

Practical Paper

Arsenic crisis of Bangladesh and mitigation measures

M. Habibur Rahman and A. Al-Muyeed

ABSTRACT

Arsenic contamination in the shallow aquifers has created the crisis and hence 4.73 million tubewells out of a total of 8.61 million have been tested for arsenic contamination and 29% of these tested tubewells have been found to be contaminated with arsenic beyond the safe limit of Bangladesh standards. Around 81% of the inhabitants of our total villages are now affected with this poison where 27% of those are beyond the Bangladesh standards and which is responsible for the health suffering of 50 million people. This paper examines this arsenic crisis and critically identifies treatment methods and technologies used for mitigation against this crisis. The common technologies that are used to treat arsenic-contaminated water are using oxidizing agents followed by flocculation and precipitation. Research groups have used this technology and finally they have developed their own methods to suit the local environment using locally available materials. Again, alternative water supply options like deep tubewells, very shallow tubewells, pond sand filters, solar disinfection, rainwater harvesting and, in many situations, surface water treatment options are very useful to mitigate this arsenic crisis in some areas. Deep tubewells, which have been widely accepted by the communities during the past few decades in Bangladesh, emerge to be a more suitable alternative option for mitigation.

Key words | arsenic contamination, Bangladesh, mitigation, safe drinking water

M. Habibur Rahman (corresponding author)
A. Al-Muyeed
Department of Civil Engineering,
Bangladesh University of Engineering and
Technology,
Dhaka,
Bangladesh
E-mail: habibr@ce.buet.ac.bd

INTRODUCTION

Arsenic is found in aquifers, usually underlying river deltas, around the world. In Bangladesh, arsenic levels are highest in the southern part of the country, presumably because the arsenic accumulated there when the Ganga and Brahmaputra rivers washed soil down from the Himalayas to the Bay of Bengal (Figure 1). Around this Bengal deltaic region, the presence of this poison in groundwater is an alarming situation and already it is reported to be the biggest arsenic calamity in the world in terms of the affected population. In West Bengal, a minimum of 6 million people belonging to 9 out of a total of 18 districts were drinking arsenic-contaminated water which contains more than 50 µg/L arsenic (Rahman *et al.* 2003). The presence of shallow aquifers with abundant groundwater, the groundwater

being free from pathogenic microorganisms and the ease of tubewell installation at affordable cost, has meant the number of domestic water supply wells, particularly in rural areas of Bangladesh, has increased by many times over the last three decades. Around 97% of the population in Bangladesh had access to drinking water. Unfortunately, arsenic contamination of primarily shallow aquifers in many parts of the country (Figure 2, Table 1) has made water extracted from these aquifers unsafe for drinking purposes and has reduced this water supply coverage (water supply within one kilometer of their home or 30 min total collection time) to around 74%. The blanket screening test data of around 4.73 million tubewells (55% of total tubewells) in around 54,000 villages (62% of total villages)

doi: 10.2166/aqua.2009.031

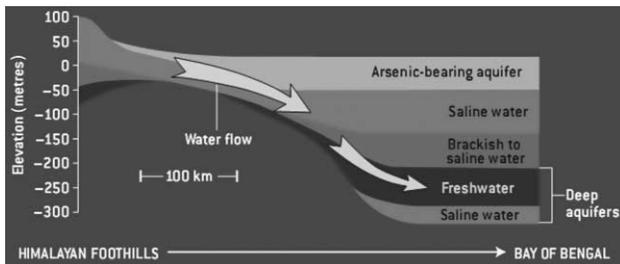


Figure 1 | North-South cut through Bangladesh Delta (Chowdhury 2004).

in the country (Table 1) shows that groundwater from approximately 1.4 million tubewells (29% of tested) is contaminated with arsenic exceeding the concentration of $50 \mu\text{g/L}$ (Bangladesh standard for drinking water). It is also apparent from the DPHE-BGS-MML (1999) and BAMWSP (2001) studies that around 25% of their tested samples exceed the concentration of $50 \mu\text{g/L}$ and 42% of tested samples exceed the concentration of $10 \mu\text{g/L}$, the provisional World Health Organization (WHO) guideline value for arsenic in drinking water. The percentage of contaminated tubewells increases if only shallow tubewells are considered. Then 27% of tested samples exceed the concentration of $50 \mu\text{g/L}$ and 46% of tested samples exceed the concentration of $10 \mu\text{g/L}$ (Table 1).

At present several thousand people are suffering from arsenic-related diseases and millions are at risk of arsenic poisoning from drinking ground water with arsenic in excess of the acceptable limit. BGS & DPHE (2001) furnish two estimates of population exposure based on the projected population of 125.5 million in 1999. The total population exposed to arsenic-contaminated water above $50 \mu\text{g/L}$ and $10 \mu\text{g/L}$ is estimated as 32.5 million (25.9% of total population) and 56.7 million (45.2%), respectively. Based on



Figure 2 | Typical community arsenic and iron removal plant.

thana (precinct) statistics the total population exposed to arsenic-contaminated water above $50 \mu\text{g/L}$ and $10 \mu\text{g/L}$ is estimated as 28.1 million (22.4%) and 46.4 million (37%), respectively. The magnitude of the problem is increasing as more information becomes available (Rahman & Al-Muyeed 2005). Thus access to safe water is an urgent human need in Bangladesh to minimize the health hazards from arsenic poisoning.

A number of treatment technologies exist that are capable of efficient removal of arsenic from water, but the socio-economic conditions that prevail in developing countries in general, and Bangladesh in particular, do not permit the implementation of most of them on cost grounds. In most cases, except for a few cities and towns, there is no centralized water supply system. Individual households or small groups have their own or community tubewells. The solution to the problem of arsenic contamination in most situations in Bangladesh demands the development of technologies that can be implemented at the household or small community level at a relatively very low cost. Hence this paper is aimed at identifying the arsenic contamination problems of groundwater in Bangladesh and then an overview of treatment methods and technologies used for arsenic removal is presented. This study also demonstrates the use of safe water supply options currently being practised in arsenic-affected areas of Bangladesh.

CAUSES OF ARSENIC CONTAMINATION

Intermittent incidents of arsenic contamination in groundwater can arise both naturally and industrially. The natural occurrence of arsenic in groundwater is directly related to the arsenic complexes present in soils. Arsenic can be liberated from these complexes under some circumstances. Since arsenic in soils is highly mobile, once it is liberated, it results in possible groundwater contamination. The alluvial and deltaic sediments containing pyrite has favored the arsenic contamination of groundwater in Bangladesh. Most regions of Bangladesh are composed of a vast thickness of alluvial and deltaic sediments, which can be divided into two major parts – the recent floodplain and the terrace areas. The floodplain and the sediments beneath them are only a few thousand years old. The terrace areas are better

Table 1 | Arsenic contamination situation in Bangladesh

| | |
|---------------------------------------------------------------------|-------------------------------------------------------|
| Total population (million) of the country in 2007 (est.) | 150.5 |
| Total area (sq. km.) of the country | 147,570 |
| Estimated total number of villages in country | 87,319 (100) [†] |
| Estimated total number of villages screened | 54,041(62) [†] |
| Estimated total number of villages not screened | 33,278 (38) [†] |
| Total number (million) of tubewells in the country | 8.61 (100) [†] |
| Total number (million) of tubewells tested for As | 4.73 (55) [†] |
| Total number (million) of tubewells marked green (safe) | 3.33 (39) [†] |
| Total number (million) of tubewells marked red (unsafe) | 1.4 (16) [†] (29% of total tested tubewells) |
| Villages where less than 40% of the tubewells are contaminated | 70,610 (81) [†] |
| Villages where 40–80% of the tubewells are contaminated | 8331 (10) [†] |
| Villages where 80–99% of the tubewells are contaminated | 6062 (7) [†] |
| Villages where all tubewells are contaminated | 2.316 (3) |
| As affected shallow tubewells above 0.05 mg/L | 27%* |
| As affected shallow tubewells above 0.01 mg/L | 46%* |
| As affected deep tubewells (strainer depth > 150 m) above 0.05 mg/L | 1%* |
| As affected deep tubewells above 0.01 mg/L | 5%* |
| Number of arsenicosis patients reported so far | 38,000 |
| Population (million) exposed to arsenic contamination > 0.05 mg/L | 28.1–32.5 (22.4–25.9%) |
| Population (million) exposed to arsenic contamination > 0.01 mg/L | 46.4–56.7 (37–45.2%) |

*% of total tested tubewells.

[†]Figure in () indicates the (%) of total as of 2006 (UNICEF 2007).

known as Madhupur and Barind Tracts and the sediments underlying them are much older than the adjacent floodplain. Most of the arsenic is occurring in the younger sediments derived from the Ganges Basin. The investigators found that there is a layer containing arsenic compounds at a depth of 20–80 m. This layer is rich in arseno-pyrite, pyrite, iron sulfate and iron oxide, as revealed by geological investigations. The researchers also inferred that, although arsenic is occurring in the alluvial sediments, the ultimate origin of arsenic is perhaps in the outcrops of hard rocks higher up the Ganges catchment. These outcrops were weather-beaten in the recent geological past and then the eroded soil was deposited in West Bengal and Bangladesh by the ancient courses of the Ganges. Arsenic in sediment or water can move in the adsorbed phase with iron, which is available in plenty in the Himalayas. Here about 100–300 mg/kg arsenic combined with iron oxides can be found in the sediments under aerobic conditions. When these

sediments were deposited in the Bengal Basin under a tidal environment, it came under anaerobic conditions. The sulfate available in the Bengal Basin was reduced to hydrogen sulfide in the presence of sulfur-reducing bacteria. Iron minerals and hydrogen sulfide rapidly bond together to form iron sulfide. Arsenic had been absorbed on the surface of the iron sulfide and produced arseno-pyrite. This mineral usually remains stable unless it is exposed to oxygen or nitrate. In the aerobic environment, arseno-pyrite is oxidized in the presence of oxygen and arsenic adsorbed by iron sulfide becomes mobilized. The groundwater in Bangladesh has declined progressively due to the excessive extraction of water for irrigation and domestic water supply, lack of water management and inadequate recharge of the aquifer. The groundwater declined beyond 8 m in 12% of the area of Bangladesh in 1986. This extent rose to 20% of the area in 1992 and 25% in 1994. The study on forecasting groundwater level fluctuation in Bangladesh indicated that

54% of the area of Bangladesh is likely to be affected up to 20 m in some areas, particularly in the northern part of the country (Safiuddin & Karim 2001). Excessive groundwater extraction may be the prime reason for creating a zone of aeration in clayey and peaty sediments containing arseno-pyrite. Under aerobic conditions, arseno-pyrite decomposes and releases arsenic that mobilizes into the subsurface water. The mobilization of arsenic is further enhanced by the compaction of aquifers caused by groundwater withdrawal.

EFFECTS ON HEALTH

Arsenic is the twelfth most abundant element in the biosphere, and is said to be essential for some animal species. But any form of arsenic compound is not desirable for human consumption. The toxic effect of arsenic species mainly depends on their chemical form, route of entry, age, sex, dose and duration of exposure. The organic form of arsenic is several orders of magnitude less toxic compared to the inorganic form. Again, trivalent arsenic (As^{3+} , arsenite) species are approximately an order of magnitude more toxic compared to the pentavalent arsenic (As^{5+} , arsenate) species. The consumption of arsenic-contaminated food and drinking water is the main source of arsenic toxicity. Skin diseases are the common effects of arsenic poisoning. Long-term exposure to excessive arsenic generally causes changes in skin pigmentation and hyperkeratosis, and promotes the development of ulceration of the skin, skin cancer and a number of internal (liver, bladder, kidney, etc.) cancers.

Around 38,000 arsenicosis patients (Table 1) have been reported in Bangladesh so far (APSU 2005). Using the EPA model and the distribution of population exposed to different levels of arsenic, LGRD (2002) estimated the incidence of excess lifetime skin cancer for different levels of arsenic contamination of drinking water for the then total population of 129.25 million in Bangladesh. The incidences of excess skin cancer are 0.29%, 0.043% and 0.012% for drinking arsenic-contaminated water at existing levels of arsenic contamination, satisfying the Bangladesh standard ($50 \mu\text{g/L}$) and satisfying the WHO guideline value ($10 \mu\text{g/L}$), respectively.

TREATMENT OF ARSENIC-CONTAMINATED WATER

Arsenic in groundwater is present mainly in nonionic trivalent (As(III)) and ionic pentavalent (As(V)) inorganic forms in different proportions, depending on the environmental conditions of the aquifer. The solubility of arsenic in water is usually controlled by redox conditions, pH, biological activity and adsorption reactions. The reducing condition at low Eh values converts arsenic into a more mobile As(III) form, whereas at high Eh value As(V) is the major arsenic species. As(III) is more toxic than As(V) and is difficult to remove from water by most techniques.

There are several methods available for the removal of arsenic from water in large conventional treatment plants. The most commonly used processes of arsenic removal from water have been described by Shen (1973), Cheng *et al.* (1994), Kartinen & Martin (1995), Hering *et al.* (1996), Joshi & Chaudhuri (1996) and Hering *et al.* (1997). A detailed review of arsenic removal technologies has been presented by Sorg & Logsdon (1978), Jekel (1994) has documented several advances in arsenic removal technologies. In view of the lowering of the standard of the US Environmental Protection Agency (EPA) for the maximum permissible levels of arsenic in drinking water, a review of arsenic removal technologies was carried out to consider the economic factors involved in implementing more stringent drinking water standards for arsenic (Chen *et al.* 1999). Many of the arsenic removal technologies have been discussed in detail in the AWWA (American Water Works Association) reference book (Pontius 1990). A review of low-cost well water treatment technologies for arsenic removal, with a list of companies and organizations involved in arsenic removal technologies, has been compiled by Murcott (2000). Comprehensive reviews of arsenic removal processes have been documented by Ahmed *et al.* (2001) and Johnston & Heijnen 2001. The AWWA conducted a comprehensive study on arsenic treatability options and evaluation of residuals management issues. Rahman *et al.* (2003) critically examined the arsenic crisis in Bangladesh and further extended examination was reviewed by Rahman & Al-Muyeed (2005).

The basic principles of arsenic removal from water are based on conventional techniques of oxidation, coprecipitation and adsorption on coagulated flocs, adsorption onto

sorptive media, ion exchange and membrane filtration. Oxidation of As(III) to As(V) is needed for effective removal of arsenic from groundwater by most treatment methods.

The most common arsenic removal technologies can be grouped into the following five categories:

- (a) oxidation,
- (b) coagulation, co-precipitation and adsorption,
- (c) ion exchange,
- (d) activated alumina,
- (e) membrane.

The principal mechanisms and technologies for arsenic removal using the above technological options are described in detail in the following subsections.

Oxidation

Arsenic occurs in water in several different forms, depending upon the pH and oxidation potential of the water. Arsenite (As^{+3}) is difficult to remove from water using the usually available treatment processes. So, many treatment systems include an oxidation step to convert arsenite to arsenate (As^{+5}). The commonly used oxidants are chlorine, ozone, permanganate, hydrogen peroxide and oxygen. These chemicals are more effective under a wide range of conditions and air oxidation may take weeks to oxidize arsenite to arsenate. But oxidation alone does not remove arsenic from solution and should be combined with removal processes like coagulation, adsorption and ion exchange.

Coagulation, co-precipitation/passive sedimentation, *in situ* oxidation, adsorption

Excellent arsenic removal is possible in coagulation and sedimentation/filtration processes either with ferric or aluminum salts if an oxidant is added. Alum coagulation is more effective at a pH of 7 or less, but iron precipitation is less sensitive to pH up to a value of 8.5 or less. Cheng *et al.* (1994) reported 99% removal of arsenic in laboratory conditions in a coagulation process under optimal conditions, and a residual arsenic concentration of 1 $\mu\text{g}/\text{L}$. The best method to determine the types and dosages of chemicals for arsenic removal by coagulation/flocculation is to conduct site-specific testing. Arsenic in the coagulation

process is removed through the following three main mechanisms (Edwards 1994): precipitation; co-precipitation and adsorption. A lime softening process can effectively remove arsenic at alkaline pH values of 11 or above. If an oxidant is added the efficiency of the process increases but removal efficiency is more sensitive to pH even with an oxidant. Kartinen & Martin (1995) reported 80% removal of arsenic at pH 10.5 or above but the removal efficiency was very low (about 15%) up to pH 10.5. When chlorine is added the removal efficiency increased to 95% at pH 11.

A number of processes remove iron and/or manganese from water by oxidizing iron and/or manganese from their soluble state (Fe^{+2}) to a higher valence (Fe^{+3}) to form a precipitate. Then arsenic can be co-precipitated with the naturally occurring iron and/or manganese (passive sedimentation process). With the use of different chemicals, Kartinen & Martin (1995) reported 90% removal of arsenic in this process. Matthes (1981) reported *in situ* oxidation of iron and arsenic in an aquifer containing high ferrous iron, high arsenite and low pH, where 29 tons of potassium permanganate was injected directly into 17 contaminated wells. This yielded a reduction of arsenic concentrations from 13,600 $\mu\text{g}/\text{L}$ to 60 $\mu\text{g}/\text{L}$, where arsenite was oxidized and co-precipitated with ferric iron. Rott & Friedle (1999) reported the use of atmospheric oxygen to reduce arsenic concentration *in situ* from approximately 20 $\mu\text{g}/\text{L}$ to 5 $\mu\text{g}/\text{L}$, and this also lowered the iron and manganese levels.

Ion exchange

This is an adsorption process in which water passes through a column containing an ion exchange resin. Pre-treatment of these resins using sodium chloride creates an abundance of chloride on the exchange sites. When arsenic-containing water passes through this resin bed, the chloride ions are exchanged for the arsenic ions such that the water exiting the beds is lower in arsenic but higher in chloride than the water entering the bed. At exhaustion, the exchange site is loaded with arsenic, which can then be regenerated by passing concentrated sodium chloride solution through the column, usually in the opposite flow direction. In this process, sulfate ions compete with arsenic for the adsorption sites and therefore higher sulfate concentration in the feed water results in a shorter resin life. In low-sulfate waters, ion

exchange resins can easily remove 95% of arsenate, and treat from several hundreds to over a thousand bed volumes before arsenic breakthrough occurs (Johnston & Heijnen 2001). Accordingly, US EPA recommends that ion exchange resins not be used in waters with > 120 mg/L sulfate or > 500 mg/L total dissolved solids, and are more effective in waters with an even lower sulfate level < 25 mg/L. Arsenite, being uncharged, is not removed and therefore an oxidation step is needed as a precursor to arsenic removal.

Activated alumina

Activated alumina, a granular form of aluminum oxide (Al_2O_3), with very high specific surface area (about $200\text{--}300\text{ m}^2/\text{g}$) could remove arsenic from water. The mechanisms of arsenic removal are similar to those of a weak base ion exchange resin, and often collectively referred to as 'adsorption', though ligand exchange and chemisorptions are more appropriate term (Clifford 1999). Arsenic removal efficiency is excellent (typically $> 95\%$) for both arsenate and arsenite, but arsenic removal capacity varies significantly and is controlled by pH (Johnston & Heijnen 2001). Arsenate removal capacity is best in the narrow pH range from 5.5–6.0, where the alumina surfaces are protonated, but acid ions are not yet concentrated enough to compete with arsenic for sorption sites (Clifford 1999; Johnston & Heijnen 2001). Phosphate and fluoride are adsorbed by activated alumina and therefore their presence reduces the arsenic removal efficiency. Activated alumina can be regenerated by flushing with a solution of 4% sodium hydroxide, which displaces arsenic from the alumina surfaces (Johnston & Heijnen 2001).

Membrane

High-pressure synthetic membranes, such as nanofiltration (NF) and reverse osmosis (RO), have pore sizes appropriate for the removal of dissolved arsenic (both arsenite and arsenate), which is in the metal ion size range. According to Waypa *et al.* (1997), the NF membrane tested performed well, comparably to the RO membranes, even though the operating pressure was much lower (40–120 psi, compared to 200–400 psi). Membrane filtration requires relatively high quality influent water. Colloids, particularly organics,

iron and manganese can foul it. The main advantages of this technology are its minimal operation and maintenance requirements, chemicals are not required and it produces no extra sludge. The main disadvantages of this system are that this requires high pressure, it is costly and water recovery rates are very low, often 10–20%.

ARSENIC REMOVAL TECHNOLOGIES PRACTISED IN BANGLADESH

A comprehensive review of low-cost well-water treatment technologies for arsenic removal with a list of companies and organizations involved in arsenic removal technologies is available in Murcott (2000). Most of the documented experiences of arsenic removal technologies include large-scale applications. In the context of the prevalence of high concentrations of arsenic in the groundwater in Bangladesh, several methods/technologies of treating water for arsenic reduction from drinking water have been tried by a number of organizations/researchers in Bangladesh to identify innovative technologies for arsenic removal in order to implement them in rural isolated communities. Most of these technologies are introduced on small experimental scales. A brief overview of some of these documented technologies is presented here.

Passive sedimentation

Arsenic has been found to co-exist with iron in a large part of Bangladesh (about 65% of the area) in excess of 2 mg/L and in many acute iron problem areas the concentration of iron is as high as 15 mg/L. In such situations, arsenic can be removed by both co-precipitation and adsorption onto the precipitated $\text{Fe}(\text{OH})_3$ by oxidation of this water during collection and subsequently storing them at the household level. This process removed more than 60% arsenic, where raw groundwater arsenic and iron concentrations were in the range of 150–713 $\mu\text{g}/\text{L}$ and 8–14 mg/L, respectively (Rahman *et al.* 2003). The rapid assessment of this technology in BAMWSP, DFID & WaterAid (2001) showed that it failed to reduce arsenic to the desired Bangladesh standard in most cases.

In situ oxidation

In situ oxidation of iron and arsenic in the aquifer has been tested under the DPHE–Danida Arsenic Mitigation Pilot Project where the aerated tubewell water is stored in a tank and then the stored water is discharged into the aquifer through a tubewell pipe under the pump head. Water collected by tubewell from such aquifers, followed by *in situ* oxidation of iron and arsenic, showed about 50% removal of arsenic.

Solar oxidation

A transparent bottle containing water is exposed to sunlight for solar oxidation of arsenic in the presence of other oxidants, followed by precipitation of arsenic with naturally occurring iron. Experiments in Bangladesh showed that the process could lower the arsenic content of water to about one-third, and removal efficiency increased to about 45–78% when 50 μL citrate or 100–200 μL (4–8 drops) of lemon juice/L is added (Rahman *et al.* 2003).

Arsenic and iron removal plants (AIRPs)

In conventional small-community-type arsenic and iron removal plants (AIRPs) (Figure 2), groundwater drawn by hand tubewell drops into a storage (aeration/sedimentation) chamber for oxidation of iron and arsenic with air to co-precipitate. Water from the storage chamber passes through a filtration chamber due to the pressure head of the aeration/sedimentation chamber and subsequently is collected in a storage tank for public use. Filtration media used for AIRPs comprise of brick chips, charcoal and sand and is periodically (3–4 times a year) backwashed. The

sludge is collected in a holding pond. Iron and arsenic removal efficiencies of these AIRPs operating in small communities are shown in Table 2. The average installation, operation and maintenance costs of a typical plant are presented in Table 4. It is evident from field surveys that these AIRPs are well accepted by their communities.

The DPHE, with support from the Dutch Government, constructed three AIRPs for piped water supply systems in small municipalities, where arsenic co-exists with iron in groundwater. In these plants, groundwater is pumped over a series of cascades (Figure 3) to aerate the water and it then passes through a filtration unit, which removes iron and arsenic precipitates. Arsenic and iron removal efficiencies of 18-DTP (1999) AIRPs are shown in Table 3. The installation costs of the treatment unit and overhead tank are presented in Table 4. The operation and maintenance costs of this plant are presently not available.

Bucket treatment unit

The bucket treatment unit developed by the DPHE–Danida project consists of two buckets (about 20 L capacities) placed one above the other. Chemicals (200 mg/L aluminum sulfate and 2 mg/L potassium permanganate) are mixed manually with arsenic-contaminated water in the upper bucket by vigorous stirring with a wooden stick for about 30–60 s and then flocculated by gentle stirring for about 90 s. Mixed water is then allowed to settle for about 1–2 h and the top supernatant is allowed to flow into the lower bucket via a plastic pipe and sand filter installed in the lower bucket (Figure 4). Although this technology performs well (with arsenic removal efficiencies in the range of 67–83%), in some cases under rural operating conditions

Table 2 | Arsenic and iron removal efficiencies in AIRPs (Rahman *et al.* 2003)

| Location of AIRP plant | Influent Fe (mg/L) | Influent As ($\mu\text{g/L}$) | Fe removal efficiency (%) | As removal efficiency (%) | As in treated water ($\mu\text{g/L}$) |
|------------------------|--------------------|---------------------------------|---------------------------|---------------------------|-----------------------------------------|
| Manikgonj | 15 | 540 | 93 | 90 | 54 |
| Chadpur | 8.9 | 808 | 92 | 84 | 129 |
| Munshiganj | 7.6 | 213 | 90 | 82 | 38 |
| Barisal | 10 | 456 | 92 | 80 | 91 |
| Chadpur | 7.6 | 260 | 84 | 78 | 57 |
| Satkhira | 6.6 | 188 | 87 | 77 | 43 |
| Gopalganj | 14 | 334 | 89 | 68 | 107 |
| Chadpur | 2.5 | 126 | 98 | 66 | 43 |

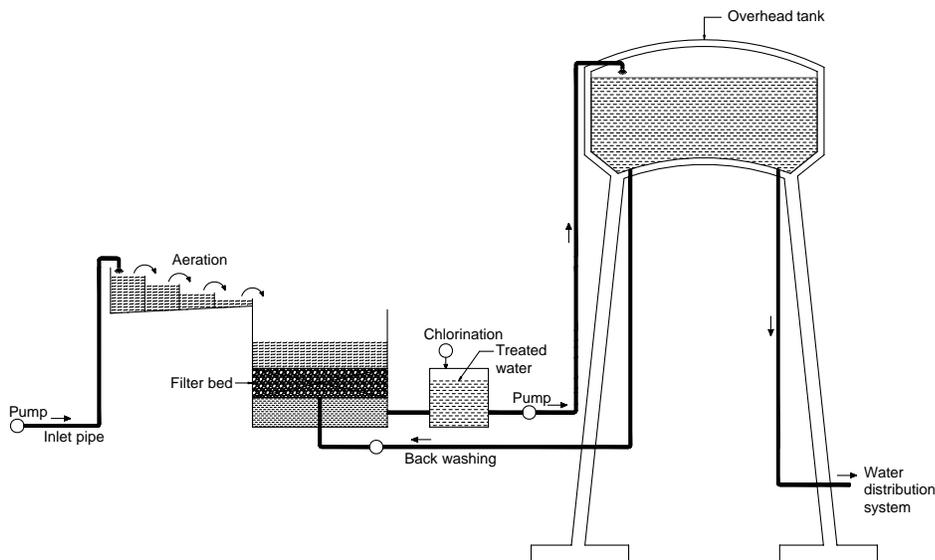


Figure 3 | 18-DTP arsenic and iron removal plant.

it fails to remove arsenic to the desired Bangladesh standard level. At present, BUET has modified the system and used 100 mg/L of ferric chloride and 1.4 mg/L potassium permanganate, and it performs very well with arsenic removal efficiency up to 94% (Rahman *et al.* 2003).

Steven institute technology

Supplied chemicals (reported to be iron sulfate and calcium hypochloride) in packets are mixed in one bucket and the mixture is transferred to another bucket (Figure 5) to separate flocs by the processes of sedimentation and

Table 3 | Arsenic and iron removal efficiencies in 18-DTP AIRPs (Rahman *et al.* 2003)

| Municipality | Influent Fe (mg/L) | Influent As ($\mu\text{g/L}$) | Fe removal efficiency (%) | As removal efficiency (%) | As in treated water ($\mu\text{g/L}$) |
|------------------|--------------------|---------------------------------|---------------------------|---------------------------|-----------------------------------------|
| Manikganj | 7.6 | 85 | 99 | 72 | 24 |
| Sathkhira Polash | 5.8 | 68 | 95 | 67 | 22 |
| Sathkhira Razzak | 3.4 | 57 | 95 | 51 | 28 |

Table 4 | Installation, operation and maintenance costs of selected presently operating water supply options (Rahman *et al.* 2003)

| Technological option | Unit cost (US\$) | Population served | Installation cost (US\$/person) | Operation and maintenance cost (US\$/person/yr) |
|----------------------------------------|------------------|-------------------|---------------------------------|-------------------------------------------------|
| Rainwater harvesting | 106 | 5 | 21.2 | 0.34 |
| Dug well | 560 | 120–150 | 4.0 | 0.01 |
| Manikgonj AIRP including overhead tank | 223,534 | 60,000 | 3.7 | – |
| PSF | 560 | 150–200 | 3.2 | 0.04 |
| Small-community type AIRP | 140 | 40–50 | 3.1 | 0.07 |
| Deep tubewell | 775 | 250–300 | 2.8 | 0.05 |
| Shrouded tubewell | 175 | 100–120 | 1.4 | 0.10 |
| Shallow tubewell | 105 | 120–150 | 0.8 | 0.06 |

Note: 1US\$ = 58 Bangladesh Taka.

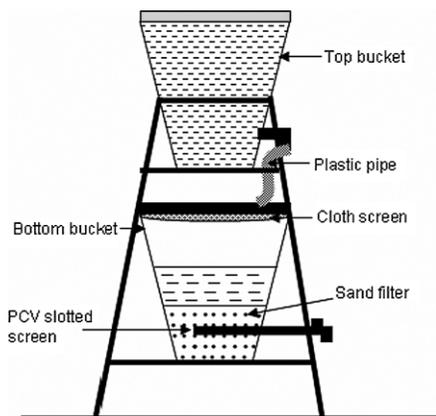


Figure 4 | Double bucket household unit.

filtration. The rapid assessment of this technology by BAMWSP, DFID & WaterAid (2001) showed that this technology was effective in reducing arsenic levels to less than 50 µg/L in the case of 80–95% of the samples tested. But the sand bed used for filtration is quickly clogged and requires washing at least twice a week.

Sono/pitcher filter

The Sono 3-pitchers (Kolshi) filter uses zero-valent iron filling and coarse sand in the top pitcher, and charcoal and fine sand in the middle pitcher (Figure 6). The bottom pitcher is used to store the treated water. The arsenic removal efficiencies of this system are in the range of 59–95% but it depends on the maintenance of the system and the quality of influent water. But if batches are left for too long, dissolved iron concentrations become unacceptably high (Ramswami *et al.* 2000). The rapid assessment of this technology by BAMWSP, DFID & WaterAid (2001)

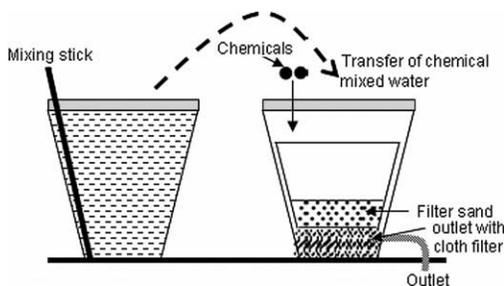


Figure 5 | Stevens Institute Technology.

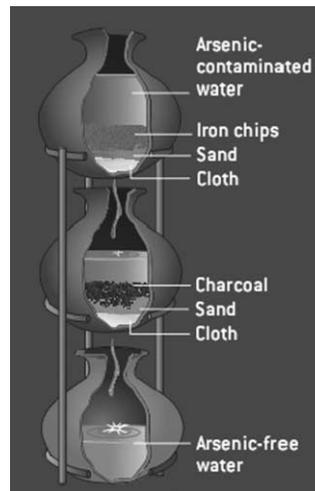


Figure 6 | Three-pitcher filter (Chowdhury 2004).

showed that this technology was effective in removing arsenic, but the system may quickly be clogged if groundwater contains excessive iron. Recently some NGOs are taking more initiatives to popularize this system in arsenic-affected areas. The applicability of these arsenic removal units should be determined through close field monitoring.

Activated alumina

Arsenic is removed by sorptive filtration through activated alumina. Some units use pretreatment (for example, oxidation, sand filtration) to increase efficiency. The Alcan enhanced activated alumina unit is simple and robust in design. No chemicals are added during treatment and the process relies wholly on the active surface of the media for adsorption of arsenic from water. Other ions present in natural water, such as iron and phosphate, may compete for active sites on alumina and reduce the arsenic removal capacity of the unit. Iron present in shallow tubewell water at elevated levels will eventually accumulate in an activated alumina bed and interfere with the flow of water through the bed. This unit can produce more than 3,600 L of arsenic-safe drinking water per day for 100 families. Apyron Technologies Inc. (USA) has developed an arsenic treatment unit in which its Aqua-Bind™ medium is used for arsenic removal from groundwater. Aqua-Bind contains activated alumina and manganese oxides that can selectively remove As(III) and As(V). The BUET-activated

alumina units have oxidation and prefiltration provisions prior to filtration through activated alumina.

Read-F arsenic removal unit

Read-F is an adsorbent produced and promoted by a company (Shin Nihon Salt Co. Ltd./Nihon Kaisui Co. Ltd, Japan), which efficiently adsorbs arsenic (both arsenate and arsenite).

Granular ferric hydroxide

Granular ferric hydroxide (AdsorpAs) is a highly effective adsorbent used for the adsorptive removal of arsenate, arsenite and phosphate from natural water. It has an adsorption capacity of 45 g/kg for arsenic and 16 g/kg for phosphorus on a dry weight basis (Pal 2001). M/S Pal Trockner (P) Ltd, India, and Sidko Limited, Bangladesh, have installed several granular ferric hydroxide-based arsenic removal units in India and Bangladesh. The proponents of the unit claim that AdsorpAs has a very high arsenic removal capacity and produces relatively small amounts of residual spent media. The typical residual mass of spent AdsorpAs is in the range of 5–25 g/m³ of treated water. The typical arrangement of the Sidko/Pal Trockner unit (Figure 7) requires aeration for the oxidation of water and prefiltration for the removal of iron flocs before filtration through the active media. Chemicon and Associates has developed and marketed an arsenic removal plant based on adsorption technology in which crystalline ferric oxide is used as an adsorbent. The unit has a prefiltration unit containing manganese oxide for oxidation of As(III) to As(V) and retention of iron precipitates.

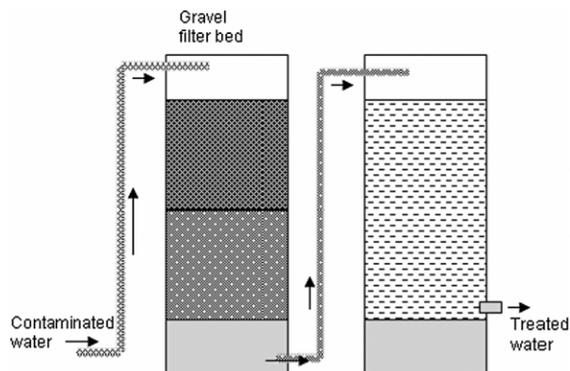


Figure 7 | Granular ferric hydroxide unit.

Ion exchange

The Tetrahedron, Inc. (Tretreat) ion exchange resin filter tested under the rapid assessment program in Bangladesh (BAMWSP, DFID & WaterAid 2001) showed promising results in arsenic removal. The performance and applicability of these arsenic removal units (Figure 8) should be determined through close field monitoring.

DPHE-Danida fill and draw unit

The fill and draw system is a community-level treatment unit designed and installed under the DPHE–Danida Project. It has a 600 L capacity (effective) tank with a slightly tapered bottom for collection and withdrawal of settled sludge (Figure 9). The tank is fitted with a manually operated mixer with flat blade impellers. The tank is filled with arsenic-contaminated water and the required quantities of oxidant and coagulant are added to the water. The water is then mixed for 30 s by rotating the mixing device at a rate of 60 revolutions per minute (rpm) and left overnight for sedimentation. The settled water is then drawn through a pipe fitted at a level a few inches above the bottom of the tank and passed through a sand bed, and is finally collected through a tap for drinking. The mixing and flocculation processes in this unit are better controlled to effect higher removal of arsenic. The experimental units installed by the DPHE–Danida Project are serving clusters of families and educational institutions.

Membrane technique

Wide spectrum reverse osmosis systems include Reid System Limited as well as MRT-1000 manufactured by

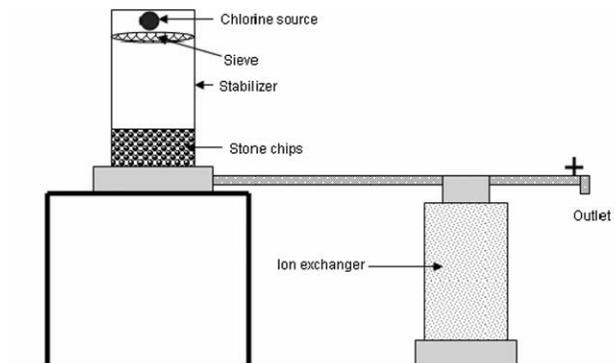


Figure 8 | Tetrahedron unit.

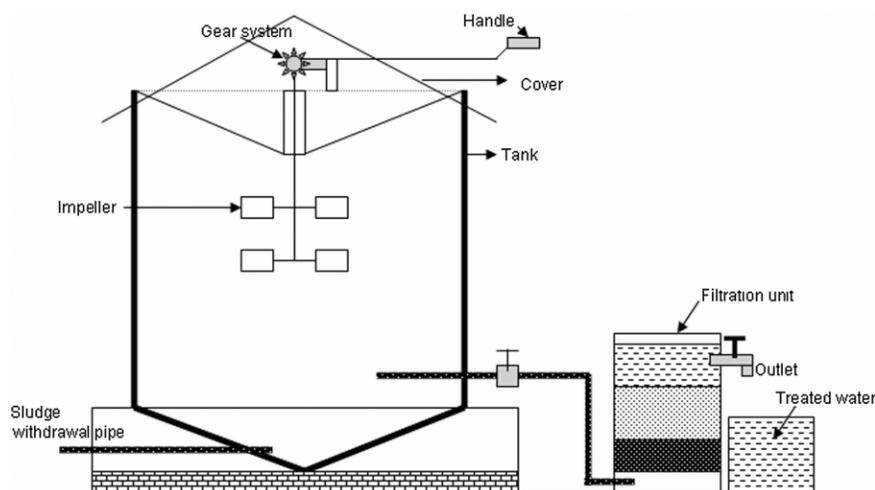


Figure 9 | DPHE–Danida fill and draw unit.

B & T Science Co. Ltd., Taiwan are promoted in Bangladesh. A nanofiltration process coupled with a bicycle pumping system was examined by *Oh et al. (2000a, b)* using arsenic-contaminated tubewell water in a rural area of Bangladesh. Arsenite was found to have a lower removal rate than arsenate in ionized form. But the capital and operational costs of these systems are relatively high.

Other arsenic removal technologies

To mitigate arsenic contamination problems in Bangladesh, a number of organizations and industries have been trying to develop indigenous arsenic removal systems and chemicals including:

- Bangladesh Council of Scientific and Industrial Research (BCSIR) filter unit,
- Sapla filter,
- Shafi filter,
- Granet home-made filter,
- Adarsha filter,
- Bijoypur clay filter,
- several cartridge filters,
- iron coated sand,
- tourmaline mineral, etc.

The performance and applicability of these arsenic removal units and chemicals should be determined through close field monitoring.

The Government of Bangladesh established environmental technology verification for arsenic mitigation (ETV-AM) with assistance from CIDA. They evaluated five technologies, and out of them Alkan, Sono-3-Kolshi, Read-F and SIDKO received provisional verification certificates. The second phase of the verification task has been started with the aim to verify 7–10 more technologies currently used in use in Bangladesh (APSU 2005). The performance of all the above-mentioned mitigation technologies of arsenic critically depend on the cost incurred by the local population. Table 5 shows a comparison of arsenic removal mechanisms and costs in Bangladesh.

COMPARISON OF ARSENIC REMOVAL TECHNOLOGIES PRACTISED IN BANGLADESH

As has been mentioned in the earlier section, in Bangladesh many technologically sound methods have been adopted by users. The relative advantages and disadvantages of different arsenic removal processes are compared in Table 6, where it is evident that even membrane nanofiltration technology may give the highest removal efficiency of arsenic, but it is imperative to consider the cost, especially for developing country like Bangladesh. The comparison of arsenic removal mechanisms considering cost is presented in Table 5 (World Bank 2008). Since the removal of arsenic primarily depends on the initial concentration of arsenic in water, the term ‘removal efficiency’ represents the reducing

Table 5 | Comparison of arsenic removal mechanisms and costs in Bangladesh (World Bank 2008)

| Type of unit | Removal mechanism | Type | Capital cost/unit (US\$) | Operation and maintenance costs/family/year (US\$) |
|---------------------------------------------|----------------------------------------------------|--------------------------------------|--------------------------|----------------------------------------------------|
| Arsenic removal unit for urban water supply | Aeration, sedimentation, rapid filtration | Urban water supply (6000 households) | 240,000 | 1–1.5 |
| Iron-arsenic removal plant | Aeration, sedimentation, rapid filtration | Community (10 households) | 200 | 1 |
| Fill and draw | Oxidation and coagulation-sedimentation-filtration | Household | 250 | 15 |
| Bucket treatment unit | Oxidation and coagulation-sedimentation-filtration | Household | 6–8 | 25 |
| Sono 45–25 | Adsorption by oxidized iron chips and sand | Household | 13 | 0.5–1.5 |
| Shapla filter | Adsorption of iron-coated brick chips | Household | 4 | 11 |

arsenic concentration at 0.05 mg/L or less than of this concentration from the sources which has more than 0.05 mg/L concentration of arsenic.

ALTERNATIVE WATER SUPPLY OPTIONS

Deep tubewell

The aquifers in Bangladesh are stratified and the deep aquifers are separated from the shallow ones by impermeable layers so arsenic-free groundwater is found in the deep aquifers except for a very few places in the north-western region. In the case of tested water samples collected from deep tubewells (strainer depth > 150 m), only 1% and 5% samples (Table 1) exceed the allowable limits of 50 µg/L and 10 µg/L, respectively. These deep tubewells are more expensive compared to shallow tubewells, but they appear to be cost-effective compared to other options presented in Table 4.

Shallow shrouded tubewell and very shallow shrouded tubewell

In many areas of Bangladesh, groundwater with low arsenic content is available in shallow or in very shallow aquifers composed of fine sand. The particle sizes of the soil are not suitable for installing a normal tubewell. An artificial sand packing is required around the screen of the tube well to get water through these very fine-grained aquifers (Figure 10). This artificial sand packing is called shrouding. Shrouding

increases the yield of the tubewell and prevents the entry of fine sand into the screen.

Infiltration gallery/well

In this technology water is allowed to infiltrate through a layer of soil/sand and so it is significantly free from suspended impurities including microorganisms usually present in surface water. Infiltration galleries can be constructed near perennial rivers or ponds. 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 the surface water source for rapid flow of water. Improvement of water quality requires good sanitary protection and disinfecting by chlorinating.

Dug well

The dug well is the most traditional method of withdrawal of groundwater in many countries of the world for domestic water supply. But degradation of dug well water quality by bacterial contamination is very common. Percolation of contaminated surface water is the most common route of pollution of well water. Satisfactory protection against bacteriological contamination is possible by sealing the well top with a watertight concrete slab (Figure 11). Water may be withdrawn by installation of a manually operated hand pump rather than the conventional bucket and rope, and then the system becomes more expensive (Table 4).

Table 6 | Comparison of As removal technologies

| Type of unit | Advantages | Disadvantages | Removal efficiency (%) |
|--------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|------------------------|
| Passive sedimentation, <i>In situ</i> oxidation, solar oxidation | Oxidizes the impurities and kills bacteria | Removal efficiency is relatively low and hence widely practised as pretreatment process in large scale treatment system | 50–60% |
| Activated alumina, ion exchange, Read-F, granular ferric hydroxide | Relatively simple technology, maintenance easy but slow process | | |
| | Available technology in the commercial market | Not applicable containing phosphate water | About 50% |
| AIRPs | Simple technology | Sludge is relatively higher | |
| | Easy practise by the user | Relatively high cost | |
| | Relatively simple in operation using hand tube-well | Sometimes maintenance is clumsy by the users | About 60–75% |
| Bucket/Sono filter | Able to serve small community demand of drinking water | Sludge is generated | |
| | Can remove iron also | Maintenance is critical considering efficiency | |
| | Very simple technology | The beneficiary people of the community need to contribute equally, which is sometimes difficult to find in the rural area | More than 90% |
| Coagulation and filtration | Household purpose use | Maintenance is needed considering scale of treatment | |
| | Removal efficiency is relatively higher | Removal efficiency is mostly depend on the maintenance of the system | |
| | Very cheap | Not applicable containing phosphate water | More than 80% |
| Membrane technology | Relatively simple in operation | Toxic sludge generation | |
| | Chemicals are available in the commercial market | Removal efficiency is relatively low | |
| | Low cost | High technology | More than 95% |
| | High removal efficiency of As removal. | High capital and operation cost | |
| | Applicable to large scale treatment. | Arsenic-rich rejected water is produced | |
| | Ability to disinfect other impurities and microbes. | May not be suitable to use in rural household areas | |
| | No toxic sludge | | |

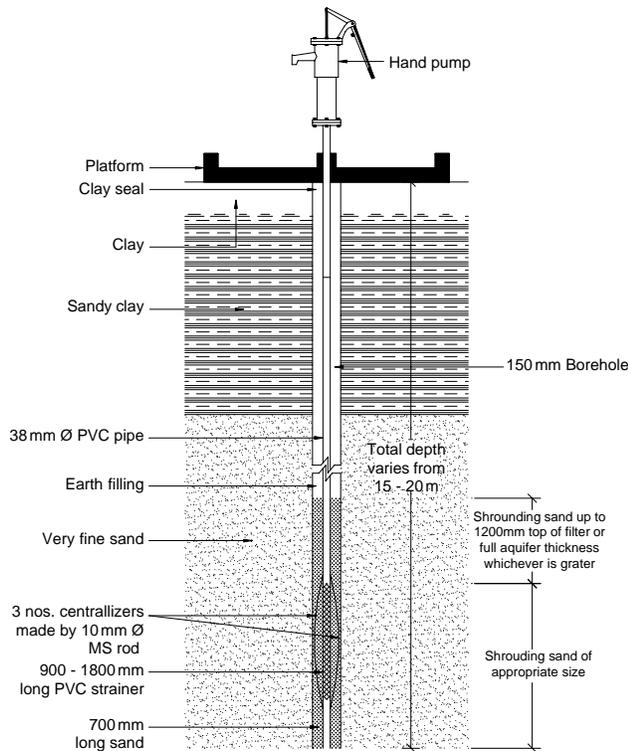


Figure 10 | Shallow shrouded tubewell.

Chlorination of the dug well is an effective means of disinfecting the water in the dug well.

Pond sand filters

Pond sand filters (PSFs, Figure 12) are basically scaled-down slow sand filters for community water supplies. They were initially developed in Bangladesh to treat low-saline pond water for domestic water supply. Slow sand filters are installed near or on the bank of a pond, which does not dry up in the dry season. The water from the pond is pumped by a manually operated hand tubewell to feed the filter bed, which is raised from the ground, and the treated water is collected through tap(s). It is tested and found that the treated water from a PSF is normally bacteriologically safe or within tolerable limits. On average, the operating period of a PSF between cleaning is usually two months, after which the sand in the bed needs to be cleaned and replaced. The treated water may require chlorinating to meet drinking water standards. The average installation, operation and maintenance costs of a typical PSF are shown in Table 4.

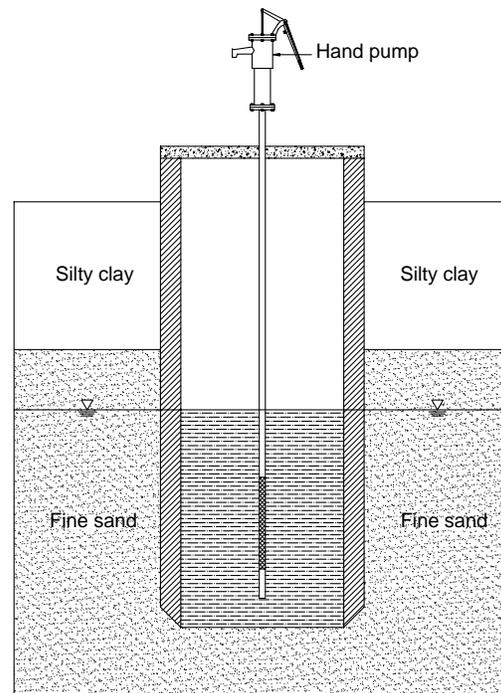


Figure 11 | Dug well.

Conventional surface water treatment plant

This may include slow sand or rapid sand filtration process. Surface water is arsenic-safe but often contains pathogenic organisms of immediate health concerns, and perennial water sources are not available in many places in Bangladesh and the investment cost is also high.

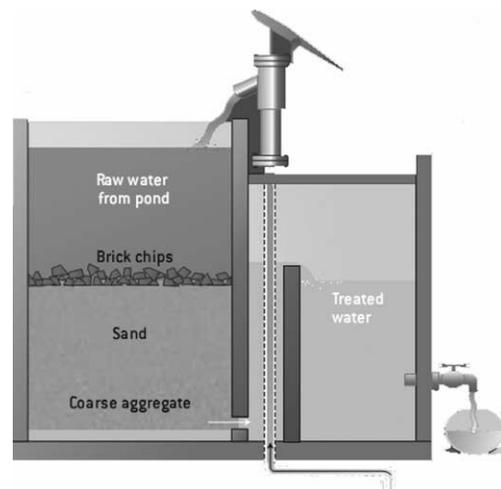


Figure 12 | Ponds sand filter.

Household/pitcher filters

Pitcher filters are constructed by stacking a number of pitchers (Kolshis), one above the other, containing different filter media as discussed earlier. Raw water is poured in the top Kolshi and filtered water is collected from the bottom one. Full effectiveness of the filtration process is obtained if the media remain in water all the time. Experimental units constructed in Bangladesh and in other countries show that the residual coliform bacteria present in the filtered water may vary from a few to several hundred (Rahman *et al.* 2003). However, improvement in general water quality by household filters is remarkable.

Solar disinfection

This is a natural process of elimination of disease-producing microorganisms using solar energy. If solar radiation is allowed to penetrate the water in a thin layer, the water is disinfected by the combined action of ultraviolet rays and temperature. If water in a transparent bottle is exposed to full sunlight for about 5 h the water is completely disinfected (EAWAG–SANDEC 1998). This method is not suitable for treatment of large volumes of water containing high turbidity.

Rainwater harvesting

In some areas of the coastal region in Bangladesh with high salinity problems, about 36% of households have been found to practise rainwater harvesting in the rainy season for drinking purpose (Hussain & Ziauddin 1989). In the present context, rainwater harvesting (Figure 13) is being seriously considered as an alternative option for water supply in Bangladesh in arsenic-affected areas. In the context of Bangladesh there are a number of advantages in favour of considering rainwater harvesting as an alternative technology. The quality of rainwater is usually good. Water is available at the point of demand and is suitable for scattered settlements. Locally available manpower and physical resources can be utilised for the development and construction of the plants. Since the water stored in the plant is situated at a higher elevation, no additional cost is involved for distribution or to send it to the users' end. There are, however, shortcomings regarding



Figure 13 | Rainwater harvesting.

the quantity, which is limited by the rainfall, and the storage system is expensive (Table 4).

Solar distillation

Experiments with solar distillation plants by Rahman (1998) showed that the average yield of a conventional solar desalination plant was around 1.4 L/m²/d. The water produced by this method is free from all chemicals including arsenic but this technology cannot produce enough water at a reasonable cost.

From the above descriptions, it is evident that there are many available options for alternative water supplies in order to get arsenic-free water. The relative advantages and disadvantages of these options are summarized in Table 7.

PROVISION OF SUSTAINABLE SAFE DRINKING WATER

The information regarding the number of mitigation/safe-water options installed (Table 8) was collected by APSU

(2005) from approximately 120 different projects/programs/pilot projects implemented by different organizations in arsenic-contaminated areas of Bangladesh. However, a few of them are general water supply improvement projects. Considering 10 households for AIRPs, rainwater harvesting for individual household and 50 households for other options in Table 8, it is estimated that these mitigation options can serve more than 4.55 million of the population or 38% of the total households in arsenic-affected areas. In addition to these water supply options (Table 8), more than 20,000 household-level arsenic removal filters and more than 100 community-based arsenic removal technologies have been operating in Bangladesh. It is apparent from Table 8 that groundwater is the main source of drinking water even in severely arsenic-contaminated areas, where more than 80% of the total (106,939) installed arsenic mitigation/safe-water options are: tubewells (70%), dug wells (5.9%), shallow shrouded tubewells (4.8%) and arsenic-iron removal plants (3.5%). Other options such as rainwater harvesting, pond sand filters, and deep-set

pumps and piped water supply systems account for 12.5%, 3.3% and around 0.2%, respectively. It is also evident from the study conducted by Jakariya (2007), who distributed more than more than 10,000 safe-water options in upazilas (sub-districts), namely Sonargaon and Jhikargacha during 1999–2001, we can identify sustainable safe drinking water options. Around 62% of the total tested tubewells in Sonargaon and around 48% in Jhikargacha were contaminated with arsenic above the Bangladesh standard. The main safe-water options promoted there were: pond sand filters, different household filter units discussed above, rainwater harvesting and installation of tubewells in deep aquifers. The community acceptability of these distributed options was then identified by Jakariya (2007) in 2004 and found that less than 2% of the provided options were found to still be in use except for two approaches: installation of tubewells in deep aquifers and switching to the tubewells that were marked safe for drinking purposes. These two approaches had emerged from people's initiatives, which are making a rapid and positive contribution to the

Table 7 | Comparison of alternative water supply options

| Type of unit | Advantages | Disadvantages |
|----------------------|---------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Deep tubewell | Ensures arsenic-free water Maintenance easy, once construction has finished | Not applicable in the coastal zones Possibility of shifting groundwater level |
| Shallow tubewell | Available technology in the commercial market | Not applicable where the groundwater level is lower |
| | Simple technology Easy practise by the user Relatively cheaper than the deep tubewell | |
| Infiltration gallery | Able to serve small community demand of drinking water | Further disinfection is needed |
| Dug well | Very simple technology Household purpose use Very cheap | Bacteria may contaminate the water |
| Pitcher filter | Relatively simple in operation Low cost | Bacteria may contaminate the water |
| Solar disinfection | Natural process Ability to disinfect other impurities and microbes | Not suitable for large volume of water |
| Rainwater harvesting | Common in coastal areas Natural water | Possibility of contamination by bacterial after storing |

Table 8 | Mitigation/safe-water options

| | |
|-----------------------------------------------------------------------------------------------------|---------------|
| Total safe water options provided (except household filters and a few arsenic removal technologies) | 106,939 |
| Tubewells | 74,809 (70) |
| Rainwater harvesting | 13,324 (12.5) |
| Dug wells | 6268 (5.9) |
| Shallow shrouded tubewells | 5080 (4.8) |
| Arsenic-iron removal plants (AIRPs) | 3771 (3.5) |
| Pond sand filter | 3521 (3.3) |
| Deep-set pump | 133 |
| Piped water supply system | 33 |

*Figure in () indicates the (%) of total.

provision of safe drinking water in arsenic-affected areas of Bangladesh. The aquifers in Bangladesh are stratified and the deep aquifers are separated from the shallow ones by impermeable layers so arsenic-free groundwater is found in the deep aquifers except for a very few places in the north-western region. Therefore, sinking of deep tubewells appears to be a promising and sustainable option for safe drinking water from uncontaminated deep aquifers with a protective overlaying impermeable layer, which have been well accepted by the communities over the past few decades.

CONCLUSION

In a critical analysis of the existing arsenic contamination problems and available safe drinking water options that have been tried to mitigate this problem in Bangladesh, the following observations and conclusions can be made.

- The blanket screening test data of around 4.73 million tubewells (55% of the total tubewells) in around 54,000 villages (62% of the total villages) of the country shows that groundwater from approximately 1.4 million (29% of tested) tubewells are contaminated with arsenic exceeding a concentration of 50 µg/L. In the case of tested water samples collected from deep tubewells (strainer depth > 150 m), only 1% and 5% of samples exceed the allowable limits of 50 µg/L and 10 µg/L, respectively (Table 1).
- The estimated population exposed to arsenic-contaminated water above 50 µg/L and 10 µg/L is in the range of

22.4–25.9% and 37–45.2%, respectively, of the total population of the country (Table 1).

- The total number of identified arsenicosis patients in Bangladesh is around 38,000 (Table 1). The incidences of excess skin cancer are 0.321%, 0.043% and 0.012% for drinking arsenic-contaminated water at the present level arsenic of contamination, satisfying the Bangladesh standard and satisfying WHO guideline value, respectively.
- It is apparent from this study that a remarkable development in arsenic removal technologies has taken place during the last few years. These arsenic removal technologies mostly utilized principles of oxidation, precipitation/co-precipitation, adsorption onto sorptive media, ion exchange and physical separation by synthetic membranes. This study revealed that a number of arsenic removal technological options have good potential for use in small isolated communities and/or municipalities, which depends on many factors including concentrations present before removal, speciation and co-occurring solutes. But no single option can serve the whole cross section of the arsenic-affected population in Bangladesh with their diverse social and economic backgrounds.
- Sinking of deep tubewells appears to be a very promising and sustainable option for safe drinking water from uncontaminated deep aquifers with a protective overlaying impermeable layer, which is common in Bangladesh. These tubewell technologies have been well accepted by communities over the past few decades.

REFERENCES

- Ahmed, M. F., Ali, M. & Adeel, Z. (eds) 2001 *Technologies for Arsenic Removal from Drinking Water*. Bangladesh University of Engineering & Technology and United Nations University, Dhaka, Bangladesh.
- APSU 2005 *The Response to Arsenic Contamination in Bangladesh: A Position Paper*. Department of Public Health Engineering, Government of Bangladesh, Dhaka, Bangladesh.
- BAMWSP 2001 *Status Report of Bangladesh Arsenic Mitigation Water Supply, Project BAMWSP* December, Dhaka, Bangladesh.
- BAMWSP, DFID & WaterAid Bangladesh 2001 *Rapid Assessment of Household Level Arsenic Removal Technologies* Final report (Phase-I and Phase-II). WS Atkins International Ltd, Dhaka, Bangladesh.
- BGS & DPHE 2001 *Arsenic Contamination of Groundwater in Bangladesh* (Kinniburgh, D. G. & Smedly, P. L. (Eds.)). Final

- Report, British Geological Survey Report WC/00/19, V-2, UK.
- Chen, H. W., Frey, M. M., Clifford, D., McNeill, L. S. & Edwards, M. 1999 Arsenic treatment consideration. *J. AWWA* **91**(3), 74–85.
- Cheng, C. R., Liang, S., Wang, H. C. & Beuhler, M. D. 1994 Enhanced coagulation for arsenic removal. *J. AWWA* **86**(9), 79–90.
- Chowdhury, A. M. R. 2004 Arsenic crisis in Bangladesh. *Sci. Am.* (August), 87–91.
- Clifford, D. 1999 Ion exchange and inorganic adsorption. In: Letterman, R. D. (ed.) *Water Quality and Treatment*. AWWA, McGraw-Hill, New York, Chapter 9.
- DPHE, BGS & MML 1999 *Groundwater Studies for Arsenic Contamination in Bangladesh*. Final Report (Phase-I). Department of Public Health Engineering (Bangladesh), Department for International Development (UK) and British Geological Survey, Dhaka, Bangladesh.
- EAWAG–SANDEC 1998 *SODIS News* no. 3, August.
- Edwards, M. 1994 Chemistry of arsenic removal during coagulation and Fe-Mn oxidation. *J. AWWA* **86**(9), 64–78.
- 18-DTP 1999 *18 District Town Project*. DPHE-Danida project report, Dhaka.
- Hering, J. G., Cheng, P. Y., Wilkie, J. A., Elimelech, M. & Laing, S. 1996 Arsenic removal by ferric chloride. *J. AWWA* **88**(4), 155–167.
- Hering, J. G., Chen, P., Wilkie, J. A. & Elimelech, M. 1997 Arsenic removal from drinking water during coagulation. *J. Env. Eng., ASCE* **123**(8), 800–807.
- Hussain, D. & Ziauddin, A. T. M. 1989 Rainwater use in Bangladesh – a case study in Dacope Upozilla. In: *Proc. 4th International Conference on Rainwater Cistern System, Aug 1989, Manila, Philipines*. p. 15.
- Jakariya M. 2007 *Arsenic in Tubewell Water of Bangladesh and Approaches for Sustainable Mitigation*. TRITA-LWR, PhD thesis 1033, Royal Institute of Technology, Stockholm.
- Jekel, M. R. 1994 Removal of arsenic in drinking water treatment. In: Nriagu, J. O. (ed.) *Arsenic in the Environment, Part 1: Cycling and Characterization*. John Wiley & Sons, Inc., New York.
- Joshi, A. & Chaudhury, M. 1996 Removal of arsenic from groundwater by iron-oxide-coated sand. *ASCE J. Environ. Eng.* **122**(8), 769–771.
- Johnston, R. & Heijnen, H. 2001 Safe water technology for arsenic removal. In: Ahmed, M. F., Ali, M. & Adeel, Z. (eds) *Technologies for Arsenic Removal from Drinking Water*. Bangladesh University of Engineering & Technology and United Nations University, Dhaka, Bangladesh, pp. 1–22.
- Kartinen, E. O. & Martin, C. J. 1995 An overview of arsenic removal process. *J. Desal.* **103**, 79–88.
- LGD 2002 *Arsenic mitigation in Bangladesh*. Ahmed, M. F. & Ahmed, C. M. (Ed.), Local Government Division (LGD), Ministry of LGRD & Co-operatives, Government of Bangladesh, Dhaka, Bangladesh.
- Matthess, G. 1981 In-situ treatment of arsenic contaminated groundwater. *Sci. Total Environ.* **21**(99), 99–104.
- Murcott, S. 2000 *A Comprehensive Review of Low-cost, Well-water Treatment Technologies for Arsenic Removal*. Available at: <http://phys4.harvard.edu/~wilson/murcott2.html>
- Oh, J. I., Uruse, T., Kitawaki, H., Rahman, M. M., Rahman, M. H. & Yamamoto, K. 2000a Modeling of arsenic rejection considering arsenic rejection considering affinity and steric effect in nanofiltration membranes. *Wat. Sci. Technol.* **42**(3–4), 173–180.
- Oh, J. I., Yamamoto, K., Kitawaki, H., Nakao, S., Sugawara, T., Rahman, M. M. & Rahman, M. H. 2000b Application of low-pressure nanofiltration coupled with a bicycle pump for the treatment of arsenic-contaminated groundwater. *J. Desal.* **132**, 307–314.
- Pontius, F. W. 1990 *Water Quality Treatment: a handbook of community water supplies*. American Water Works Association, McGraw-Hill, New York.
- Rahman, M. H. 1998 Pilot desalination project: Bangladesh. *WHO Regional Publ., (Research Abstracts) Southeast Asia Series* **16**(5), 11–15.
- Rahman, M. H. & Al-Muyeed, A. 2005 Strategy to mitigate As exposure from drinking water. *J. Wat. Supply Res. Technol.* *AQUA* **54**(6), 397–401.
- Rahman, M. H., Rahman, M. M., Watanabe, C. & Yamamoto, Y. 2003 Arsenic contamination of groundwater in Bangladesh and its remedial measures. *Proc. UNU-NIES International Workshop on Arsenic Contamination in Groundwater-Technical and Policy Dimensions*. United Nations University, Tokyo, Japan, pp. 145.
- Ramswami, A., Isleyen, M. & Tawachsupa, S. 2000 Zero-valent iron for treatment of high arsenic water. In: *Proc. 4th International Conference on Arsenic Exposure and Health Effects, SEGH, San Diego, CA, Society of Geochemistry and Health, USA*. pp. 96–102.
- Rott, U. & Friedle, M. 1999 Eco-friendly and cost-efficient Removal of Arsenic, Iron and Manganese by means of Subterranean Groundwater Treatment. In: *Proceedings, IWSA XXII World Congress and Exhibition, Buenos Aires, Argentina*.
- Safiuddin, M. & Karim, M. 2001 Groundwater arsenic contamination in Bangladesh: cause, effects and remediation. *Proc. 1st IEB Int. Conf., Chittagong, Bangladesh*. Inst. of Engineers, Bangladesh, p. 25.
- Shen, Y. S. 1973 Study of arsenic removal from drinking water. *J. AWWA* **65**(8), 543–548.
- Sorg, T. J. & Logsdon, G. S. 1978 Treatment technology to meet the interim primary drinking water regulations for inorganics: Part 2. *J. AWWA* **70**(7), 379–393.
- UNICEF 2007 *Arsenic Mitigation in Bangladesh*. Available at: <http://www.unicef.org/bangladesh/Arsenic.pdf>
- Waypa, J., Elimelech, M. & Hering, J. G. 1997 Arsenic removal by RO and NF membranes. *J. AWWA* **89**(10), 102–114.
- World Bank 2008 *Arsenic Mitigation Technologies in South and East Asia*. World Bank Report vol III, paper III, pp. 168–186.