Development of An Activated Alumina Based Household Arsenic Removal Unit

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Abstract

The people of Bangladesh have been facing arsenic contamination of drinking water supplied by hand pump tubewells. At present, the most feasible short-term solution of this problem appears to be treatment of tubewell waters through suitable and low cost technologies. The groundwaters of Bangladesh contain both As(III) and As(V) and in addition high concentration of iron is also present in most of the groundwaters. Activated alumina adsorption process is very efficient in removing As(V) from water; while As(III) is poorly removed. The naturally occurring iron degrades the performance of an alumina bed by fouling and clogging the bed. However, the iron can be beneficially used to remove part of the arsenic in the water through co-precipitation and adsorption. A system has been developed to improve the performance of alumina columns through efficient pretreatment of natural groundwater. The pretreatment steps include oxidation of As(III) and removal of iron. Through the pretreatment steps the problems of iron have been eliminated; while its beneficial use has been ensured. The developed system is suitable for any adsorbent or ion exchange resin. A detail assessment of the performance of the technology at household level has been carried out recently. The findings reveal that the arsenic removal efficiency of the technology is excellent. It removes iron very efficiently and an appreciable amount of manganese is also removed. The removal/addition of other water quality parameters is insignificant. However, unhygienic practices of the users may result in bacterial contamination of the treated water. The problems identified regarding users' acceptability of the technology can be minimized significantly with minor modification of the present design.

INTRODUCTION

A wide spread contamination of shallow groundwaters of Bangladesh has been reported and over 25% of the hand pump tubewells is producing arsenic contaminated water (DPHE/DFID/BGS, 2000). This is a serious public health concern as hand pump tubewell water is the major source of drinking water for almost all of her population. Thousands of people are reported to have already been suffered from arsenicosis by drinking arsenic contaminated water and millions are at risk of arsenic toxicity due to exposure to arsenic contaminated tubewell water (EES/DCH, 2000; Rahman et al., 2000; DPHE/DFID/BGS, 2000). The most important measure needed to combat the arsenic problem is to provide arsenic safe drinking water to the exposed people. Unless suitable alternative drinking water sources are made available, arsenic removal from the shallow tubewell water through simple and low cost technologies appears to be an immediate and short term solution of this problem. In this perspective, a household arsenic removal unit (ARU) based on activated alumina has been developed. A household system has been preferred over a community system because of the fact that the community-managed systems have not yet been proved successful in Bangladesh. This paper presents the development steps and an evaluation of the performance of the arsenic removal unit.

DEVELOPMENT CONSIDERATIONS

Apart from arsenic, the majority of groundwaters of Bangladesh show the presence of high iron and manganese concentrations (DPHE/DFID/BGS, 2000). It has been found that handpump tubewell water in 65% of the area in Bangladesh contains iron in excess of 2 mg/L and in many acute iron problems areas, the concentration of dissolved iron is higher than 10 mg/L. Many groundwaters also show high phosphorous concentration. However, nitrate and sulfate concentrations are normally low. In groundwaters, arsenic occurs both in reduced [As(III)] and oxidized [As(V)] forms and the ratio of As(III) to As(V) varies significantly ranging from less than 0.1 to greater than 0.9.

Activated alumina adsorption is an efficient process for removing As(V) from water, but the removal capacity is very low for As(III). A laboratory study was carried out at BUET on the effectiveness of activated alumina in removing arsenic from both synthetic and natural groundwaters under a number of experimental conditions (Ahmed and Jalil, 1999). The study revealed that As(V) is much more effectively removed than As(III) and the smaller alumina particles are more effective than the coarser particles. Presence of chloride in water has no effect on the removal efficiency while sulfate and phosphate have significant effect only at very high concentrations. However, the presence of iron in water has a very significant effect on the performance of alumina columns. Due to exposure of groundwater to air, the supersaturated free carbon dioxide is removed from the water and oxygen content of the water increases. As a result the pH value of water is raised and the dissolved iron [Fe(II)] is oxidized to [Fe(III)] producing insoluble iron precipitates [$Fe(OH)_3$] through hydrolysis. The water becomes turbid due to the presence of the iron precipitates/flocs. When this water is passed through an alumina column, the iron precipitates foul the bed by attaching to the surfaces of alumina particles and clogging the pores of the column - leading to a progressive deterioration of the column performance. As water flows, the active sites of alumina becomes occupied increasingly by iron precipitates. The precipitates block the adsorption of arsenic species resulting in reduction of the arsenic removal efficiency of the column. At the same time, the flow rate through the bed is progressively reduced due to clogging of the pores by iron flocs and the column may become non operable within a short time depending on the size and amount of iron flocs in the flowing water. However, during iron precipitation, arsenic is co-precipitated and adsorbed. Moreover, iron flocs accumulated in an alumina column provide an adsorption mass for arsenic in the flowing water (Ahmed and Jalil, 1999). The disadvantages of presence of naturally occurring iron can be eliminated and its beneficial use in removing a part of the arsenic can be derived if iron is removed from groundwater prior to passing through an alumina column. Hence in developing an efficient arsenic removal unit based on activated alumina, the following pre-treatments must be considered : (i) oxidation of As(III) to As(V), and (ii) removal of iron.

Oxidation of As(III) to As(V)

At household level, oxidation of As(III) can be achieved by both bleaching powder and potassium permanganate. Bleaching powder usually causes an unpleasant taste in the treated water and there is also the risk of formation of trihalomethanes. Moreover, it is a very unstable chemical and the quality of bleaching powder available in the open market of Bangladesh varies widely, it is very difficult to ensure the proper dosing of bleaching powder. On the other hand, potassium permanganate is a stable chemical and easily available locally. However, it produces a color in the treated water making it less attractive for drinking. If the problem of color can be solved, potassium permanganate is preferable as an oxidizing agent. Therefore in developing the ARU, potassium permanganate has been chosen as the oxidant and a sand filter has been developed to remove the residual color. Tests were conducted to determine the optimum dose of potassium permanganate for oxidation of arsenic. It was found that a permanganate dose of around 1.0 mg/L is enough to oxidize as high as 500 ppb As(III) (Ali et al, 2001).

Pretreatment for Iron Removal

Experiments were conducted to remove naturally occurring iron in groundwater by adopting simple aeration followed by flocculation and sedimentation. Macro iron flocs settled easily but micro iron flocs could not be removed from the supernatant water in this way, which subsequently deteriorated the performance of alumina columns (Ahmed and Jalil, 1999). Sand filtration of the supernatant water was perceived as a solution of this problem.

Sand Filter

A sand filter was designed to remove both the color and micro iron flocs (Ali et al., 2001). Initially, a number of filters were prepared with sand passing # 30 sieve and retaining on # 40 sieve and using variable depth of bed ranging from 10 cm to 30 cm. After pre-oxidation and settling of macro flocs in settling tank the supernatant water was allowed to flow through the sand filters. An efficient color and iron removal was achieved with sand bed of minimum 20 cm depth.

DESIGN OF ARSENIC REMOVAL UNIT

In designing the household arsenic removal unit, it was assumed that 40 to 50 liters of water per family per day would be required for drinking and cooking purposes. It was also assumed that the maximum arsenic concentration in the treated water would be within the current Bangladesh Drinking Water Standard of 50 ppb. The unit operations and processes involved in the arsenic removal system are mixing of oxidant and aeration, precipitation, flocculation, co-precipitation and adsorption, sedimentation, screening and filtration and activated alumina adsorption. The ARU consists of three sub-units namely oxidation-sedimentation unit, filtration unit and adsorption unit. A brief description of the units and their operation is given below.

Oxidation–Sedimentation Unit

It consists of a 25L plastic bowl fitted with a plastic tap near the base for controlling the outflow. Raw water is fed into the bowl where a number of operations and processes take place. Potassium permanganate solution is added to arsenic contaminated raw water using a dropper. After the dosing, the water is vigorously agitated with a wooden stick for complete mixing and aeration. As a result, the As(III) present in the water is oxidized to As(V) and the dissolved iron precipitates. The precipitates are then flocculated through slow mixing with the wooden stick. The water is allowed to stand under quiescent condition for about one hour for settling of the iron flocs. Co-precipitation and adsorption of arsenic occur during these operations. The supernatant water is then allowed to flow to the filtration unit through a rubber tube. The bowl has a lid to prevent the contamination of feed water from external sources.

Filtration Unit

The down flow filtration unit consists of a 20 cm deep sand layer in a 22 L plastic bucket. At the bottom part of the sand layer, there is a plastic strainer of 1.5 inches diameter and it is connected to a tap. The sand filter removes the iron flocs coming along with water from the oxidation-sedimentation unit. It also removes the residual color of potassium permanganate. A cloth screen is placed on the sand filter to remove a part of the micro flocs with the purpose of increasing the filter run. Further removal of arsenic was achieved through adsorption on the iron flocs retained on the screen and in the interstices of the sand bed. The filtration unit is covered with a lid so that external contamination can be prevented. The filtrate comes out through the under-drain system and enters into the activated alumina adsorption unit.

Activated Alumina Adsorption Unit

The unit consists of a down flow adsorption column made of 37 mm diameter plastic pipe containing 22 cm deep activated alumina granular particles (mesh size- 28x48). A level indicator is fitted with the adsorption unit with a mark on it and the water level should be kept below the mark to prevent overflow. This can be done easily by controlling the tap of the filtration unit. The water coming from the filtration unit flows through the alumina column and the treated water is collected from an outlet fitted at the bottom of the adsorption unit.

The three sub-units of the arsenic removal system are assembled in a suitable iron frame. It should be noted that although the arsenic removal system has been developed based on activated alumina, the system is applicable for any other suitable adsorptive material or ion exchange resin. Figure 1 shows the details of the arsenic removal unit.

EVALUATION OF PERFORMANCE OF THE ARU

WS/Atkins of United Kingdom carried out an independent, comparative assessment of the performance and acceptability of nine arsenic removal technologies at household level through a two phase project under BAMWSP (Bangladesh Arsenic Mitigation Water Supply Project) (WS/Atkins, 2000; BAMWSP/DFID/WAB, 2001). The arsenic removal unit developed at BUET was included in the project. The major findings related to the BUET ARU is briefly discussed here.

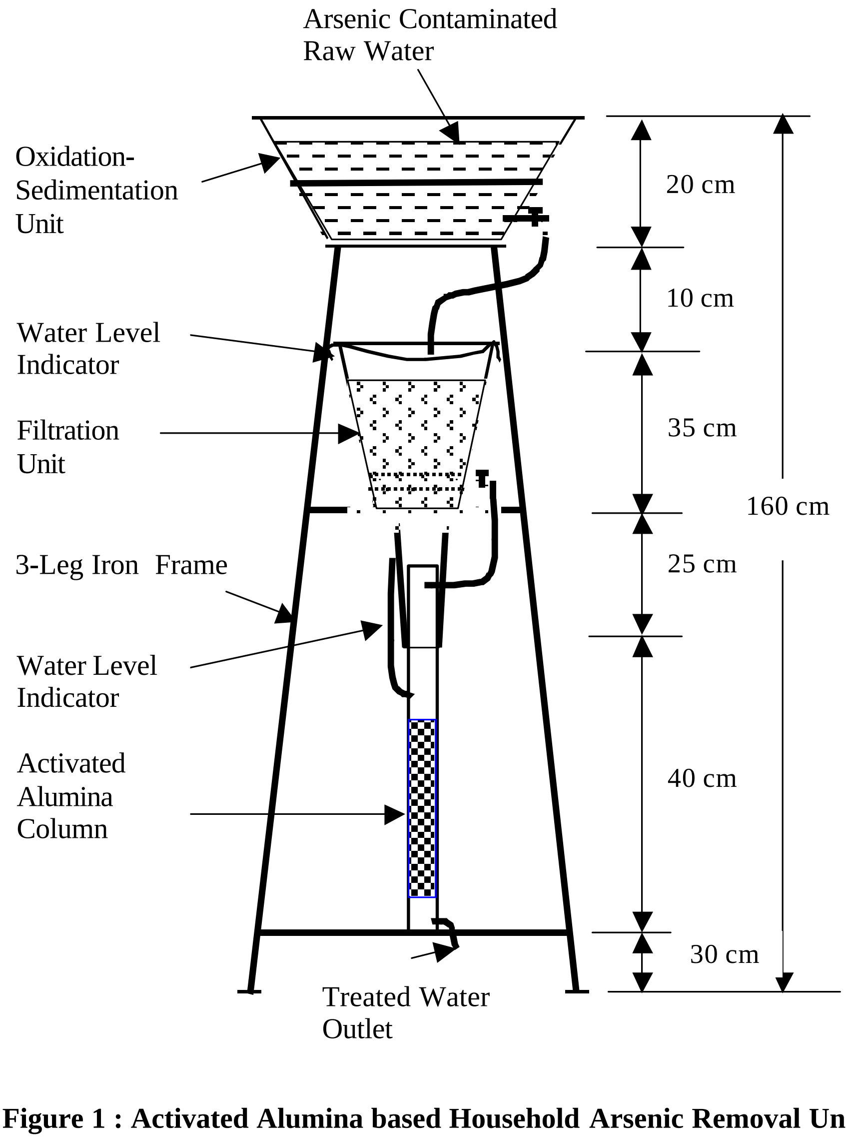

Figure 1 : Activated Alumina based Household Arsenic Removal Unit.

Phase I

The field based performance study of the BUET ARU was carried out in four areas of Bangladesh (Sitakunda of Chittagong, Ishwardi at Pabna, Hajigonj at

Chandpur and Kalaroa at Satkhira). At each area, five tubewells were selected and three replicates of the ARU were run at every well and the units were operated by the project team. Four paired samples (feed and treated waters) for every replicate were tested for a number of water quality parameters. Data from the feedwaters demonstrated broad differences in groundwater chemistry among the four test areas. Performance of the BUET ARU on an area by area basis is illustrated in Figure 2.

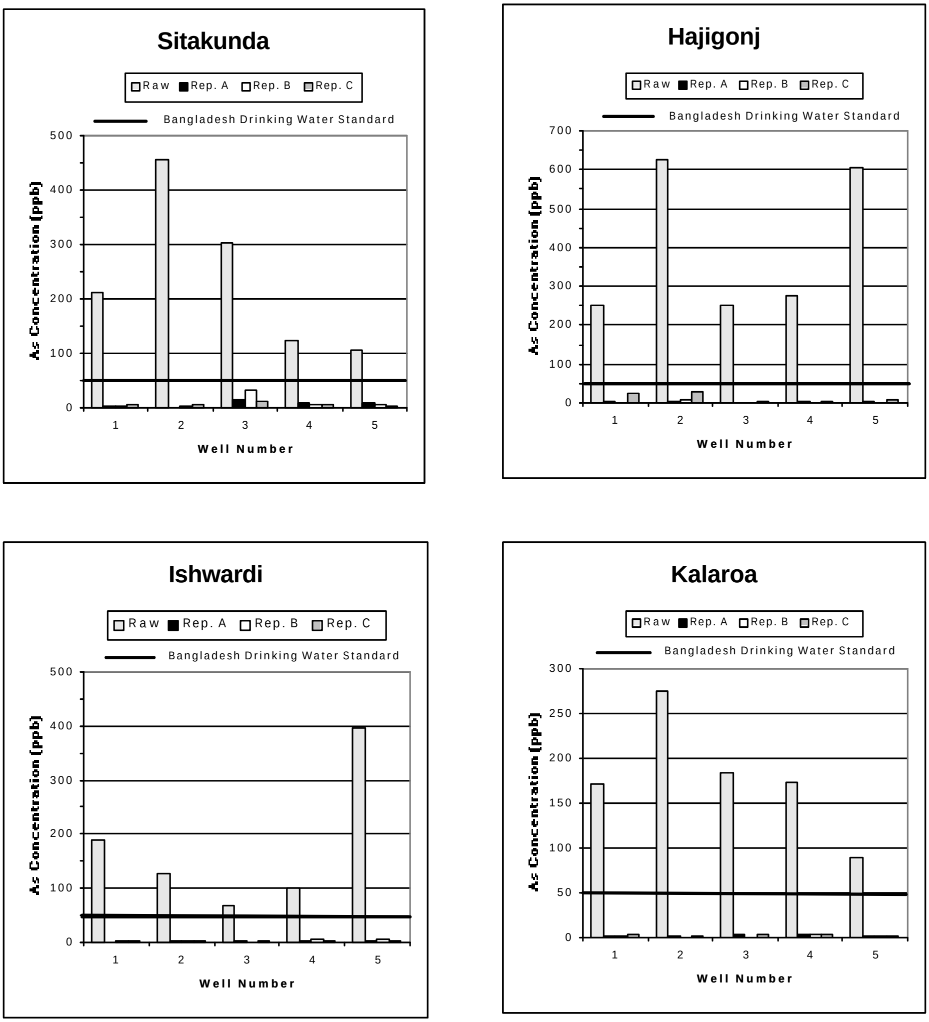

Figure 2: Arsenic Removal by BUET Arsenic Removal Unit from Groundwaters in Four Areas of Bangladesh

Figure 2 shows that BUET ARU removes arsenic very efficiently reducing the concentration much below 50 ppb level although there are much variation on the water chemistry among the four areas. The average of feed mean arsenic concentrations in the four areas were 240 ppb, 402 ppb, 176 ppb and 179 ppb and after treatment the average effluent arsenic concentrations reduced down to 7.5 ppb, 5.5 ppb. 3.1 ppb and 2.2 ppb respectively, indicating excellent arsenic removal efficiency of the technology. However, in a few cases, there were some differences in the arsenic removal performance among the three replicates which may be due to occasional instrumental error in the arsenic measurement.

Phase II

The survey areas for field based performance and acceptability assessment in Phase II were those as in Phase I except Sitakunda. At each area, nine tubewells were selected and three replicates of the BUET technology were supplied. One replicate was run per well and eight paired samples (feed and treated waters) for every unit were tested for a number of water quality parameters. The units were operated by owners of the wells.

Technical Performance

Arsenic Removal

Data from the feed-waters demonstrated broad differences in groundwater chemistry among the three test areas. At Hajigonj, silicon, boron and potassium concentrations were high and alkalinity, calcium, barium and strontium levels were low compared to the other areas. At Ishwardi, phosphorous and iron concentrations were low while, alkalinity, manganese and sulphur were high compared to Hajigonj and Kalaroa waters. Performance of the BUET ARU on an area by area basis is illustrated in Figure 3.

Despite the broad differences in the water chemistry, Fig. 3 shows that the BUET ARU removes arsenic very efficiently reducing the concentration much below 50 ppb. The average arsenic concentration in the feed water for all the areas was 238 ppb while the average treated water arsenic concentration was 5.5 indicating over 97% arsenic removal. However, there were some variations from area to area which may be due to the variation in the iron content of the feed waters. Generally, presence of iron in higher concentrations enhanced the removal of arsenic through co-precipitation and adsorption.

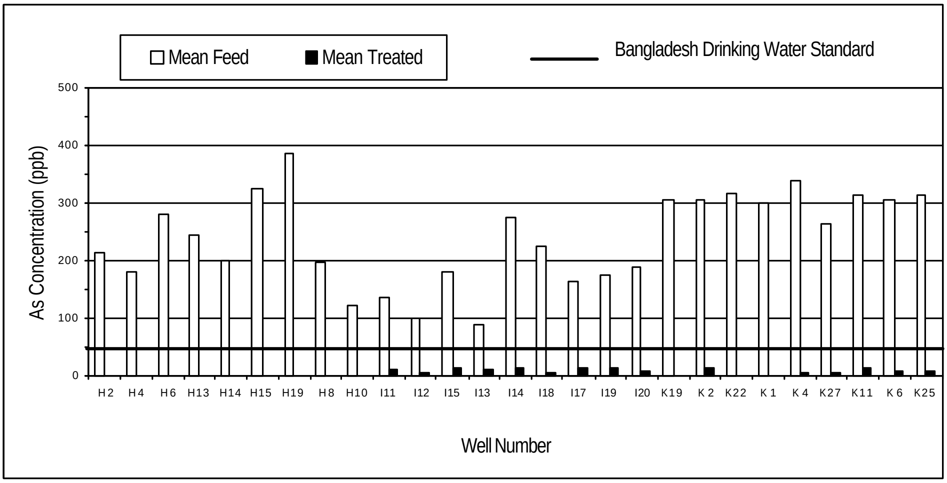

Figure 3: Arsenic Removal by BUET Arsenic Removal Unit from Groundwaters in Three Areas of Bangladesh ('H' stands for Hajigonj, 'I' for Ishwardi, and 'K' for Kalaroa).

Removal/Addition of other Key Parameters

Iron, redox potential, manganese, aluminum, chloride, phosphate, Sulphate, alkalinity, pH, conductivity and some other parameters in the feed waters and treated waters were measured to assess the change in water quality by the BUET ARU. The removal/addition of more important parameters from the view point of drinking water quality is depicted in Figure 4. From the figure it is observed that both total and ferrous iron are removed from the water during the treatment. Manganese is removed but not as efficiently as Fe(II) because oxidation of Mn(II) is a slower process. BUET ARU removes aluminum at Hajigonj and Ishwardi but appears to add it at Kalaroa in some cases. The reason for this is not clear. Phosphate is reduced in small amount while sulphate is added to Kalaroa waters which can not be explained.

Bacteriological Performance

Bacteriological quality of the feed waters and treated waters were determined at all the three areas. Test results revealed that fecal coliforms were rarely detected in most of the feed waters samples. For treated water samples, the fecal coliform counts per 100 mL were low (less than 10) in most cases in Hajigonj and

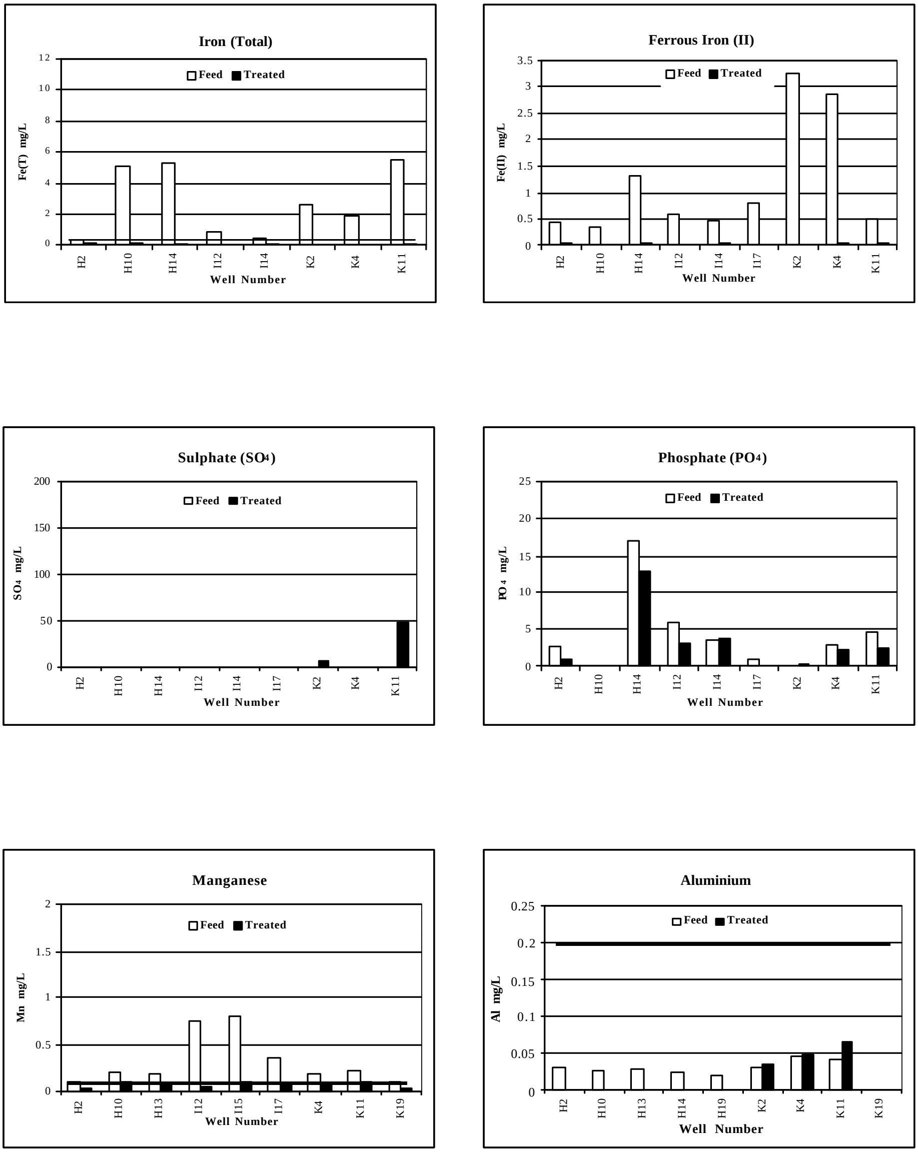

Figure 4: Iron (Fe), Manganese (Mn), Aluminum (Al), Phosphate (PO_4) and Sulphate (SO_4) Concentrations in Feed and Treated Waters.

Ishwardi, and only two cases showed the count around 20. But in Kalaroa, high fecal coliform counts greater than 100 no. per 100 mL) were detected. It was also revealed that once contaminated, the sand filters harboured bacteria and were not readily flushed by further clean batches of water. Surely, the bacterial contamination source was external and unhygienic practices of the users were the most probable reason. Hence personal hygiene of the users should be improved to get rid of the problem. However, as an additional safety measure, weakly bleaching or hot water treatment of the ARU should be practiced.

Comparison with Other Technologies

A comparative study of seven technologies in terms of arsenic removal was carried out at Sonargaon, Narayangonj. The technologies were (i) Alcan enhanced activated alumina (Alcan), (ii) BUET arsenic removal unit (BUET), (iii) DPHE/Danida two bucket system (DPHE/Danida), (iv) GARNET home-made filter (GARNET), (v) Sono 3-kolshi method, (vi) Steven's Institute Technology (Stevens), and (vii) Tetrahedron Ion Exchange Resin Filter (Tetrahedron). Three replicates of each technologies were set up at a well and the volumes of water passing through the technologies were recorded in terms of 20 litre batches. The feed water arsenic concentration was 0.332 mg/L and the water was turbid. The variations in effluent arsenic content and flow rate with cumulative volume of water passed for all the technologies are illustrated in Figure 5. From the Figure it appears that for the particular water at Sonargaon, the Alcan, BUET, Sono and GARNET technologies performed consistently well reducing arsenic concentrations below 50 ppb in the treated water samples. But in terms of low arsenic concentrations in the effluent, BUET ranked 1 followed by Sono, Alcan and GARNET. The GARNET did well in this particular case, the probable reason might be the high iron content of the feed water. DPHE/Danida performance was the worst producing effluent having arsenic concentrations more than 50 ppb for all the treated water samples, the reason for this is not clear. The Stevens performance was not consistent, sometimes the effluent arsenic concentration exceeded 50 ppb level, the quality of chemicals and improper operation might be the reasons for this. The performance of the Tetrahedron was the least consistent, sometimes producing effluent with very low arsenic content and sometimes the effluent concentrations exceeding 50 ppb level. Improper chlorination might be the possible cause.

For each technology, the flow rate is progressively reduced due to accumulation of iron flocs in the system. Upon maintenance following the specified procedure, the flow rate increases significantly. So, the flow rate do vary considerably depending on the frequency of maintenance. The impact and importance of maintenance is illustrated by the increase in flow rates following

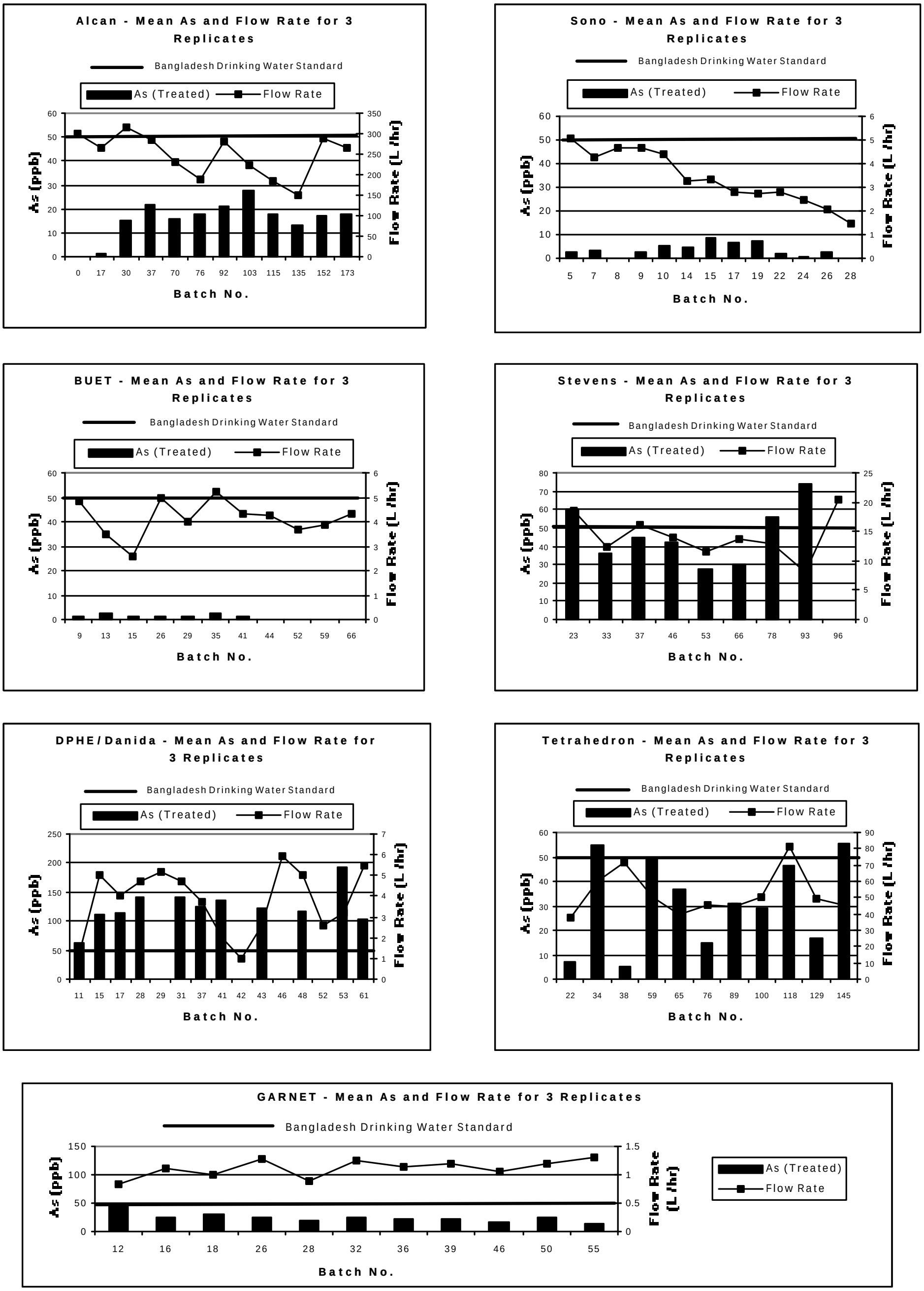

Figure 5: Comparison Among Different Arsenic Removal Technologies Regarding Arsenic Removal and Flow Rate

maintenance (Fig. 5). The Sono developed a 'crust' in top kolshi resulting in a progressively lower output. A comparison of flow rates among the technologies reveals that for the particular water at Sonargaon, Stevens and Tetrahedron would comfortably provide sufficient drinking water for a household. The BUET, DPHE/Danida and Sono are close to provide enough water for a household with one unit, whilst the GARNET would fail to do this.

Social Assessment

Acceptability to users of the BUET ARU was assessed through questionnaire survey in each of the three areas. Fifteen different criteria including flow rate, taste, smell, ease of operation, cost, ease of movement, ease of maintenance, waiting time, physical structure and cleaning frequency were set in the questionnaire. The householders indicated their willingness to pay upto Tk. 1000 for a BUET ARU (the present cost being Tk. 1500 but mass production would lower the unit cost) and to spend Tk. 30-50 a month for operation and maintenance. The majority, however, were willing to pay between Tk. 300 and Tk. 500. Most of them preferred to use an ARU on an individual basis, since collective management would create problems.

A number of practical problems were identified through the questionnaire survey. They were (i) frame is flimsy and liable to fall over, (ii) tubes and column are not well sealed and prone to leakage, (iii) too tall for average villager to reach the top bowl, (iv) pipette and bottle of reagent are hard to dispense accurate dosage without getting reagent on hand, (v) adjusting flow rate to designated mark on the level indicator tube, usually find water flowing from the tube, (vi) connection tubes are hard to wash and easily contaminated, (vi) sand bucket and cloth become dirty, and (vii) waiting time is long. Hence the users' acceptability of the technology was not so good.

From the response of the users, it appears that they were not properly and adequately trained to run the units. It was the main reason for some of the identified problems. Some other problems can be eliminated by taking due care during fabrication of the unit. From the users' point of view, the significant limitations seem to be the height, flow control devices and flow rate. Hence, the design of BUET ARU should be modified in terms of height reduction, improvement of the flow control devices and increasing the flow rate. This improvement can be achieved with minor modification of the present design. The redesign is underway to make the unit more user friendly and socially acceptable.

Summary and Conclusions

The development process of a household BUET technology based on activated alumina adsorption process for arsenic removal has been described here. An assessment of the performance of the BUET ARU at household levels has also been discussed. The following conclusions can be made on the BUET ARU:

- Groundwater chemistry has been adequately considered in developing the unit. The beneficial use of naturally occurring iron in groundwater has been ensured in removing arsenic in the technology.

- A few unit operations and processes have been added as pretreatment to increase the capacity of the alumina adsorption unit.

- Arsenic removal efficiency of the technology is excellent irrespective of feed water quality. It removes iron very efficiently and appreciable amount of manganese is also removed. The removal/addition of other water quality parameters is insignificant.

- Lack of personal hygiene of users may result in bacterial contamination of the treated water. Weekly chlorination or hot water treatment of the ARU should be practiced.

- Users' acceptability of the technology was not so good mainly due to height of the unit, difficulty in flow control and inadequate flow rate. These limitations should be corrected to increase its acceptability.

ACKNOWLEDGEMENT

The authors express their gratitude to BAMWSP for including the BUET ARU in the project "Rapid Assessment of Household Level Arsenic Removal Technologies". They also acknowledge the support of UNICEF, Bangladesh and DPHE to carry out the study "The Effectiveness of Activated Alumuna in Removing Arsenic from Groundwater".

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