design IV-2	7.08	6.89	7.99	0.15	885	744	398	382	393	357
17	Design IV-3	6.89	7.18	0.90	0.31	681	638	372	343	409	346

Table 2 shows that in most cases fecal coliform counts were higher in filtered water than in raw water, with an average of 52 cfu/100 mL in treated water. Bacteriological contamination most likely is caused by contamination of filter media by caretakers during routine operation and maintenance, and by the generally poor hygiene practices typical of rural Bangladesh. However, sanitary inspection scores showed no significant correlation with bacteriological quality of treated water. None of the plants assessed in this study use any disinfection of the treated water. In the Design-III IRPs linked with dug wells, disinfection is carried out by adding bleaching powder to the filter bed and the dug well itself at specific time intervals; but this process does not appear to be very effective and coliform counts in both the raw and treated water were relatively high.

4. Conclusion

The community filters assessed in this study are based on more or less the same principle, involving some form of aeration, followed by filtration through a media consisting of locally available materials (sand, brick chips and charcoal). Almost all the units appear to be very effective in removing iron from groundwater. However, the As and Mn removal efficiencies of the units vary significantly, depending on the design of the unit and the raw water quality. The data from this study did not allow a detailed evaluation of factors affecting As removal; however, Fe has been found to promote As removal through adsorption onto Fe(III) solids that form on oxidation of Fe(II) and co-precipitation, which is consistent with the observation in this study of better As removal in filters having higher Fe levels in raw water. Mn removal appeared to be a function of raw Mn levels, as well as design factors such as aeration, cross-sectional area and bed depth. Although operation and maintenance is likely to have a significant influence on filter performance, because of lack of reliable information on operation and maintenance practices, this issue could not be addressed in this study. The near-universal contamination of filtered water with fecal coliforms is of concern. In addition to promoting improved O&M of filter units and proper hygiene practices, effective design (e.g. use of bio-sand filtration) and disinfection processes should be developed to make the treated water bacteriologically safe. It should be pointed out that disinfection processes (e.g. addition of bleaching powder) should be carried out post-filtration (e.g. in a storage chamber or at the household) since disinfection before filtration may destroy microbial populations that probably play a key role (e.g. in mediating the redox reactions) in iron and manganese removal.

Presently, no specific design criteria (e.g. detention time, face velocity, surface over-flow rate, media size range and grading) are followed for IRP design. Variation in raw water quality is also not taken into consideration in the designs. These result in non-uniform and often poor performance of the removal units. More studies should be carried out to better understand the removal mechanisms, including possible mechanisms of Mn oxidation within filter beds, in community groundwater treatment plants and for development of design criteria for better treatment units for simultaneous removal of Fe, As, and Mn. The costs of the different designs reviewed in this study are broadly similar, at approximately US$1 per person served, except for Design-IV which is relatively costly (possibly because of the use of three RCC chambers). Given the superior performance of the Design-I for removal of Fe, Mn, and As, this design could be taken as a starting point for further refinement. Revisions in design should strive not only for improved technical efficacy but also to ensure that units can be easily operated and maintained by users, especially the women who are responsible for household water management in Bangladesh.

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