Water Quality, Mitigation Measures of Arsenic Contamination and Sustainable Rural Water Supply Options in Bangladesh

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Abstract. Arsenic contamination of groundwater has created a serious public health issue in Bangladesh and West Bengal (India), because groundwater is widely used for drinking, household and agricultural purposes. Given the magnitude of the problem of groundwater contamination facing Bangladesh, effective, acceptable and sustainable solutions are urgently required. Different NGOs (Non-government organizations) and research organizations are using their extensive rural networks to raise awareness and conduct pilot projects. The implication of the result from the previous studies is robust, but costly arsenic reduction technologies such as activated alumina technology, and As and Fe removal filters may find little social acceptance, unless heavily subsidized. This review paper analysed the quality of surface water and groundwater, all mitigation measures and the most acceptable options to provide sustainable access to safe-water supply in the rural areas of Bangladesh. Although there are abundant and different sources of surface water, they can not be used for drinking and household purposes due to lack of sanitation, high faecal coliform concentration, turbidity and deterioration of quality of surface water sources. There are a few safe surface water options; and also there are several methods available for removal of arsenic and iron from groundwater in large conventional treatment plants. This review paper presented a short description of the currently available and most sustainable technologies for arsenic and iron removal, and alternative water supply options in the rural areas.

Introduction

Arsenic (As) poisoning of groundwater has caused a serious public health crisis in Bangladesh and West Bengal (India). The old deltaic plain of southwestern Bangladesh, the north and eastern parts of the active deltaic plain of the southern coast, and the Meghna River basin have been severely impacted by arsenic. In contrast, northwestern and southeastern Bangladesh has been less affected by arsenic poisoning. Arsenic contamination is primarily confined to shallow aquifers (10–70 m) below the surface, which are screened in Holocene alluvial and deltaic deposits (Ravenscroft et al., 2005). Aquifers associated with high-As groundwater are typically reducing and composed of gray to black sand (Anawar et al., 2003; McArthur et al., 2004). Sediment concentrations of As are related to grain size, and generally range from about 1 mg/kg in sandy sediments to 20 mg/kg in clay layers (Harvey et al., 2002; Anawar et al., 2003).

Traditionally, rural water supply, to a great extent, was based on protected ponds before and during early stage of installation of tubewell. Sinking of tubewells under community water supply schemes in rural Bangladesh began in 1928. There are about 1,288,222 nos. of ponds in Bangladesh having an area of 0.114 ha per pond and 21.5 ponds per mauza (BBS, 1997). In Bangladesh in the 1970s, to diminish a cholera epidemic, millions of shallow tubewells were installed to tap groundwater, changing the main source of drinking water from surface water to groundwater. With decreased mortality rates resulting from waterborne diseases, the campaign was declared a success until the detection of the first arsenicism cases in the 1990s, which were linked to excessive arsenic in the groundwater (Caldwell et al., 2003). Arsenic contamination in Bangladesh was soon recognized to be a major public health emergency (Atkins et al., 2007).

Given the magnitude of the problem of groundwater contamination facing Bangladesh, effective, acceptable and sustainable solutions are urgently required. Different NGOs (Non-government organizations) are using their extensive rural networks to raise awareness and conduct pilot projects. Private companies are sponsoring research on arsenic removal units and testing their effectiveness. What is the value of arsenic-free drinking water to the rural people of Bangladesh is closely connected with how the rural people look at the arsenic problem. The value of arsenic-free drinking water to rural people is influenced by their risk perceptions, and has important implications for social acceptability of arsenic mitigation technologies being promoted. Evidently, if rural people do not have much concern for arsenic contamination despite its known dangers, and place a low value on arsenic-free drinking water, then the cost of mitigation technologies may turn out to be a major hindrance to
their promotion among the rural households. Ahmad et al. (2005) estimated that the rural people in arsenic-affected areas of Bangladesh place a low value on arsenic-free drinking water. It is about 10–14 percent of the amount they are willing to pay for piped water and only about 0.2–0.3 percent of the average household income. The implication of the result from the previous studies is that robust but costly arsenic reduction technologies such as activated alumina technology may find little social acceptance, unless heavily subsidized. The objective of this review paper is to analyse the quality of surface water and groundwater, all mitigation measures for arsenic and iron removal, and the most acceptable options to increase sustainable access to safe-water supply in the rural areas of Bangladesh.

I: Sources of water. The sources of water in Bangladesh are surface water, rainwater and groundwater. The availability of water in terms of quantity and quality, present situation and problems associated with the sources have been discussed in the following sub-sections.

a) Surface water. Surface water is abundant in the wet season in Bangladesh. An estimated 795,000 million cubic meter (Mm³) of surface water is discharged through the Ganges-Brahmaputra system, in the downstream of the confluence of the Ganges and the Brahmaputra. This is equivalent to 5.52 m deep water over a land area of 144,000 km². In the dry season, water scarcity persists in many areas and surface water irrigation systems in the country compete for this available water in the dry season resulting in decrease of the perennial water bodies.

Surface waters receive pollutants from agricultural, industrial, domestic and municipal sources, human and livestock fecal pollution (Knapp et al., 2011). Concentration of silt content in turbulent water in the monsoon is high. Similarly algal growth in stagnant water bodies in the dry season is also very high. Insanitary practices of people have greatly contributed to the deterioration of quality of surface water sources. The faecal coliform concentration in most surface water sources lies in the range of 500 to several thousand per 100 ml (Kamruzzaman and Ahmed, 2006). The use of surface water for drinking purpose requires clarification and disinfection by elaborate treatment processes. The availability of surface water in the dry season is also a constraint for the development of dependable small and large scale surface water treatment plants for water supply.

b) Reduction of cholera by simple filtration. Islam et al. (2001) showed that tube-well water samples from Matlab, Bangladesh contained zoopelankton and bacteria outside the accepted limits recommended by the World Health Organization for drinking water. It is concluded that water from tube-wells should be treated if used as drinking water. Colwell et al. (2003) developed a simple filtration procedure which can remove zooplankton, most phytoplankton, and particulates >20 µm from water before use. Effective deployment of this filtration procedure in villages of rural Bangladesh yielded a 48% reduction in cholera (P < 0.005) compared with the control.

II: Safe water options from surface waters

a) Protected ponds. A protected pond in a community can provide water for drinking purpose with minimal treatment and for other domestic uses without treatment. The biological quality of water of these ponds is extremely poor due to unhygienic sanitary practices and absence of any sanitary protection. Many of these ponds are made chemically and bio-chemically contaminated for fish culture and runoff from the agricultural fields supplied with agrochemicals. In order to maintain good quality water, the protected ponds shall not receive surface discharges or polluting substances and should only be replenished by rain and groundwater infiltration.

b) Pond sand filters. A prospective option for development of surface water based water supply system is the construction of community type Slow Sand Filters (SSFs) commonly known as Pond Sand Filters (PSFs). It has been tested and found that the treated water from a PSF is normally bacteriologically safe or within tolerable limits (WaterAid Bangladesh, 2006). The problems encountered are low discharge and difficulties in washing the filter beds. Since these are small units, community involvement in operation and maintenance is absolutely essential to keep the system operational. Although PSF has a very high bacterial removal efficiency, it may not remove 100% of the pathogens from heavily contaminated surface water. In such cases, the treated water may require chlorination to meet drinking water standards. The major limitations mentioned are as follows: Operation and maintenance are difficult; Not suitable for heavily contaminated ponds; People complained of foul taste in pond water and many resorted to using it for cooking only; Conflicts with fish culture. It is difficult to find an appropriate/reserve pond for installation of PSF.

c) Combined filters. A combined filter consisting of roughing filters and a slow sand filter is successful in reduction of very high turbidities and coliform counts. It is introduced to overcome some of the difficulties encountered in PSF. The PSF cannot operate effectively when the turbidity of surface water exceeds 30 mg/L. The low discharge and requirement of frequent washing of the filter beds are common in Bangladesh due to high turbidity and seasonal algal bloom in pond water. Operation and maintenance are relatively easy; and less frequent attention is needed for longer duration of operation between cleaning.

d) Household filters. Surface water containing impurities can be clarified by a pitcher filter unit or a small sand filter at the household level. Pitcher filters are constructed by stacking a number of clay pitchers (Kalshis), one above the other, containing different filter media like charcoal and sands. Raw water is poured in the top Kalshi and filtered water is collected from the bottom one. In this process, water is mainly clarified by the mechanical straining and adsorption depending on the type of filter media used. The pitcher and other small household filters cannot completely remove micro-organisms if these are
present in large numbers in raw water; and these are not suitable for high-turbid water and have difficulty in cleaning and keeping the system operational. However, improvement of water quality by household filters is remarkable (Chowdury et al., 2000).

e) Rainfall. An average annual rainfall of 2.40 m within the country partly replenishes surface water sources; and the rainwater can be used for development of a rainwater based water supply system. The availability of rainwater is limited by the rainfall intensity, distribution over the year and availability of suitable catchment area. Storage, maintenance and management of quality of water from bacteriological perspective are also significant problems in Bangladesh.

f) Rainwater harvesting. The rainwater harvesting can be a very useful and acceptable potential source of safe water for drinking, cooking and dishwashing purposes for the water scarce areas and the arsenic contaminated areas in Bangladesh (Islam et al., 2010). In some areas of the coastal region with high salinity problem, about 36 percent households have been found to practice rainwater harvesting in the rainy season for drinking purpose (Chowdury et al., 1987; Hussain and Zimuddin, 1989). In the present context, rainwater harvesting is being seriously considered as an alternative option for water supply in Bangladesh in the arsenic affected areas. The quality of rainwater is comparatively good, but it is not free from all impurities and some bacteriological contamination. The system is easy and independent and therefore suitable for scattered settlements. Local materials and craftsmanship can be used in construction of rainwater system. No energy costs are incurred in running the system. The initial cost may prevent a family from installing a rainwater harvesting system. The water availability is limited by the rainfall intensity and available roof area. Mineral-free rainwater has a flat taste and may also cause nutrition deficiencies. The poorer segment of the population may not have a roof suitable for rainwater harvesting. Cleanliness of roof and storage tank is critical in maintaining good quality of rainwater. The first run off from the roof should be discarded to prevent entry of impurities from the roof. If the storage tank is clean, the bacteria or parasites carried with the flowing rainwater will tend to die out.

g) Solar distillation and solar disinfection. Solar energy available in Bangladesh can be used for solar distillation of contaminated water in crisis areas. Presence of pathogenic organisms even in apparently clear arsenic safe surface water is a hindrance for use as drinking water. These organisms can be destroyed or inactivated by solar disinfection using solar energy. It has been shown that if water in a transparent bottle is exposed to full sunlight for about 5 hours, the water is completely disinfected (EAWAG-SANDEC, 1998). The water produced by solar distillation is free from all chemicals including arsenic, but cannot produce enough water at a reasonable cost. The method is not suitable for treatment of large volumes of water containing high turbidity. The system requires further development for cost effective use in water supply in the rural areas.

h) Groundwater. In the context of very high prevalence of diarrhoeal diseases in Bangladesh, groundwater, being usually free from disease producing micro-organisms, received priority as a source of water for water supply. Since 1928, an estimated 6–8 million hand tubewells have been sunk in Bangladesh to provide drinking water to 97% of the population (DPHE, 2000). Groundwater is the main source of water supply in urban and rural areas of Bangladesh. Except for few hilly regions Bangladesh is entirely underlain by water-bearing aquifers at depths varying from zero to 20 m below ground surface. Groundwater can be easily abstracted by installation of wells for the development of water supply systems that is replenished in the monsoon. Groundwater is generally clear, colorless with little or no suspended solids, relatively constant temperature and free from disease-producing micro-organisms. But arsenic in groundwater has become a great concern for water supply in Bangladesh.

III: Magnitude of arsenic problem in Bangladesh. The study conducted by British Geological Survey (BGS), Department of Public Health Engineering (DPHE) and Mort MacDonald Limited (MML) in two phases showed that arsenic concentration of 42% of all tubewell samples exceeded 10 µg/L (maximum acceptable limit by WHO, 1993) and 25 % exceeded 50 µg/L (BGS and DPHE, 2001). When only shallow tubewells are considered, 46% and 27% exceeded 10 µg/L and 50 µg/L, respectively. In case of deep tubewell (150 m) samples, arsenic content of only 5% exceeded 10 µg/L and 1% exceeded 50 µg/L (BGS and DPHE, 2001). The BGS-DPHE studies gave two estimates of population exposure based on projected population of 125.5 million in 1999 (BGS and DPHE, 2001). The estimates of total population exposed to As concentration above 50 and 10 µg/L using the kriging method were 35.2 million and 56.7 million, respectively. According to the multistage model developed by United States Environmental Protection Agency (EPA, 2002), the Bangladesh Standard of 50 µg/L is associated with a higher risk of 30 per 10,000 population.

IV: Arsenic diseases, socio-economic correlates and social problems. Arsenic is a known carcinogen. Chronic arsenic poisoning results from long-term exposure to this heavy metal. The commonly reported symptoms of chronic arsenic exposures are melanosis (hyperpigmentation, depigmentation etc.), keratosis, cancerous gangrene (Zaman, 2001), peripheral vascular disorder, skin cancer and a number of internal cancers. The most commonly manifested disease in Bangladesh so far is skin lesions. Early symptoms include skin pigmentation, gangrene, and keratosis which generally develop over an incubation period of 5–10 years after initial exposure (WHO, 2001). Incubation differs from person to person depending on the amount of arsenic intake, nutritional status, and immunity of the individual (Anawar et al., 2002). After 10–20 years of prolonged exposure to arsenic, persons often develop skin, lung, bladder, liver, and/or kidney
cancer (Gou and Lu, 1994; Rahman, 1999). Prolonged drinking of arsenic contaminated water has implications for children's cognitive and psychological development (Asadullah and Chaudhury, 2011) and neurodevelopmental impairment in children (Wasserman et al., 2004). A recent report maintains that arsenic-tainted tubewell water is contributing to nearly 125,000 cases of skin cancer and killing 3000 in Bangladesh each year (Clarke, 2003). Nearly 40,000 people with the skin lesions symptoms of arsenicosis have been identified (UNICEF, 2007). Hadi and Parveen (2004) reported that the prevalence of arsenicosis was associated with socio-economic factors like age, sex, education and the economic status of the household indicating age and economic status as significant predictors of arsenics controlling for education and gender (Caldwell et al., 2003; Paul, 2004; Johnston and Sarker, 2007). Besides its toxicity, groundwater arsenic contamination creates widespread social problems for its victims and their families in Bangladesh (Hussain et al., 2005). There is, for instance, a tendency to ostracise arsenic-affected people, arsenicosis being thought of as a contagious disease.

V: Arsenic contamination awareness. There is an immediate need to understand not only the extent of arsenic knowledge among rural residents of Bangladesh, but also to raise awareness of the symptoms of arsenic exposure among people in both affected and unaffected areas (Paul, 2004). There are also gaps in arsenic knowledge regarding the diseases caused by arsenic poisoning and mitigating measures available to prevent contamination. It is important to assess the grassroots knowledge residents have of the problem. What do rural residents in Bangladesh, the beneficiaries of the remedial activities, think about the arsenic contamination problem? Are they aware of the problem? How accurate is their knowledge about contamination? Of late, the issue of behavioral influence factors other than awareness has been attracting more attention. Research findings suggest that distance to the nearest safe well (Hoque et al., 2004; Opar et al., 2007), education (Opar et al., 2007), and social barriers for women (Hoque et al., 2004) are related to risk mitigation behavior.

VI: Arsenic mitigation measures and arsenic-safe water supply options. Because chronic arsenic poisoning has no immediate cure, prevention is the best response. Preventive measures depend largely on the consumption of arsenic-free water and early diagnosis of arsenic contamination. The arsenic safe modes of water supplies are piped water in urban areas, deep tubewells (DTWs), uncontaminated shallow tubewells (STWs), shallow shrouded tubewell (SST), very shallow shrouded tubewell (VSS), dug well, infiltration gallery and alternative water supply options such as pond sand filters, rainwater harvesting etc. However, these safe shallow tubewells may turn into unsafe in future. Another approach is the removal of arsenic from contaminated water by using different treatment methods. Several filter methods are currently available in Bangladesh (Ahmed, 2000; Akman and Higano, 2002). The social acceptance of different mitigation measures showed that people prefer deep tubewells, piped water supply (Hoque et al., 2004), and switching to arsenic-safe wells (Van Geen et al., 2002). Mosler et al. (2010) reported that social factors explained greater variance in the consumption of drinking water from deep tubewells than did situational and personal factors. In an overall regression, social factors played the biggest role. The institutional shortcomings and scientific and technological indeterminacies such as the debate about the best mitigation measures are the major hindrances for success in arsenic mitigation (Ahmed et al., 2006; Atkins et al., 2007). Another possible reason could be the lack of knowledge on and consideration of people's acceptance and use of mitigation options.

a) Shallow Shrouded Tubewell and Very Shallow Shrouded Tubewell. In many areas, particularly coastal areas, groundwater with low arsenic content is available in very shallow and shallow aquifers composed of fine sand at shallow depth. This may be due to accumulation of rainwater in the topmost aquifer or dilution of arsenic contaminated groundwater by fresh water recharging each year by surface and rain waters. However, the particle size of soil and the depth of the aquifer are not suitable for installing a normal tubewell. To get water through these very fine-grained aquifers, an artificial sand packing is required around the screen of the tubewell. This artificial sand packing, called shrouding, increases the yield of the tubewell and prevents entry of fine sand into the screen. Over-pumping may yield contaminated water. Therefore, periodical monitoring of water quality is essential in this system. Installation of low capacity pumps may prevent over exploitation of shallow aquifers. The systems may be considered suitable for drinking water supply for small settlements where water demand is low (DPHE, 2000).

b) Deep Tubewell. The deep aquifers in Bangladesh have DTWs and are an excellent option for avoiding high As concentrations (Hug et al., 2011). In Bangladesh two types of deep tubewells are constructed, manually operated small diameter tubewell similar to shallow tubewells and large diameter power operated tubewells called production well. However, there are many areas where the separating impermeable layers are absent and aquifers are formed by stratified layers of silt and medium sand. The deep tubewells in those areas may yield arsenic safe water initially but likely to increase arsenic content of water with time due to mixing of contaminated and uncontaminated waters. However, recharge of deep aquifer by infiltration through coarse media and replenishment by horizontal movement of water are likely to keep the aquifer arsenic free even after prolong water abstraction.

c) Dug Well. Dug well is the oldest method of groundwater withdrawal for water supplies. The water of the dug well has been found to be free from dissolved arsenic and iron even in locations where tubewells are contaminated due to the exposure of dug well water to open air and agitation during water withdrawal that can cause precipitation of dissolved arsenic and iron. It is very difficult to protect
the water of the dug well from bacterial contamination. Percolation of contaminated surface water is the most common route of pollution of well water. The upper part of the well lining and the space between the wall and soil require proper sealing. The construction of an apron around the well can prevent entry of contaminated used water at the well site by seepage into the well. Disinfection of well water may be continued during operation by pot chlorination.

d) Infiltration Gallery/Well. Infiltration Galleries (IG) or wells can be constructed near perennial rivers or ponds to collect infiltrated surface waters for all domestic purposes. Since the water infiltrates through a layer of soil/sand, it is significantly free from suspended impurities including microorganisms usually present in surface water. Again, surface water being the main source of water in the gallery/well, it is free from arsenic. If the soil is impermeable, well graded sand may be placed in between the gallery and surface water source for rapid flow of water. The accumulated water requires good sanitary protection or disinfection by pot chlorination. Sedimentation of clayey soils or organic matters near the bank of the surface water source interfere with the infiltration process and require regular cleaning by scraping a layer of deposited materials.

VII: Treatment of arsenic contaminated water. There are several methods available for removal of arsenic from water in large conventional treatment plants. The most commonly used technologies include oxidation, co-precipitation and adsorption onto coagulated flocs, lime treatment, adsorption onto sorptive media, ion exchange resin, membrane techniques, nanofiltration and reverse osmosis (Shen, 1973; Cheng et al., 1994; Kartinen and Martin, 1995; Hering et al., 1996 and 1997; Joshi and Chaudhuri, 1996). Since or before the year 2000, many small scale arsenic removal technologies have been developed, field tested and used under action research programs in Bangladesh and India. The following subsections present a short review of the currently available in (Table 1) and most sustainable technologies with the intention to update the technological development in arsenic and iron removal, understand the problems, prospects and limitations of different treatment processes as alternative water supply options in the rural areas of Bangladesh.

a) Oxidation. Arsenic is present in groundwater in As(III) and AS(V) forms in different proportions. Most treatment methods are effective in removing arsenic in pentavalent form using iron oxide or alumina-based filter. Arsenite and dissolved iron can be oxidized by solar oxidation (Wegelin et al., 2000), oxygen, ultraviolet radiation in presence of oxygen (Young, 1996), ozone, free chlorine, hypochlorite, permanganate, hydrogen peroxide and fulton's reagent. But atmospheric oxygen, hypochlorite and permanganate are commonly used for oxidation in developing countries. Air oxidation of arsenic is very slow and can take weeks for oxidation (Pierce and Moore, 1982) but chemicals like chlorine and permanganate can rapidly oxidize arsenite to arsenate under wide range of conditions.

b) Arsenic attenuation by oxidized aquifer sediments in deep aquifer. In many areas of Bangladesh, shallow high-As aquifers are underlain by oxidized sediments that are considered Pleistocene in age and have groundwater concentrations of As b10 µg/L (BGS and DPHE, 2001; Harvey et al., 2002). These sediments are various shades of olive to brown in color because of Fe(III) oxide minerals. Organic carbon concentrations are b0.1% (McArthur et al., 2004; Swartz et al., 2004). There is a risk that excessive groundwater withdrawal from these deeper oxidized aquifers could induce infiltration of high-As groundwater and contaminate the deeper aquifers (Harvey et al., 2002; van Geen et al., 2003). Therefore, the capacity of oxidized sediments for As attenuation by adsorption is important to the long-term viability of deeper aquifers for water supply.

c) Subsurface iron and arsenic removal for shallow tube well. Subsurface iron and arsenic removal has the potential to be a cost-effective technology to provide safe drinking water in rural decentralized applications, using existing shallow tube wells. van Halem et al. (2010) constructed a community-scale test facility in Bangladesh for injection of aerated water into an anoxic aquifer with elevated iron (0.27 mmol/L) and arsenic (0.27 mmol/L) concentrations. The injection (oxidation) and abstraction (adsorption) cycles were monitored at the test facility and simultaneously simulated in the laboratory with anoxic column experiments. These high removal efficacies did not follow the adsorptive-catalytic oxidation. Some other (bio)logist or transport) processes have contributed to the system’s efficacy.

d) Arsenic and Fe removal modified ceramic filter. Aeration or biological oxidation followed by solid liquid separation like sedimentation and filtration through sand or other media is the most commonly used treatment methods for Fe removal (Michalakos et al., 1997; Ellis et al., 2000). Adopting these techniques, a simple ceramic filter unit made of clay soil and rice bran is available in rural households of Bangladesh for the removal of Fe from groundwater, however, some portion of As in groundwater could be removed through adsorption and co-precipitation with Fe hydroxides flocs. Shafiquzzaman et al. (2011) suggested that a simple modification of this inexpensive ceramic filter using iron net and iron oxidizing bacteria substantially increased 18% more As removal and Fe in the As contaminated region. Bangladesh Council of Scientific and Industrial Research (BCSIR) have developed an arsenic removal system like BCSIR Filter Unit, which uses the process of coagulation/precipitation with an iron based chemical followed by sand filtration.
filtration of the water through a bucket sand filter (Meng et al., 2001). This technology uses two buckets, one to mix chemicals (reported to be iron sulphate and calcium hypochlorite) supplied in packets and the other to separate flocs by the processes of sedimentation and filtration. This household treatment process removed arsenic from approximately 300 μg/L in the well water to less than 50 μg/L. Water treatment with coagulants such as aluminium alum (Al₂(SO₄)₃·18H₂O), ferric chloride (FeCl₃) and ferric sulfate (Fe₂(SO₄)₃·7H₂O) are effective in removing arsenic from water. Ferric salts have been found to be more effective in removing arsenic than alum on a weight basis and effective over a wider range of pH usually between 6.0 and 8.5 (Ahmed and Rahman, 2000). BUET has constructed and tested iron coated sand based small scale unit for the removal of arsenic from groundwater (Joshi and Choudhuri, 1996). Shapla filter, a household arsenic removal unit, has been designed with iron coated brick dust as an adsorption medium and works on the same principles as iron coated sand described above. The unit is effective in removing arsenic from drinking water.

**j) Community-based water options for arsenic mitigation.** Sarkar et al. (2005) developed the fixed bed activated alumina column process for well-head arsenic removal process. Community level arsenic removal units use regenerable arsenic-selective adsorbents (Sarkar et al., 2010). Upon exhaustion, the adsorbents are regenerated in a central facility by a few trained villagers. The process of regeneration reduces the volume of disposable arsenic-laden solids by nearly two orders of magnitude and allows for the reuse of the adsorbent material. Finally, the arsenic-laden solids are contained on well-aerated coarse sand filters with minimum arsenic leaching. Household PoU

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<td>Arsenic attenuation by oxidized</td>
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units using adsorbent media or coagulants will always generate arsenic-laden sludge or solids. Coordinating collection and safe disposal of sludge or used media from individual households poses a level of complexity and enforcement effort that are difficult to sustain in remote villages. The well-head community-based units reduce such management problems two hundred times. Even for household units, the villagers (mostly village women) need to come everyday to the existing well-head units to collect water. Thus, having a simple-to-operate arsenic removal system mounted on the well-head unit provides continued collective vigilance with regard to color (caused by iron), smell (due to biological activity) or other abnormal behaviors that may otherwise go unnoticed for household units. According to our estimates, both fixed and operating costs of the community-based well-head unit are significantly lower than the total sum of the same for two hundred household units.

**g) Indigenous filters.** There are several filters available in Bangladesh that use indigenous material as arsenic adsorbent. Red soil rich in oxidized iron, clay minerals, iron ore, iron scrap or fillings, and processed cellulose materials are known to have capacity for arsenic adsorption. Some of the filters manufactured using these materials include: Sono 3-Kolshi Filter, Granet Homemade Filter, Chari Filter, Adansha Filter, Shafi Filter, and Bijoypur Clay/Processed Cellulose filter (Ahmed, 2001).

**h) Demand-based water supply.** Based on an extensive field-based study, Hoque et al. (2004) recommended that a cluster-based piped water system is more preferable and gets proper consideration for arsenic affected areas when selecting appropriate water options rather than household based options or the development of new low-cost options. Piped water supply is the ultimate goal of safe water supply to the consumers, because (1) water can be delivered to the close proximity of the consumers, (2) piped water is protected from external contamination, (3) better quality control is possible, and (4) water of required quantity can be collected at ease. In respect of convenience in collection and use, only piped water can compete with existing system of tubewell water supply. But it is a very difficult and costly option for scattered population in the rural areas. It can be a feasible option for clustered rural settlements and urban fringes. Water can be made available through house connection, yard connection or standpost depending on the financial condition of the consumers. The water can be produced as per demand by sinking deep tubewell in arsenic-safe aquifer or treatment of surface or even arsenic contaminated tubewell water by community type treatment plants.

Discussions and Conclusion

A lot of pilot works and research have been done for the technological development in arsenic removal from groundwater-based rural water supply for the last few years. A comparison of different arsenic removal processes is shown in Table 1. All the technologies described in this paper have their merits and demerits and are being refined to make suitable in the rural condition. The modifications based on the pilot-scale implementation of the technologies are in progress in order to improve effectiveness in As and Fe removal, reduce the capital and operational cost of the systems, make the technology user friendly, overcome maintenance, and sludge management problems.

There are different types of As removal and safe water options available for water supply in the arsenic affected areas. The quality and quantity of water, reliability, cost and convenience of collection of water of the different alternative options vary widely. Among the cheaper options providing water to arsenic-exposed populations, the deep tubewell can provide water at nominal operation and maintenance cost. But deep tubewells are not feasible to provide arsenic free water at some places in Bangladesh. Dug/ring well is the next option, which can provide water at moderate installation and nominal operation and maintenance cost. It is not yet fully known whether the quality of water can be maintained at desired level, and arsenic content remains at safe level under conditions of proper sanitary protection. Piped water supply can be provided at a higher cost and relatively higher operation and maintenance costs, but the convenience and health benefits would be enormous. Because water of adequate quantity and relatively superior quality for all domestic purposes including sanitation will be available at residences or close proximity of the residences. The increase in the number of household reduces costs, but it would be difficult to get clustered houses in most places in rural areas. Installation of community rainwater harvesting system may be cheaper but management of such a system may be difficult.

References

