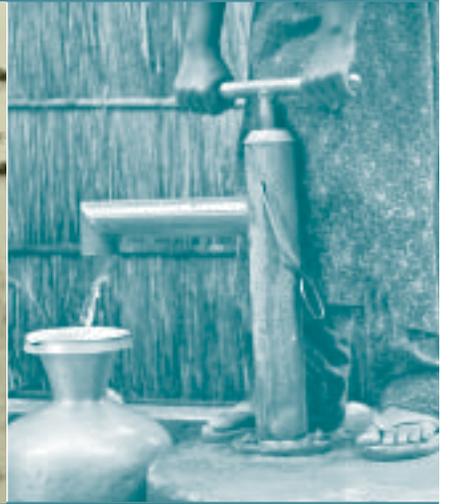


Paper 3

Arsenic Mitigation Technologies in South and East Asia

This paper was prepared by Professor Feroze Ahmed (Bangladesh University of Engineering and Technology) with contributions from Khawaja Minnatullah (World Bank/WSP) and Amal Talbi (World Bank).



Summary

1. This paper presents the technologies for treatment of arsenic-contaminated water, arsenic detection and measurement technologies, and alternative safe water options. After a brief introduction (chapter 1), chapter 2 examines the principles of arsenic removal from drinking water and explores the major technologies associated with each. Chapter 3 describes the laboratory and field methods of arsenic detection and measurement. Chapter 4 presents alternative options for arsenic-safe water supplies. Chapter 5 analyzes some operational issues related to the mitigation options presented in the paper.
2. The objective of the paper is to provide technical staff in governments, development organizations, nongovernmental organizations and other interested stakeholders with up-to-date information on the technical aspects of arsenic mitigation in order to familiarize them with the most commonly used mitigation methods. For treatment of arsenic-contaminated water, there are four basic processes: (a) oxidation-sedimentation; (b) coagulation-sedimentation-filtration; (c) sorptive filtration; and (d) membrane techniques. For alternative water supply options, there are four main options: (a) use of an alternative safe aquifer, accessed by a deep tubewell or dug well; (b) use of surface water employing, for example, a pond sand filter or multistage filters; (c) use of rainwater; and (d) piped water supply based on either ground or surface water.
3. The paper is designed as a tool to inform the decision-making process when deciding which arsenic mitigation option is best suited to a particular project. It lays out the advantages and disadvantages of each mitigation method, and the related operational issues.



1. Introduction

Arsenic is present in the environment and humans all over the world are exposed to small amounts, mostly through food, water, and air. But the presence of high levels of arsenic in groundwater, the main source of drinking water in many countries around the world, has drawn the attention of the scientific community. Groundwater, free from pathogenic microorganisms and available in adequate quantity via tubewells sunk in shallow aquifers in the flood plains, provides low-cost drinking water to scattered rural populations. Unfortunately, millions are exposed to high levels of inorganic arsenic through drinking this water. It has become a major public health problem in many countries in South and East Asia and a great burden on water supply authorities. Treatment of arsenic contamination of water, in contrast to that of many other impurities, is difficult, particularly for rural households supplied with scattered handpump tubewells. In developing countries like Bangladesh and India the high prevalence of contamination, the isolation and poverty of the rural population, and the high cost and complexity of arsenic removal systems have imposed a programmatic and policy challenge on an unprecedented scale.

Source substitution is often considered more feasible than arsenic removal. The use of alternative sources requires a major technological shift in water supply. Treatment of arsenic-contaminated water for the removal of arsenic to an acceptable level is one of the options for safe water supply. Since the detection of arsenic in groundwater, a lot of effort has been mobilized for treatment of arsenic-contaminated water to make it safe for drinking. During the last few years many arsenic detection and test methods and small-scale arsenic removal technologies have been developed, field-tested, and used under different programs in developing countries. This short review of these technologies is intended as an update of the technological developments in arsenic testing, arsenic removal, and alternative water supplies. It is hoped that the review will be of assistance to those involved in arsenic mitigation in South and East Asian countries.

2. 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 value 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 difficult to remove from water by most techniques.

There are several methods available for removal of arsenic from water in large conventional treatment plants. The most commonly used processes of arsenic removal from water have been described by Cheng and others (1994), Hering and others (1996), Hering and others (1997), Kartinen and Martin (1995), Shen (1973), and Joshi and Chaudhuri (1996). A detailed review of arsenic removal technologies has been presented by Sorg and Logsdon (1978). Jekel (1994) has documented several advances in arsenic removal technologies. In view of the lowering of the standard of the United States 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 and others 1999). Many of the arsenic removal technologies have been discussed in details 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, Ali, and Adeel (2001), Johnston, Heijnen, and Wurzel (2000), and Ahmed (2003). The AWWA conducted a comprehensive study on arsenic treatability options and evaluation of residuals management issues (AWWA 1999).

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 four categories:

- Oxidation and sedimentation
- Coagulation and filtration
- Sorptive filtration
- Membrane filtration

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

Oxidation-Sedimentation Processes

Most treatment methods are effective in removing arsenic in pentavalent form and hence include an oxidation step as pretreatment to convert arsenite to arsenate. Arsenite can be oxidized by

oxygen, ozone, free chlorine, hypochlorite, permanganate, hydrogen peroxide, and Fulton's reagent, but atmospheric oxygen, hypochloride, and permanganate are commonly used for oxidation in developing countries. The oxidation processes convert predominantly noncharged arsenite to charged arsenate, which can be easily removed from water.

Atmospheric oxygen is the most readily available oxidizing agent and many treatment presses prefer oxidation by air. But air oxidation of arsenic is a very slow process and it can take weeks for oxidation to occur (Pierce and Moore 1982). Air oxidation of arsenite can be catalyzed by bacteria, strong acidic or alkali solutions, copper, powdered activated carbon, and high temperature (Edwards 1994). Chemicals such as chlorine and permanganate can rapidly oxidize arsenite to arsenate under a wide range of conditions. Hypochloride is readily available in rural areas but the potency (available chlorine) of the hypochloride decreases when it is poorly stored. Potassium permanganate is also readily available in developing countries. It is more stable than bleaching powder and has a long shelf life. Ozone and hydrogen peroxide are very effective oxidants but their use in developing countries is limited. Filtration of water through a bed containing solid manganese oxides can rapidly oxidize arsenic without releasing excessive manganese into the filtered water.

In situ oxidation of arsenic and iron in the aquifer has been tried in Bangladesh under the Arsenic Mitigation Pilot Project of the Department of Public Health Engineering (DPHE) and the Danish Agency for International Development (Danida). The aerated tubewell water is stored in feed water tanks and released back into the aquifers through the tubewell by opening a valve in a pipe connecting the water tank to the tubewell pipe under the pump head. The dissolved oxygen in water oxidizes arsenite to less-mobile arsenate and the ferrous iron in the aquifer to ferric iron, resulting in a reduction of the arsenic content in tubewell water. Experimental results show that arsenic in the tubewell water following in situ oxidation is reduced to about half due to underground precipitation and adsorption on ferric iron. The method is chemical free and simple and is likely to be accepted by the people but the method is unable to reduce arsenic content to an acceptable level when arsenic content in groundwater is high.

Chlorine and potassium permanganate are used for oxidation of As(III) to As(V) in many treatment processes in Bangladesh and India. SORAS (solar oxidation and removal of arsenic) is a simple method of solar oxidation of arsenic in transparent bottles to reduce arsenic content of drinking water (Wegelin and others 2000). Ultraviolet radiation can catalyze the process of oxidation of arsenite in the presence of other oxidants such as oxygen (Young 1996). Experiments in Bangladesh show that the process on average can reduce the arsenic content of water to about one-third of the original concentration.

As a process, passive sedimentation has received considerable attention because of rural people's habit of drinking stored water from pitchers. Oxidation of water during collection and subsequent storage in houses may cause a reduction in arsenic concentration in stored water. Experiments conducted in Bangladesh showed zero to high reductions in arsenic from drinking water by passive sedimentation. Arsenic reduction by plain sedimentation appears to be

dependent on water quality and in particular the presence of alkalinity and precipitating iron in water. Passive sedimentation, in most cases, failed to reduce arsenic to the desired level of $50 \mu\text{g L}^{-1}$ in a rapid assessment of technologies conducted in Bangladesh (BAMWSP-DFID-WaterAid 2001).

Coagulation-Sedimentation-Filtration Processes

In the process of coagulation and flocculation, arsenic is removed from solution through three mechanisms:

- Precipitation: The formation of insoluble compounds
- Coprecipitation: The incorporation of soluble arsenic species into a growing metal hydroxide phase
- Adsorption: The electrostatic binding of soluble arsenic to external surfaces of the insoluble metal hydroxide (Edwards 1994)

Precipitation, coprecipitation, and adsorption by coagulation with metal salts and lime followed by filtration is a well-documented method of arsenic removal from water. This method can effectively remove arsenic and many other suspended and dissolved solids from water, including iron, manganese, phosphate, fluoride, and microorganisms, reducing turbidity, color, and odor and resulting in a significant improvement in water quality. Thus removal of arsenic from water using this method is associated with other ancillary health and aesthetic benefits.

Water treatment with coagulants such as aluminium alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$), ferric chloride (FeCl_3), and ferric sulfate ($\text{Fe}_2(\text{SO}_4)_3 \cdot 7\text{H}_2\text{O}$) is effective in removing arsenic from water. Oxidation of As(III) to As(V) is required as a pretreatment for efficient removal. It has been suggested that preformed hydroxides of iron and aluminium remove arsenic through adsorption, while in situ formation leads to coprecipitation as well (Edwards 1994). In alum coagulation the removal is most effective in the pH range 7.2–7.5, and in iron coagulation efficient removal is achieved in a wider pH range, usually between 6.0 and 8.5 (Ahmed and Rahaman 2000). The effects of cations and anions are very important in arsenic removal by coagulation. Anions compete with arsenic for sorptive sites and lower the removal rates. Manning and Goldberg (1996) indicated the theoretical affinity at neutral pH for anion sorption on metal oxides as:



The presence of more than one anion can have a synergistic effect on arsenic removal. Addition of either silicate or phosphate has some effects on arsenic removal but presence of both can reduce arsenate removal by 39% and arsenite removal by 69% (Meng, Bang, and Korfiatis 2000). Based on arsenic removal studies in Bangladesh, Meng and Korfiatis (2001) concluded that elevated levels of phosphate and silicate in Bangladesh well water dramatically decreased adsorption of arsenic by ferric hydroxides.

The technologies developed based on the coagulation-sedimentation-filtration process include:

- Bucket treatment unit
- Stevens Institute technology
- Fill and draw treatment unit
- Tubewell-attached arsenic treatment unit
- Iron-arsenic treatment unit

The bucket treatment unit, developed by the DPHE-Danida Project and improved by the Bangladesh University of Engineering and Technology (BUET), is based on coagulation, coprecipitation, and adsorption processes. It consists of two buckets, each with a capacity of 20 liters, placed one above the other. Chemicals are mixed manually with arsenic-contaminated water in the upper red bucket by vigorous stirring with a wooden stick and then flocculated by gentle stirring for about 90 seconds. The mixed water is allowed to settle and then flow into the lower green bucket and water is collected through a sand filter installed in the lower bucket. The modified bucket treatment unit shown in figure 1 has been found to be very effective in removing iron, manganese, phosphate, and silica along with arsenic.

The Stevens Institute technology also uses two buckets, one to mix chemicals (iron coagulant and hypochloride) supplied in packets and the other to separate flocs using the processes of sedimentation and filtration (figure 2 see page 174). The second bucket has an inner bucket with slits on the sides to help sedimentation and keep the filter sand bed in place. The chemicals form visible large flocs when mixed (by stirring with a stick). Clean water is collected through a plastic pipe fitted with an outlet covered with a cloth filter to prevent the entry of sand. The efficiency of the system has been described by Meng and Korfitis (2001).

Figure 1. Double Bucket Household Arsenic Treatment Unit (Ali and Others, 2001)

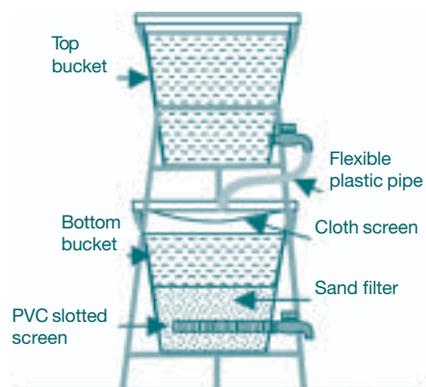
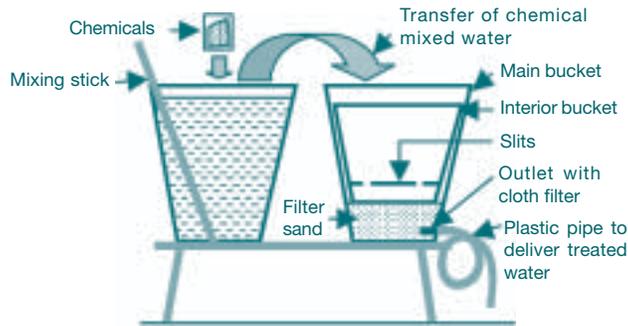


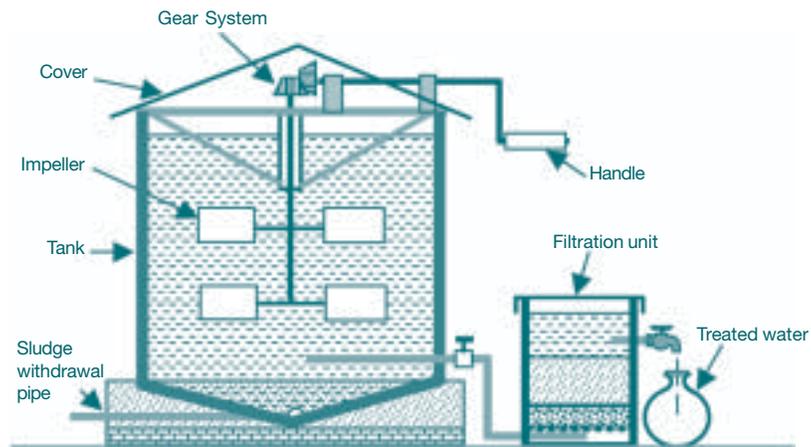
Figure 2. Stevens Institute Technology (Drawn by Ahmed, 2003)



The fill and draw system is a community-level treatment unit designed and installed under the DPHE-Danida Project. It has a 600 liter capacity (effective) tank with a slightly tapered bottom for collection and withdrawal of settled sludge (figure 3). The tank is fitted with a manually operated mixer with flat blade impellers. The tank is filled with arsenic-contaminated water and the required quantity of oxidant and coagulant are added to the water. The water is then mixed for 30 seconds by rotating the mixing device at the 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.

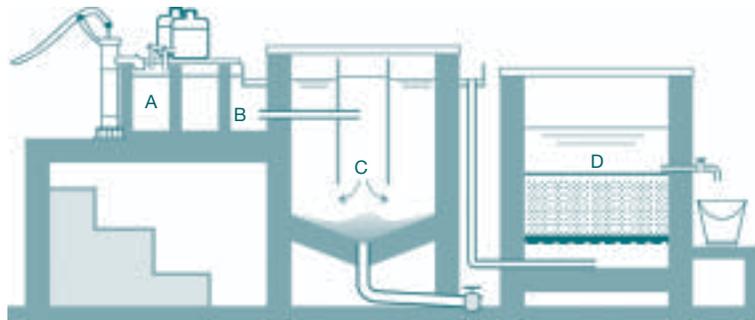
The tubewell-attached arsenic removal unit was designed and installed by the All India Institute of Hygiene and Public Health (AIIPH&PH) (figure 4). The principles of arsenic removal by alum

Figure 3. DPHE-Danida Fill and Draw Arsenic Removal Unit (Drawn by Ahmed, 2003)



coagulation, sedimentation, and filtration have been employed in this compact unit for water treatment at the village level in West Bengal, India. The arsenic removal plant, attached to a handpump-operated tubewell, has been found effective in removing 90% of the arsenic from tubewell water. The treatment process involves the addition of sodium hypochloride (Cl₂) and aluminium alum in diluted form, mixing, flocculation, sedimentation, and upflow filtration in a compact unit.

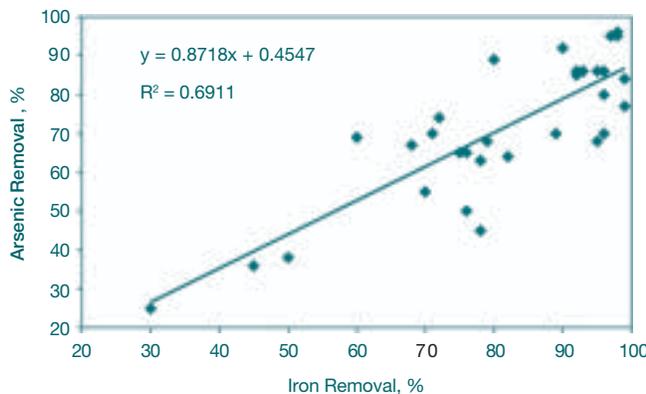
Figure 4. Tubewell-Attached Arsenic Removal Unit designed by All India Institute of Hygiene and Public Health (Ahmed and Rahman, 2000)



A - Mixing; B - Flocculation; C - Sedimentation; D - Filtration (upflow)

Iron-arsenic removal plants use naturally occurring iron, which precipitates on oxidation and removes arsenic by adsorption. Several models of iron-arsenic removal plants have been designed and installed in Bangladesh. A study suggests that As(III) is oxidized to As(V) in the plants, facilitating arsenic removal (Dahi and Liang, 1998). The iron-arsenic removal relationship with good correlation in some operating iron-arsenic removal plants has been plotted in figure 5. Results shows that most iron removal plants can lower arsenic content of tubewell water to half to one-fifth of the original concentration. The main problem is to keep the community system operational through regular washing of the filter bed.

Figure 5. Correlation between Iron and Arsenic Removal in Treatment Plants (Dhai and Liang, 1998)



Some medium-scale iron-arsenic removal plants with capacities of 2,000–3,000 m³ day⁻¹ have been constructed for water supplies in district towns in Bangladesh. The main treatment processes involve aeration, sedimentation, and rapid sand filtration with provision for addition of chemicals if required. The units operating on natural iron content of water have efficiencies varying between 40% and 80%. These plants are working well except that the water requirement for washing the filter beds is very high. Operations of small and medium-sized iron-arsenic removal plants in Bangladesh suggest that arsenic removal by coprecipitation and adsorption on natural iron flocs has good potential for arsenic content up to about 100 µg L⁻¹.

Water treatment by the addition of quick lime (CaO) or hydrated lime (Ca(OH)₂) also removes arsenic. Lime treatment is a process similar to coagulation with metal salts. The precipitated calcium hydroxide (Ca(OH)₂) acts as a sorbing flocculent for arsenic. Excess lime will not dissolve but remains as a thickener and coagulant aid that has to be removed along with precipitates through sedimentation and filtration processes. It has generally been observed that arsenic removal by lime is relatively low, usually between 40% and 70%. The highest removal is achieved at pH 10.6 to 11.4. McNeill and Edward (1997) studied arsenic removal by softening and found that the main mechanism of arsenic removal was sorption of arsenic onto magnesium hydroxide solids that form during softening. Trace levels of phosphate were found to slightly reduce arsenic removal below pH 12 while arsenic removal efficiency at lower pH can be increased by the addition of a small amount of iron. The disadvantage of arsenic removal by lime is that it requires large lime doses, in the order of 800–1,200 mg L⁻¹, and consequently a large volume of sludge is produced. Water treated by lime would require secondary treatment in order to adjust pH to an acceptable level. Lime softening may be used as a pretreatment to be followed by alum or iron coagulation.

Sorptive Filtration

Several sorptive media have been reported to remove arsenic from water. These are activated alumina, activated carbon, iron- and manganese-coated sand, kaolinite clay, hydrated ferric oxide, activated bauxite, titanium oxide, cerium oxide, silicium oxide, and many natural and synthetic media. The efficiency of sorptive media depends on the use of an oxidizing agent as an aid to sorption of arsenic. Saturation of media by different contaminants and components of water takes place at different stages of the operation, depending on the specific sorption affinity of the medium to the given component. Saturation means that the sorptive sites of the medium have been exhausted and the medium is no longer able to remove the impurities. The most commonly used media for arsenic removal in small treatment plants include:

- Activated alumina
- Granulated ferric oxide and hydroxide
- Metallic iron
- Iron-coated sand or brick dust
- Cerium oxide
- Ion exchange media

Arsenic removal by activated alumina is controlled by the pH and arsenic content of water. Arsenic removal is optimum in the narrow pH range from 5.5 to 6.0 when the surface is positively charged. The efficiency drops as the point of zero charge is approached and at pH 8.2, where the surface is negatively charged, the removal capacities are only 2–5% of the capacity at optimal pH (Clifford 1999). The number of bed volumes that can be treated at optimum pH before breakthrough is dependent on the influent arsenic concentration. The bed volume can be estimated using the following equation, where As is the initial arsenic concentration in water in micrograms per liter (Ghurye, Clifford, and Tripp 1999):

$$\text{Bed volume} = 210,000 (\text{As})^{-0.57}$$

The actual bed volume is much lower due to the presence of other competing ions in natural water. Arsenic removal capacities of activated alumina have been reported to vary from 1 mg g⁻¹ to 4 mg g⁻¹ (Fox 1989; Gupta and Chen 1978). Clifford (1999) reported the selectivity of activated alumina as:

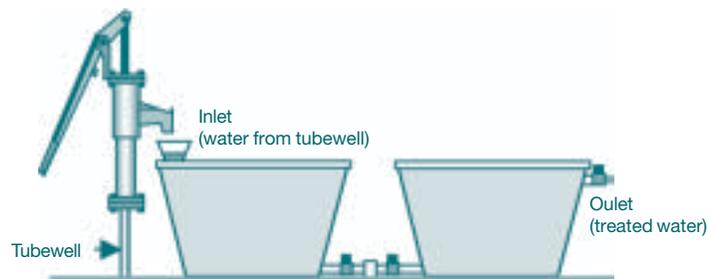


Regeneration of saturated alumina is carried out by exposing the medium to 4% caustic soda (NaOH), either in batch or by flow through the column resulting in high-arsenic-contaminated caustic waste water. The residual caustic soda is then washed out and the medium is neutralized with a 2% solution of sulfuric acid rinse. During the process about 5–10% of the alumina is lost and the capacity of the regenerated medium is reduced by 30–40%. The activated alumina needs replacement after 3–4 regenerations. As with the coagulation process, prechlorination improves the column capacity dramatically. The activated alumina-based sorptive media used in Bangladesh and India include:

- BUET activated alumina
- Alcan enhanced activated alumina
- Apyron arsenic treatment unit
- Oxide (India) Pvt. Ltd.
- RPM Marketing Pvt. Ltd.

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 arrangement is shown attached to a tubewell in figure 6 (see page 178). The unit is simple and robust in design. No chemicals are added during treatment and the process wholly relies 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 flow of water through the bed. The unit can produce more than 3,600 liters of arsenic-safe drinking water per day for 100 families. Apyron Technologies Inc. (United States of America) has developed an

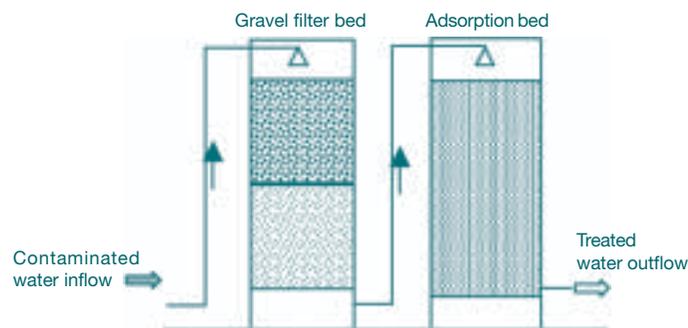
Figure 6. Alcan Enhanced Activated Alumina Unit (Drawn by Ahmed, 2003)



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.

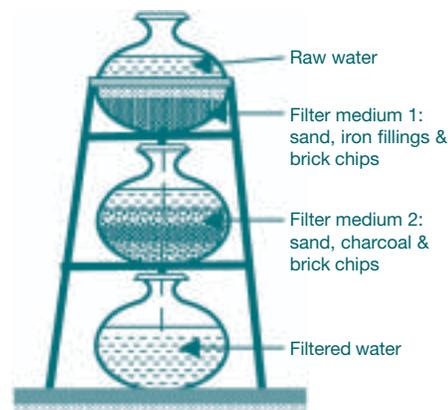
Granular ferric hydroxide (AdsorpAs®) is a highly effective adsorbent used for the adsorptive removal of arsenate, arsenite, and phosphate from natural water. It has an adsorption capacity of 45g kg^{-1} for arsenic and 16 g kg^{-1} for phosphorus on a dry weight basis (Pal 2001). M/S Pal Trockner (P) 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 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 $5\text{--}25\text{ g/m}^3$ of treated water. The typical arrangement of the Sidko/Pal Trockner unit (figure 7) requires aeration for oxidation of water and prefiltration for removal of iron flocs before filtration through 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-Based Arsenic Removal Unit (Pal, 2001)



The Sono 3-Kolshi filter shown in figure 8 uses zero valent iron filings (cast-iron turnings), sand, brick chips, and wood coke to remove arsenic and other trace metals from groundwater in Bangladesh (Munir and others 2001; Khan and others, 2000). The filtration system consists of three kalshi (burned clay pitchers), widely used in Bangladesh for storage of drinking and cooking water. The top kalshi contains 3 kg cast-iron turnings from a local machine shop or iron works and 2 kg sand on top of the iron turnings. The middle kalshi contains 2 kg sand, 1 kg charcoal, and 2 kg brick chips. Brick chips are also placed around the holes to prevent leakage of finer materials. Tubewell water is poured in the top kalshi and filtered water is collected from the bottom kalshi.

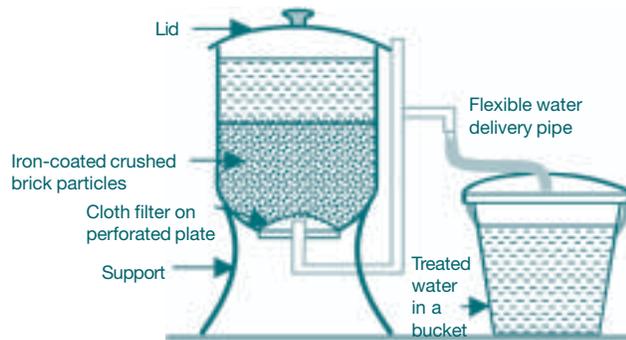
Figure 8. Three Kalshi Filter for Arsenic Removal (Drawn by Ahmed, 2003 based on Khan and Others, 2000)



Nikolaidis and Lackovic (1998) showed that 97% of arsenic can be removed by adsorption on a mixture of zero valent iron filings and sand through formation of coprecipitates, mixed precipitates, and adsorption onto the ferric hydroxide solids. Thousands of units using this technology were distributed in arsenic-affected areas but the feedback from the users was not very encouraging. If groundwater contains excess iron the one-time use unit quickly becomes clogged. Field observations indicated that the iron filings bond together into solid mass over time, making cleaning and replacement of materials difficult. The unit has been renamed Sono 45-25 arsenic removal technology and the materials of the upper two units have been put into two buckets to overcome some of the problems mentioned above.

The BUET iron-coated sand filter was constructed and tested on an experimental basis and found to be very effective in removing arsenic from groundwater. The unit needs pretreatment for the removal of excess iron to avoid clogging of the active filter bed. Iron-coated sand is prepared following a procedure similar to that adopted by Joshi and Chaudhuri (1996). The Shapla arsenic filter (figure 9 see page 180), a household-level arsenic removal unit, has been developed and is

Figure 9. Shapla Filter for Arsenic Removal at Household Level by IDE (Ahmed, 2003)



being promoted by International Development Enterprises (IDE), Bangladesh. The adsorption medium is iron-coated brick chips manufactured by treating brick chips with a ferrous sulfate solution. It works on the same principle as iron-coated sand. The water collected from contaminated tubewells is allowed to pass through the filter medium, which is placed in an earthen container with a drainage system underneath.

The READ-F arsenic filter is promoted by Shin Nihon Salt Co. Ltd., Japan, and Brota Services International, Bangladesh, for arsenic removal in Bangladesh. READ-F displays high selectivity for arsenic ions under a broad range of conditions and effectively adsorbs both arsenite and arsenate. Oxidation of arsenite to arsenate is not needed for arsenic removal, nor is adjustment of pH required before or after treatment. The READ-F is ethylene-vinyl alcohol copolymer-borne hydrous cerium oxide in which hydrous cerium oxide ($\text{CeO}_2 \cdot n\text{H}_2\text{O}$) is the adsorbent. Laboratory tests at the BUET and field testing of the materials at several sites under the supervision of the BAMWSP showed that the adsorbent is highly efficient in removing arsenic from groundwater (Shin Nihon Salt Co. Ltd. 2000). One household treatment unit and one community treatment unit based on the READ-F adsorbent are being promoted in Bangladesh. The units need iron removal by sand filtration to avoid clogging of the resin bed by iron flocs. In the household unit both the sand and resin beds have been arranged in one container while in the community unit sand and resin beds are placed in separate containers. READ-F can be regenerated by adding sodium hydroxide and then sodium hypochloride and finally washing with water. The regenerated READ-F needs neutralization by hydrochloric acid and washing with water for reuse.

The SAFI filter is a household-level candle filter developed and used in Bangladesh. The candle is made of composite porous materials such as kaolinite and iron oxide on which hydrated ferric oxide is deposited by sequential chemical and heat treatment. The filter works on the principle of adsorption filtration on the chemically treated active porous composite materials of the candle.

The ion exchange process is similar to that of activated alumina; however, the medium is a synthetic resin of relatively well defined ion exchange capacity. The synthetic resin is based on a cross-linked polymer skeleton called the matrix. The charged functional groups are attached to

the matrix through covalent bonding and fall into strongly acidic, weakly acidic, strongly basic, and weakly basic groups (Clifford 1999). The resins are normally used for removal of specific undesirable cations or anions from water. The strongly basic resins can be pretreated with anions such as Cl^{-1} and used for the removal of a wide range of negatively charged species, including arsenate. Clifford (1999) reports the relative affinities of some anions for strong-base anion resins as:

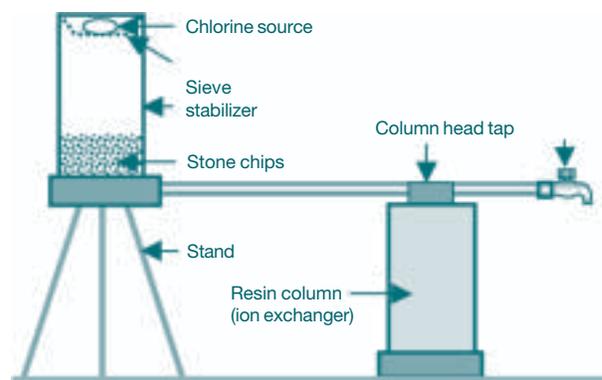


The arsenic removal capacity is dependent on sulfate and nitrate contents of raw water, as sulfate and nitrate are exchanged before arsenic. The ion exchange process is less dependent on the pH of water. Arsenite, being uncharged, is not removed by ion exchange. Hence, preoxidation of As(III) to As(V) is required for removal of arsenite using the ion exchange process. The excess oxidant often needs to be removed before the ion exchange in order to avoid damage of the sensitive resins. Development of ion-specific resin for exclusive removal of arsenic can make the process very attractive.

Tetrahedron (United States) promoted ion exchange-based arsenic removal technology in Bangladesh (figure 10). About 150 units were installed at various locations in Bangladesh under the supervision of the BAMWSP. The technology proved its arsenic removal efficiency even at high flow rates. It consists of a stabilizer and an ion exchanger (resin column) with facilities for chlorination using chlorine tablets. Tubewell water is pumped or poured into the stabilizer through a sieve containing the chlorine tablet. The water mixed with chlorine is stored in the stabilizer and subsequently flows through the resin column when the tap is opened for collection of water. Chlorine from the tablet dissolved in the water kills bacteria and oxidizes arsenic and iron.

Water System International (WSI) India has developed and patented an ion exchange process for arsenic removal from tubewell water. The so-called bucket of resin unit is encased in a rectangular container placed adjacent to the tubewell. There are three cylinders

Figure 10. Tetrahedron Arsenic Removal Technology (Drawn by Ahmed, 2003)



inside the container. Water in the first cylinder is mixed with an oxidizing agent to oxidize As(III) to As(V) while As(V) is removed in the second cylinder, which is filled with WSI-patented processed resin. The treated water is then allowed to flow through a bed of activated alumina to further reduce residual arsenic from water. Ion Exchange (India) Ltd. has also developed and marketed an arsenic removal community-level plant based on ion exchange resin.

Membrane Techniques

Synthetic membranes can remove many contaminants from water including bacteria, viruses, salts, and various metal ions. They are of two main types: low-pressure membranes, used in microfiltration and ultrafiltration; and high-pressure membranes, used in nonofiltration and reverse osmosis. The latter have pore sizes appropriate to the removal of arsenic.

In recent years, new-generation membranes for nonofiltration and reverse osmosis have been developed that operate at lower pressure and are less expensive. Arsenic removal by membrane filtration is independent of pH and the presence of other solutes but is adversely affected by the presence of colloidal matters. Iron and manganese can also lead to scaling and membrane fouling. Once fouled by impurities in water, the membrane cannot be backwashed. Water containing high levels of suspended solids requires pretreatment for arsenic removal using membrane techniques. Most membranes, however, cannot withstand oxidizing agents. EPA (2002) reported that nonofiltration was capable of over 90% removal of arsenic, while reverse osmosis provided removal efficiencies of greater than 95% when at ideal pressure. Water rejection (about 20–25% of the influent) may be an issue in water-scarce regions (EPA 2002). A few reverse osmosis and nonofiltration units have been successfully used in Bangladesh on an experimental basis.

Comparison of Arsenic Removal Technologies

Remarkable technological developments in arsenic removal from rural water supply based on conventional arsenic removal processes have taken place during the last five years. The relative advantages and disadvantages of different arsenic removal processes are compared in table 1.

Competition between arsenic removal technologies is based on a number of factors. Cost appears to be a major determinant in the selection of treatment option by users. The available costs of some of the arsenic removal technologies have been summarized in table 2. The costs of similar technologies in India are also compared in table 3.

Table 1. Comparison of Main Arsenic Removal Technologies

Technology	Advantages	Disadvantages
Oxidation and sedimentation: air oxidation, chemical oxidation	<ul style="list-style-type: none"> • Relatively simple, low cost, but slow process (air) • Relatively simple and rapid process (chemical) • Oxidizes other impurities and kills microbes 	<ul style="list-style-type: none"> • Processes remove only some of the arsenic • Used as pretreatment for other processes
Coagulation and filtration: alum coagulation, iron coagulation	<ul style="list-style-type: none"> • Relatively low capital cost • Relatively simple in operation • Common chemicals available 	<ul style="list-style-type: none"> • Not ideal for anion-rich water treatment (e.g. containing phosphates) • Produces toxic sludge • Low removal of As(III) • Preoxidation is required • Efficiencies may be inadequate to meet strict standards
Sorption techniques: activated alumina, iron-coated sand, ion exchange resin, other sorbents	<ul style="list-style-type: none"> • Relatively well known and commercially available • Well-defined technique • Many possibilities and scope for development 	<ul style="list-style-type: none"> • Not ideal for anion-rich water treatment (e.g. containing phosphates) • Produces arsenic-rich liquid and solid wastes • Replacement/regeneration is required • High-tech operation and maintenance • Relatively high cost
Membrane techniques: nanofiltration, reverse osmosis	<ul style="list-style-type: none"> • Well-defined and high removal efficiency • No toxic solid wastes produced • Capable of removal of other contaminants 	<ul style="list-style-type: none"> • High capital and running costs • High-tech operation and maintenance • Arsenic-rich rejected water is produced

Table 2. Comparison of Arsenic Removal Mechanisms and Costs in Bangladesh

Type of unit	Removal mechanism	Type	Capital cost/unit(US\$)	Operation and maintenance costs/family/year (US\$)
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
SAFI filter	Adsorption	Household	40	6
Bucket treatment unit	Oxidation and coagulation-sedimentation-filtration	Household	6–8	25
Fill and draw	Oxidation and coagulation-sedimentation-filtration	Community (15 households)	250	15
Arsenic removal unit for urban water supply	Aeration, sedimentation, rapid filtration	Urban water supply(6,000 households)	240,000	1–1.5
Sidko	Adsorption by granular Fe(OH) ₃	Community (75 households)	4,250	10
Apyron	Adsorption by Al-Mn oxides (Aqua-Bind™)	Community (65 households)	Taka 0.01/L/100ppb arsenic concentration in water	
Iron-arsenic removal plant	Aeration, sedimentation, rapid filtration	Community (10 households)	200	1

Table 3. Comparison of Costs of Different Arsenic Treatment Technologies in India

Technology (manufacturer)	Treatment process	Type	Capacity	Cost (US\$)
AMAL (Oxide India Catalyst Pvt. Ltd., WB)	Adsorption by activated alumina	Household Community	7,000–8,000 L 1,500,000 L/cycle	50 1,250; 400/charge
RPM Marketing Pvt. Ltd.	Activated alumina + AAFS-50 (patented)	Community	200,000/cycle	1,200; 500/charge
All India Institute of Hygiene & Public Health	Oxidation followed by coprecipitation-filtration	Household Community	30 L/d 12,000 L/d	5 1,000
Public Health Engineering Department, India	Adsorption on red hematite, sand, and activated alumina	Community	600–1,000 L/h	1,000
Pal Trockner Ltd., India	Adsorption by ferric hydroxide	Household Community	20 L/d 900,000 L/cycle	8 2,000; 625/charge
Chemicon & Associates	Adsorption by ferric oxide	Community	2,000,000 L/cycle	4,500; 400/charge
Ion Exchange (India) Ltd.	Adsorption by ion exchange resin	Community	30,000 L/cycle	2,000

3. Laboratory and Field Methods of Arsenic Analysis

Analysis of groundwater for arsenic has become a routine procedure in the assessment of the quality of water for the development of groundwater-based water supply. The need for stringent water quality standards and guidelines has given rise to demand for analysis of arsenic at trace levels. Laboratory analytical methods are relatively more accurate than field testing but involve considerable measurement skills and costs. The extent and nature of contamination in many countries demands large-scale measurements of arsenic for screening as well as monitoring and surveillance of water points. Developing countries with limited laboratory capacity have adopted low-cost semiquantitative arsenic measurement by field test kits to accomplish the huge task of screening and monitoring. This section provides a short overview of laboratory and field methods of analysis of arsenic in water.

Laboratory Methods

A variety of analytical methods for laboratory determination of arsenic has been described in literature but many of them essentially employ similar principles. The most common methods prescribed for use after proper validation by international and national standard methods include atomic absorption spectrometry (AAS), inductively coupled plasma (ICP), anodic stripping voltammetry (ASV), and silver diethyldithiocarbamate (SDDC) spectrometric method. AAS is a sensitive single-element technique with known and controllable interference. Both hydride generation (HG) and graphite furnace (GF) AAS methods are widely used for analysis of arsenic in water. ICP atomic emission spectrometry (AES) and mass spectrometry (MS) are multielement techniques, also with known and controllable interference. ASV is a useful technique for analysis of dissolved arsenic and arsenic speciation but needs special precautions for accuracy. The SDDC spectrometric method has been widely used for its simplicity and low cost but suffers from interference and reproducibility. A summary of laboratory analytical techniques, with important features, is presented in table 4 (Rasmussen and Anderson 2002; Khaliqzaman and Khan 2003).

Field Test Kit

Laboratory methods of arsenic measurement are costly and the number of laboratories with arsenic measurement capabilities is too few in the developing countries to meet present needs. Field test kits have been developed for detection and measurement of arsenic by different institutions and agencies in Bangladesh and in other countries. The detection and semiquantative measurement of arsenic by all field test kits is based on the Gutzeit procedure, which involves the conversion of all arsenic in water into As(III) by reduction, and then formation of arsine gas by further reduction using nascent hydrogen in an acid solution in a Gutzeit generator. The technique is also known as the mercuric bromide stain method (APHA-AWWA-WEA 1985). Presently available arsenic test kits have been developed adopting various modifications of the method. The arsine, thus liberated, produces a yellow to brown stain on a vertical paper strip impregnated

Table 4. Laboratory Analysis Methods for Arsenic

Techniques ^a	Method detection limit (mg L ⁻¹)	Sample size (ml)	System cost (thousands US\$)	Comments	Methods ^b
HG-AAS	0.05–2	50	20–100	Single element	ISO 11969 (1990) SM 3114BC (1998) EPA 1632 (1996) ASTM 2972-93B (1998)
GF-AAS	1–5	1–2	30–100	Single element	ISO/CD 15586 (2000) SM 3113B(1998) EPA 200.9 (1994) ASTM 2972-93C (1998)
ICP-AES	35–50	10–20	60–200	Multielement	SM 3120B(1998) EPA 200.7 (1994)
ICP-MS	0.02–1	10–20	150–400	Multielement	SM 3125B (1998) EPA 200.8 (1994)
ASV	0.1–2	25–50	5–20	Only free dissolved arsenic	EPA 7063 (1996)
SDDC	1–10	100	2–10	Single element	ISO 6595 (1982) SM 3500 (1998)

^a Abbreviations used:

ASV	<i>anodic stripping voltammetry</i>
GF-AAS	<i>graphite furnace-atomic absorption spectrometry</i>
HG-AAS	<i>hydride generation-atomic absorption spectrometry</i>
ICP-AES	<i>inductively coupled plasma-atomic emission spectrometry</i>
ICP-MS	<i>inductively coupled plasma-mass spectrometry</i>
SDDC	<i>silver diethyldithiocarbamate</i>

^b Abbreviations used/references:

ASTM	<i>American Society for Testing and Materials (ASTM 1998)</i>
CD	<i>Committee Draft</i>
EPA	<i>Environmental Protection Agency, United States</i>
ISO	<i>International Organization for Standardization (ISO 1982, 1996, 2000)</i>
SM	<i>Standard Method</i>

with mercuric bromide. The amount of arsenic present in the water is directly related to the intensity of the color. The color developed on mercuric bromide-soaked paper is compared either with a standard color chart or measured by a photometer to determine the arsenic concentration of the water sample. In some field test kits the generated arsine is passed through a column containing a roll of cotton moistened with lead acetate solution to absorb hydrogen sulfide gas, if any is present in the gas stream. The important features of some arsenic field test kits are summarized in table 5 (see page 188).

Table 5. Comparison of Arsenic Field Test Kits

Kit type	Manufacturer	Range ($\mu\text{g L}^{-1}$)	Cost (US\$)	Comments
E-Mark kit	M/S E-Mark, Germany	100–3,000 (old) 5–500 (new)	50–100	Colors match with ranges of arsenic concentration.
HACH kit	HACH Company, USA	10–500 (50 ml sample) 350–4,000 (9.6 ml sample)		One-time use for 100–300 tests
Econo Quick™	Industrial Test Systems Inc., USA	10–1,000		
AIH&PH kit	All India Institute of Hygiene and Public Health (AIH&PH)	Yes/No type at $50 \mu\text{g L}^{-1}$	40–60	Produces color if concentration exceeds $50 \mu\text{g L}^{-1}$. One-time use
Aqua kit	Aqua Consortium (India)	Yes/No type at $50 \mu\text{g L}^{-1}$		
AAN-Hironaka kit	Dr. Hironaka, Fukuoka City Inst. For Hygiene & Environment, Japan	20–700	Not on sale	Colors match with range of arsenic concentration. One-time use for 100 tests
NIPSOM kit	NIPSOM, with technical assistance from AAN-Hironaka	10–700	40–80	
GPL kit	General Pharmaceuticals Ltd., Dhaka	10–2,500		
BUET kit	BUET, Dhaka	10–700	Not on sale	
Digital Arsenator	Wagtech International	<10–500	1,250	Quantitative values obtained

A number of researchers and organizations have evaluated the performance of arsenic field test kits. The National Environmental Engineering Research Institute, Nagpur, India, evaluated the Asian Arsenic Network (AAN) kit (0.02 – 0.70 mg L^{-1}), the National Institute of Preventive and Social Medicine (NIPSOM) kit, the Merck kit (0.10 – 3.0 mg L^{-1}), the Aqua kit, and the AIH&PH kit (NEERI-WHO 1998). The Shriram Institute for Industrial Research, India, studied the performance of five different arsenic field test kits used in India (SIIR 1998). NGO Forum for Drinking Water Supply and Sanitation, Bangladesh, in collaboration with the School of Environmental Studies, Jadavpur University, Calcutta, West Bengal, India, evaluated the NIPSOM kit, the General Pharmaceutical Ltd. (GPL) kit, the Merck kit (0.025 – 3.0 mg L^{-1}), and the Arsenator (NGO Forum-JU 1999). In Bangladesh the performance of some arsenic test kits was evaluated as a requirement for the procurement of field test kits by the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP 2001).

Recently, several arsenic field test kits were tested for their efficacy under the EPA's Environmental Technology Verification Program. The performances of the field test kits were evaluated for accuracy, precision, linearity, method detection limit, matrix interference effects, operator bias, and rate of false positives or false negatives. The EPA issued verification reports and verification statements for these arsenic field test kits (Abbgly and others 2002; EPA 2003)

The accuracy of arsenic measurement using the mercuric bromide stain method depends on many factors. The first consideration is the method's ability to eliminate the effects of interfering substances such as sulfide. The second consideration is the generation of arsine gas, which can be achieved in several ways. Most kits use zinc, which may contain arsenic as an impurity and interfere with the process. The advantage of using the chemicals in tablet form can be availed in the case of arsine generation using sodium tetrahydroborate (NaBH_4) and aminosulfonic acid. An excess amount of the reducing agent is required in this case to produce sufficient hydrogen gas to strip the arsine gas out of the solution and transfer it to mercuric bromide paper. The passing of arsine gas through mercuric bromide paper gives more reliable results at low concentrations than passing it over the surface of a small strip of mercuric bromide paper inserted into the reactor. The third consideration is that quantification of the arsenic concentration by visual comparison is subjective and varies from person to person. The faint yellow color is not discernible to the average human eye. Again, for better results, the color comparison should be made as soon as possible as the light-sensitive stain changes color rapidly. The results obtained by arsenic field test kits are, therefore, very much dependent on the type and quality of chemicals, preparation, the preservation and age of the chemicals, the quality of water, the quality of equipment, the operator's skill, and the procedure of measurement (Jalil and Ahmed 2003).

The costs of equipment for arsenic measurement are shown in tables 4 and 5. The equipment costs of most laboratory methods are very high. Operation and maintenance costs are also very high. Further, the service facilities of laboratory equipment manufacturers are not always available in developing countries. Semiquantitative measurement using arsenic field test kits can be done at low cost, making them affordable in developing countries, though the level of accuracy is lower than with laboratory tests.

4. Alternative Water Supply Options

The shallow tubewell technology in alluvial aquifers of recent origin in the South Asia Region, which provided drinking water at low cost, has been found to be contaminated with arsenic in many places. This unexpected calamity has exposed millions of people in contaminated areas to unsafe water. The risk has been magnified by the existence of very high levels of arsenic in tubewell water in areas where the percentage of contaminated tubewells is also very high. In the absence of an alternative source, people in such hotspots often have an unfortunate choice between continuing to drink arsenic-contaminated water or using unprotected surface water and exposing themselves to the risk of waterborne diseases. Arsenic toxicity has no known effective treatment, but drinking arsenic-free water can greatly reduce the symptoms. Apart from treatment of arsenic-contaminated water, potential alternative water sources for arsenic-safe water supplies include:

- Deep tubewell
- Dug or ring well
- Rainwater harvesting
- Treatment of surface water
- Piped water supply

Deep Tubewell

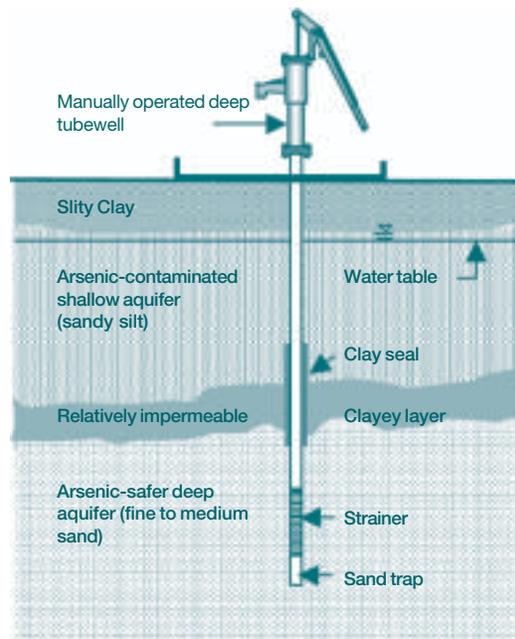
Aquifers are water-containing rocks that have been laid down during different geological time periods. Deeper aquifers are often separated from those above by relatively impermeable strata that keep them free of the arsenic contamination of shallower aquifers¹. A study in Bangladesh by the British Geological Survey (BGS) and the DPHE has shown that of tubewells with a depth greater than 150 m, only about 1% have levels of arsenic above 50 $\mu\text{g L}^{-1}$, and 5% have arsenic levels above 10 $\mu\text{g L}^{-1}$ (BGS-DPHE 2001). As such, deep aquifers separated from shallow contaminated aquifers by impermeable layers can be a dependable source of arsenic-safe water.

The presence of a relatively impermeable layer separating a deep uncontaminated aquifer from a shallow contaminated aquifer is a prerequisite for installation of a deep tubewell for arsenic-safe water. The annular spaces of the boreholes of the deep tubewells must be sealed, at least at the level of the impermeable strata, to avoid percolation of arsenic-contaminated water (figure 11). It is very difficult to seal a small-bore tubewell but technological refinement using clay as a sealant is ongoing. A protocol for the installation of deep tubewells for arsenic mitigation has been developed in Bangladesh (Government of Bangladesh 2004).

In the coastal area of Bangladesh proven arsenic-safe deep aquifers protected by overlying thick clay layers are available for the development of safe water supplies. In other areas, arsenic-safe aquifers separated from arsenic-contaminated shallow aquifers are available but extensive and very costly hydrogeological investigations are required to delineate those

¹ In some areas, e.g. China, the deeper aquifers may be arsenic-affected. See paper 1.

Figure 11. Deep Tubewell with Clay Seal (Ahmed, 2004)



aquifers. In the meantime, installation of deep tubewells following a deep tubewell protocol will continue through examination of water quality and soil strata in test boreholes in the prospective deep tubewell areas.

However, there are many areas where 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 are likely to experience an increase in the arsenic content of water over time due to mixing of contaminated and uncontaminated waters. However, recharge of deep aquifers by infiltration through coarse media and replenishment by the horizontal movement of water are likely to keep such aquifers arsenic free even after prolonged water abstraction. Information about the configuration of an aquifer and its recharge mechanism is critical for the installation of deep tubewells.

Experience in the design and installation of tubewells shows that reddish sand produces the best-quality water in terms of dissolved iron and arsenic. The reddish color of sand is produced by oxidation of iron on sand grains in a ferric form that will not release arsenic or iron in groundwater. On the contrary, ferric iron-coated sand will adsorb arsenic from groundwater. This mechanism is probably responsible for the relative freedom from arsenic of the Dhaka water supply, in contrast to the arsenic contamination that occurs in surrounding areas. Hence, installation of tubewells in reddish sand, if available, should be safe from arsenic contamination.

Dug or Ring Well

Dug wells are the oldest method of groundwater withdrawal for water supply. The water from dug wells has been found to be relatively free from dissolved arsenic and iron, even in locations where tubewells are contaminated. The reasons for this are not fully known, but possible explanations include:

- The oxidation of dug well water due to its exposure to open air and agitation during water withdrawal can cause precipitation of dissolved arsenic and iron.
- Dug wells accumulate groundwater from the top layer of a water table, which is replenished each year by arsenic-safe rain and percolation of surface waters through the aerated zone of the soil. The fresh recharges also dilute contaminated groundwater.

A study in an acute arsenic problem area shows that frequent withdrawal of water initiates ingress of arsenic-contaminated water into dug wells and reduces the subsequent in situ oxidation that, under normal operating conditions, increases the oxygen content of water and the reduction of arsenic. Since the upper layer of soil contains organic debris, dug well water is often characterized by bad odor, high turbidity and color, and high ammonia content. Dug wells are also susceptible to bacterial contamination. Percolation of contaminated surface water is the most common cause of well water pollution. Satisfactory protection against bacteriological contamination is possible by sealing the well top with a watertight concrete slab, lining the well, and constructing a proper apron around the well. Water may be withdrawn through the installation of a manually operated handpump. Completely closed dug wells have good sanitary protection but the absence of oxygen can adversely affect the quality of the water.

Construction and operational difficulties have been encountered in silty and loose to medium-dense sandy soils. Sand boiling interferes with the digging, and sometimes leads to collapse of dug wells. Constructed dug wells are also gradually filled up during operation by sand boiling.

Water in the well needs chlorination for disinfection after construction. Application of lime also improves the quality of dug well water. Disinfection of well water should be continued for open dug wells during operation by pot chlorination, but controlling the chlorine dose in dug well water is difficult.

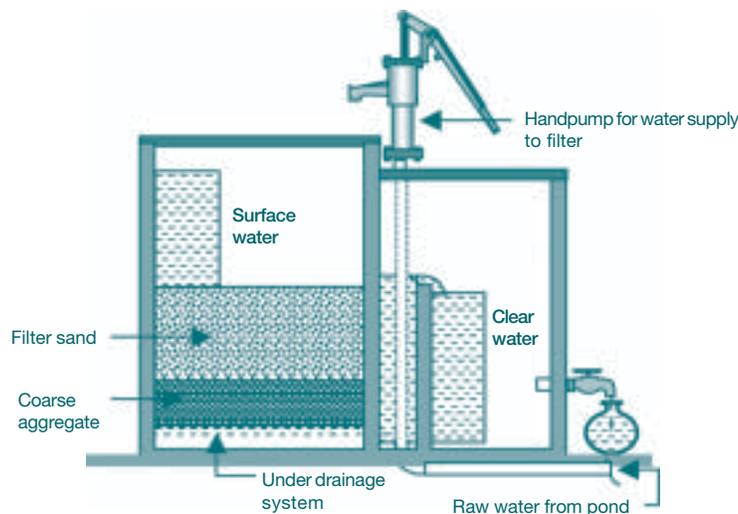
Surface Water Treatment

A prospective option for the development of a surface water-based water supply system is the construction of community slow sand filters, commonly known as pond sand filters in Bangladesh, where they were originally designed for the filtration of pond water. This is a package-type slow sand filter unit developed to treat surface waters, usually low-saline pond water, for domestic water supply in coastal areas. The water from the pond or river is pumped by

a manually operated tubewell to feed the filter bed, which is raised from the ground (figure 12). The treated water is collected through a tap. Tests have found that treated water from a pond sand filter is normally bacteriologically safe or within tolerable limits. The sand in the filter bed usually needs to be cleaned and replaced every two months. The operating conditions for slow sand filters include:

- Low turbidity, not exceeding 30 nephelometric turbidity units (NTU)
- Low bacterial count
- No algal bloom, absence of cyanobacter
- Free from bad smell and color

Figure 12. Pond Sand Filter for Treatment of Surface Water (Ahmed and Others, 2002)



A protected surface water source is ideal for slow sand filtration. The problems encountered when the above operating conditions are not maintained include low discharge, the need for frequent washing, and poor effluent quality. Since these are small units, community involvement in their operation and maintenance is absolutely essential in order to keep the system operational. By June 2000, the DPHE had installed 3,710 pond sand filter units, a significant proportion of which remain out of operation due to poor maintenance, drying of the source, or excessive contamination of the water source.

The package-type slow sand filter is a low-cost technology with very high efficiency in turbidity and bacterial removal. It has received preference as an alternative water supply system for medium-size settlements in arsenic-affected areas. Although pond sand filters have a very high bacterial removal efficiency they may not reduce bacterial count to acceptable levels in cases of

heavily contaminated surface water. In such cases, the treated water may require chlorination to meet drinking water standards.

A combined filter consisting of roughing filters and a slow sand filter is needed when the turbidity of water exceeds 30 NTU. The roughing filters remove turbidity and color to levels acceptable for efficient operation of the slow sand filter. Small-scale conventional surface water treatment plants involving coagulation-sedimentation-filtration and disinfection can be constructed to cope with variable raw water quality for community water supplies but the cost will be relatively high.

Rainwater Harvesting

Rainwater harvesting can be an alternative source of drinking water in arsenic-contaminated South Asian countries. The relative advantages and disadvantages of rainwater harvesting are shown in table 6. A rainwater-based water supply system requires a determination of the storage tank capacity and the catchment area for rainwater collection in relation to the water requirement, rainfall intensity, and distribution. The availability of rainwater is limited by the rainfall intensity and availability of a suitable catchment area. The unequal distribution of rainwater over the year in Asian countries requires a larger storage tank for uninterrupted water supply throughout the year. This storage tank constitutes the main cost of the system.

The catchment area for rainwater collection is usually the roof, which is connected to the storage tank by a gutter system. Rainwater can be collected from any type of roof but concrete, tiles, and metal roofs give clean water. The corrugated iron sheet roofs commonly used in Bangladesh and India perform well as catchment areas. The poorer segments of the population are in a

Table 6. Advantages and Disadvantages of Rainwater Collection System

Advantages	Disadvantages
<ul style="list-style-type: none"> The quality of rainwater is comparatively good 	<ul style="list-style-type: none"> The initial cost may prevent a family from installing a rainwater harvesting system
<ul style="list-style-type: none"> The system is independent and therefore suitable for scattered settlements 	<ul style="list-style-type: none"> Water availability is limited by the rainfall intensity and available roof area
<ul style="list-style-type: none"> Local materials and craftsmanship can be used in construction of rainwater system 	<ul style="list-style-type: none"> Mineral-free rainwater has a flat taste, which may not be liked by many
<ul style="list-style-type: none"> No energy costs are incurred in running the system 	<ul style="list-style-type: none"> Mineral-free water may cause nutrition deficiencies in people who are on mineral-deficient diets
<ul style="list-style-type: none"> Ease of maintenance by the owner/user 	<ul style="list-style-type: none"> The poorer segment of the population may not have a roof suitable for rainwater harvesting
<ul style="list-style-type: none"> The system can be located very close to the consumption point 	<ul style="list-style-type: none"> May not last through the entire dry season.

Figure 13. Plastic Sheet Catchment (Ahmed and others, 2002)



disadvantageous position in respect to the utilization of rainwater as a source of water supply. These people have smaller thatched roofs or no roof at all to be used as a catchment for rainwater collection. A thatched roof can be used as a catchment area by covering it with polyethylene but it requires good skills to guide water to the storage tank. In coastal areas of Bangladesh, cloths fixed at four corners with a pitcher underneath are used during rainfall for rainwater collection. A plastic sheet, as shown in figure 13, has been tried as a catchment for rainwater harvesting for people who do not have a roof suitable for rainwater collection. The use of land surface as a catchment area and underground gravel or sand-packed reservoirs as storage tanks can be an alternative system of rainwater collection and storage. In this case, the water has to be

channeled towards the reservoir and allowed to pass through a sand bed before entering underground reservoirs. This process is analogous to recharge of underground aquifers by rainwater during the rainy season for utilization in the dry season.

The quality of rainwater is relatively good but it is not free of all impurities. Analysis of stored rainwater has shown some bacteriological contamination. Cleanliness of the roof and storage tank is critical to maintaining the good quality of rainwater. The first runoff 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 off. Some devices and good practices have been suggested to store or divert the first foul flush away from the storage tank. In case of difficulties in the rejection of first flow, cleaning of the roof and gutter at the beginning of the rainy season and their regular maintenance are very important to ensure better quality of the rainwater. The storage tank requires cleaning and disinfection when the tank is empty or at least once in a year. Rainwater is essentially lacking in minerals, the presence of which is considered essential in appropriate proportions. The mineral salts in natural ground and surface waters sometimes impart a pleasing taste to water.

Piped Water Supply

Piped water supply is the ultimate goal of safe water supply to the consumer because:

- Water can be delivered to close proximity of the consumers.
- Piped water is protected from external contamination.

- Better quality control through monitoring is possible.
- Institutional arrangements for operation and maintenance are feasible.
- Water of required quantity can be collected with ease.

In terms of convenience in collection and use, only piped water can compete with the existing system of tubewells for water supply. 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 affordability of each option to the consumer. The water can be produced, according to demand, by sinking deep tubewells into an arsenic-safe aquifer or by treatment of surface water or even arsenic-contaminated tubewell water by community-level treatment plants. Rural piped water supply has received priority for arsenic mitigation in Bangladesh and a large number of pilot schemes by different organizations are under implementation. It appears that piped water supply will be a suitable option for populations living in clustered settlements, but it will be a difficult and costly option for scattered populations.

Cost Comparison of Alternative Water Supply Options

As has been discussed in this chapter, a variety of alternative technological options is available for water supply in arsenic-affected areas. The cost of arsenic mitigation will depend on the type of technology adopted. The costs of installation and operation of some major technological options available from various organizations involved in arsenic mitigation are summarized in table 7.

The quality and quantity of water, reliability, cost, and convenience of collection of water vary widely for the various options. Deep tubewells can provide water at nominal operation and maintenance costs but they are not feasible, nor able to provide arsenic-free water, at all locations. Dug or ring wells can provide water at moderate installation and nominal operation and maintenance costs. It is not yet fully known whether the quality of water can be maintained at desired levels. Bacteriological quality is likely to remain at safe levels under conditions of proper sanitary protection. Piped water supply can be provided at a higher cost and with relatively higher operation and maintenance costs but the convenience and health benefits are much greater because water of adequate quantity and relatively superior quality for all domestic purposes, including sanitation, becomes available at or near residences. Increasing the number of households connected reduces average costs. Available data suggest that the average cost of piped water supply becomes lower than other options when the number of households exceeds 500 (see paper 4). The relative cost of installation for a rainwater harvesting system at household level with only about 50% reliability is very high. Installation of community rainwater harvesting systems may be cheaper, but management of such systems may be difficult.

Table 7. Costs of Alternative Technological Options in Arsenic-Affected Areas

Alternative Technological options	No. of households per unit	Unit cost (US\$)	Operation and maintenance costs/year (US\$)	Comments
Rainwater harvesting	1	200	5	Low reliability
Dug or ring well	25	800	3	Depth about 8 m
Deep tubewell	50	900	4	Depth about 300 m
Pond sand filters process	50	800	10–20	Slow sand filter
Surface water treatment process	1,000	15,000	3,000	Conventional
Piped water supply	1,000	40,000	800	Systems are based on arsenic-safe groundwater

Source: Government of Bangladesh 2002.

5. Operational Issues

The presence of arsenic in low concentration and the need to reduce it to levels associated with desired health benefits have given rise to many operational difficulties. Measurement of arsenic at low concentration is difficult, as is the monitoring of treatment system performance. Validation of the claims of proponents concerning the performance of treatment technologies and arsenic measurement devices is an important requirement. Safe disposal of toxic sludge and spent media is an environmental concern. The technologies based on patented media or processes and imported components may face operational difficulties due to lack of availability and supply of materials and components.

Operational issues are very important for small-scale water treatment facilities at the household and community levels. It is not possible to make an institutional arrangement for operation, repair, and maintenance of small water supply systems. People's participation and capacity building at the local level are considered vital for keeping the system operational. There are many examples of failure of small water supply systems in the absence of initiatives, commitment, and ownership of the system. In many cases, the small system may be more costly due to scaling down of a conventional system for water treatment.

Technology Verification and Validation

Quite a lot of development of arsenic treatment and measurement technologies has taken place over the last five years in response to demand. Verification and validation of the claims of these technologies are needed to help buyers select the right technology. The EPA has developed protocols for validation of arsenic treatment technologies and arsenic field test kits under its Environmental Technology Verification Program. The protocols have been developed in collaboration with the Environmental Technology Verification Program in Canada and Bettle Laboratories, United States (EPA 2003). The WHO has developed generic protocols for adoption in South-East Asia Region countries (WHO 2003).

A systematic evaluation of arsenic mitigation technologies is being conducted under the Environmental Technology Verification–Arsenic Mitigation Program by the Bangladesh Council of Scientific and Industrial Research in collaboration with the Ontario Centre for Environmental Technology Advancement, Canada. Generic and technology-specific test protocols consistent with environmental and operative conditions in Bangladesh have been developed for this verification program. The program has thus far completed verification of five arsenic removal technologies in Phase I (BCSIR 2003). An additional 14 technologies are pending for verification in Phase II of the program.

Verification of some technologies in Bangladesh shows that their performance is very much dependent on pH, and the presence of phosphate and silica in natural groundwater. Most of the technologies do not meet the claims of the proponents concerning treatment capacity. A reduction in the rated capacity will further increase the cost of treatment per unit volume of water.

Sludge Disposal

Since arsenic cannot be destroyed all arsenic treatment technologies ultimately concentrate arsenic in sorption media, sludge, or liquid media. A variety of arsenic-rich solids and semisolids, such as arsenic-saturated hydrous ferric or aluminium oxides and other filter media, are generated from arsenic removal processes. Regeneration of activated alumina and ion exchange resins results in various liquid wastes that may be acidic, caustic, saline, and too arsenic rich for simple disposal. Hence, environmentally safe disposal of sludge, saturated media, and liquid wastes rich in arsenic is a concern.

The EPA has developed a toxic characteristic leaching procedure (TCLP) test to identify wastes likely to leach toxic chemicals into groundwater. The permissible level for TCLP leachate is generally 100 times higher than the maximum contaminant level in drinking water, for example 5,000 $\mu\text{g L}$ for leached arsenic when the acceptable level in drinking water is 50 $\mu\text{g L}$. Sludge leaching more than 5,000 $\mu\text{g L}$ of arsenic would be considered hazardous and would require disposal in a special hazardous waste landfill. The TCLP test was conducted on different types of wastes collected from arsenic treatment units and materials in Bangladesh (Eriksen-Hamel and Zinia 2001; Ali and others 2003). It has been observed that in almost all cases arsenic leaching was very minor. Arsenic leaching tests were conducted at the BUET using different extraction fluids. For all extractants arsenic concentration in the column effluents was initially very high, but then dropped sharply (Ali and others 2003). Several researchers also conducted TCLP tests on sludge resulting from arsenic removal with aluminium and ferric salts and found arsenic in leachate in the range of 9–1,500 $\mu\text{g L}$ (Brewster 1992; Chen and others 1999). These arsenic levels in leachate are well below the level required for classification as hazardous wastes. It appears that most sludge would not be considered hazardous even if the WHO guideline value of 10 $\mu\text{g L}^{-1}$ for arsenic in drinking water were considered.

Hazardous wastes are often blended into stable waste or engineering materials such as glass, brick, concrete, or cement block. There is a possibility of air pollution or water pollution downstream of kilns burning brick containing arsenic-contaminated sludge due to volatilization of arsenic during burning at high temperatures. In Hungary experiments showed that some 30% of arsenic in the coagulated sludge was lost to atmosphere in this way (Johnston, Heijnen, and Wurzel 2000). Sludge or spent filter media with low arsenic content can be disposed of on land or in landfills without significant increase in the background concentration of arsenic. Wastes with high concentration of arsenic may need solidification or confinement before final disposal.

Costs

The cost of arsenic removal technology is an important factor for its adoption and sustainable use in rural areas. The cost of the technologies depends on many factors such as the materials used for fabrication of components, quantity of media or chemicals used, and quality of groundwater.

Most of the technologies have been installed and are being operated under field testing and pilot-scale operations. Hence the costs of installation, operation, and maintenance of all the arsenic removal systems are not known or are yet to be standardized based on modifications to suit the local conditions. The available costs and system capacities of some arsenic removal technologies are presented in tables 2 and 3. The costs of alternative water supply systems are presented in table 7.

The unit costs of water produced by different water supply systems to meet present service levels have been calculated on the basis of annualized capital recovery using an annual interest rate of 12% (table 8). It has been assumed that the arsenic-safe water required per family for drinking and cooking is 45 L/day. However, the water production capacity of most alternative water supply systems is much higher than this and can serve additional users, or provide existing users with more water for all household purposes. If the full water production capacities of these systems are utilized the cost per unit volume of water is greatly reduced.

Table 8. Cost of Water Supply Options for Arsenic Mitigation

Technology	Tech life (years)	Annualized capital recovery (US\$) ^a	Operation & maintenance cost/year (US\$)	Water output (m ³)	Unit cost (US\$/m ³)
Alternative water supply:					
Rainwater harvesting	15	30	5	16.4	2.134
Deep tubewell	20	120	4	820 4,500	0.151 0.028 ^b
Pond sand filter	15	117	15	820 2,000	0.161 0.066 ^b
Dug or ring well	25	102	3	410 1,456	0.256 0.072 ^b
Conventional treatment	20	2,008	3,000	16,400	0.305
Piped water	20	5,872	800	16,400 73,000	0.375 0.084 ^b
Arsenic treatment (households) based on:					
Coagulation-filtration	3	3	25	16.4	1.70
Iron-coated sand/ brick dust	6	0.9	11	16.4	0.73
Iron filings	5	3	1	16.4	0.24
Synthetic media	5	1.2	29	16.4	1.84
Activated alumina	4	3.2	36	16.4	2.39
Arsenic treatment (community) based on:					
Coagulation-filtration	10	44	250	246	1.21
Granulated ferric hydroxide/oxide	10–15	500–600	450–500	820–900	1.20
Activated alumina	10–15	30–125	500–520	164–200	3.20
Ion exchange	10	50	35	25	3.40
Reverse osmosis	10	440	780	328	3.72
As-Fe removal (air oxidation-filtration)	20	32,000	7,500	730,000	0.054

^a The capital recovery/amortization factor has been calculated using the formula:

$$\frac{(1+i)^N}{((1+i)^N - 1) / i}$$

where i = interest rate and N = number of years.

^b Development of full potential of the system.

6. Conclusions

The problem of treatment of arsenic-contaminated water arises from the requirement for its removal to very low levels to meet the stringent drinking water quality standards and guideline values for arsenic. Arsenic removal technologies have improved significantly over the last few years but many of the technologies do not work satisfactorily for natural groundwater. Reliable, cost-effective, and sustainable treatment technologies are yet to be identified and further developed. All the technologies have their strengths and weaknesses and are being refined to accommodate rural conditions. Modifications based on pilot-scale implementation of the technologies are in progress with the objectives of:

- Improving efficiency of arsenic removal
- Reducing capital and operation cost of the systems
- Making the technology user friendly
- Overcoming maintenance problems
- Resolving sludge and arsenic concentrates management problems.

Because of the cost and operational complexity of arsenic removal technologies, alternative water supply options are often given preference in arsenic mitigation. Surface water of desirable quality is not always available for low-cost water supply, while the cost of treatment of surface water using conventional coagulation-sedimentation-filtration and disinfection processes is very high. Rainwater harvesting as a household option is also costly. Dug wells do not produce or maintain water of desirable quality in all locations and are difficult to construct in some areas.

The technologies are site specific and there are various considerations for selection of a particular technology in any given locality. Some of the important considerations for the development of sustainable water supply options for purposes of arsenic mitigation are:

- The profile of the beneficiaries and settlement pattern
- Present water supply system and level of arsenic in the drinking water
- Possible alternative sources of water for water supply
- Relative risk and cost of development of water supply system
- The level of technical and managerial capacity building needed
- Affordability and willingness to pay.

A lot of effort has been spent developing the performance of arsenic field test kits. Although the accuracy of arsenic detection and measurement by field test kits is not fully satisfactory, it is a convenient tool for testing water in rural areas. Field test kits are being widely used and will continue to be used in the near future until a network of in-country laboratories is established for testing arsenic at a reasonable cost. It is therefore essential to improve the performance of the field test kits and implement quality assurance programs for field-based measurement with back-up support from available in-country laboratories to meet the present need.

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