

Chapter 6: Safe Water Technology

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Previous chapters have documented the serious health effects that are posed by ingestion of arsenic through drinking water. While some palliative treatment of arsenicosis patients is possible, it is clear that the first step in treating patients, and preventing others from falling sick, is to identify safe sources of water for drinking and cooking in arsenic-affected areas. This chapter will present a brief overview of safe drinking water supply technologies that can provide arsenic-free¹ drinking water, either through identifying an arsenic-free source or by removing arsenic from contaminated water. The main focus of this chapter is on rural and peri-urban settings, though many of the technologies discussed are applied in central water supply systems as well, and a few examples of centralized arsenic removal are given.

Conventional water supplies are briefly discussed, but as these systems are extensively described elsewhere, the reader is referred to authoritative documents for more detailed information. Arsenic removal technologies are less well documented in standard water supply texts, though a large and growing literature exists in technical journals. In addition, many other valuable papers are found in seminar and conference proceedings, particularly in Latin America and Asia. Since many of these resources are less accessible for some readers, this chapter presents a detailed review of arsenic removal technologies. Many of these technologies are under development, and a sample protocol is presented for evaluation of new technologies for arsenic removal, as well as a more general framework for selection of an appropriate approach in a given socioeconomic and environmental context. A series of case studies are presented of technological responses to arsenic contamination at municipal, community, and household levels. The final section presents some general conclusions and identifies areas where more knowledge or research is required.

¹ No water is ever completely free of arsenic – trace levels will always be present, even if they cannot be measured. In this chapter the term ‘arsenic-free’ is taken to mean free from unsafe levels of arsenic.

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Acronyms and abbreviations

Units of measurement

m	meters
M	moles, molar
meq/mL	milliequivalents per milliliter
mg/L	milligrams per liter, equivalent to parts per million (ppm)
mM	millimolar
MW	molecular weight
µg/L	micrograms per liter, equivalent to parts per billion (ppb)
ppm	parts per million
ppb	parts per billion
psi	pounds per square inch

Technical terms

BOD	Biochemical oxygen demand
EBCT	Empty bed contact time
HAO	Hydrous aluminum oxide
HFO	Hydrous ferric oxide
MCL	Maximum contaminant level
NF	Nanofiltration
NTU	Nephelometric turbidity units
POU	Point of use
PZC	Point of zero charge
RO	Reverse osmosis
SODIS	Solar disinfection
SORAS	Solar removal of arsenic
TC	Total coliforms
TCLP	Toxicity characteristic leaching procedure
TDS	Total dissolved solids
THM	Trihalomethanes
TOC	Total organic carbon

Organizations

AWWA	American Water Works Association
BGS	British Geological Survey
BRAC	Bangladesh Rural Advancement Committee
DPHE	Department of Public Health Engineering
ENSIC	Environmental Sanitation Information Center
IRC	International Reference Centre for Water Supply and Sanitation
ITP	Intermediate Technology Publications
MML	Mott MacDonald, Ltd.
NGO	Non-governmental organization
UNEP	United Nations Environment Programme
UNICEF	United Nations Children's Fund
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

Executive Summary

In areas where the drinking water supply contains unsafe levels of arsenic, the immediate concern is finding a safe source of drinking water. There are two main options: finding a new safe source, and removing arsenic from the contaminated source. In either case, the drinking water supplied must be free from harmful levels of arsenic, but also from bacteriological contamination, and other chemical contaminants. This chapter reviews available technologies for source substitution and arsenic removal. The main focus is on rural and peri-urban areas, though centralized systems are briefly discussed.

Source Substitution

Three main sources of water can be considered as substitutes for contaminated water: groundwater, rainwater, and surface water. Much has been written about these sources, so this chapter offers only a brief review, with key references.

- **Groundwater** is largely free from harmful bacteria and fecal contamination, though a poorly designed or constructed well can become contaminated from surface water. To prevent this, wells should be grouted around the borehole, and finished at the surface with a concrete platform, with good drainage away from the well.

Most commonly, groundwater is reached through boreholes, drilled either by hand or machine. When drilling in arsenic-affected areas, precautions should be taken to make sure that safe aquifers do not become contaminated. If a borehole must penetrate a contaminated aquifer to reach safe water below, the borehole should be grouted after drilling is completed.

In some areas, groundwater can have naturally occurring water quality problems aside from arsenic, such as high levels of iron, manganese, nitrate, chloride, or fluoride. Before promoting new sources of groundwater, the chemical quality should be tested in laboratories.

- **Rainwater** is free from arsenic, and if properly collected, can provide a safe drinking water source. Bacterial contamination is a concern, but this can be minimized by collecting rain from a roof (galvanized metal makes a good collection surface). Tree branches should not overhang the roof, and the roof should periodically be cleaned. Water can be collected through gutters, and piped into a storage tank. Tanks can be built of many materials, but ferrocement (cement with wire reinforcement) is strong and inexpensive, and also can keep the water pH near neutral. When rain first begins to fall, especially at the end of a dry season, roof water should be allowed to run off for 10-15 minutes before collection, to clean the roof.

Close to urban areas, and when metal roofs are used, collected rainwater can contain unsafe levels of lead and zinc, and possibly other metals. Typically, collected rainwater contains low levels of bacteria (fecal and total coliform counts average 5-15 and 25-75 per 100 ml, respectively). Water quality testing should be done to ensure that collected water meets relevant standards. In some cases, rainwater may be the safest source of drinking water available, even if low levels of bacteria are present.

Often, rainfall is seasonal, and large storage tanks would be required to bridge the dry season. While water can be safely stored for long periods, the large tanks may be too expensive. In such cases, small storage tanks provide an inexpensive and convenient water source during the rainy season, and other sources should be found for the dry season.

- **Surface water** requires more treatment than groundwater or rainwater, since it usually has very high bacterial contamination. In order to ensure that treatment is always effective, it is

important to include multiple barriers to contamination. The most effective treatment appropriate at the rural, community level, is slow sand filtration, followed by a safety dose of chlorine. In slow sand filtration, surface water passes through prefilters, and is then filtered through 80-100 cm of sand. A bio-layer develops near the surface of the sand, which can effectively destroy most pathogens. Operation of the slow sand filter may be improved through pretreatment with bank infiltration, sedimentation or roughing filtration. The use of roughing filters, in particular, permits effective treatment of water containing higher levels of turbidity, color, and pathogens. This 'multi-stage filtration' is a robust and reliable treatment method in rural communities, and for small and medium size municipalities.

Slow sand filtration will not efficiently remove arsenic or agricultural chemicals such as pesticides. It is important to test the water quality of the unfiltered water to make sure that arsenic and pesticides are not present. Likewise, for bacteria, the cleaner the source water, the cleaner the treated water will be. Ponds and other surface water sources used for slow sand filtration should be protected: latrines should not be located near the water, and people and animals should not bathe nearby. Slow sand filters must be regularly cleaned, and the top few centimeters of sand in the filter should be scraped off. After cleaning, the filter will need several days to 'ripen', and treat water effectively. During this ripening period, filtered water should be disinfected before drinking.

Solar disinfection, or *SODIS*, is a promising new technology that uses clear plastic bottles to purify water. Bottles are filled with clear water and left in the sun for several hours. The combination of ultraviolet radiation and high temperature is able to destroy most pathogens. *SODIS* will not improve the chemical quality of water, but it can provide an inexpensive, easy way to improve microbiological quality.

Surface water may also be purified by drawing the water from shallow wells located close to the surface water body. This 'bank infiltration' can improve the chemical as well as microbiological quality of water, and is becoming more popular in Europe.

Arsenic Removal

In some areas source substitution may be impossible during part or all of the year, or may be very expensive. Arsenic removal may be more appropriate in these situations. Since arsenic removal is not covered in many standard texts, this chapter examines removal technologies in more detail.

- **Coagulation and filtration** is the most common arsenic removal technology. By adding a coagulant such as alum, ferric chloride, or ferric sulfate to contaminated water, much of the arsenic can be removed. If arsenic is present as arsenite, the water should be oxidized first, using chlorine, permanganate, ozone, or other oxidants. After adding the coagulant, the water should be stirred, allowed to settle, and filtered for best results. Coagulation improves parameters such as turbidity and color, and can reduce levels of organic matter, bacteria, iron, manganese, and fluoride, depending on operating conditions.

Coagulation with ferric salts works best at pH below 8. Alum has a narrower effective range, from pH 6-7. If pH is above 7, removal may be improved by adding acid to lower pH. In general, the higher the coagulant dose, the better the arsenic removal. Typical doses are 5 to 30 mg/L ferric salts or 10 to 50 mg/L alum. If the source water has high levels of phosphate or silicate, coagulation may be less effective. However, sulfate, carbonate, and chloride have little effect on removal rates.

- **Ion exchange resins** are commercially produced, synthetic materials that can remove some compounds from water. Most commonly they are used in water softening, but some resins are very good at removing arsenic. These resins only remove arsenate, so if the raw water

contains arsenite, it should be oxidized first. Other compounds, including sulfate, nitrate, nitrite, and chromate, are also removed to some degree by most arsenic removal resins.

Ion exchange resins usually come as sand-like grains, and are used in packed beds or columns, most often with an Empty Bed Contact Time (EBCT) of 1.5 to 3 minutes. A bed can typically treat several hundred to a thousand bed volumes before the resin must be regenerated. The amount of water a bed can treat is largely independent of arsenic concentration and pH. Instead, run lengths are largely determined by sulfate levels, since sulfate can quickly saturate the resin. For this reason, ion exchange resins are only appropriate in waters with under 120 mg/L sulfate, and work best with waters with under 25 mg/L sulfate. High levels of dissolved solids (TDS > 500 mg/L) will also shorten run times.

Resins will not adsorb iron, but if the raw water contains high levels of dissolved iron, the iron can precipitate out and clog the filter. When the resin is saturated, it can easily be regenerated with a simple brine solution. Regenerated resin can be used over and over again.

- **Activated alumina**, like ion exchange resins, is commercially available in coarse grains. Activated alumina is used in packed beds, with longer EBCTs (about 5 to 8 minutes) than ion exchange resins. Activated alumina beds usually have much longer run times than ion exchange resins, typically several tens of thousands of beds can be treated before arsenic breakthrough. Activated alumina works best in slightly acidic waters (pH 5.5 to 6) – above pH 7 removal efficiency drops sharply. The main factors controlling bed run length are pH and arsenic concentration. Concentrations of other solutes have a relatively small effect.

For best results, raw water containing arsenite should be oxidized before treatment. Phosphate, sulfate, chromate and fluoride are also removed by activated alumina, but nitrate is not. Saturated activated alumina can be regenerated with flushing with strong base followed by strong acid. Regenerated media loses some volume and eventually must be replaced. Like ion-exchange resins, activated alumina beds can be clogged by precipitation of iron.

- **Membrane methods** for arsenic removal include reverse osmosis and nanofiltration. These make use of synthetic membranes, which allow water through but reject larger molecules, including arsenic, chloride, sulfate, nitrate, and heavy metals. The membranes must be operated at high pressures, and usually require pretreatment of the raw water. Household level membrane units usually only treat about 10% of the water, resulting in a large waste stream. Municipal membrane units can achieve higher total recovery rates by using membranes in series. Currently available membranes are more expensive than other arsenic removal options, and are more appropriate in municipal settings, where very low arsenic levels are required. However, membrane technology is advancing rapidly, and it is conceivable that future generations of membranes could be used effectively in rural settings.
- **Other techniques** exist for arsenic removal, but are less well documented. When arsenic-rich water also contains high levels of dissolved iron, iron removal will also remove much of the arsenic. Many new materials are being tested for arsenic removal, including low-tech iron-coated sand and greensand, novel iron-based sorbents, and specially engineered synthetic resins. Some of this research is promising, but these technologies are still under development.

All arsenic removal technologies generate some kind of arsenic-rich waste. These wastes are generally not hazardous to handle, but special care must be taken in disposing of them, especially at centralized plants. At the community or household level, the volume of waste generated is usually not enough to have a major environmental impact, and stabilized wastes can be disposed of with other solid wastes, solidified in concrete, buried, or discarded in sanitary latrines.

Selection of an appropriate technology

With so many options available for source substitution, and so many different types of arsenic removal technology, it is not always clear which alternate water source is best for a given setting. In all cases, technologies should meet several basic **technical criteria**. Water supply options must first of all be able to produce water of the required **quality**, both chemical and bacteriological. Systems should also be able to supply water in adequate **quantity**, throughout different seasons. Technologies should be reliable and **robust**, with little opportunity for errors to occur through systemic weaknesses or through user error. As community systems will be operated by non-technical community members, it is important that **operational safety** be ensured. Finally, technologies should not have an undue adverse effect on the **environment**.

Technologies meeting these technical criteria can be evaluated under several **socioeconomic criteria**. First, the systems must be **economically feasible** for members of affected communities. Users can be expected to contribute to costs, but most new water supply systems will require some level of subsidy. Introduction of new technologies requires **institutional capability**, for aspects such as production and delivery of materials, training, quality control, and monitoring. **Gender** impacts should be considered, so that the workload of women and girls is not increased. New options must be **convenient**, or people will not use them. New technologies require behavioral change on the part of the user for optimal use, health and hygiene impact, so **communication** interventions should be considered. Finally, technologies must be **socially acceptable** to community members in order to be successful as a long-term safe water supply option.

Ideally, after considering the above technical and socioeconomic criteria, one technology would clearly emerge as a superior option. In reality, this is unlikely – each option will have benefits and disadvantages. In some cases one option alone will not suffice, and a combination of systems will need to be used – e.g. rainwater collection during the wet season and arsenic removal during the dry.

The key to selecting an appropriate technology (or technologies) is to involve community members in all stages of the process, from technology selection to operation and maintenance. In this way, a sense of ownership can be generated, and an appropriate, sustainable technology can be selected. To allow water users to make their own informed choice, they need information about a wide range of options. Until water users understand the problem of arsenic contamination and its impact on their health, and have reliable information about safe alternatives, they will be unwilling and unable to make an informed choice to change their water use patterns. The biggest challenges ahead lie in applying the technologies described in this chapter in poor, rural settings, and in enabling those communities to choose safe sources of water for drinking and cooking.

6.1 Safe drinking water supply

In most industrialized countries, access to safe drinking water is nearly universal, and is often taken for granted. This access has come as the result of massive public expenditures, though now more and more water supply agencies are being privatized.

In contrast, access is typically lower in developing countries, where economies are weaker, and infrastructure is not as developed. The situation is the worst for the poorest people in developing countries, who often have no access to piped water supply. It has been estimated that 20-30% of urban residents in the developing world rely on water vendors, who sell water at prices much higher than piped water would cost. These families typically spend one fifth of their income on water, though the poorer segments pay a larger proportion (Cairncross and Kinnear, 1991). In rural areas, piped distribution systems are generally not available, and women and children must spend many hours each day collecting water from rivers, ponds, and wells. One analysis calculated that in Africa alone, women and children spend over 40 billion hours annually collecting water for household use (de Rooy and Doyle, 1992).

The economic impact of convenient access to a safe drinking water source, along with the prospect of reducing the drudgery associated with water collection, provide sufficient justification for safe drinking water supply initiatives. Yet the main reason for water supply interventions is associated with public health.

The largest public health impact of unsafe drinking water is diarrhoeal disease, which contributes to the deaths of some 1.9 million children every year. In addition, about a third of the population of the developing world is infected with intestinal worms. These and several other diseases can be reduced through better sanitation, hygiene and water supply (UNICEF, 1999a). Safe water initiatives, notably the International Drinking Water Supply and Sanitation Decade, from 1981 to 1990, have focused on improving both the quantity and quality of drinking water supplies, and on increasing use of sanitary means of excreta disposal.

Because of such interventions, access to safe drinking water has improved dramatically, especially in rural areas, over the last twenty years, as shown in **Table 6.1**. This has contributed, along with advances in sanitation and treatment of diarrhea, to a significant reduction in diarrhoeal disease and general improvements to children's health. The infant mortality rate in developing countries has dropped dramatically – from 137 per thousand in 1960 to 66 per thousand in 1996. Over the same time period, the under-five mortality rate also dropped by over half, from 216 per thousand to 97 per thousand (UNICEF, 1998). Even in the last ten years, child deaths from diarrhoeal diseases in developing countries have declined by more than a third, mainly due to increased use of oral rehydration therapy, improvements in sanitation and access to safe water, and subsequent behavioral change (UNICEF, 1999a).

Table 6.1: Drinking water and sanitation access in developing countries

	Water supply service coverage (%)			Sanitation service coverage (%)		
	Rural	Urban	Total	Rural	Urban	Total
1980	29	75	43	13	53	25
1990	63	93	73	28	73	44
2000	69	92	79	34	81	53

Source: (WHO/UNICEF, 2000)

Notes: 1) Figures should be regarded as rough approximations.

2) 1980 data exclude People's Republic of China, for which statistics are unavailable.

- 3) After 1980, many countries adopted a more stringent definition of sanitation, and therefore only a rough comparison of 1980 and later data can be made.

One main strategy in the quest for safe drinking water has been the shift away from surface water. Surface water can be heavily contaminated with fecal pathogens, especially in areas where sanitary disposal of excreta is not practiced. In contrast, groundwater is typically free of microbiological contamination. Rather than attempt to disinfect surface water, it is often more economical to abstract groundwater, which requires little or no treatment for pathogen removal. Even so, proper storage and handling of water is essential to prevent contamination of safe water by users.

Reflecting the goal of reduction of diarrhoeal disease, water quality testing has focused heavily on microbiological tests. Water was tested for inorganic parameters only when a taste or color problem was apparent (e.g. high iron or chloride) in the area. It is now clear that both groundwater and surface water can contain harmful levels of other hazardous compounds, many of which cannot be detected by sight or taste alone. WHO has set Guideline Values for 17 inorganic compounds which have adverse health effects, 27 organic constituents, 33 pesticides, and 17 disinfectants or disinfectant byproducts (WHO, 1993). Obviously it is not feasible, or necessary, to test every water source for all 94 of these constituents, particularly for small systems. Fortunately, few of these compounds commonly occur naturally, and testing can therefore be limited to compounds that are known or suspected to have been applied by humans, or to exist naturally in the local environment.

Since the discovery of widespread occurrence of fluoride and arsenic in groundwater in various parts of the world, and in view of the increasing contamination of groundwater from agricultural chemicals, public regulatory and surveillance organizations have begun more widespread monitoring of drinking water quality parameters. It remains unfeasible to test all water sources for all parameters, but water producers should consider carefully their drinking water sources, and consider whether more comprehensive water quality testing is warranted. In many developing countries only limited water quality testing is done routinely. Large water providers should at least initially test source waters for compounds of health concern that are known to sometimes contaminate drinking water supplies, such as fluoride, arsenic, manganese, nitrate, nitrite, and trace elements such as heavy metals. A useful overview of inorganic compounds of health significance sometimes found in groundwater and conditions leading to their mobilization is given by Edmunds and Smedley (Edmunds and Smedley, 1996). Other compounds of health concern listed by the WHO, including chlorinated solvents, aromatic hydrocarbons, pesticides, and disinfectants, do not occur naturally in groundwater. Drinking water supplies should be tested for these compounds when there is reason to suspect that human application of such chemicals in agriculture or industry may have contaminated the drinking water source.

When arsenic contamination is identified, the immediate priority must be to find a safe alternate source of drinking and cooking water for affected communities. Alternate sources must be not only arsenic-free, but also microbiologically safe – it would be a serious mistake to revert back to unsafe use of surface water sources. In some cases, there may be no one technology that can provide communities with a sustainable, continuous, affordable, safe water supply. If a year-round safe water source is not currently available, it may be necessary as a short-term solution to use one source during wet seasons (e.g. groundwater, rainwater) and another during dry seasons (e.g. removing arsenic from contaminated water). If a completely satisfactory, arsenic-free water source cannot be established, the short-term goal should be to reduce arsenic levels in drinking water as much as possible, as quickly as possible, even if regulatory standards cannot be immediately met. It should be recalled that health effects of arsenic are dose-dependent, and a partial solution is better than no solution. However the long-term goal should be affordable and

convenient sources of safe drinking water meeting all regulatory standards for every community. The implementation of a temporary solution should not be used as a reason to delay design and implementation of a long-term plan.

6.2 Sources of arsenic-free drinking water

When a drinking water source is found to contain unsafe levels of arsenic, one mitigation option is to install another water supply point, drawing from arsenic-free sources. This source should be sufficient for drinking and cooking needs, though with centralized water supply systems it is usually necessary to provide water of high quality for all needs.

In municipal plants with multiple production wells or surface sources, it may be possible to blend low-arsenic and high-arsenic waters to meet a regulatory standard. However, wherever possible, full source substitution would be preferable to blending. In the short term, or in emergency situations, safe water for cooking and drinking needs can even be transported into affected areas, either as bottled water or in tanks². It will nearly always be more cost effective, however, to find a local source of water that is either arsenic-free or can be treated.

There are three main sources of water to be considered for substitution for contaminated water: groundwater, rainwater, and surface water.

6.2.1 Groundwater

Groundwater quality

Where available and of good quality, groundwater is usually the most acceptable source for drinking water supply. Due to the natural filtering of aquifer materials, and long underground retention times, groundwater typically has very little pathogenic contamination, and requires little or no disinfection. In contrast, surface water is often heavily polluted with fecal material as a result of poor sanitation and hygiene practices. Surface water is also more susceptible to chemical contamination from industrial or agricultural runoff, such as heavy metals, pesticides, or nitrate.

However, groundwater quality should not be taken for granted. In very shallow aquifers, bacterial contamination is possible, and even likely if the wellhead is poorly protected. In addition to arsenic, other inorganic constituents in groundwater can cause health or aesthetic problems, notably iron, manganese, nitrate, chloride, and fluoride. Other contaminants listed in the WHO Guideline Values should be tested for if their presence is suspected, either from human activity or from naturally occurring sources (WHO, 1993).

If some existing groundwater supplies are found to be arsenic-free, these will usually be the most preferred water source, at least in the short term. The simple act of testing all of a community's wells for arsenic is valuable in that it will identify safe, as well as unsafe, wells. People can be encouraged to share safe water resources, though if safe wells are scarce or absent, this may not be feasible. If safe wells are privately owned, the owners may be reluctant to allow others access to the wells, out of concern for privacy or a fear that increased use will result in increased maintenance and replacement costs. In some cultures, women are the main water collectors, but also have limited social mobility, and privacy concerns can make sharing of a household well uncomfortable or unacceptable. The complicated issue of women's role in water collection is

² Bottled water is not necessarily free from unsafe levels of inorganic contaminants: a recent water quality survey of 56 bottled European mineral waters found that only 15 would meet drinking water standards for all parameters where action levels are defined. Nine percent of the mineral waters tested contained arsenic ranging from 10 to 20 µg/L (Misund et al., 1999).

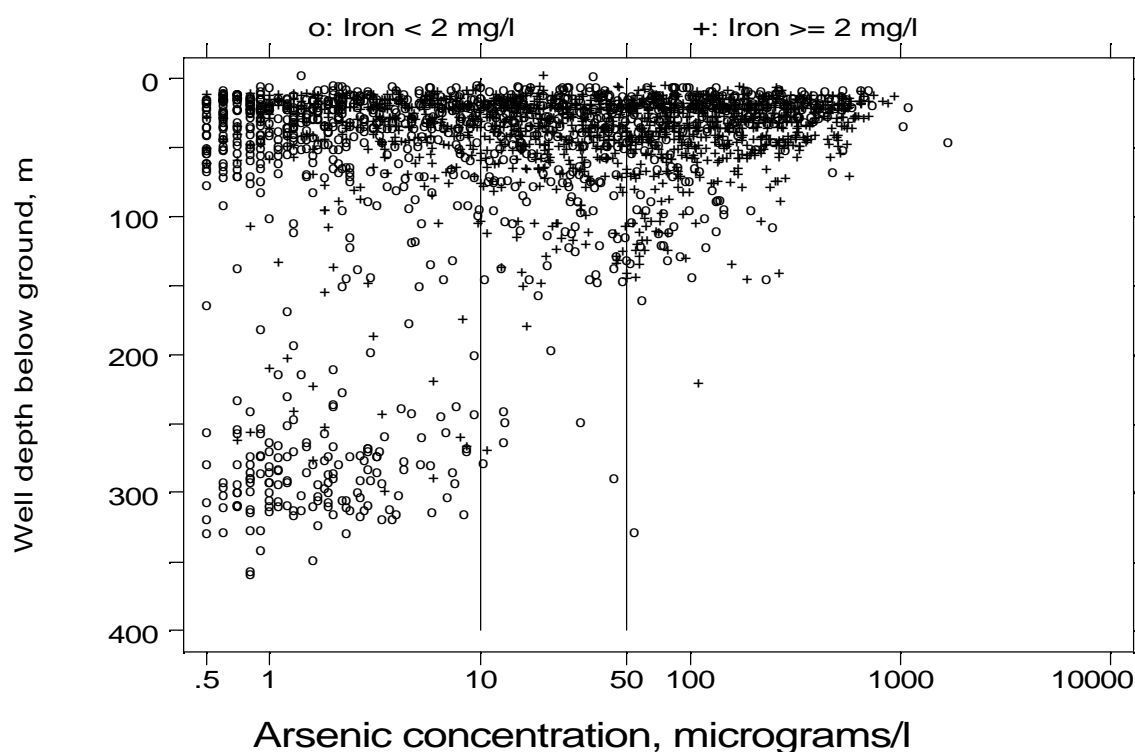
discussed more fully in a series of IRC reports (van Wijk-Sijbesma, 1985; van Wijk-Sijbesma, 1998).

Based on an understanding of the geological origins of contamination, it may be possible to identify areas or strata that are at relatively low risk of arsenic contamination. In some areas arsenic contamination is confined to highly localized sedimentary deposits. If these hot spots are identified through widespread arsenic testing, new wells can be preferentially installed in relatively safe areas. In areas where some geological units are arseniferous and others are not, it is important to avoid cross-contamination, which can occur in several ways. In some cases, the arsenic-rich zones may be naturally in hydraulic connection with arsenic-free zones. By pumping water from arsenic-free zones, arsenic-rich water may be induced to flow into previously uncontaminated strata, and eventually may reach the well. In other cases, the arsenic-rich and arsenic-free zones may be separated by low-permeability materials such as clays. Drilling can disturb this natural barrier, and the borehole itself (specifically, the annular space around the well pipe) may provide a high-permeability conduit from one zone to another. When wells are drilled with mechanical rotary rigs, it is possible to inject impermeable material such as grouting or clay into this annular space at the level of the impermeable layer, to prevent this kind of contamination. However, in many developing countries, grouting is not used, either to save money or because the drilling technologies are not compatible with grouting.

Arsenic-free wells might become contaminated over time through a third mechanism: arsenic could initially be present in a stable, solid form in aquifer sediments. If the geochemistry of the pore water, especially the pH and redox potential, should change, arsenic could become mobilized, and make its way into the abstracted groundwater.

Box 6.1: Deep aquifer in Bangladesh

In Bangladesh, the most serious arsenic contamination is seen in shallow tubewells, while only a few deep tubewells have been shown to contain high levels of arsenic. A major hydrogeological survey found that in surveyed areas, while over 40% of wells less than 100 m deep (n=1662) exceeded the Bangladesh drinking water standard of 50 µg/L, less than 1% of the wells deeper than 150 m (n=317) exceeded the limit. The deeper wells are less prone to arsenic contamination because they are screened in a pre-Pleistocene aquifer. These aquifer sediments are millions of years old, and any arsenic present has probably been flushed out, or is present in a stable solid form. The shallow wells, in contrast, are screened in Holocene aquifers that are only thousands of years old, and have not been completely flushed since deposition. These shallow sediments are rich in organic matter, which creates the reducing conditions that encourage mobilization of arsenic, as well as elevated iron levels (DPHE/BGS/MML, 1999).

Figure 6.1: Arsenic and well depth in Bangladesh (DPHE/BGS/MML, 2000)

Note: vertical lines at 10 and 50 $\mu\text{g/l}$ represent the WHO Guideline Value and Bangladesh Standard, respectively. (Editors: you may wish to redraw or copy the similar figure from the GSACB Phase I report – Volume S2, Figure 5.7 - to get a prettier image, but it doesn't have the iron breakdown. I assume you will redraft the figure to make it prettier, - especially the legend and text - please contact me if you need the data.)

Accordingly, there have been many calls for interventions to prioritize installation of new deep tubewells in arsenic affected areas. However, experience from neighboring West Bengal suggests that deep tubewells may not always remain arsenic-free. In one village eight new tubewells with depths of 140 m were installed that initially showed safe levels of arsenic, but within a year of installation, all had reportedly become unsafe. This is not inconsistent with **Figure 6.1**, which shows significant arsenic contamination between 100 and 150 m in Bangladesh. In West Bengal, one deeper well (260 m) also showed arsenic contamination (Mandal et al., 1996).

At present, not enough is known about the deep aquifer in these areas to say with certainty whether or not its groundwater will remain arsenic-free. It must be remembered that the absence of arsenic in deep wells indicates the controlling influence of geology and geochemistry, not of depth. Two equally deep tubewells in different parts of Bangladesh might draw water from different aquifers with radically different chemical composition. In the coastal belt, deep tubewells have operated for decades without becoming contaminated with salt from the overlying brackish aquifer, which suggests that cross-contamination is not likely. However, since deep tubewells in Bangladesh have almost exclusively been installed in a relatively small coastal zone where the shallow aquifer is saline, the extent and properties of the deep aquifer further inland are not well known. It is to be expected, however, that the thick impermeable clay layer that separates the two aquifers in coastal areas will thin towards the inland, which may increase the possibility of cross-contamination. More hydrogeological work will need to be conducted before the long-

term viability of the pre-Pleistocene aquifer as a source of arsenic-free water can be determined.
END BOX

Systems for groundwater exploitation

Groundwater resources can be accessed in five main ways: sub-surface dams, protected springs, hand-dug wells, hand-drilled borewells, and machine drilled borewells. These are described in detail in the UNICEF Water Handbook (UNICEF, 1999b). Machine and hand-drilled borewells are the most common systems, though in hilly areas spring protection may be more economical. An extensive literature exists on water pumping technology, the interested reader is referred to (IRC, 1981), (Arlosoroff et al., 1987), and (IRC, 1988).

6.2.2 Rainwater

Rainwater collection can provide a safe, arsenic-free source of drinking water if weather conditions are appropriate. When properly collected and stored, rainwater can keep a fairly constant water quality for months.

Collection

In areas with low population density and hard rocks surfaces (rock outcrops or cement), rainwater can be collected from the ground surface by constructing microdams to channel surface runoff into underground storage tanks. In more densely populated areas, rooftop collection is more common. Corrugated iron roofs are ideally suited for this purpose, though terra cotta or wood tiles, or concrete roofs are also acceptable. Thatched roofs are not appropriate for rainwater collection, as the collected water is high in organic matter. These roofs, however, can be made suitable with the simple use of inexpensive plastic sheeting. Roofs should be cleaned thoroughly at the beginning of every rainy season, regular maintenance is also crucial.

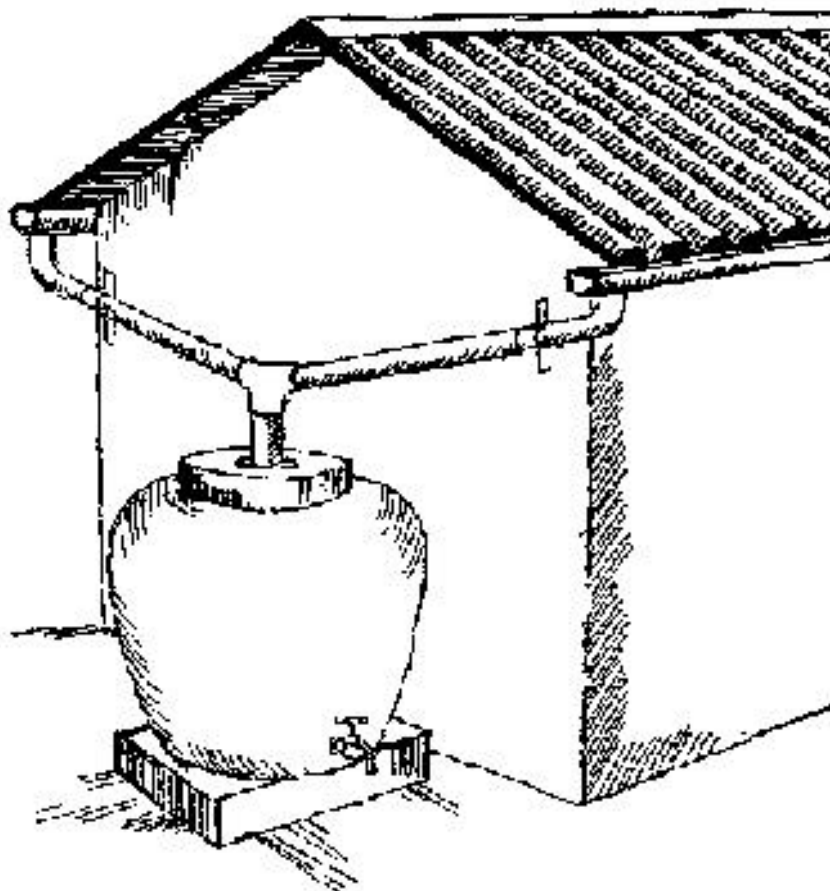
Water is collected from the roof surface in gutters, which are connected to a storage tank with a downpipe. In order to minimize the amount of contamination and organic matter in collected water, a fine mesh netting or coarse sand filter should be placed between the downpipe and the storage tank. This will also help to keep insects and small animals out of the tank, and has been shown to improve water quality, and reduce the risk of mosquito breeding.

When rain falls after a dry period, water should not be collected for the first ten to fifteen minutes, in order to clean the collection surface. This ‘first flush’ can be achieved through use of a bypass valve, or through a variety of simple designs.

Storage

A rainwater storage tank should be completely covered, and have a tap or pump for withdrawing water, to prevent contamination from users. If water is stored in open containers, or users dip cups or pitchers in a tank to retrieve water, the stored water can easily become contaminated with fecal pathogens.

Figure 6.2: Rooftop catchment with tank (after UNICEF, 1999b, p. 40)



The amount of storage required will depend on local rainfall patterns, especially on the extent of dry seasons. If rainfall is scarce or absent for several months, large tanks will be required, or alternate sources of drinking water used during the dry season. In rainy periods, small, inexpensive tanks are able to provide adequate storage for most household needs.

Aboveground tanks can be made of locally available materials such as brick or cement. Ferrocement (cement reinforced with iron mesh or wires) is much stronger than cement, so ferrocement tanks can be thinner and less expensive than simple cement or brick tanks. Prefabricated plastic tanks can also be used, though these are not as easy for rural users to repair, and may impart a taste to the stored water. Tanks should be cleaned at least annually, and if possible, disinfected.

Underground storage tanks can be quite large, and have smaller unit capital costs. However, underground tanks are more vulnerable to contamination from surface waters, flooding, and animal invasion, more difficult to clean, and require the use of a pump to draw water to the surface.

Water Quality

The bacteriological quality of rainwater will depend on the collection and storage methods. In a well-designed system, pathogenic bacteria counts are low in collected rainwater, and the conditions (lack of light or food source) do not promote their growth. Under these conditions

pathogen levels will actually decrease with storage, rather than increase. Typically, some coliform bacteria can be found in collected rainwater, but usually the bacteria are not fecal in origin (Pacey and Cullis, 1986).

Several reviews of bacteriological quality of rainwater have been made: in some cases, fecal and total coliform counts are extremely low (e.g. Dillaha and Zolan, 1985), but more commonly low levels of coliform bacteria are found. Typical fecal and total coliform counts in water collected from rooftops average 5-15 and 25-75 per 100 ml, respectively (e.g. Pinfold et al., 1993; Appan, 1997; Simmons et al., 1999a). By examining the ratio of fecal coliforms to fecal streptococci, Appan showed that approximately 80% of the fecal contamination was of non-human origin, presumably from animal droppings on the rooftop (Appan, 1997). Simmons and others found similar coliform counts in rural New Zealand, though occasionally counts were significantly higher (maximum total and fecal coliforms were 19,000 and 840 per 100 ml). Two samples showed *Cryptosporidium*, but none showed *Giardia*, *Campylobacter*, or *Legionella pneumophila* (Simmons et al., 1999a).

Yaziz and others found moderate levels of coliform bacteria in rainwater collected from rooftops, and showed that the highest counts were in the first samples collected during a rainfall. When samples were collected after a 'first flush' equivalent to 35 liters per 100 square meters of roof catchment area, no fecal coliforms could be detected, and total coliforms were reduced by over 50% (Yaziz et al., 1989).

If bacterial quality of stored water is unacceptable, disinfection may be required (see **Section 6.2.4**).

The chemical composition of collected rainwater is very different from that of surface or groundwater. Rainwater is very low in dissolved minerals, and as such is relatively corrosive. This lack of minerals may also cause mineral deficiency in the diets of poorly-nourished consumers.

Due to atmospheric carbon dioxide, rainwater is naturally slightly acidic. Industrial activity, especially production of sulfurous aerosols, can result in the well-known phenomenon of acid rain, which can extend well beyond zones of industrial activity. Acid rain has been documented in rainwater collection systems: drinking water collected from rooftops in Singapore was found to have pH as low as 4.2 (Appan, 1997). The pH of collected rainwater can be raised slightly through storage in ferrocement tanks.

Natural arsenic levels in rainwater are low, generally less than 1 µg/L (Andreae, 1980), though industrial sources, notably smelters and coal plants, can emit arsenic compounds and potentially contaminate rainwater. Likewise, in urban settings, rainwater may have elevated concentrations of human-caused pollutants such as hydrocarbons and heavy metals. Several water quality studies have documented elevated lead levels in rainwater collected from rooftops (e.g. Yaziz et al., 1989; Chang and Crowley, 1993; Thomas and Greene, 1993; Appan, 1997), often at several times the WHO Guideline value of 50 µg/L. In some cases this is most likely due to atmospheric contamination, rather than leaching from roof materials, since similar levels have been found in rainwater collected directly, and in waters collected from metal and concrete roofs (Yaziz et al., 1989). However, others report elevated lead levels in rural New Zealand, where atmospheric lead should be low. Lead levels were highest in houses using lead or galvanised iron flashing (Simmons et al., 1999b).

Especially when rainwater is acidic, other contaminants can be leached from roof catchment or tank materials. Terra cotta and concrete materials can result in highly alkaline waters (Chang and Crowley, 1993). When rainwater is collected from corrugated sheet metal roofs, elevated zinc

levels are commonly reported, typically ranging from 2-6 mg/L (Yaziz et al., 1989; Appan, 1997), sometimes exceeding the WHO Guideline value³ of 3.0 mg/L.

In addition to being microbiologically and chemically safe, it is important that collected rainwater have a taste that is acceptable to users. Rainwater is much less mineralized than surface water and groundwater, which can give the water a flat taste which some may find objectionable. In parts of South America, ground tree bark is added to rainwater to improve taste; elsewhere crushed seeds, curd from sour milk, or tree leaves are used in the same way (Pacey and Cullis, 1986).

Although collected rainwater commonly contains low levels of coliform bacteria, in many cases it is of much better microbiological quality than other available water sources. Chemical parameters, especially pH and lead and zinc levels, should be monitored regularly to ensure that appropriate water quality standards are met. In most cases, however, the relative purity of rainwater makes it an attractive option in areas with uniformly high arsenic levels in other water sources. A large literature on the collection, storage, treatment, and distribution of rainwater exists, drawing on experiences from around the world. For more detailed information, the reader should consult the excellent reports produced by ENSIC (Gould, 1991), IRC (IRC, 1981; IRC, 1990), ITDG (Pacey and Cullis, 1986; Cullis and Pacey, 1991; Gould and Nissen-Petersen, 1999), and UNEP (UNEP, 1983). In recent years, several valuable websites have been set up with ready reference material on the application of rainwater collection and storage. Many such sites exist, two good introductory sites containing many links are (IRCSA, 2001) and (EU, 2001).

6.2.3 Surface Water

Surface water presents more of a challenge than groundwater or rainwater in that it is usually heavily contaminated with fecal bacteria. Other contaminants may be contributed from agricultural sources, such as nitrates, phosphates, and pesticides. Finally, surface water is more vulnerable to industrial contamination. In urban and peri-urban areas, surface water often receives untreated wastes from industrial factories, untreated solid wastes, and urban runoff. As a result surface waters can have very high biochemical oxygen demands (BOD), and be seriously contaminated with organic compounds and trace metals.

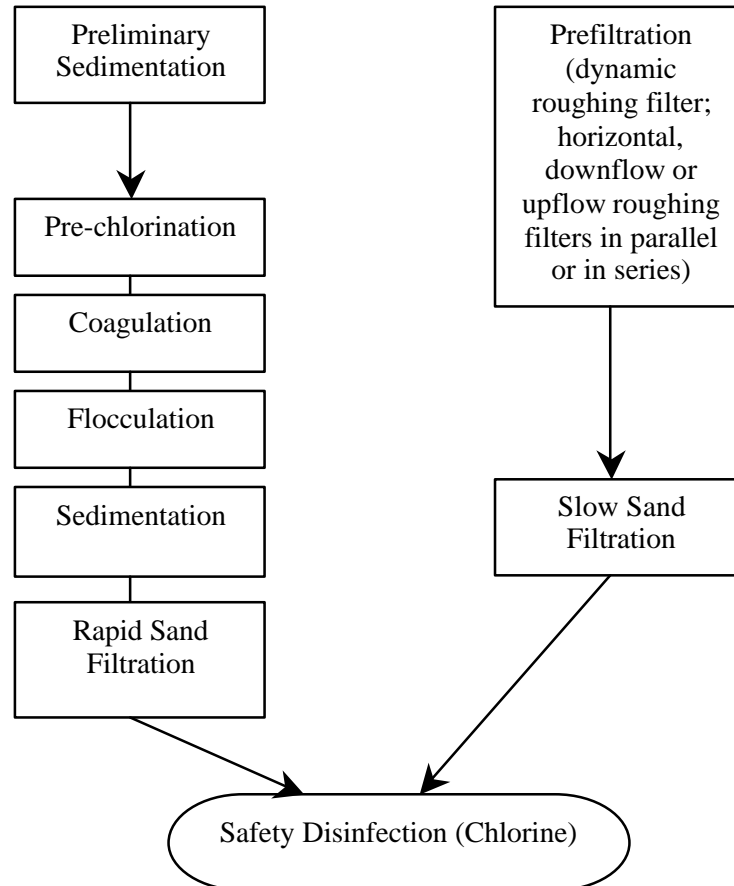
Surface water can also have naturally high levels of inorganic compounds, eroded from source rocks upstream, that can cause human health problems. The well-documented case of arsenic contamination of drinking water in Chile arose from the use of rivers which drain arsenic-rich rocks in the Andes. Unsafe levels of arsenic have also been reported in surface waters of Argentina, Ghana, and Bangladesh (see **Chapter 1**). If surface water resources are to be turned to in areas showing elevated arsenic levels in groundwater, it is imperative that surface water sources also be tested.

In spite of the higher risk of contamination, in many cases surface water is the only feasible water source, and various low-cost, low-tech options for water treatment are available. Surface water treatment in municipal treatment plants is a highly engineered process, and such plants must be operated by trained professionals. In smaller, community level treatment plants, simpler equipment is usually used, systems are operated by non-technical community members, and the risk of system failure is higher. The only proven method for treating contaminated surface water in this type of setting is by means of a multiple-barrier system, in which several processes are used in series, which progressively remove bacterial and other contaminants. This design protects

³ The guideline value for zinc is based on aesthetic grounds, relating to taste and appearance. WHO has not set a health-based guidance value for zinc in drinking water.

against the transmission of pathogens in the event that one barrier should fail. Two typical multiple-barrier series for community water supply are shown in **Figure 6.3** (WHO, 1997b).

Figure 6.3: Multiple barriers to microbiological contamination in surface water treatment



The first treatment system shown above makes use of three main stages: pre-treatment, addition of coagulant and subsequent removal of solids, and a safety chlorination of the filtered water. The second system depicted above makes use of prefiltration and slow sand filtration in place of chemical addition. This system would require fewer operator inputs.

Preliminary Sedimentation

The first stage of surface water treatment is typically storage and preliminary sedimentation to remove coarse suspended solids that could clog filters or reduce disinfection efficiency. This is especially needed in tropical areas where rivers often have high silt loads. Preliminary sedimentation tanks can remove at least 50%, and up to 90% of turbidity and suspended solids. If the tanks are open to the atmosphere, sunlight may promote algae growth. Preliminary sedimentation is usually followed by a primary disinfectant dose, as shown above, to improve subsequent coagulation and to prevent the growth of algae and slime in treatment tanks.

Coagulation and Filtration

The majority of pathogen removal takes place during coagulation and filtration. Coagulants such as alum or ferric salts are added to the water, and form small solid particles (flocs) which aggregate (flocculate) and settle out of suspension. This settling, or sedimentation, most commonly takes place in horizontal-flow tanks, where water slowly moves from one end to the other, though in more advanced systems other designs such as upward-flow or spiral-flow tanks are sometimes used. Sedimentation can be improved by use of plate and tube settlers, though these devices may cause problems with clogging and odors (Metcalf & Eddy, 1991). Following sedimentation, the remaining suspended solids are removed by passing the water through filter beds of sand or anthracite (rapid sand filtration).

Coagulation and filtration can effectively reduce turbidity and suspended solids. When coagulation and filtration systems are managed properly, removal of 90 to 99% of bacteria and viruses, and over 90% of protozoa can be expected (Salvato, 1992, p. 346). However, a safety dose of chlorine should be given following filtration, to destroy any remaining pathogens, and impart a residual disinfectant to the water. Chlorination at any stage of treatment can produce harmful disinfection by-products, depending upon the dose and composition of the treated water. The health risks posed by these by-products are smaller than the risks posed by pathogens, so disinfection should not be neglected simply to avoid by-product formation. For a full review of the issue of disinfection by-products of chlorination, see (Singer, 2000). Coagulation and filtration can also remove dissolved constituents such as phosphorus, metal ions, and natural organic matter, under correct operating conditions.

Slow sand filtration

An inexpensive alternate to coagulation and filtration is slow sand filtration, one of the oldest technologies for surface water treatment. The first stage in slow sand filtration is some sort of coarse prefiltration (often through gravel or coconut husk) to remove gross particulate matter. The prefilter feeds into the main tank, which contains a thick bed of sand. The water level in the tank is always kept well above the sand bed, providing a driving pressure and preventing the filter from drying out. Water moves through the sand beds at about 0.2 m/h, and passes into a storage tank, fitted with taps for users to draw water from.

Slow sand filtration can effectively remove suspended solids larger than about 2 microns. A detailed description of particulate removal in slow sand filtration is given in (Weber-Shirk and Dick, 1997). Pathogens are removed through a combination of physical, chemical, and biological processes, the last of which is the most important. After the filter has been in operation for some time, a layer of microbes develops near the top of the sand bed. In this zone, called the *schmutzdecke*, predatory microbes attack and consume pathogens in the influent water, such as viruses, bacteria, protozoal cysts (including *Giardia*, and *Cryptosporidium*, which is resistant to chlorination), and helminth eggs (Bellamy et al., 1985a; Cairncross and Feacham, 1993). In a well-operated slow sand filter pathogen removal may exceed 99% (WHO, 1997b). Nonetheless, slow sand filtration is typically followed by a safety disinfection with chlorine (IRC, 1978; IRC, 1982b).

After one to three months of operation, slow sand filters can become clogged, and the driving pressure must be restored by scraping off the top few centimeters of sand, including the *schmutzdecke*. After this scraping, the filter will require several days to 'ripen', and become effective again, depending on the water quality and temperature. After ripening the filter can be commissioned again. After many scrapings, when the sand bed reaches some minimum depth (usually about 45 cm) then new sand or the scraped and washed sand is added to the bottom of the sand bed. This necessarily involves a complete removal of the remaining sand bed. The

replacement sand is not simply put on top of the remaining sand bed, because the older sand is already 'inoculated' with micro-organisms.

Table 6.2: Typical removal efficiencies in slow sand filtration

Source: (Bellamy et al., 1985b; Ellis, 1985; Huck, 1987; Rachwal et al., 1988; Hrubec, 1991; and Fox et al., 1994), as cited in (Galvis et al., 1998)

<i>Water quality parameter</i>	<i>Effluent or removal efficiency</i>	<i>Comments</i>
Turbidity	< 1 NTU	The level of turbidity and the nature and distribution of particles affect the treatment efficiency
Enterobacteria	90 to 99.9%	Affected by temperature, filtration rate, size, uniformity and depth of sand bed, cleaning operation
Enteroviruses and <i>Giardia</i> cysts	99 to 99.99%	High removal efficiencies, even directly after cleaning (removal of the <i>schmutzdecke</i>)
<i>Cercaria</i>	100%	In good operation and maintenance conditions virtual complete removal is obtained
True color	25 to 30%	Color associated with organic material and humic acids
TOC	< 15 - 25%	TOC, total organic carbon
THM precursors	< 25%	Precursors of trihalomethanes
Iron, manganese	30 to 90%	Iron levels above 1 mg/l reduce filter run length

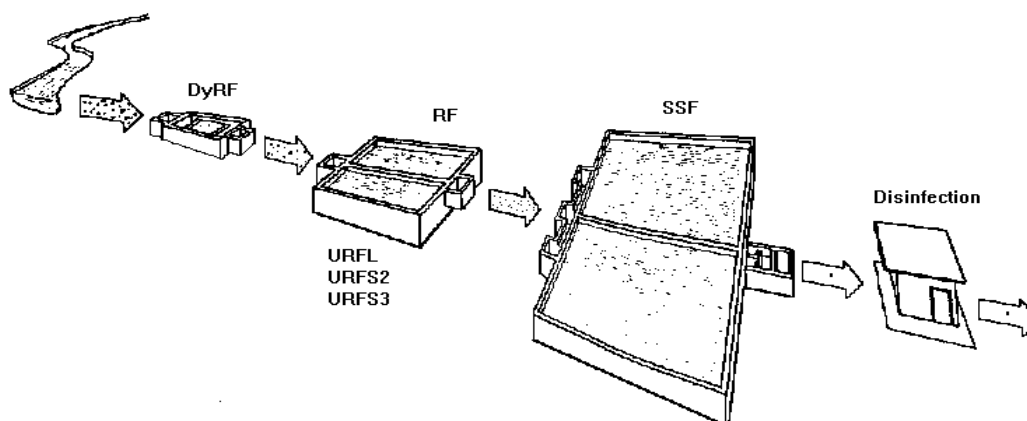
Several detailed overviews of slow sand filtration are given by the WHO and IRC: (Huisman, 1974; IRC, 1982b; Raman et al., 1987). The American Water Works Association has published a useful manual for the design and construction of slow sand filters (Hendricks, 1991). Recently, a regular international conference on slow sand filtration and biological filtration has been established: the proceedings from these conferences contain many valuable papers about recent research (Graham and Collins, 1994; Graham and Collins, 1996).

Slow sand filtration works best with relatively clear source waters. An influent turbidity of under 10 NTU is recommended, though somewhat higher levels can be tolerated for short periods (IRC, 1982b). Recent work in Colombia has shown that the use of more rigorous pre-filtration steps can allow treatment of surface water with higher turbidity and pathogen loads. This system is called multi-stage filtration, and uses various types of upflow and/or downflow coarse gravel prefilters in combination with conventional slow sand filtration to provide much better treatment than slow sand filtration alone. Multi-stage filtration is discussed in detail in an IRC technical paper (Galvis et al., 1998).

An innovation in multi-stage filtration that has improved operation, particularly by increasing the intervals between cleaning of slow sand filters has been the 'dynamic roughing filter'. This is essentially a coarse downflow roughing filter of gravel, with an overflow mechanism. When the gravel bed becomes clogged, water flows to waste instead of into subsequent filters, protecting them from excessive suspended loads. If the source water is relatively clean, a dynamic roughing filter, followed by slow sand filtration and disinfection may be adequate to consistently provide safe water. If the raw water is less pure, additional roughing filters may be required between the dynamic roughing filter and the slow sand filter. **Figure 6.4** shows a multiple-stage filtration

system consisting of a dynamic roughing filter, one or more upflow roughing filters, a slow sand filter, and a disinfection step. This system illustrates the concept of multiple barriers to ensure that finished water will remain safe, even if one component should fail.

Figure 6.4: Multi-stage filtration (Galvis et al., 1998)



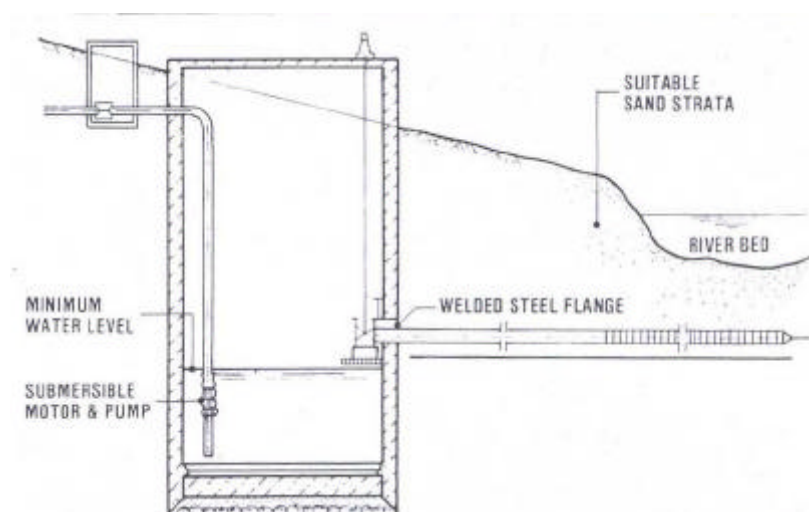
Simple filtration can also be applied at the household level to reduce suspended solids. Household sand filters, candle filters, and cloth filtration can all improve the physical quality of water. Such simple filtration will reduce fecal contamination to some extent, but should always be followed by disinfection (WHO, 1997b).

Bank infiltration

An alternative to constructing engineered sand filters to remove suspended solids and pathogens from surface water is to make use of naturally occurring sediments in the subsurface. In bank infiltration (also called induced recharge), a shallow well or series of wells are installed in the vicinity of a river or lake. When water is pumped from the well(s), the local groundwater flow patterns are changed. If the water table is lowered below the level of the river or lake, surface water will be induced to enter the aquifer and flow towards the well. If the shallow groundwater is contaminated with arsenic, it may be possible to induce arsenic-free recharge from surface water bodies, and develop a safe drinking water source. The introduction of oxygenated water might also reduce the mobility of the dissolved arsenic present in the groundwater. However, to date there are no documented examples of bank infiltration in arsenic-affected areas.

In order to allow sufficient filtration and bacterial purification to take place, wells should be installed at least 20 m, and preferably 50 m or more away from the surface water source. Underground travel times should be at least three weeks, and preferably more than two months. One benefit of bank infiltration is that water can be abstracted from the well even during the dry season, when the surface water source may dry up, if the well screen is located below the dry season water table (IRC, 1981). Bank infiltration can improve the chemical as well as microbiological quality of surface water. Phosphate and trace metals, in particular, are likely to be removed by adsorption onto sediments during infiltration (Stute et al., 1997). A bank infiltration system is shown in **Figure 6.5**.

Figure 6.5: Bank Infiltration (IRC, 1981)



Box 6.2: Bank infiltration in Hungary

Hungary has developed what is probably the largest bank infiltration system in Europe. The municipal water works in the capital, Budapest, has installed a network of shallow wells (typically 6-10 meters deep) on two large islands in the Danube river. Supply wells are most often sited 100-300 m from the shore, but in some cases are as close as 30 meters. Isotopic tests have shown that the abstracted water is very young, and almost entirely derived from the river. However, bacteriological quality is good, and the water requires little treatment – only iron and manganese removal from some wells, and safety chlorination in all cases to provide a residual for distribution. Underground tunnels deliver the water to the capital and surrounding areas, meeting the needs of some 4.5 million inhabitants, or about 45% of the country’s population. Similar bank infiltration systems supply water to most major settlements on the Danube. Source: (Csanady, 1999) END BOX

6.2.4 Disinfection

Delivered water can contain pathogens which were either present in the raw water source, or were introduced during water production, storage and delivery. Pathogens can occur in water derived from groundwater, rainwater, or surface water, though the risks are greatest with surface water, because of the raw water quality. Physical or chemical disinfection is the most effective and reliable way to reduce the number of microorganisms in drinking water to acceptable levels. Disinfection can be practiced at either community or household levels. A comprehensive manual reviewing the needs for and limitations of disinfection in small communities is given by the Water Research Centre (WRC, 1989).

Physical Disinfection

Boiling can effectively kill ova, cysts, bacteria, and viruses present in water. Water should be brought to a full rolling boil, and maintained for one minute. Water boils at lower temperatures at higher altitudes, so for every 1000 meters of elevation an additional minute of boiling should be required. Boiling is generally not recommended for several reasons: it requires a large amount of fuel; it may give the water a flat, unpleasant taste; there is a risk that people may heat the water without boiling, and consider the water purified. Boiling in closed kettles can concentrate some

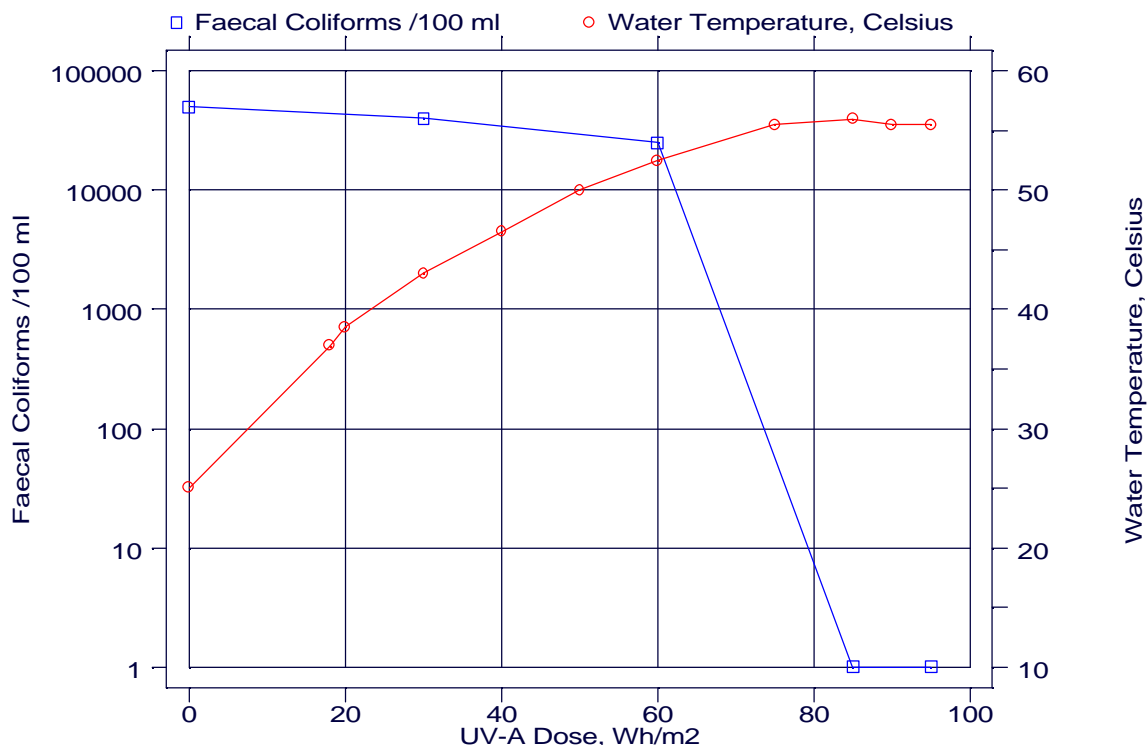
volatile organic compounds. Large-scale boiling is not a feasible option for drinking water in most cases because fuel costs would be prohibitive (WHO, 1997b).

Ultraviolet radiation can effectively kill pathogens. Electrical ultraviolet lamps have been used to irradiate water, and several schemes have been developed to utilize solar energy for disinfection (Acra et al., 1989; EAWAG, 1999).

The Swiss research center EAWAG has shown that by storing water in clear bottles and exposing them to at least 4 hours of sunlight, over 99% pathogen removal can be achieved. The sunlight both heats and irradiates the water, and these two processes have a synergistic effect on pathogen removal. Raw water must have low turbidity (<30 NTU), for radiation to penetrate sufficiently. Bacteria, viruses, *Giardia* and *Cryptosporidium* cysts, and parasite eggs can all be effectively inactivated through the combination of ultraviolet radiation and elevated water temperature. **Figure 6.6** shows that in one study, pathogen inactivation was initially low, but as water temperature rose above about 50°C, the effects of radiation and elevated temperature acted synergistically, resulting in increased inactivation efficiency. This technique, called SODIS (Solar Disinfection) involves very minimal capital and operational costs, and is promising, both for use in arsenic-affected areas, and for rural water supply in general. Large field tests of SODIS are currently being conducted in a number of countries in South America, Africa, and Asia (EAWAG, 1999).

Whether solar or artificial radiation is used, disinfection will be less effective in turbid waters, since suspended particles will scatter the radiation. Dissolved iron and manganese can also interfere with the efficacy of ultraviolet disinfection.

Figure 6.6: Temperature and pathogen removal in SODIS treatment (after EAWAG, 1999, Technical Note #1)



Chemical Disinfection

Chemical disinfectants include ozone and several chlorine compounds. In rural areas, the most common forms of chlorine are liquid bleach (sodium hypochlorite, about 1% available chlorine); bleaching powder (calcium hypochlorite, up to 30% available chlorine); and high-test hypochlorite (50-70% available chlorine). Chlorine compounds are very reactive and if improperly stored, available chlorine levels can be much lower than expected. The appropriate chlorine dose will depend on the chemical and physical composition of the water, and should be sufficient to satisfy both the chlorine demand and to produce a free residual of 0.5 mg/L. A minimum contact time of 30 minutes is recommended.

Various systems have been developed for chlorination at community and household levels (WRC, 1989; WHO, 1997b). Chlorine disinfection has several obvious advantages: it is very effective at pathogen reduction, and the free residual provides some protection against contamination during storage or transportation. However, if too little or too much chlorine is added, serious problems can arise: in the former case, users may incorrectly believe that the water is pathogen-free, while in the latter case the water may be unpalatable because of a strong chlorine taste⁴. Especially at community and household levels, it can be very difficult to ensure that the correct dose of chlorine is delivered. Even when the optimal dose of chlorine is achieved, water users unaccustomed to chlorinated water may find the taste unpleasant, and may choose to abandon chlorination. In both industrialized and developing countries, experience has shown that users have chosen unsafe sources over safe waters with too strong a chlorine taste.

6.3 Technologies for arsenic removal

In some areas, arsenic-contaminated water will be abundant, and arsenic-free sources scarce or polluted with other compounds. In these areas it may be most efficient to remove arsenic from the contaminated water, at least as a short term measure. Many technologies have been developed for the removal of arsenic. Most of the documented experience has been with large municipal treatment plants, but some of the same technologies can be applied at community or household levels.

All of the technologies for arsenic removal rely on a few basic chemical processes, which are summarized below:

- Oxidation/reduction: reactions that reduce (add electrons to) or oxidize (remove electrons from) chemicals, altering their chemical form. These reactions do not remove arsenic from solution, but are often used to optimize other processes.
- Precipitation: Causing dissolved arsenic to form a low-solubility solid mineral, such as calcium arsenate. This solid can then be removed through sedimentation and filtration. When coagulants are added and form flocs, other dissolved compounds such as arsenic can become insoluble and form solids, this is known as coprecipitation. The solids formed may remain suspended, and require removal through solid/liquid separation processes, typically coagulation and filtration.
- Adsorption and ion exchange: various solid materials, including iron and aluminum hydroxide flocs, have a strong affinity for dissolved arsenic. Arsenic is strongly attracted to sorption sites on the surfaces of these solids, and is effectively removed from solution. Ion exchange can be considered as a special form of adsorption, though it is often considered separately. Ion exchange involves the reversible displacement of an ion adsorbed onto a solid

⁴ For health reasons, WHO recommends that chlorine in drinking water not exceed 5.0 mg/L. In practice water becomes unpalatable at much lower chlorine levels (WHO, 1993).

surface by a dissolved ion. Other forms of adsorption involve stronger bonds, and are less easily reversed.

- Solid/liquid separation: precipitation, co-precipitation, adsorption, and ion exchange all transfer the contaminant from the dissolved to a solid phase. In some cases the solid is large and fixed (e.g. grains of ion exchange resin), and no solid/liquid separation is required. If the solids are formed *in situ* (through precipitation or coagulation) they must be separated from the water. Gravity settling (also called sedimentation) can accomplish some of this, but filtration is more effective. Most commonly, sand filters are used for this purpose.
- Physical exclusion: some synthetic membranes are permeable to certain dissolved compounds but exclude others. These membranes can act as a molecular filter to remove dissolved arsenic, along with many other dissolved and particulate compounds.
- Biological removal processes: bacteria can play an important role in catalyzing many of the above processes. Relatively little is known about the potential for biological removal of arsenic from water.

Boiling does not remove arsenic from water; in fact it will concentrate arsenic, as some water will be lost as steam. In many developing countries, though, boiling is known to ‘purify water’ because it effectively kills pathogens. Education campaigns may need to specifically dispel the myth that boiling water can reduce the risk of arsenic poisoning. Boiling of water could be used to remove arsenic as part of a distillation process, in which the steam is collected and condensed. However, this is unlikely to be a practical option.

Most of the established technologies for arsenic removal make use of several of these processes, either at the same time or in sequence. All of the removal technologies have the added benefit of removing other undesirable compounds along with arsenic – depending on the technology, bacteria, turbidity, color, odor, hardness, phosphate, fluoride, nitrate, iron, manganese, and other metals can be removed.

Historically, the most common technologies for arsenic removal have been coagulation with metal salts, lime softening, and iron/manganese removal. Since the WHO Guideline Value for arsenic in drinking water was lowered from 50 to 10 $\mu\text{g/L}$ in 1993, several countries have lowered their drinking water standards, in some cases to below 10 $\mu\text{g/L}$. In 2001, the USEPA lowered the U.S. drinking water standard from 50 to 10 $\mu\text{g/L}$. Coagulation processes are sometimes unable to efficiently remove arsenic to these low levels. As a result, various alternate technologies have been developed or adapted that are capable of removing arsenic to trace levels. These advanced treatment options include ion exchange, activated alumina, and membrane methods such as reverse osmosis and nanofiltration. While these technologies have all been shown to be effective in lab or pilot studies, there is still relatively little experience with full-scale treatment. In addition, a number of novel removal technologies are under development, some of which show great promise.

The main arsenic removal technologies are presented below, along with a brief description of how removal efficiency is affected by arsenic concentration and speciation, pH, and the presence of other dissolved constituents. The interested reader is referred to key references for each technology. A more detailed review of arsenic removal technologies is presented in (Sorg and Logsdon, 1978). Though dated, this paper gives a good overview of the mechanisms involved in arsenic removal. In a more recent review, Jekel has documented several advances in arsenic removal technologies (Jekel, 1994). A review was made considering economic factors in implementing an anticipated new, lower drinking water standard to be set by the USEPA (Chen et al., 1999). Many of the technologies are discussed in detail in an AWWA reference book, though the focus is not on arsenic removal (Letterman, 1999). Recently a compilation has been made

identifying companies and organizations that are involved in arsenic removal technologies, a listing on the Internet includes contact details (Murcott, 2000).

6.3.1 Oxidation

Most arsenic removal technologies are most effective at removing the pentavalent form of arsenic (arsenate), since the trivalent form (arsenite) is predominantly non-charged below pH 9.2 (See **Figure 1.X** (Editor: refer to pH-Eh chart from Chapter 1)). Therefore, many treatment systems include an oxidation step to convert arsenite to arsenate. Oxidation alone does not remove arsenic from solution, and must be coupled with a removal process such as coagulation, adsorption or ion exchange.

Air oxidation

Atmospheric oxygen is a readily available oxidizing agent, however the kinetics of air oxidation of arsenic are very slow, taking weeks (Pierce and Moore, 1982). Cherry and others showed that even when distilled water spiked with arsenite (pH 7) is saturated with oxygen, arsenic speciation stays relatively unchanged for days (Cherry et al., 1979). When water is saturated with air instead of pure oxygen, dissolved oxygen levels are much lower, so oxidation rates are even slower. Kim and Nriagu have reported half-lives of arsenite in water saturated with oxygen and air as 2-5 and 4-9 days, respectively (Kim and Nriagu, 2000). Air oxidation of arsenite can be catalyzed by bacteria, strong acidic or alkali solutions, copper, powdered activated carbon, and higher temperature (Edwards, 1994).

Reduction of arsenate in the absence of oxygen is also quite slow, though thermodynamically favorable (Ferguson and Gavis, 1972; Edwards, 1994).

Chemical oxidation

Arsenite can also be directly oxidized by a number of other chemicals, including gaseous chlorine, hypochlorite, ozone, permanganate, hydrogen peroxide, and Fenton's reagent ($\text{H}_2\text{O}_2/\text{Fe}^{2+}$). Some solids such as manganese oxides can also oxidize arsenic. Ultraviolet radiation can catalyze the oxidization of arsenite in the presence of other oxidants, such as oxygen. Direct UV oxidation of arsenite is slow, but may be catalyzed by the presence of sulfite (Ghurye and Clifford, 2000), ferric iron (Emett and Khoe, 2001) or citrate (EAWAG, 1999).

Chlorine is a rapid and effective oxidant, but may lead to reactions with organic matter, producing toxic trihalomethanes as a by-product. Also, locally available chlorine in developing countries can be of uncertain quality. The amount of chlorine added will depend on the composition of the water. Doses generally range from 0.8 to 2.0 mg/L, with the goal of at least 0.2 mg/L residual chlorine, to provide protection against microbial contamination after treatment. Chlorine is widely available globally, though if improperly stored it can lose its potency rapidly.

In Europe, and increasingly in the USA, ozone is being used as an oxidant. In developing countries, ozone has not been widely used. An ozone dose of 2 mg/L, contacted with the water for 1 minute prior to filtration, has been shown to be effective in oxidizing iron and manganese, at the same time removing arsenic and other metals to below detection limits (Nieminski and Evans, 1995). At a similar ozone dose, arsenite was shown to have a half-life of approximately 4 minutes (Kim and Nriagu, 2000). Ozone is also a potent disinfectant, but unlike chlorine, does not impart a lasting residual to treated water.

Permanganate effectively oxidizes arsenite, along with Fe(II) and Mn(II). It is a poor disinfectant, though it can produce a bacteriostatic effect. Potassium permanganate (KMnO_4) is widely available in developing countries, where it is used as a topical antibiotic for minor cuts. It is

relatively stable with a long shelf life. Residual manganese in treated water should not exceed the WHO guideline of 0.5 mg/L (WHO, 1993).

Hydrogen peroxide may be an effective oxidant if the raw water contains high levels of dissolved iron, which often occur in conjunction with arsenic contamination. The ferric ions formed will precipitate the oxidized arsenic directly (Jekel, 1994).

Solid manganese oxides have long been known to oxidize arsenite (Oscarson and al, 1981). Recently, this knowledge has been used to advantage in arsenic removal systems, where beds containing manganese oxide convert arsenite to arsenate, eliminating the need for dosing with a liquid or gas oxidant. Oxidation is effective over a wide pH range and does not release excessive manganese to solution. (Driehaus et al., 1998). Recently, other research has shown that the rate of oxidation is rapid (Chiu and Hering, 2000; Daus et al., 2000).

6.3.2 Coagulation and filtration

The most heavily documented treatment methods for arsenic removal involve coagulation and filtration, either using metal salts or lime softening. This treatment can effectively remove many suspended and dissolved constituents from water besides arsenic, notably turbidity, iron, manganese, phosphate and fluoride. Significant reductions are also possible in odor, color, and potential for trihalomethane formation. Thus coagulation and filtration to remove arsenic will improve other water quality parameters, resulting in ancillary health and esthetic benefits. However, the optimal conditions vary for removal of different constituents, and coagulation to remove arsenic may not be optimal for removal of other compounds, notably phosphate and fluoride.

Arsenic removal with metal salts has been shown since at least 1934 (Buswell, 1943). The most commonly used metal salts are aluminum salts such as alum, and ferric salts such as ferric chloride or ferric sulfate. Ferrous sulfate has also been used, but is less effective (Jekel, 1994; Hering et al., 1996; Hering et al., 1997). Excellent arsenic removal is possible with either ferric or aluminum salts, with laboratories reporting over 99% removal under optimal conditions, and residual arsenic concentrations of less than 1 µg/L (Cheng et al., 1994). Full-scale plants typically report a somewhat lower efficiency, from 50% to over 90% removal.

Alum and ferric salts dissolve upon addition to water, forming amorphous hydrous aluminum and ferric oxides⁵ (HAO and HFO, respectively), which are relatively insoluble in circumneutral pH ranges. These metal hydroxides form gelatinous flocs that bind to other flocs and settle out of solution, scavenging many dissolved and particulate materials in the process. Vigorous stirring is usually required to ensure uniform mixing for optimal coagulation. If water is soft and of low alkalinity it may be necessary to add alkalinity to ensure floc formation. Sometimes polymers or colloidal substances such as clays are added to improve flocculation and sedimentation (Gulledge and O'Connor, 1973). Cheng and others have shown that addition of 2-4 mg/L of cationic polymer allows coagulant dose to be reduced by two-thirds while maintaining good arsenic removal (Cheng et al., 1994). Thus polymers or clays can be used to improve arsenic removal efficiency, and to reduce the volume of sludge generated. Sludges are usually not regenerated, but disposed of directly.

⁵ When ferric salts dissolve, the ferric ion forms an amorphous solid with oxygen and hydroxyl groups. This is variously called amorphous iron oxyhydroxide, iron (oxy)hydroxide, hydrous ferric oxide (HFO), and ferrihydrite. As this solid ages, the atoms arrange themselves into more ordered groupings, and form minerals such as the coarsely crystalline goethite, and eventually the highly structured hematite (Fe₂O₃).

Mechanisms of Removal

During coagulation and filtration, arsenic is removed through three main mechanisms (Edwards, 1994):

- precipitation: the formation of the insoluble compounds $\text{Al}(\text{AsO}_4)$ or $\text{Fe}(\text{AsO}_4)$
- coprecipitation: the incorporation of soluble arsenic species into a growing metal hydroxide phase
- adsorption: the electrostatic binding of soluble arsenic to the external surfaces of the insoluble metal hydroxide.

All three of these mechanisms can independently contribute towards contaminant removal. In the case of arsenic removal, direct precipitation has not been shown to play an important role. However, coprecipitation and adsorption are both active arsenic removal mechanisms. Some studies suggest that coprecipitation is the more important removal mechanism, by showing that HFO formed *in situ* can remove approximately five times as much arsenic from contaminated water as preformed HFO (Edwards, 1994). Others, however, hold that adsorption is the dominant mechanism for arsenic removal, at least at high coagulant doses (Hering et al., 1996). For a detailed analysis of operative mechanisms in arsenic removal, the interested reader is referred to the papers of Edwards and Hering cited above.

Numerous studies have shown that filtration is an important step to ensure efficient arsenic removal. After coagulation and simple sedimentation, HAO and HFO – along with their sorbed arsenic load – can remain suspended in colloidal form. Hering and others showed that coagulation and sedimentation without filtration achieved arsenate removal efficiencies of 30%; after filtration through a 1.0 micron filter, efficiency was improved to over 96%. Only marginal improvements were made by reducing the filter size to 0.1 micron (Hering et al., 1996). In field applications, some plants improve arsenic removal with two-stage filtration (Sancha, 1999b).

Box 6.3: Sorbent capacity

It is convenient to consider sorbents in terms of their maximum adsorption density. Adsorption density is simply the amount of sorbate (arsenic, in this case), that is adsorbed onto the sorbent (HFO or HAO). At some point, called the maximum adsorption density, or adsorption capacity, the sorbent becomes saturated, and can retain no more sorbate. Adsorption capacities are reported either on a molar (moles arsenic sorbed per mole sorbent) or on a weight basis (typically g arsenic per kg sorbent).

Table 6.3 : Molecular weights of compounds used in arsenic removal

Compound	Chemical Formula	Molecular weight (grams/mole)
Aluminum	Al	27.0
Iron	Fe	55.8
Arsenic	As	74.9
Arsenate	AsO_4^{3-}	139
Arsenite	AsO_3^{3-}	123
Alum (reagent)*	$\text{Al}_2(\text{SO}_4)_3 \cdot 18(\text{H}_2\text{O})$	666 (333 g/mole Al)

Alum (commercial)*	$\text{Al}_2(\text{SO}_4)_3 \cdot 14(\text{H}_2\text{O})$	602 (301 g/mole Al)
Ferric chloride	FeCl_3	162
Ferric sulfate	$\text{Fe}_2(\text{SO}_4)_3$	400 (200 g/mole Fe)

* Note: reagent-grade alum is more hydrated than commercial grade, so doses reported in the academic literature do not exactly match doses used in most applications. Doses should be calculated based on actual aluminum content, either using molar or mass units.

If the arsenic adsorption capacity for a hypothetical sorbent were reported as one mole of arsenic per mole aluminum (complete coverage), this would be equivalent to 75 grams of arsenic sorbed per 27 grams of aluminum added, or 75 g As / 333 g alum (since one mole of alum contains two moles of aluminum). The capacity would most likely be given as 225 mg As/g alum. In reality, sorbents usually have lower molar capacities. When reading capacities given on a weight basis, it is important to note whether the reported capacity is for arsenic (MW 75) or for arsenate (MW 139). Likewise, coagulant doses are sometimes given in terms of the coagulant and sometimes in terms of the metal ion (e.g. 16.2 mg/L FeCl_3 is equivalent to 5.6 mg/L Fe).

END BOX

Removal of arsenate

Arsenate is relatively easy to remove from water, since it bears a negative charge in natural waters above pH 2.2, and is electrostatically attracted to the positive charge on metal hydroxide surfaces. Fresh, preformed HFO and HAO have reported maximum arsenic adsorption capacities in the range of 0.1 M As(V)/M Fe or Al. When the sorbents are formed *in situ*, capacities are much higher, in the vicinity of 0.5 to 0.6 M As(V)/M Fe or Al. This difference reflects the effects of coprecipitation: preformed hydroxides only remove arsenic through adsorption, while *in situ* formation leads to coprecipitation as well (Edwards, 1994).

The percentage of arsenate removed by coagulation is chiefly controlled by pH and coagulant dose, and is largely independent of initial arsenic concentration. Adsorption is theoretically favored at a pH below a sorbent's point of zero charge, since the positively charged surface can attract the arsenate anion. Laboratory tests have shown that arsenate adsorption onto HFO is optimal below pH 8, and below pH 7 for HAO. Adjustment of pH will often result in greater improvements in efficiency than increasing coagulant dose (Sorg and Logsdon, 1978; Edwards, 1994; Hering et al., 1996).

HFO remains stable and relatively insoluble at pH levels as low as 4-5, but HAO becomes much more soluble below pH 6, and above pH 8. Consequently effective arsenic removal with alum is restricted to a relatively narrow pH range around pH 6-7 (Hering et al., 1997).

Figure 6.7: Arsenate removal by coagulation (after Hering et al., 1997, Figure 1) (PENDING)

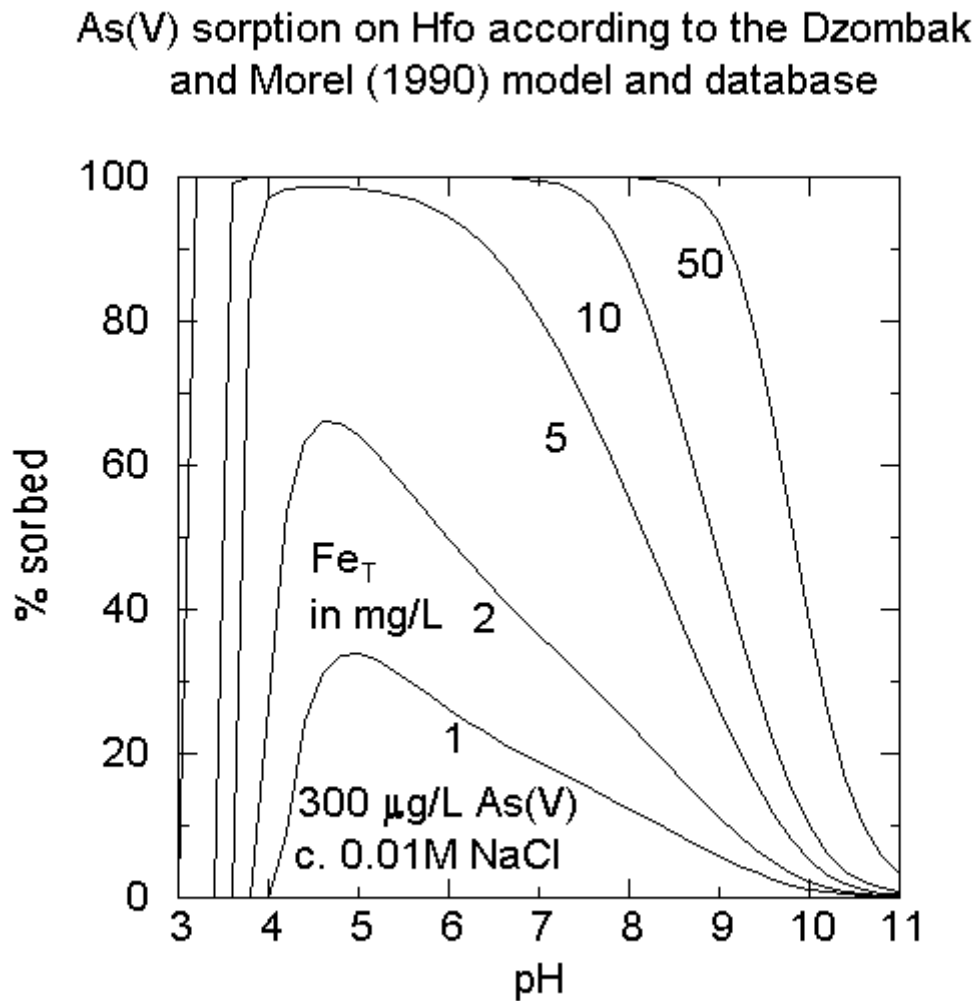
Figure 6.8: Arsenate adsorption onto preformed HFO (DPHE/BGS/MML, 1999, Volume S4)

Figure 6.8 shows the theoretical adsorption capacity of HFO over a wide range of pH and iron doses. Below pH 4-5 HFO will dissolve when in chemical equilibrium, though equilibrium may not be reached during the relatively short coagulation and filtration treatment.

Optimal dosing will depend on the specific water chemistry and required removal efficiency, but typical doses range from 5 to 30 mg/L FeCl_3 . A similar graph for HAO would show a similar drop in removal efficiency at high pH, though the drop would occur at slightly lower pH since HAO has a lower point of zero charge than HFO. However, the graph would show a sharp decrease in removal efficiency below pH 6, due to the increased solubility of HAO. Alum doses are generally higher, typically ranging from 10 to 50 mg/L.

The laboratory data plotted in **Figure 6.7** show much better arsenic removal for a coagulant dose of approximately 2 mg/L Fe than in **Figure 6.8**, because the HFO was formed *in situ*, allowing coprecipitation to occur along with adsorption. In general, smaller amounts of sorbent will be needed if coagulation and flocculation take place *in situ*.

Over the pH range where both HFO and HAO are insoluble (roughly pH 6-7) ferric salts and alum are equally efficient at arsenate removal, on a molar basis. However, on a weight basis,

ferric salts are significantly superior. This difference is due to the higher molecular weight of alum, which consists of aluminum and sulfate bound to eighteen water molecules, compared to the unhydrated ferric chloride (see **Box 6.3**) (Hering et al., 1996). One mole of aluminum as alum weighs approximately twice as much as one mole of iron as ferric chloride. Therefore, it takes about twice as much alum as ferric chloride (by weight) in order to produce a comparable amount of sorbent. Field research in Chile in the 1980s showed that HFO was superior to HAO because it led to larger flocs with better sedimentation, and is efficient over a wider pH range (Sancha, 1999a). The highly hydrated state of alum does confer one benefit over ferric chloride – the solid is stable under humid conditions, whereas ferric chloride can absorb water from air and lose its consistency.

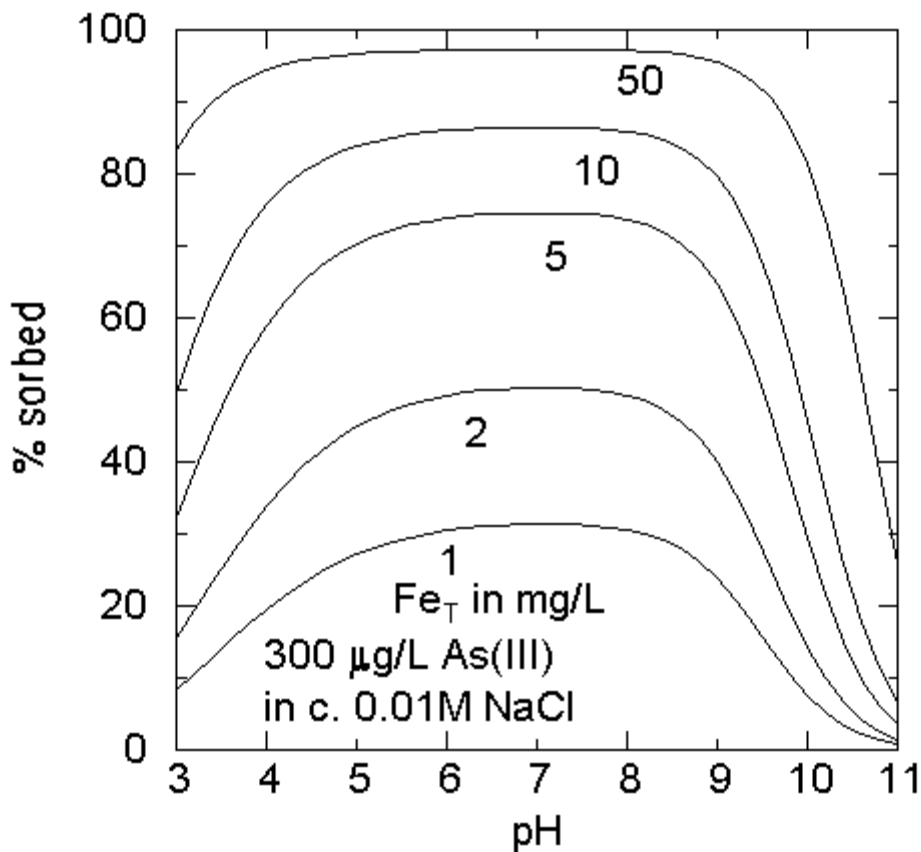
Removal of arsenite

Arsenite is uncharged in most natural waters (below pH 9.2) and as such is more difficult to remove, since there is no electrostatic attraction to charged solids. Alum is very ineffective at removal of arsenite, with maximum surface densities of approximately 0.04 M As/M Al for preformed HAO, about one third the density reported for arsenate (Edwards, 1994). Ferric salts are much more efficient, with reported maximum surface densities on preformed HFO ranging up to 0.4 M As/M Fe, which is significantly higher than the comparable density for arsenate! Edwards offers several explanations for this anomalous reporting, the most convincing of which is that ferric solids oxidize the arsenite, forming arsenate and ferrous ions, which are subsequently reoxidized to ferric iron by oxygen, causing co-precipitation of arsenate (Edwards, 1994). Most researchers, however, have reported arsenite removal with HFO to be somewhat less effective than arsenate removal.

Adsorption of arsenite onto HFO is relatively insensitive to pH within most natural waters, and is theoretically favored from about pH 5 to 8 (Sorg and Logsdon, 1978). However, one laboratory study that examined arsenite removal through coagulation, rather than adsorption onto preformed HFO, found arsenite removal to be best at extreme pH values (4 and 9), and lowest at pH 6. The authors propose that this unexpected result is due to the formation of smaller flocs at extreme pH values, which would have a larger surface area for adsorption. A second possible explanation is that even over the short period between formation and application, the surface of the HFO may undergo significant structural evolution, altering its sorption capacity (Hering et al., 1996). The unexpected findings reported by both Edwards and Hering indicate that arsenite removal with HFO is still not completely understood.

Figure 6.9: Arsenite adsorption onto HFO (DPHE/BGS/MML, 1999, Volume S4)

As(III) sorption on Hfo according to the Dzombak and Morel (1990) model and database

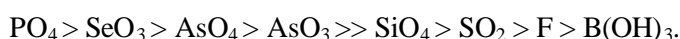


Effects of competing ions

Arsenic removal through coagulation will be affected by the presence of other anions and cations. Some anions will lower removal rates, by competing with arsenic for sorption sites and lowering the surface charge. Cations, in contrast, can increase the positive surface charge, and enhance arsenic adsorption. Relatively few studies have examined these types of effects. Those that have, however, agree on certain fundamental principles:

- effects of co-occurring solutes will be most pronounced when adsorption density is nearing saturation;
- arsenite makes a weaker bond than arsenate with metal oxides, and is thus more likely to be displaced by competing anions; and
- surface complexation chemistry is complex, particularly when multiple anions are present.

At near-neutral pH, Manning and Goldberg give the theoretical affinity for anion sorption on metal oxides as (Manning and Goldberg, 1996):



Phosphate is the anion considered most likely to compete with arsenic for adsorption sites, because of its strong affinity for metal oxides, and its similarity to the arsenate ion. Phosphate has been shown to mobilize arsenic in soils contaminated with lead pesticides (Davenport and Peryea, 1991; Peryea, 1991; Peryea and Creger, 1994; Peryea and Kammereck, 1997). Recently Meng and others showed that phosphate can reduce arsenite removal in coagulation with ferric salts (see **Table 6.4**) (Meng et al., 2000).

Dissolved silicate is usually found in much higher concentrations than phosphate, and can interfere with removal of both arsenate and arsenite. Ghurye and others report that in slightly basic waters (pH > 7) silicate levels above 15-30 mg Si/L can reduce arsenate removal efficiency (Ghurye et al., 1999). Meng and others report that arsenite removal rates declined from 95% to under 50% with the addition of 18 mg/L Si. Arsenate removal decreased by 13%. The authors argue that silicate reduces arsenic removal efficiency in two ways: by competing directly for adsorption sites, and by changing the electrostatic properties of the HFO surface (Meng et al., 1999; Meng et al., 2000).

Elevated levels of sulfate and carbonate can slightly reduce arsenite removal rates, but have little effect on arsenate removal (Wilkie and Hering, 1996; Meng et al., 1999; Meng et al., 2000).

Ammonium can interfere with floc formation, and thus indirectly reduce arsenic removal rates (Csanady, 1999). Natural organic matter also somewhat reduces the efficiency of arsenite removal at pH 4 through 9. In contrast, the presence of calcium and magnesium can enhance arsenic removal, by increasing the positive charge on the HFO surface. (Hering et al., 1996; Wilkie and Hering, 1996; Hering et al., 1997).

Meng and others have also shown that competing anions can have a synergistic effect. The following table shows that the addition of either silicate or phosphate has only a minor effect on removal of arsenate. When both anions are added, however, removal drops by some 40%.

Table 6.4 : Effects of anions on removal of arsenite and arsenate in coagulation (Meng et al., 2000)

	Arsenite removal %	Arsenate removal %
310 mg/L Cl	95	99
133 mg/L HCO ₃	74	99
18 mg/L Si	48	86
1.9 mg/L P	38	96
18 mg/L Si + 133 mg/L HCO ₃	45	96
1.9 mg/L P + 133 mg/L HCO ₃	33	63
1.9 mg/L P + 18 mg/L Si	31	61
1.9 mg/L P + 18 mg/L Si + 133 mg/L HCO ₃	26	59

Note: initial arsenic = 300 µg/L; total Fe(III) = 6.7 mg/L; equilibrium pH = 6.9 ± 0.1; matrix is simulated Bangladesh groundwater (2.5 mM CaCl₂, 0.82 mM MgCl₂, 2.2 mM NaCl); settled water was filtered with a 0.45 µm filter.

Most of the competitive effects noted above were seen in laboratory studies using relatively low coagulant doses. The competitive effects can be overcome by using higher coagulant doses. If competing anions (particularly phosphate and silicate) are present, the amount of coagulant required may be higher than standard values reported in the literature. For this reason, and because of the synergistic effects noted above, it is important to conduct bench-scale testing using the actual water to be treated when designing field-scale arsenic removal systems.

Lime Softening

Lime softening is a similar process to coagulation with metal salts. Lime ($\text{Ca}(\text{OH})_2$) hydrolyzes and combines with carbonic acid to form calcium carbonate, which acts as the sorbing agent for arsenic removal. This process is typically used only with very hard waters, and shifts the pH of treated water markedly higher, in the range of 10-12.

Early jar-test studies found that at pH 10.5 and higher, nearly 100% removal of arsenate is possible; the maximum arsenite removal was found to be about 80% at pH 11.1 (Logsdon et al., 1974). More recently, McNeill and Edwards examined arsenic removal during softening in detail, and found the main removal mechanism to be sorption of arsenic onto magnesium hydroxide solids that form during softening. Like Logsdon and others, they found arsenate removal to be excellent above pH 11, and much poorer at pH 10. Arsenic removal at lower pH can be greatly improved by the addition of low levels of iron, but when carbonate is present this effect is less pronounced. Trace levels of phosphate were found to slightly reduce arsenic removal, especially below pH 12 (McNeill and Edwards, 1997).

McNeill and Edwards found arsenite removal to be very poor, with arsenite sorption densities about an order of magnitude less than for arsenate. However, Dutta and Chaudhuri showed that arsenite levels could be reduced by over 90% using lime softening supplemented with a powdered coal additive (Dutta and Chaudhuri, 1991). The authors theorize that arsenite is directly adsorbed, but others suggest that the carbon could catalyze arsenic oxidation (Jekel, 1994).

Disadvantages of lime softening for arsenic removal are that large coagulant doses are required, on the order of 800-1200 mg/L, and consequently a large volume of sludge is produced. Also the operating pH is rather extreme, and strong acids would probably be needed to adjust the pH after treatment.

Variations on conventional coagulation and filtration

While conventional coagulation with iron salts, alum, and lime are the most common applications of coagulation and filtration, many variations are possible.

Researchers from the Australian Nuclear Science and Technology Organization have developed an arsenic removal system based on coagulation and filtration with ferric sulfate. Instead of using a chemical oxidant, the ANSTO system uses the ultraviolet radiation in natural sunlight to catalyze both the oxidation of arsenite and the formation of HFO (Khoe and Emett, 1999).

As mentioned above, settling can be improved by addition of synthetic polymers or clays during coagulation. Brewster has further shown that standard coagulation and filtration can be improved by addition of a polymer and by pumping the contaminated water through an electrochemical cell during treatment (Brewster, 1992).

In some cultures plant products are used as natural coagulants. The crushed seeds of moringa trees (*Moringa oleifera lam* and *Moringa peregrina fiori*) are particularly effective coagulants,

comparing favorably with alum in terms of removal of turbidity. A dosing rate of 200 mg crushed seeds per liter of water is suggested as optimal (IRC, 1982a).

Seeds of red sorrela (*Hibiscus sabdariffa*) can be dried, crushed, and mixed with sodium carbonate in a 9:1 ratio, then mixed with water and heated to produce a milky coagulant solution. Neither red sorrela nor moringa has been evaluated for arsenic removal (IRC, 1982a).

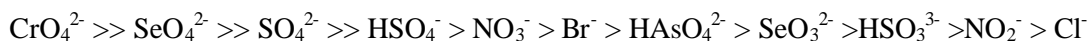
6.3.3 Ion-Exchange Resins

Synthetic ion exchange resins are widely used in water treatment to remove many undesirable dissolved solids, most commonly hardness, from water. These resins are based on a cross-linked polymer skeleton, called the 'matrix'. Most commonly, this matrix is composed of polystyrene cross-linked with divinylbenzene. Charged functional groups are attached to the matrix through covalent bonding, and fall into four groups (Clifford, 1999):

- Strongly acidic (e.g. sulfonate, $-\text{SO}_3^-$)
- Weakly acidic (e.g. carboxylate, $-\text{COO}^-$)
- Strongly basic [e.g. quaternary amine, $-\text{N}^+(\text{CH}_3)_3$]
- Weakly basic [e.g. tertiary amine, $-\text{N}(\text{CH}_3)_2$]

The acidic resins are negatively charged, and can be loaded with cations (e.g. Na^+), which are easily displaced by other cations during water treatment. This type of cation exchange is most commonly applied to soften hard waters.

Conversely, strongly basic resins can be pretreated with anions, such as Cl^- , and used to remove a wide range of negatively charged species. Clifford gives the following relative affinities of some common anions for a type 1 strong-base anion resins (Clifford, 1999):



Different resins will have differing selectivity sequences, and resins have been developed specifically to optimize removal of sulfate, nitrate, and organic matter. Various strong-base anion exchange resins are commercially available which can effectively remove arsenate from solution, producing effluent with less than 1 $\mu\text{g}/\text{L}$ arsenic. Arsenite, being uncharged, is not removed. Analysts have taken advantage of this specificity to develop procedures for analytical differentiation of arsenite and arsenate (e.g. Ficklin, 1983; Edwards et al., 1998). Therefore, unless arsenic is present exclusively as arsenate, an oxidation step will be a necessary precursor to arsenic removal.

Conventional sulfate-selective resins are particularly suited for arsenate removal. Nitrate-selective resins also remove arsenic, but arsenic breakthrough occurs earlier. Most commonly, resins are pretreated with hydrochloric acid, to establish chloride ions at the surface, which are easily displaced by arsenic (Ghurye et al., 1999), though the resin can be primed with other anions such as bromide or acetate (Edwards et al., 1998). Packed beds are commonly designed to have an Empty Bed Contact Time (EBCT) of 1.5 to 3 minutes.

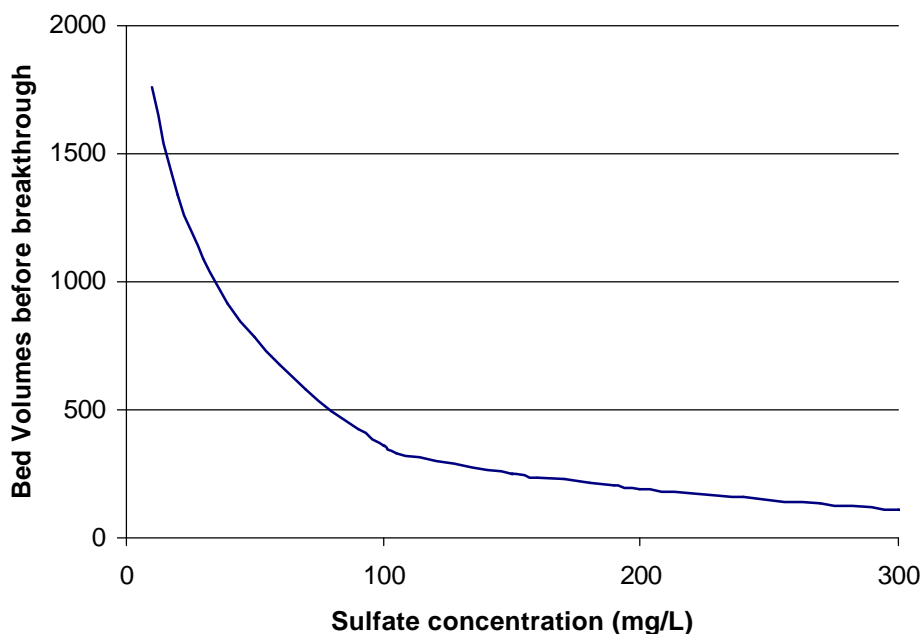
Arsenate removal is relatively independent of pH and influent concentration. On the other hand, competing anions, especially sulfate, have a strong effect. The number of bed volumes that can be treated before arsenic breakthrough (defined as 10% of the influent concentration) can be roughly estimated with two simple formulas: (Clifford and Majano, 1993; cited in Chen et al., 1999).

$$\text{For } [\text{SO}_4^{2-}] < 120 \text{ mg/L: Bed Volumes} = -606 * \ln[\text{SO}_4^{2-}] + 3,150$$

$$\text{For } [\text{SO}_4^{2-}] > 120 \text{ mg/L: Bed Volumes} = -200 * \ln[\text{SO}_4^{2-}] + 1,250$$

where $[\text{SO}_4^{2-}]$ is the initial sulfate concentration in mg/L. In low-sulfate waters, ion exchange resin can easily remove over 95% of arsenate, and treat from several hundreds to over a thousand bed volumes before arsenic breakthrough occurs. Accordingly, the USEPA recommends that ion exchange resins not be used in waters with >120 mg/L sulfate or >500 mg/L TDS, and will be most effective in waters with even lower sulfate levels (<25 mg/L) (USEPA, 2000).

Figure 6.10: Bed volumes treated with ion exchange resin



Ion exchange capacity, analogous to the adsorption capacity discussed in the previous section, is a measure of the number of exchange sites, and is usually measured in milliequivalents (meq) per mL (wet volume, including pore spaces). The dry-weight capacity (meq/g) can be more precise, and is sometimes used in scientific research. The operating capacity measures actual performance of resins under environmental conditions, and is always less than the advertised exchange capacity, due to incomplete regeneration and contaminant leakage. For a particular sorbate, capacity can be converted from meq/mL to mg/mL by multiplying by the molecular weight (75 in the case of arsenic). Typical theoretical exchange capacities of strong base anion exchange resins range from 1 to 1.4 meq/mL, (Clifford, 1999) or 3.0 to 4.2 meq/g dry weight. This would imply a maximum sorption capacity of approximately 315 mg As/g. However, actual reported capacities are typically much lower. One study using laboratory reagents found the maximum operational capacity for arsenate removal of a strong-base anion exchange resin to be about 64 mg As/g (Baes et al., 1997). Under field conditions, capacity will be lower, especially in waters with high TDS or sulfate levels.

Ion exchange resins are easily regenerated by flushing with concentrated salt solutions (1.0 M NaCl is commonly used). Clifford has demonstrated that this brine can be reused 20-30 times, in spite of increasingly concentrated arsenic levels in the regenerant. Recovery of arsenic is nearly complete (85 to 100%). Regenerated media generally have slightly lower arsenic capacities than virgin media, but after three to four regenerations no further loss in capacity occurs. Some systems take advantage of this by regenerating resin beds daily or even more frequently. Regeneration could easily be done by water users with a moderate amount of training.

One drawback of ion exchange is that exhausted resins, unlike activated alumina, have chromatographic properties such that exhausted resin can release nearly all previously removed arsenic over a few bed volumes, resulting in ‘arsenic peaking’ with concentrations several times higher than the influent (Edwards et al., 1998; Ghurye et al., 1999). A second drawback is that resins can be fouled by precipitation of iron or manganese oxides: these metal coatings can reduce flow rates, and prevent contact between arsenic and the resin (Fox, 1989). These coatings themselves may adsorb arsenic, but this does not make use of the ion-exchange properties of the resin. Furthermore, colloidal iron may pass through the resin bed, and could transport adsorbed arsenic, causing significant leakage through the bed (Ghurye et al., 1999). Advantages of ion exchange resins, however, include easy regeneration, applicability over a wide pH range, and overall improvements in water quality, through the removal of chromate, selenate, nitrate, and nitrite.

6.3.4 Activated Alumina

Activated alumina is a granulated form of aluminum oxide (Al_2O_3) with very high internal surface area, in the range of 200-300 m^2/g . This high surface area gives the material a very large number of sites where sorption can occur, and activated alumina has been widely used for removal of fluoride. In the early 1970s Bellack accidentally discovered that activated alumina could remove arsenic from water (Bellack, 1971; Sorg and Logsdon, 1978).

The mechanisms of arsenic removal are similar to those of a weak base ion exchange resin, and are often collectively referred to as ‘adsorption’, though ligand exchange and chemisorption are technically more appropriate terms (Clifford, 1999). The kinetics of arsenic removal onto the alumina surface are slower than those of ion exchange resins, and some arsenic leakage is often noted in activated alumina systems.

Arsenic removal efficiency is excellent (typically > 95%), for both arsenate and arsenite, but arsenic capacity varies significantly, and is controlled primarily by pH and influent arsenic concentration and speciation. Arsenate removal capacity is best in the narrow range from pH 5.5 to 6.0, where the alumina surfaces are protonated, but acid anions are not yet concentrated enough to compete with arsenic for sorption sites (Trussell et al., 1980; Rosenblum and Clifford, 1984; Clifford, 1999). Typically, activated alumina has a point of zero charge (PZC), below which the surface is positively charged, and above which the surface bears a negative charge, at pH 8.2. Arsenic removal capacity drops sharply as the PZC is approached, and above pH 8.5, is reduced to only 2-5% of capacity at optimal pH (Clifford, 1999). For neutral and basic waters, therefore, pH adjustment may be necessary for effective arsenic removal.

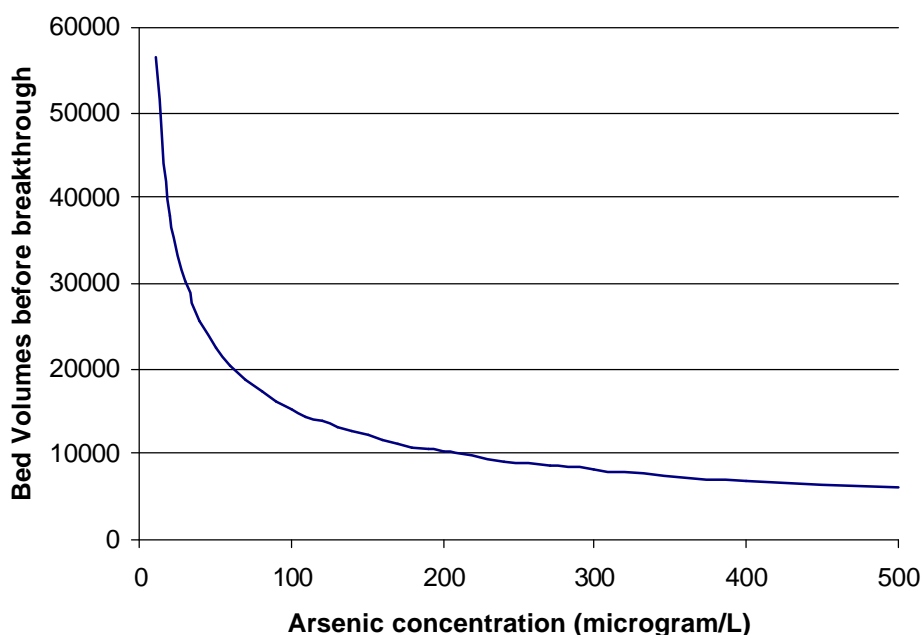
Figure 6.11: Effect of pH on arsenate adsorption onto activated alumina (after Clifford, 1999)

[Editors, I have sent a photocopy of this figure to WHO Geneva, contact me if you need another – RJ]

Fine (28-48 mesh) particles of activated alumina are typically used for arsenic removal, with an Empty Bed Contact Time of five to eight minutes (Rubel and Woosely, 1979). When operated in the optimal pH range, activated alumina beds have much longer run times than ion exchange resins. The number of bed volumes that can be treated at optimal pH before arsenate breaks through is mainly controlled by the influent arsenic concentration, and can be estimated with the following equation: (Ghurye et al., 1999)

$$\text{Bed Volumes} = 210,000 * [\text{As}]^{-0.57}$$

where [As] is the initial arsenate concentration in micrograms per liter.

Figure 6.12: Bed volumes treated with activated alumina

Frank and Clifford reported an arsenate capacity (at pH 6) of about 1.6 g/L of activated alumina, consistent with an earlier reported capacity of 4 mg/g, assuming a bulk density of 0.5 kg/L (Gupta and Chen, 1978). Fox reported a somewhat lower capacity of 1 mg/g, but this is likely due to the elevated pH (7.4-8.0) of the influent water (Fox, 1989).

Effects of arsenic speciation

The Frank and Clifford study showed that under optimal conditions, activated alumina could treat an influent containing 100 µg/L arsenate for 10,000 to 20,000 bed volumes before gradual breakthrough was observed, consistent with **Figure 6.12**. Arsenite, in contrast, broke through completely after only a few hundred bed volumes (Frank and Clifford, 1986).

Other researchers, however, have found that activated alumina can remove arsenite for longer run lengths. Datta and others showed that after pretreatment with caustic soda, activated alumina can remove over 1000 bed volumes of arsenite in lab water, and several thousands of bed volumes of groundwater containing a mixture of arsenite and arsenate (Datta et al., 1997). Likewise, Clifford and Lin found that activated alumina performed better than expected in removing arsenite from natural waters. At pH 6, approximately 9000 bed volumes of groundwater containing 31 µg/L arsenite and 57 µg/L arsenate were treated before effluent exceeded the MCL of 50 µg/L. At pH 7.2, however, only 1900 bed volumes could be treated, highlighting the strong dependency on pH (Clifford and Lin, 1991). These findings suggest that the aluminum oxide surface may catalyze oxidation of arsenite to arsenate, as manganese oxides are known to do.

Effects of co-occurring solutes

The sorption sites on the activated alumina surface are also attractive to a number of anions other than arsenate: Clifford reports the selectivity sequence of activated alumina in the pH range of 5.5 to 8.5 as (Clifford, 1999):



Trussell and others reported a similar selectivity sequence, but included phosphate as the second most preferred anion, after hydroxyl, and placed fluoride above arsenate in the sequence (Trussell et al., 1980).

Because of activated alumina's strong selectivity for arsenate, competing anions pose less of a problem than with ion exchange resins. Sulfate, and to a lesser extent, chloride, have been shown to reduce capacity, but the competition effect is not as dramatic as with ion exchange resins (Rosenblum and Clifford, 1984). Phosphate and fluoride are also sorbed onto activated alumina, producing improvements in drinking water quality, but at the same time reducing arsenic removal potential.

Activated alumina can be regenerated by flushing with a solution of 4% sodium hydroxide, which displaces arsenic from the alumina surface, followed by flushing with acid, to re-establish a positive charge on the grain surfaces. Regeneration is more difficult, and less complete (generally 50-80%) than with ion exchange resins (Clifford, 1986). Some of the arsenic remains irreversibly bound to the alumina, and the caustic and acid treatment dissolves some of the alumina, reducing the bed volume. Therefore, after a certain number of regeneration cycles, fresh activated alumina must be added to make up the lost media. Relatively little is known about the effectiveness of activated alumina after multiple regenerations, though limited experience suggests that run lengths will be approximately 25% shorter (Ghurye et al., 1999).

The advantages of activated alumina are that simple removal systems can be developed at community or household levels that require no chemical addition. Since activated alumina can treat thousands of bed volumes before breakthrough, filters could be operated for months before the media need to be changed or regenerated. Activated alumina will also remove selenite, fluoride, sulfate, and chromate. Disadvantages include the possibility that the media will be fouled or clogged by precipitated iron, the relatively narrow pH range for optimal operation, and the relative difficulty of regeneration. Also, compared with ion exchange resins, a significantly longer EBCT is required.

Box 6.4: Residual aluminum in treated waters

Both activated alumina and alum are composed of aluminum. There has been a good deal of controversy about health risks associated with aluminum levels in drinking water, particularly about a possible link with Alzheimer's disease. Several studies have shown that the brain tissues of patients with Alzheimer's disease have elevated aluminum levels (Harrington et al., 1994; Walton et al., 1995). A few studies have found a significant link between aluminum in drinking water and incidence of Alzheimer's disease and other forms of dementia (e.g. Martyn et al., 1989; Crapper-McLachlan et al., 1991; Martyn et al., 1997). Investigations are complicated by the large numbers of forms or species of dissolved aluminum, and because of the tendency of aluminum to form natural colloids with organic carbon, fluoride, and sulfate (Smith et al., 1996). The link between neurological effects and aluminum in drinking water is particularly elusive because the average adult intake of aluminum from food is 5 mg/day (WHO, 1998), which tends to be much higher than any intake from drinking water.

The 1993 WHO Guidelines for Drinking Water Quality did not set a health-based guideline for aluminum. However, aluminum in drinking water can cause several practical problems, such as discoloration of treated water and formation of floc in piped distribution systems. WHO remarked that "although further studies were needed, the balance of epidemiological and physiological evidence did not support a causal role for aluminum in Alzheimer disease. An aluminum concentration of 0.2 mg/L in drinking water provided a compromise between the practical use of aluminum salts in water treatment and discoloration of distributed water" (WHO, 1993).

WHO subsequently conducted a detailed review of health effects of aluminum through various exposure routes. Twenty available epidemiological studies were evaluated, and half of the high quality studies found a relationship between aluminum in drinking water and Alzheimer's disease or dementia, but the other half did not. Even in those studies that found links, relative risks were small (<2), and confidence intervals broad.

“Hazards to neurological development and brain function from exposure to aluminum have been identified through animal studies. However, aluminum has not been demonstrated to pose a health risk to healthy, non-occupationally exposed humans. There is no evidence to support a primary causative role of aluminum in Alzheimer's disease (AD), and aluminum does not induce AD pathology *in vivo* in any species, including humans... There is insufficient health-related evidence to justify revisions to existing WHO Guidelines for aluminum exposure in healthy, non-occupationally exposed humans. As an example, there is an inadequate scientific basis for setting a health-based standard for aluminum in drinking water.” (WHO, 1997a, p. 11)

In an addendum to the GDWQ, WHO noted that under good operating conditions, large water treatment plants should be able to use alum while ensuring residual aluminum levels of less than 0.1 mg/L. For smaller facilities, 0.2 mg/L is a practicable level for aluminum in finished waters (WHO, 1998).

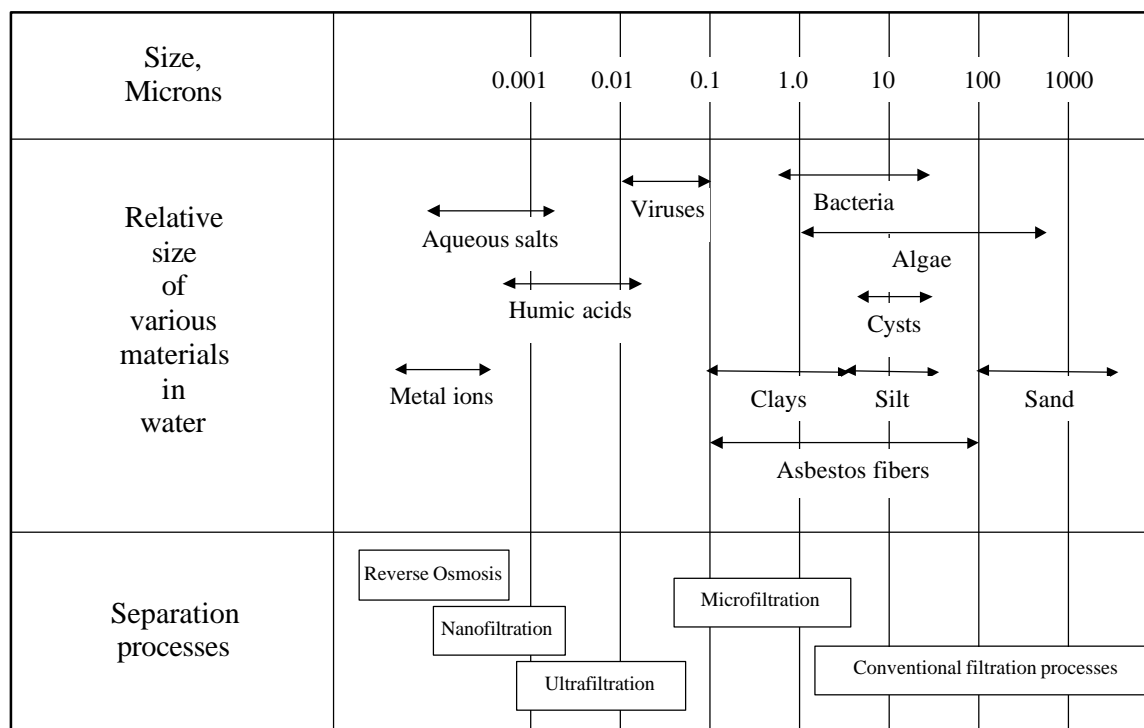
Surveys of aluminum in waters treated with alum show that residual levels sometimes exceed these levels, but generally average around 0.01 – 0.1 mg/L (WHO, 1997a). A review of rural defluoridation units composed of activated alumina found residual aluminum to be less than 0.01 mg/L in 75% of cases, but above 0.2 mg/L in 17% of cases (Iyengar, 1999). END BOX

6.3.5 Membrane methods

Synthetic membranes are available which are selectively permeable: the structure of the membrane is such that some molecules can pass through, while others are excluded, or rejected. Membrane filtration has the advantage of removing many contaminants from water, including bacteria, salts, and various heavy metals.

Two classes of membrane filtration can be considered: low-pressure membranes, such as microfiltration and ultrafiltration; and high-pressure membranes such as nanofiltration and reverse osmosis. Low-pressure membranes have larger nominal pore sizes, and are operated at pressures of 10-30 psi. The tighter high-pressure membranes are typically operated at pressures from 75 to 250 psi, or even higher (Letterman, 1999).

Figure 6.13: Pore size of various membranes, and size of materials subject to filtration (redrawn after Letterman, 1999)



From the above figure it is clear that reverse osmosis (RO) and nanofiltration (NF) membranes have pore sizes appropriate for removal of dissolved arsenic, which is in the ‘metal ion’ size range.

When membranes were first evaluated for arsenic removal in the 1980s, cellulose-acetate RO membranes were operated at high pressures (typically 400 psi), and good arsenate rejection was reported (>90%) (Schneider and Middlebrooks, 1983; Clifford, 1986). However, arsenite rejection was less efficient (<70%), and oxidation was difficult because residual oxidants could damage the membranes (e.g. Fox, 1989). In the mid-90s NF membranes, which are more permeable and can be operated at pressures less than 100 psi, were also found effective for arsenic removal (Legault et al., 1993; Waypa et al., 1997). Both RO and NF membranes are most often operated in lateral configurations, in which only a small amount of the raw water (10-15%) passes through the membrane as permeate. In household systems, where only a small amount of treated water is required for cooking and drinking, this low recovery rate may be acceptable. Municipal systems achieve higher recovery rates (80 to over 90%) by using multiple membrane units in series.

In recent years, a new generation of RO and NF membranes have been developed that are less expensive and operate at lower pressures, yet allow improved flux and are capable of efficient rejection of both arsenate and arsenite. Waypa and others have showed that some of the new membranes, operated at pressures ranging from 40-400 psi, were able to reject from 96-99% of both arsenate and arsenite in spiked natural waters. The authors attribute this rejection of arsenite to the relatively large molecular weight of both arsenate and arsenic, rather than charge repulsion. At these high arsenic rejection rates, membrane filtration can result in extremely low arsenic levels in treated water.

Arsenic removal was found to be independent of pH and the presence of co-occurring solutes, but was somewhat improved at lower temperatures. Interestingly, the NF membrane tested performed comparably to the RO membranes, even though the operating pressure was much lower (40-120 psi, compared to 200-400 psi) (Waypa et al., 1997).

Membrane filtration requires a relatively high-quality influent water. Membranes can be fouled by colloidal matter in the raw water, particularly organic matter. Iron and manganese can also lead to scaling and membrane fouling. To prevent fouling, reverse osmosis filters are almost always preceded by a filtration step.

Membrane filtration has the advantage of lowering the concentrations of many other components in addition to arsenic. Even ultrafiltration (UF) membranes are able to remove over 99.9% of bacteria, *Giardia* and viruses. Also, the membrane itself does not accumulate arsenic, so disposal of used membranes would be simple. Operation and maintenance requirements are minimal: no chemicals need be added, and maintenance would consist of ensuring a reasonably constant pressure, and periodically wiping the membrane clean. The main disadvantages are low water recovery rates (typically only 10-20% of the raw water passes through the membrane), the need to operate at high pressures, relatively high capital and operating costs, and the risk of membrane fouling. Also, particularly with RO, the treated water has very low levels of dissolved solids, and can be very corrosive, and deficient in minerals which can be important micronutrients for humans. A comprehensive discussion of the many issues involved in membrane technology is found in (Mallevalle et al., 1996).

High-pressure membrane methods are currently more expensive than other arsenic removal methods (household units in the United States cost upwards of \$1000), and are only used when very low arsenic levels are required in the treated water, generally in conjunction with some other primary treatment process such as coagulation. However, recent advances made in membrane technology are promising. If improvements continue to be made, particularly in operating low-pressure systems at high recovery rates, membrane removal could become a feasible and cost-effective technology for arsenic removal in developing settings.

6.3.6 Emerging technologies

The four technologies described above (coagulation and filtration, ion exchange resin, activated alumina, and membrane removal) are fairly well documented, even though some of the systems have only come into prominence in recent decades. In recent years, a tremendous amount of research has been conducted to identify novel technologies for arsenic removal, particularly low-cost, low-tech systems that can be applied in rural areas. Most of these technologies rely on oxidation of arsenite, followed by filtration through some sort of porous material, where arsenic is removed through adsorption and coprecipitation. Many of these systems make use of iron compounds, which have a very strong affinity for arsenic. A brief, though not exhaustive, review of some of the most documented technologies is given below.

Fe-Mn Oxidation

Conventional iron and manganese removal can result in significant arsenic removal, through coprecipitation and sorption onto ferric or manganic hydroxides. The mechanisms involved are the same as in coagulation and filtration, as discussed above. Much time and effort has been expended on developing reliable, low-cost technologies for iron removal. Most low-cost technologies for arsenic and manganese removal rely on aeration and filtration through porous media such as sand and gravel. Several systems that have been applied in developing countries are described in (IRC, 1982a) and (Cairncross and Feacham, 1993). Any technology that effectively removes iron and manganese could be evaluated to see if arsenic is also removed

effectively. In this respect arsenic removal is more convenient than that of fluoride, which does not undergo oxidation, and is not removed by coprecipitation with iron.

Edwards has commented that the contribution of manganese oxidation to arsenic removal is likely to be minimal compared to iron oxidation, unless manganese concentrations are extreme (>3 mg/L). In contrast, even removal of 1 mg/L Fe(II) is theoretically able to sorb 83% of a 22 $\mu\text{g/L}$ arsenate solution (Edwards, 1994).

In Taiwan, Shen and others attempted to remove arsenic from groundwater through simple aeration and sedimentation. Iron and manganese levels were elevated at 0.8 and 0.12 mg/L, respectively. After one full day of settling, arsenic concentration was reduced from 800 $\mu\text{g/L}$ by only 9%; even after 15 days, removal was only 50%. Iron concentrations in the sedimented water were not reported; poor arsenic removal may be related to poor iron oxidation (Shen, 1973). It seems likely, though, that the influent iron concentration was too low to effectively remove arsenic. In contrast, Clifford and Lin showed that 60% of a 188 $\mu\text{g/L}$ arsenate influent could be removed by oxidative precipitation of 2 mg/L Fe(II) (Clifford and Lin, 1991).

In Bangladesh and West Bengal, elevated arsenic concentrations are often associated with high iron and manganese levels. One survey in Bangladesh found that over 80% of arsenic-affected tubewells (>50 $\mu\text{g/L}$) also contained iron levels of 2 mg/L or more. However, iron alone is not a good indicator of arsenic: 30% of the wells with safe levels of arsenic also had 2 mg/L iron or more (DPHE/BGS/MML, 1999). Because of the link between arsenic and iron levels, and the affinity of arsenic for iron hydroxides, there have been calls for a simple solution to arsenic contamination: simple storage of pumped water to allow iron to settle out, scavenging arsenic in the process. While this is an appealing idea, successful application of this type of 'passive Fe-Mn oxidation' is not simple, for several reasons:

- iron removal is not always easily accomplished. Some waters contain iron in a form that is slow to oxidize, or may be complexed with organic material that impedes oxidation and filtration. Precipitation may not occur if alkalinity is low;
- without a filtration step, much of the iron can remain suspended as colloidal matter, even after oxidation;
- arsenite is not as strongly bound to iron as arsenate, if the waters contain mostly arsenite arsenic removal will be less efficient; and
- when water is stored in household containers, there is a high risk of bacterial contamination.

The Swiss research agency, EAWAG, is exploring the possibility of catalyzing iron and arsenic oxidation with lemon juice and sunlight in order to remove arsenic from iron-rich waters. A major advantage of this approach is that the treatment also disinfects the treated water, like the solar disinfection (SODIS) discussed in **Section 6.2**. This solar removal of arsenic (SORAS) project is in the early stages of testing in Bangladesh, early results suggest that arsenic removal is limited to 50-75%. This technology would be best applied at the household level, using locally available plastic bottles.

When considering passive Fe-Mn oxidation, particularly at the household level, careful pilot studies should be made using the local waters and local storage conditions, in order to assess the effectiveness of this technique, and the possibility of pathogenic contamination. It should be noted that chlorine addition would improve oxidation of both iron and arsenic, and would provide protection against bacterial growth. However, as discussed above, chlorination at the household level involves difficulties in ensuring the correct dose, and the potency of the chlorine agent.

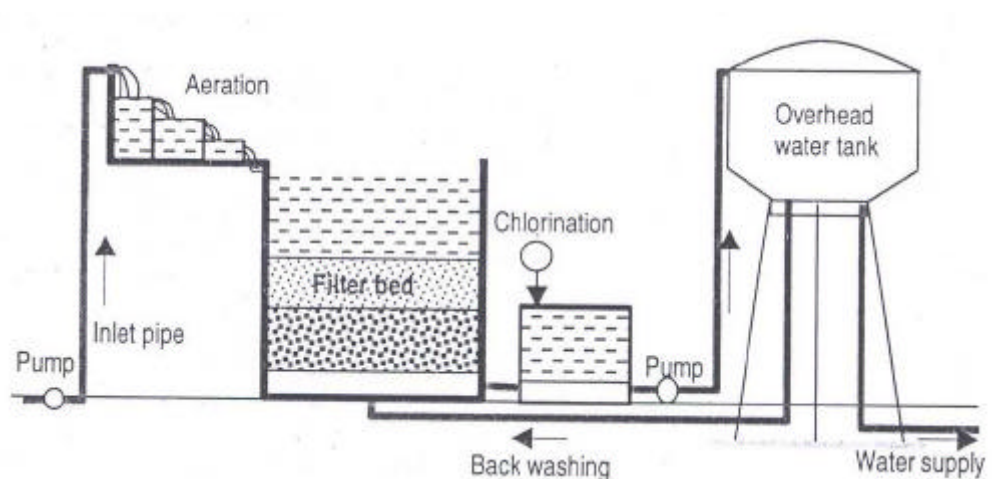
Box 6.5: 18-DTP Arsenic Removal Plants in Bangladesh

With support from the Dutch Government, the Bangladesh government has constructed three arsenic removal plants in small municipalities. These plants are basically iron removal plants, and add no chemicals, but pump groundwater over a series of cascades to aerate the water. Filtration then removes the resulting iron and arsenic precipitate, and the water is chlorinated and stored in an elevated tank for distribution. Water stored in the tank is periodically used to backwash the filters. The waste water is stored in sludge ponds, and sludge is removed once or twice annually. Arsenic removal efficiency varies considerably, and seems to improve with higher iron levels:

Table 6.5: Arsenic removal in three 18-DTP plants

Municipality	Influent iron (mg/L)	Iron removal efficiency (%)	Influent arsenic ($\mu\text{g/L}$)	Arsenic removal efficiency (%)
Satkira Razzak	3.4	95	57.0	51
Satkira Polash	5.8	95	67.5	67
Manikganj	7.6	99	84.8	72

Source: (18-DTP, 1999)

Figure 6.14: 18-DTP Arsenic removal plant design

Source: (Ahmed and Rahman, 2000)

Although removal rates are not very high, in all cases it is effective enough to bring waters into compliance with the Bangladesh drinking water standard of $50 \mu\text{g/L}$. Plant managers experimented with addition of coagulants (4 mg/L FeCl_3) and oxidants (0.9 mg/L bleaching powder), but found that arsenic removal efficiency was not significantly improved. END BOX

Box 6.6: WaterAid in Bangladesh

In Bangladesh, the British NGO WaterAid, collaborating with their local partner VERC, investigated the possibility of storing groundwater to allow iron to oxidize and settle out as a means of arsenic removal. In the experimental site, a village in southeastern Bangladesh, water supply consisted of approximately 200 private shallow tubewells, some three quarters of which produced water with arsenic levels over $50 \mu\text{g/L}$. Iron levels were also high in many, though not all wells. Water was collected from the contaminated wells, and stored in covered pitchers for 12-

24 hours. The effects of enhanced aeration, achieved by pouring water repeatedly from one pitcher to another, were also evaluated.

The NGO workers found that in some cases, good arsenic removal was effected by passive sedimentation of iron-rich waters. Influent concentrations were reduced from over 500 µg/L to below 50 µg/L in some cases. However, in some cases, little or no change in arsenic level was produced. Contrary to expectations, the best arsenic removal did not occur in waters with the highest iron levels – in fact some of the waters that showed no arsenic reduction contained over 5 mg/L iron. Arsenic removal was not significantly improved by attempts to enhance aeration. Other chemical parameters such as pH, alkalinity, and hardness were also measured, but the only significant correlation noted was a tendency for better arsenic removal in waters with lower electroconductivity.

One clear trend, however, was noted. Freshly collected water was of very high microbiological quality, but after being stored in pitchers for twelve hours, very high fecal coliform counts were found. Apparently the pitchers, in spite of regular hand scrubblings, harbor reserves of fecal bacteria which are effectively incubated during home storage. END BOX

Sorption onto other metal oxides

Besides activated alumina, other metal oxides have strong affinities for arsenic, and can serve as effective sorbents, and in some cases as oxidants. Quartz is very poor at removing arsenic under most environmental conditions, because the mineral surface is negatively charged above a pH of 2. However, quartz sand, or indeed any other granular media, can be made highly sorptive by coating the grains with metal oxides. In recent years many researchers have used this principle to develop low-cost arsenic removal methods using locally available materials.

Vaishya showed that sand from the Ganges river, which presumably is rich in iron coatings, could remove arsenite from solution, with a reported capacity of 0.024 mg/g. Removal was found to be pH-dependent, and best from pH 7-9 (Vaishya and Agarwal, 1993).

Joshi and Chaudhuri showed that iron oxide coated sand (IOCS) is able to remove both arsenite and arsenate. A simple fixed bed unit was able to treat about 160-190 bed volumes of water containing 1000 µg/L arsenite and 150-165 bed volumes of water with 1000 µg/L arsenate. Flushing with 0.2 N sodium hydroxide regenerates the media. The authors propose that this media would be very useful for domestic arsenic removal units (Joshi and Chaudhuri, 1996). This technique may be most appropriate for arsenate removal: Viraraghavan and others found that quartz sand coated with iron oxides was initially able to remove arsenite, but that breakthrough occurred relatively quickly (Viraraghavan et al., 1999). Khaodhiar and others showed that IOCS could effectively remove copper and chromium, as well as arsenate (Khaodhiar et al., 2000). Lombi and others investigated the kinetics of arsenite and arsenate adsorption onto IOCS, and found that adsorption was relatively slow: about half of the arsenic was adsorbed within ten hours, and after five days removal exceeded 97% (Lombi et al., 1999).

A similar coated sand material can be prepared using manganese dioxide instead of iron. Since MnO₂ is a good oxidant, this material can remove arsenite as well as arsenate. In fact, the treated sand was able to remove 80% of a 1 mg/L solution of arsenite within two hours, but slightly less than 70% of an equivalent solution of arsenate. A prototype household unit was developed, which could treat about 150 bed volumes of 1 mg/L arsenic (half arsenite and half arsenate) before breakthrough (Bajpai and Chaudhuri, 1999).

Greensand is a granular material composed of the mineral glauconite, which has been coated with manganese oxide. It is a natural zeolite, and has strong ion exchange properties, and will remove iron, manganese, arsenic, sulfide, and many other anions. Like manganese dioxide coated sand,

greensand surface is strongly oxidizing, and is thus able to remove both arsenite and arsenate. The media is typically recharged by application of potassium permanganate, which not only reestablishes the oxidizing environment, but deposits a fresh layer of manganese oxide on grain surfaces (Ficek, 1996). Viraraghavan and others showed that greensand could reduce arsenite levels from 200 µg/L by about 40% in the absence of iron. When ferrous iron was also present, arsenite removal improved to above 80% (Subramanian et al., 1997; Viraraghavan et al., 1999). Little information is available about the capacity of greensand for arsenic removal, or the effects of pH or competing anions on arsenic removal.

Several proprietary iron-based adsorption materials have been developed recently. Granular ferric hydroxides are being used in full scale systems in Germany (Driehaus et al., 1998), and similar materials have been developed in Canada and the United States. These materials generally have high removal efficiency and capacity. For a review of proprietary arsenic removal technologies, the reader is directed to (Murcott, 2000).

Metal oxides need not be supported in a granular matrix. Lin and Gan showed that 20 mL of a sorbent consisting of ferric hydroxides supported on paper pulp could be used to treat 30 liters of water, reducing arsenic levels from 67 µg/L to below the drinking water standard (Lin and Gan, 1991). Low and Lee investigated the potential of chrome sludge for arsenic removal. They found that the sludge rapidly removed arsenate from solution, and had commendable sorption capacity of 21 mg/g (Low and Lee, 1995).

Sorption onto reduced metals

Most of the above processes rely on arsenate adsorption onto surfaces of metal oxides. However, arsenic also has a strong affinity to reduced metal surfaces, such as sulfides. A few researchers have taken advantage of this property to remove arsenic through reduction and sorption.

Lackovic and others have demonstrated that zero-valent iron filings can be used either in situ or ex situ to reduce arsenate, and produce ferrous iron. The ferrous ions precipitate out with sulfide, which is also added to the system. Arsenite is removed either through coprecipitation or adsorption onto pyrite. This system is promising for use in rural areas, because of the low cost of materials, and the simple operation. However, treated water is very high in ferrous iron, and must undergo iron removal treatment before distribution or consumption (Lackovic et al., 2000). A similar system using zero-valent iron to treat water stored in individual homes was tested in Bangladesh and West Bengal. Arsenic removal was approximately 95% for highly contaminated waters, containing 2000 µg/L arsenic in the presence of sulfate at pH 7. Removal is rapid, but if batches are left for too long, dissolved iron concentrations become unacceptably high (Ramaswami et al., 2000). Similarly, Kuhlmeier has shown that packed columns containing pyrite can remove inorganic and organic arsenic compounds (Kuhlmeier and Sherwood, 1996).

Box 6.7: Three Kolshi Filter in Bangladesh

A simple arsenic removal system has been developed in Bangladesh, based on a traditional sand filtration water purification system. Three 18-L clay pitchers (called *kolshi*) are stacked vertically in a metal rack. The top pitcher contains coarse sand and metal iron filings, the second pitcher wood charcoal and fine sand, and the third serves as storage. Arsenic-rich groundwater is poured into the top pitcher, and trickles through small holes into the second and third pitchers. One unit costs about \$5, and flow rates average 2.6 to 2.9 liters per hour.

Laboratory tests show that the three *kolshi* filter can remove arsenic from groundwater containing a wide range of arsenic concentrations (80 to over 1000 µg/L). Arsenite proportions in the groundwater ranged from 40% to near total, and were typically greater than 70%. Filtered water

generally contained from 5-30 µg/L arsenic, all as arsenate. In some cases arsenic removal exceeded 99%.

Field testing of two hundred units confirms this impressive finding: after one week of operation, 90% of the filters produced water in which no arsenic could be detected using field kits, and 7% produced water with significantly reduced but detectable arsenic levels. Iron levels were also dramatically reduced, in some cases from over 1 mg/L to below 0.1 mg/L. After four months of operation, the filters were still operating efficiently.

This system shows great promise in that it is highly effective, inexpensive, easy to operate, and is similar a traditional water treatment method. A significant drawback of the three *kolshi* filter is that treated water can easily become contaminated with faecal bacteria, either during transport of the water from the well, or storage in the household. Bacteria may also be present in the media, if it is not sterilized. Field tests showed that some slight contamination occurred before filtration (15% of samples showed some contamination, with a maximum of 130 TC/100 ml), but that bacteria counts increased dramatically during filtration and storage: nearly two thirds of treated samples showed counts higher than 100 TC/100 ml, and a fifth had levels above 10,000 TC/100 ml. It may be possible to reduce the risk of bacterial contamination by sterilizing the media before filter construction.

Source: (Rasul et al., 1999; DPHE/UNICEF/BRAC, 2000)

END BOX

Ion exchange and adsorption

Ion exchange resins developed for removal of anions such as sulfate and nitrate have proven to be reasonably effective at removing arsenic, as discussed above. As materials engineering becomes more advanced, researchers are increasingly able to design novel ion-exchange materials with surficial properties that are particularly specific to arsenate. In particular, several researchers have found that copper-doped materials have a strong, specific affinity for arsenate (e.g. Rajakovic and Mitrovicm, 1992; Ramana and Sengupta, 1992; Lorenzen et al., 1995). Fryxell and others have developed a novel mesoporous silica sorbent which makes use of Cu(II)-based functional groups. This material has a higher ion exchange capacity (75 mg As/g) than conventional resins, and shows a stronger affinity for arsenate and chromate than for sulfate or nitrate. Therefore, unlike the conventional resins, these materials will not release chromatographic peaks of arsenic when exposed to high levels of sulfate (Fryxell et al., 1999).

While conventional synthetic ion exchange resins are the most commonly used media in ion exchange, costs are relatively high (\$USD 2-5 per liter of wet resin). A variety of naturally occurring materials also have high ion exchange capacities, sometimes after chemical pretreatment. Many of these materials are not pure ion exchangers: some arsenic removal is through less reversible chemisorption. Especially in developing countries, researchers have been evaluating the potential of these materials for use as low-cost arsenic removal systems.

Zeolites are naturally occurring minerals with a crystalline structure characterized by large internal pore spaces. Accordingly, they have very large surface areas, and ion exchange capacities: zeolites were used extensively for water softening, before the development of synthetic resins with faster exchange rates, higher capacity, and longer life. A few arsenic removal studies have been conducted with zeolites.

Natural zeolite minerals such as clinoptilolite and chabazite have a strong affinity for both arsenite and arsenate. A chabazite filter was able to remove 1000 µg/L arsenate from over 235 bed volumes before arsenic was detected in the effluent (Bonnin, 1997). Adsorption of arsenate

onto natural zeolites can be improved by organically modifying the zeolite structure (Misaelides et al., 1998).

Chitosan and chitin are natural polyaminosaccharides occurring in crustacean shells, that have good ion exchange properties. Shellfish wastes containing chitosan have been used to remove arsenic from water contaminated by mining wastes (Luong and Brown, 1984). Elson and others investigated a mixture of chitosan and chitin, and found a relatively low arsenic removal capacity of about 0.01 mg As/g (Elson et al., 1980).

The ion exchange properties of modified coconut coir dust have been investigated for a variety of anions, including nitrate, chromate, selenate, and arsenate. Coconut coir dust, composed chiefly of cellulose and lignin, is chemically modified to have secondary and tertiary amine functional groups, similar to a weakly basic ion exchange resin. Chromate, nitrate, and selenate were efficiently removed by the resulting media, but arsenate removal was less good, with a maximum capacity of about 6.5 mg As/g, about one tenth of the capacity of a synthetic anion exchange resin also evaluated. However, the material is inexpensive and could be produced at low expense in many tropical countries. No attempts were made to regenerate the media (Baes et al., 1997).

A similar material has been produced out of ground rice husks, which are modified with an ammonium treatment to produce 'quaternized rice husk'. Arsenate removal from highly concentrated solutions (100,000-600,000 µg/L) was good, but dependent on pH, with maximum removal of about 80% from pH 6 through 10. The estimated maximum sorption capacity was over 19 mg As/g. Chromate, sulfate, and to a lesser extent, nitrate, all diminished arsenic removal rates (Lee et al., 1999).

Fly ash, a by-product of coal combustion in power stations, has a very strong affinity for arsenate. Diamadopoulos and others found that a lignite-based fly ash was able to remove 80% of arsenate from solution, with an optimal pH of 4. The arsenic capacity was nearly 28 mg As/g. Desorption studies showed that very little arsenic could be removed from the fly ash, indicating that chemisorption rather than ion exchange is the likely removal mechanism (Diamadopoulos et al., 1993). One drawback of the use of fly ash is that when arsenic-rich coal is combusted, the resulting fly ash can have very high concentrations of arsenic, up to 47% by weight (Dutre and Vandecasteele, 1998).

Activated carbon has a high surface area, which attracts many dissolved compounds, and allows the removal of organic compounds, including compounds that can give water an undesirable taste or color. Activated carbon may remove arsenic for a short time, but as the surface is not very selective for arsenic, overall capacity for arsenic removal is low (Sorg and Logsdon, 1978).

In Situ arsenic immobilization

When arsenic is mobilized in groundwater under reducing conditions, it is possible to immobilize the arsenic by creating oxidized conditions in the subsurface. In Germany, in order to remediate an aquifer containing high-arsenite, high ferrous iron, low-pH groundwater, Matthes injected 29 tons of potassium permanganate directly into 17 contaminated wells, oxidizing arsenite, which coprecipitated out with ferric oxides. Mean arsenic concentrations were reduced by over 99%, from 13,600 to 60 µg/L (Matthes, 1981). More recently, atmospheric oxygen was used to reduce arsenic concentrations *in situ* from approximately 20 to 5 µg/L, while iron and manganese levels were also lowered (Rott and Friedle, 1999).

Under reducing conditions, and in the presence of sulfur, arsenic can precipitate out of solution and form relatively insoluble arsenic sulfides. In theory, reductants and/or sulfide could be injected into contaminated groundwater to promote formation of sulfide minerals, and consequent sequestration of arsenic (Ahmed and Rahman, 2000).

In situ immobilization has the great advantage of not producing any wastes that must be disposed of. However, experience is limited, and the technique should be considered with caution. Oxidants are by definition reactive compounds, and may have unforeseen effects on subsurface ecological systems, as well as on the water chemistry. Care must also be taken to avoid contaminating the subsurface by introducing microbes from the surface. Also, at some point pore spaces can become clogged with precipitates, particularly if dissolved iron and manganese levels are high in the untreated water.

6.3.7 Waste disposal

All of the arsenic removal methods at some point produce an arsenic-rich waste stream, which must be disposed of in a safe manner. Typically municipal water plants are accustomed to handling chemicals and disposing of wastes. At community and household levels, operators will need to be given special training in responsible handling of wastes. In addition, some of the techniques described above require additional chemicals, either during routine operation or for media regeneration; the disposal of all these potentially hazardous waste materials must be considered when designing any arsenic removal system.

Liquid Wastes

The regeneration of activated alumina and ion exchange resins results in various liquid waste streams that may be too acidic, caustic, saline, or arsenic-rich for simple disposal. Arsenic can be isolated from these liquid wastes through coagulation and filtration as described above. The resulting liquid waste will have low arsenic levels, but may require additional pH correction for safe disposal. Ion exchange regenerant brines may be too saline for safe surface disposal, but once arsenic is removed through coagulation, the regenerant can be reused.

Solid Wastes

A variety of arsenic-rich solids can be generated in arsenic removal. The most common include saturated filters and sludges such as hydrous ferric or aluminum oxides (HFO and HAO). Arsenic levels in wastes will depend on influent concentrations, but may reach several hundred mg/kg dry weight. Depending on costs, it may be economical to dispose of saturated filters rather than regenerating them. The stability of these solids needs to be evaluated when considering disposal options. If arsenic is likely to leach out of the solids after disposal, the wastes may require a specially constructed hazardous waste disposal facility, or additional treatment to immobilize arsenic. If the arsenic is so tightly bound to the solid wastes that it will not leach out, the wastes can be disposed of along with other municipal solid wastes.

Landfill disposal and the TCLP

The United States Environmental Protection Agency has developed a lab procedure called the toxicity characteristic leaching procedure (TCLP) to identify wastes likely to leach dangerous concentrations of certain known toxic chemicals into groundwater. The TCLP duplicates the conditions that solid waste would be exposed to in a typical sanitary landfill.

The TCLP involves crushing the solid waste to a certain size, soaking the solids in a weakly acidic solution for 18 hours, and measuring the resulting liquid (leachate) for toxic chemicals. EPA has produced a list of 39 regulated contaminants and set permissible levels for TCLP leachate, generally at one hundred times the drinking water MCL.

If the leachate exceeds the permissible level for any of the specified chemicals (or if the waste is ignitable, corrosive, or reactive) the waste is considered hazardous, and must be disposed of in a special hazardous waste landfill.

Several researchers have conducted TCLP tests on sludges resulting from arsenic removal by coagulation with Al and Fe salts, and produced leachates with arsenic levels of 0.009-1.5 mg/L (Brewster, 1992; Chen et al., 1999). These levels are all well below the current level required for classification as hazardous waste. These studies suggest that where HAO and HFO are used for arsenic removal, the resulting sludges will not require any special disposal.

One TCLP test made on arsenic-rich zeolites found no detectable arsenic in the leachate (Bonnin, 1997). No information is currently available on TCLP tests of arsenic-rich sludges from lime softening, or of exhausted activated alumina or ion-exchange resins.

Note that if the solid waste is not deposited in a landfill, but subjected to some other solid waste disposal, such as incineration or disposal under reducing conditions, the TCLP may not be an appropriate tool to assess the stability of the solid waste. Studies have shown that arsenic adsorbed onto iron hydroxides in aquifer materials can be mobilized under high pH conditions (Mariner et al., 1996) or reducing conditions generated by solid waste (Puls et al., 1992) or industrial effluents (Lieberman, 1996).

Other disposal options

Arsenic removal systems could be designed so that the removal media (metal hydroxide, ion exchange resin, activated alumina, etc., perhaps encased in a cartridge or sack) would be provided by a central distributor, who would be responsible for collecting and processing the spent media. This approach has many advantages, especially in rural settings. A trained specialist is more likely to be able to consistently perform chemical regeneration or stabilization procedures, and certain economies of scale might be realized. The main challenge in implementing such a system would be to ensure that the distribution network was strong enough to reliably pick up the spent material as needed, and supply new sorbent. Most of the sorbents give no obvious indication when they are exhausted, they simply cease to work.

Hazardous wastes are often made less hazardous by blending the wastes into stable solid materials such as glass, brick, or cement. Extremely arsenic-rich wastes such as coal fly ash have been successfully stabilized through solidification in brick or cement. When solidifying with brick, there is the risk that some of the arsenic will volatilize during brick firing, and possibly contaminate air and water downwind of the kiln smokestack. In Hungary, experiments showed that some 30% of arsenic in the coagulant sludge was lost to the atmosphere in this way.

Solidification with cement is better documented. Dutre mixed fly ash with lime and cement, and subjected the resulting solid (approx. 10% arsenic by weight) to a leaching test similar to the TCLP. Arsenic concentrations in the resulting leachate averaged 5 mg/L, which would constitute borderline hazardous waste under the EPA definition (Dutre and Vandecasteele, 1998). Similarly, the Bengal Engineering College in India has immobilized arsenic-rich HFO sludge in cement (30% sludge by weight), conducted TCLP testing on the cement, and found the leachate to have negligible arsenic levels (Gupta et al., 2000).

A recent study of arsenic chemistry in sewage sludge concluded that redox potential and pH were the most important controls on speciation and solubility of arsenic after disposal. Arsenic solubility was highest under mildly reducing conditions, due to the dissolution of iron hydroxide compounds. Under very reducing conditions, arsenic solubility is limited by the formation of insoluble sulfides. At near neutral pH values, biomethylation was found to be an important process, converting inorganic arsenic into organic compounds, particularly dimethylarsinic acid

(Carbonell-Barrachina et al., 2000). Some researchers in West Bengal and Bangladesh have advocated mixing arsenic-rich sludges with animal manure, so that bacteria can methylate the inorganic arsenic, transforming it into less toxic and volatile compounds. At Jadavpur University, over 90% of arsenic bound in sludge was found to be removed in this way (Chakraborti, 1999), but further documentation is required.

Box 6.8: Disposal of arsenic-rich sludge generated at the household level

Only a small percentage of water collected, perhaps 10-30%, is used for drinking and cooking, the rest is typically used for washing, bathing, and household chores. Furthermore, domestic water consumption typically accounts for only a fraction (5-15%) of the water used by humans. Irrigation is by far a larger drain on water resources. Ideally, no arsenic-contaminated water would be used for any purpose, but in areas where arsenic is endemic, the first priority should be to provide safe water for drinking and cooking. The use of contaminated water for other purposes, while not desirable in the long term, does not pose the same direct threat to human health that contaminated drinking water does.

In Bangladesh, a family of six drinking highly contaminated water (say, 500 µg/L arsenic) will need approximately thirty liters per day for drinking and cooking. If a household arsenic removal system is used, some 15 milligrams of arsenic will need to be removed from water daily. This translates to about 5 grams, or 1/6 of an ounce, of arsenic per year, assuming that the family has no other sources of water for drinking and cooking.

Obviously, it would not be safe to ingest this amount of arsenic, either day-by-day or at one dose. This amount of arsenic might be fatal – the fatal dose of arsenic trioxide in humans is reported to range from 70 to 180 mg (WHO, 1980a, p. 88). However, the toxicity of arsenic varies considerably according to the solubility of the ingested form, and arsenic bound onto sludges or other solid wastes will be much less soluble than arsenic trioxide. In any case, the amount of arsenic ‘generated’ by a single household can be considered environmentally insignificant, when compared to the amounts of contaminated water that is collected for household chores, or especially for irrigation.

Irrigated crops can require from less than 0.5 to over 2 m of irrigation water annually, depending on crop type, soil type, and precipitation. A typical requirement to produce a crop in an arid environment is 1.2 m/year (Chang et al., 1995). The FAO recommends a limit of 100 µg/L arsenic for irrigation waters, but permits levels of up to 2000 µg/L “for use up to 20 years on fine textured soils of pH 6.0 to 8.5” (Ayers and Westcot, 1976). The US and Canada also have standards of 100 µg/L for irrigation waters (Chang et al., 1995). At this concentration, 1.2 kg of arsenic could be applied annually per hectare.

With this perspective, the household annual production of 5 grams of arsenic is insignificant. Waste should still be handled responsibly - it is not recommended to simply discard arsenic-rich sludges on the ground, since children are known to consume significant amounts of dust and dirt. However, the sludge could be deposited along with other solid wastes, mixed with animal manure, or simply flushed down toilets or sanitary latrines. Even if the small amount of arsenic bound to the sludge were to dissolve in a properly constructed latrine or septic tank, latrines and septic tanks are generally well isolated from drinking water sources, and the arsenic would not easily make its way into drinking water. END BOX

Concerns about the possible health threats posed by handling and disposing of arsenic-rich wastes should be weighed against the much greater, and definitely known risks of continuing to drink contaminated water. At least at the household level, wastes from arsenic removal can be handled responsibly and safely without causing a significant health risk.

6.3.8 Summary

The following table summarizes some of the key technologies for arsenic removal, with special reference to experiences gained from field level application. Research needs are also identified. Arsenic removal efficiency will vary according to many site-specific chemical, geographic, and economic conditions, so actual applications may vary from the generalizations listed below. Because of the many factors that can affect arsenic removal efficiency (including arsenic concentration, speciation, pH and co-occurring solutes), any technology should be tested using the actual water to be treated, before implementation of arsenic removal systems at the field scale.

Table 6.6: Summary of technologies for arsenic removal

Technology	Removal Efficiency		Institutional experience and issues
	As (III)	As (V)	
Coagulation with iron salts	++	+++	Well proven at central level, piloted at community and household levels. Phosphate and silicate may reduce arsenic removal rates. Generates arsenic-rich sludge. Relatively inexpensive.
Coagulation with alum	-	+++	Proven at central level, piloted at household levels. Phosphate and silicate may reduce arsenic removal rates. Optimal over a relatively narrow pH range. Generates arsenic-rich sludge. Relatively inexpensive
Lime softening	+	+++	Proven effective in laboratories and at pilot scale. Efficiency of this chemical process should be largely independent of scale. Chiefly seen in central systems in conjunction with water softening. Disadvantages include extreme pH and large volume of waste generated. Relatively inexpensive, but more expensive than coagulation with iron salts or alum because of larger doses required, and waste handling.
Ion exchange resins	-	+++	Pilot scale in central and household systems, mostly in industrialized countries. Interference from sulfate and TDS. High adsorption capacity, but long-term performance of regenerated media needs documentation. Waters rich in iron and manganese may require pre-treatment to prevent media clogging. Moderately expensive. Regeneration produces arsenic-rich brine.
Activated alumina	+/ ++	+++	Pilot scale in community and household systems, in industrialized and developing countries. Arsenite removal is poorly understood, but capacity is much less than for arsenate. Regeneration requires strong acid and base, and produces arsenic-rich waste. Long-term performance of regenerated media needs documentation. Waters rich in iron and manganese may require pre-treatment to prevent media clogging. Moderately expensive.
Membrane methods	-/ +++	+++	Shown effective in laboratory studies in industrialized countries. Research needed on removal of arsenite, and efficiency at high recovery rates, especially with low-pressure membranes. Pretreatment usually required. Relatively expensive, especially if operated at high pressures.
Fe-Mn oxidation	?	+/ +/ +++	Small-scale application in central systems, limited studies in community and household levels. More research needed on which hydrochemical conditions are conducive for good arsenic removal. Inexpensive.
Porous media sorbents (iron oxide coated sand, greensand, etc.)	+/ ++	+/ +/ +++	Shown effective in laboratory studies in industrialized and developing countries. Need to be evaluated under different environmental conditions, and in field settings. Simple media are inexpensive, advanced media can be relatively expensive.
In situ immobilization	++	+++	Very limited experience. Long-term sustainability and other effects of chemical injection not well documented. Major advantage is no arsenic-rich wastes are generated at the surface, major disadvantage is the possibility of aquifer clogging. Should be relatively inexpensive.

Key: +++ Consistently > 90% removal
 ++ Generally 60 – 90% removal
 + Generally 30 – 60% removal
 - < 30% removal
 ? Insufficient information

6.4 Evaluation and selection of arsenic-free water supply technologies

When considering sources and water supply technologies for arsenic mitigation, selection should be on the basis of avoidance or of a substantial and consistent reduction of the ingestion of

arsenic. Each source has specific characteristics relating to quality, quantity, reliability, user acceptability and costs that will determine its applicability in different contexts.

In most instances choice is not straightforward and no one source or technology is likely superior in a given situation. Rather it will be necessary to undertake a risk assessment considering the range of parameters pertinent to the locality and situation, before one can list solutions that are adequate, suitable and appropriate. Previous sections and documents referred to therein describe in more detail the functioning and effectiveness of the various technologies now available.

The purpose of this section is to describe a protocol for the selection of an arsenic-free water supply technology or hybrid set of arsenic mitigation technologies. The protocol will need to lead to the consideration and selection of suitable technologies that meet the conditions of producing water that is safe bacteriologically and from the perspective of arsenic. The criteria to be met are found in the WHO Guidelines for Drinking Water Quality (WHO, 1993) and national guidelines or standards. The protocol developed in the following pages has a bias to the requirements and capacities of the household or a small community. The latter is an important consideration as it is implicitly assumed that no higher skill based capacity is available for operation and maintenance or water quality monitoring. Technologies applied should be able to function consistently in the absence of such skills.

The protocol involves a set of five technical criteria that should be met for any technology to be considered as technically appropriate. Technically appropriate systems are then examined with respect to six socioeconomic criteria to evaluate the practicability of the system.

6.4.1 Technical criteria

Five main criteria are proposed. Water supply options must first of all be able to produce water of the required **quality**. The system should also be able to supply water in adequate **quantity**, through out different seasons. Technologies should be reliable and **robust**, in that there is little opportunity for errors to occur, either through inherent systemic weaknesses, or through user error. As these systems will be operated by non-technical community members, it is important that **operational safety** be ensured. Finally, technologies should not have an undue adverse effect on the **environment**.

Water quality

For a technology to be suitable, the resultant water should be microbiologically safe and have a concentration of arsenic (and other relevant chemicals) that meets WHO guidelines or nationally determined standards. Another aspect of water quality to be considered is feed water quality: some treatment systems will require pre-treatment of the feed water (e.g. pH correction, sedimentation) for efficient operation.

An assessment has to be made how a proposed mitigation solution compares with the situation before intervention. If an option removes the arsenic risk but substitutes for it another threat, the net result may be just as poor for the health of the family. Not only bacterial water quality, but also other contaminants that may be present in the alternate source water or introduced through the treatment (e.g. pesticides or heavy metals) should be considered.

Household arsenic removal technologies should be subjected to rigorous testing at laboratory and pilot scale before being tested and monitored in a larger field sample. These technologies should consistently perform as anticipated, not only in the laboratory or in supervised field conditions, but also in the households of community members. They should be able to produce good water even when the technology is subject to a certain degree of “abuse” such as may be caused by improper mixing, use beyond indicated safe removal capacity of a filter, shortcuts, etc. Removal technologies should be such that their presentation (sachet, pill or adsorbent layer), operation and

functioning (mixing, settling), storage and abstraction, favor correct operation at the household and community level. They should be designed to minimize the likelihood that local users will modify the dose or application method.

The concept of the multiple barrier series discussed earlier in the context of enhanced protection against the transmission of pathogens in surface water systems should be applied when designing or scrutinizing technologies.

Technologies that do not conform to these technical criteria are suspect and should only be applied when alternative options carry even higher health risks or risks of failing to meet critical performance indicators.

Water quantity

Preference is given to water supply solutions that are able to provide safe water throughout the year. In many parts of the world, water resources, land and capital for impounding water, and declining ground water reserves do not allow for the establishment of comprehensive year round solutions anymore. Especially in developing countries, population pressure, limitations in funds and professional capacity, and competing economic needs make it ever more difficult to secure a good quantity of good water for domestic purposes all year round.

Domestic water needs are manifold. Water is needed for drinking, cooking, food preparation, dishwashing, bathing, laundry, cattle, sanitation and other cleaning activities around the house. The first three water needs demand bacteriologically and chemically safe water, generally about 7-10 liters per capita per day.

If all water needs can not be met from one perennial safe water supply system, it is necessary to assist the community to make an inventory of the sources of water that are used by households and clusters of houses in the community. Sources for drinking should be classified as safe, acceptable or bad, based on bacterial and arsenic quality. Periods of safe or convenient usage during the year should be established. The risk of contamination or deterioration should be recorded, as well as a historical record of reliability and ownership or control of the source. The information can be gathered and ranked by community members. The resulting information is an essential decision making tool for the household, the community and public health field staff in designing or deciding on feasible water supply solutions. The risk of the solution failing, whether known or unknown to the user, should be considered, especially if failure means a return to the pre-intervention solution.

The ultimate solution or set of solutions should provide sufficient water for drinking and cooking for everyone in the household or the community, throughout the year and inclusive of locations members of the household frequent daily, such as the school, fields, factory, mosque, etc.

Robustness

Safe water supply technologies should be reliable and robust, able to provide water of the required quantity and quality, even under suboptimal conditions. All systems have some potential for breakdown, but this likelihood should be minimized, and local operators should ideally have the skills, materials and motivation needed to correct most problems.

Some technologies involve microbiological or chemical treatment of water resources; many of these systems have limited run times before replacement, and cleaning or regeneration is required. Users may not be able to tell easily whether or not a treatment process is working. People will assume the treated water is safe to drink: if system failure occurs, and is not readily identified, users can unknowingly consume unsafe water. Technologies would ideally have an indicator telling users when to perform maintenance or replacement. A well falling dry is an obvious indicator, as can be the color or taste of water produced by a poorly run treatment plant.

Indicators are more difficult in the case of arsenic removal technologies. Indicators might be developed based on the volume of water treated, by use of a water meter. Some sorbents reportedly make changes to water chemistry while operational (e.g. change in pH) that could be used as monitoring indicators. Finally, if reliable arsenic field kits are available, users could directly monitor treated water quality themselves.

As novel arsenic mitigation technologies are introduced, it is necessary to ensure that adequate water quality and performance surveillance systems are set up to monitor and evaluate the effectiveness of the technology and its application. For domestic systems it will often not be feasible to do this monitoring continuously, but it may still be advisable to contract out field work on a regular basis to ensure correct functioning of the technology. This task may be coordinated by public health institutes. Shortcomings identified can subsequently be corrected and become part of public information programmes. Community based arsenic mitigation technologies will need to be monitored for compliance on a continuous basis.

The **reliability** of any arsenic-free solution is dependent on the risk of poor operation. Wells can provide safe water, but poor hygiene in storing drinking water in the household can reintroduce bacterial contamination. Similarly, discipline (and habit) is required to manually mix a pre-measured quantity of reagents in a bucket of water so as to produce arsenic-free water. Putting in a sufficient quantity of mixture, stirring it as indicated, allowing water to settle, etc. can all be critical to the effectiveness of a removal process. Technical applications and innovations should ensure that the reliability of the process is guaranteed to a large degree even when it is not operated under optimal conditions. For instance, in traditional water treatment systems using surface water sources, the application of the multi-barrier concept will lead to greater reliability in producing water of the required quality.

Operational Safety

Users should not have to expose themselves to undue health risks during standard operation or maintenance of the technology. For technologies that require chemical addition, a key safety criterion should be that the chemicals used are safe in handling and can be stored safely. For community level systems, the safety of caretakers and operators should be considered; for household level systems, chemicals should be stored in a place safe from curious children.

Environmental soundness

The technology to be employed should in its production and application not cause any undue environmental risks. This applies to the ecological effects that may be caused by abstraction, transport and disposal of water and wastewater, as well as to disposal of chemical waste during production or generated when using chemical mixtures. Developed protocols for environmental impact assessment and technical tests such as the TCLP (see **Section 6.3.7**) can be useful in evaluating the environmental safety of a process. It should be recalled that the TCLP is meant to assess stability within a sanitary landfill, and may not be an appropriate measure for assessing environmental impacts in other conditions. The magnitude of the negative environmental impact of technologies such as arsenic removal should be kept in perspective, relative to environmental contamination from other sources such as irrigation and non-drinking water uses.

6.4.2 Socioeconomic criteria

In the previous paragraphs a set of more or less absolute technical criteria have been discussed that any technology or a water supply option will have to meet. To make a technology sustainable and successful, various other non-technical criteria need to be considered as well. These may not

directly influence the capability of the technology to function but could hamper effectiveness and widespread application.

In this section six main categories of socioeconomic criteria are proposed against which technologies, hybrids or combinations of technologies should be evaluated. These categories are: economic considerations; institutional considerations; gender considerations; convenience; communication considerations; and social acceptability. Many of these parameters are discussed extensively in programme development and appraisal manuals (e.g. Narayan, 1993; DFID, 1998; European Economic Commission, 1998). Readers are invited to consult these publications for more detail on these important development issues.

Economic Considerations

Public subsidies are extensively used to meet both the capital and running cost of water and sanitation schemes. This is normally done from an economic or income redistribution perspective.

In the case of arsenic however, the consequences of limited or no sustained access to safe, arsenic-free water by the poorer section of society, and thus continued exposure, will be an increase in social and health costs. While accepting that the application of subsidy is always difficult, it is clear that tailored solutions are appropriate to ensure that all those who need, can indeed drink arsenic-free water. Safe drinking water is a basic human right and national governments and society at large should ensure that all members of society have equitable access to meet basic needs for safe drinking water.

BOX 6.9: The right to safe drinking water

Several international statements express a basic human right to safe drinking water. For example, the Convention of the Rights of the Child states in article 24.2(c) that

"States Parties shall pursue full implementation of this right (of access to quality health care services) and, in particular, shall take appropriate measures: ... to combat disease and malnutrition.... through, *inter alia*, the application of readily available technology and through the provision of adequate nutritious food and clean drinking water, taking into consideration the dangers and risks of environmental pollution..."

The Convention of the Rights of the Child was adopted and opened for signature, ratification and accession by General Assembly resolution 44/25 (November 20, 1989). It entered into force on September 2, 1990. It has been signed by all countries of the world, except for the United States and Somalia.

END BOX

Different safe water options offer different degrees of water security and convenience, and come with different price tags for capital investment and operation and maintenance. Ideally, every household should have the ability to obtain sufficient drinking water safe from arsenic and pathogens, either in the individual home or through a community level arrangement. To meet this goal, government policy, social marketing and the public/private sector continuum should ensure that a range of proven technical solutions are available and known to the consumer. To meet the needs of different socioeconomic groups in society, differently priced solutions and packages must be available in the market. The range of options on offer might include (but is not limited to): cheap and expensive arsenic removal systems; piped and bottled water; water collected from a central distribution point; water delivered to the home regularly; community level treated surface water systems; and household based rain water collection and storage.

Which of the available options will be affordable for a given group of users will depend on local socioeconomic conditions and on government policies with respect to initial subsidies to offset

the cost of investment to the consumer. However, to allow communities and individual water users to make their own informed choice a wide range of options should be available.

Institutional Considerations

The successful introduction and application of any water supply system will require change and adaptation to the new situation. Various actors, legal provisions, incentives and disincentives determine the way in which this change is going to be managed. Clearly, the institutional set-up and responsibilities of the various seen and unseen stakeholders is critical to the implementation and management of the process of introduction and application. Awareness raising, technology identification and verification, application and monitoring of arsenic mitigation will require coordination and understanding by various public and private representatives.

Lack of appreciation of the institutional conditions and pre-requirements at various levels, can easily scuttle the whole project. Ways to engender institutional change are nowadays at the forefront of many development processes and many useful books have been written about it. The following paragraphs are therefore limited to some aspects of institutional development as one may find in a less-developed country.

Establishment of the water supply solution in a community or household will require institutional mechanisms and safeguards relating to:

- Production and delivery through private sector and NGOs (including local dealers, contractors and artisans)
- Product quality control and monitoring by independent third party (government agency, NGO) or the principal /consumer
- financing options through banks and credit/grant providers
- development/upgrading of local technical know-how for operation and maintenance, including repair, and for the availability of spares; preferably among small-scale local private sector and NGOs
- training and capacity building to ensure proper handling and operation of the technology or the water supply option in the community or household
- the potential for promoting the options locally, for acquisition of or participation in (participatory or commercial development of) the option , as well as for its sustained use
- (for hybrid systems) ease of management of different sources/systems (including control over sources/operations)
- surveillance of water quality and consumer behavior by independent third party (government or NGO) to avoid health risks and promote continued improvement and cost efficiency
- incremental upgrading of the water supply service, e.g. by increased storage in case of rainwater harvesting, by moving from a deep tube well to a DTW with motorized pump and overhead tank and (yield permitting) a small reticulation system.

The relative importance of the considerations listed above will differ greatly between technologies and options. The importance will also be viewed differently by different actors depending on their role and on the risk they are taking in establishing or marketing the option. In this respect it may be worthwhile to put forward that venture capital (sometimes in the form of development (aid) grants) and subsidy can play an important role in creating a marketable situation. At the same time these economic interventions can obscure sustainable marketability and application of a technology in the absence of favorable financial conditions.

Box 6.10: Hypothetical example of effects of initial subsidization

As an example, let us say that a safe water treatment system is introduced into a hypothetical, arsenic-affected area, with a supportive financing environment. Fifty systems are installed as part of an agreement with an initial donor. The systems work and are evaluated positively, but the manufacturer is not prepared to continue sales in the absence of conducive financial conditions as these have been cut from the second phase of the project. Due to the limited number of systems established no O&M system or effective dealership is set up. Within a year or two the systems start breaking down, and what looked promising after two years is a failure after four due to inadequate consideration of the overall establishment cycle. END BOX

Stakeholders at every level will have to critically appraise the importance of institutional elements on sustainability, O&M and recurrent costs before deciding to embark on the adoption of the water supply option.

Gender considerations

Water is most often the concern of women and girls, though at times sons and husbands join the chore of collecting water. Surely the concern for safe drinking water is to be shared by women and men. Reality dictates that designers have to assume that the main burden will still be on the womenfolk, even though through awareness raising and proper design a more balanced division of labor is encouraged. The technologies or solutions that are put forward should preferably offer an opportunity for more sharing in water collection and treatment among the members of the household. They should certainly not add to the burden already carried by the women. It means that ergonomically, culturally and time wise the technology should at least be gender-neutral if not favoring part of the burden to be taken up by men.

Water security, i.e. the sustained availability of sufficient water for human consumption and for other domestic chores, will remain the concern of the women in the household. In the process of information gathering and consultation the suggestions and concerns of women should be reflected in the options shortlisted by and available to the community and individual households. The cost and effort of using the water supply option eventually selected should be acceptable and sustainable for women and men, the young and the elderly. For further reading on this subject, the reader is referred to (van Wijk-Sijbesma, 1985; van Wijk-Sijbesma, 1988; van Wijk-Sijbesma, 1998).

Convenience

Even if a technology meets all of the above technical criteria and is cost-effective, the time and effort required to collect water from the system must be reasonable. The convenience criterion should take into account the effort required to go to the safe communal source and wait in a queue for one's turn to collect water, or the time needed to collect contaminated water, bring it to the household, and treat it with arsenic removal methods. If consumers find waiting time at communal sources inordinately long, or treatment technologies too slow, they may choose to return to the old, unsafe sources. Poor understanding by users of the risk of exposure to arsenic or the effect of slackening of discipline, may lead to continued or regular use of contaminated sources by some or all water collectors in the household. Relaxation of safe water discipline can not be underestimated and should be countered by peer-support groups at community level, primary health care staff and public information campaigns.

Similarly, planners should appreciate the various social aspects of access to a water source. Physical access may be granted, at times or always, initially and not anymore after neighbors fell out with each other over an unrelated matter. Even if access is unrestricted, the social pressure on its use that may be building up over time may create (perceived) dependencies that will lead users

to look for more convenient alternatives, which may be less safe. A sensitivity to these issues will help planners adjust choices available to users.

Communication considerations

Any option needs to be explained and promoted to the user. The strongest advocacy is usually achieved by inviting current and satisfied users of the same background as the target group to share information. Options that are already common in the country can thus easily be promoted through person-to community contacts or through different communication media

New options need more time to get accepted as communities and households want to have reasonable proof that this new option is good for them in their circumstances. Whatever is the case, all options need to be clearly understood by the users and they need to be able to ascertain in detail what benefits and limitations the options bring them. Incomplete understanding of new water supply options with respect to arsenic avoidance or removal may prevent users from reducing their arsenic intake, thus leaving the population at risk. Likewise, users must be aware of the continued need for good hygiene practices and personal cleanliness in order to prevent the transmission of disease. It is critical that government or NGO workers monitor the behavior of water users following communication interventions, in order to ensure full understanding and compliance.

This concern can not be underestimated in the introduction of any behavioral change intervention and needs careful appraisal before approving or promoting wide-scale application of the technology or option. Effective methods for communication for behavioral change are covered in detail in **Chapter 7**.

Social acceptability

Finally, any solution must be socially acceptable to community members in order for it to be successful as a long-term safe water supply option. This issue has already been addressed implicitly in previous sections: any technology fulfilling all of the previously mentioned criteria will almost inevitably be socially acceptable. However, a few points are worth making.

Any option should preferably blend into the existing water supply background. It should be suitable and sustainable in terms of the local topography, hydrology, socio-cultural conditions, settlement pattern and population density, etc. It should also be effective in local condition, and the options put forward for community or household selection should certainly have a substantially higher effectiveness than other options that were evaluated.

The technologies that will be most readily adopted by communities are those that are familiar to them, or are at least new applications based on familiar materials and supplies.

6.4.3 Feasibility

Several critical aspects of the introduction of a technology or an application have been discussed in the preceding sections. Depending on socio-economic status and infrastructure development in a location it may or may not be feasible to introduce a particular technology at a given time. Poverty or other priorities in the face of serious challenges to the household or the community may not allow some solutions to be proposed confidently. Non-availability of electricity, frequent and lengthy black-outs, or other power related problems may prevent proper use of equipment, while difficulties in obtaining or importing spare parts and treatment media may cause health risks due to breakdown, use beyond indicated life time, or even bypassing of the treatment system.

The planner and/or manufacturer will have to consider all critical location-specific aspects and decide how feasible it is to propose a particular treatment option in light of the feasibility of the technology performing as intended.

6.4.4 Environmental Technology Verification

In recent years the process of environmental technology verification (ETV) has been developed to ascertain whether corrective processes introduced to reduce or avoid problems that threaten human health or the environment, actually perform as claimed. In the case of water supply technology, ETV can be applied to specific commercial-ready products based on the principles reviewed in **Section 6.3**. Both the USEPA and the Ontario Centre for Environmental Technology Advancement (OCETA) have developed ETV protocols for evaluation of commercially available arsenic removal systems. The difference between the protocol described in this section and an ETV protocol is that the former applies to technical processes in general, and the latter involves specific market-ready products applying these processes. ETV programs generally require collection of performance data under a range of operating conditions, and sophisticated quality assurance and control measures.

Clearly, the principles underlying ETV need to be applied to all water supply options proposed to avoid or reduce arsenic, and should in fact be applied in a broader sense to all water supply options.

BOX 6.11: Verifying arsenic mitigation technologies in Bangladesh

In the period since the detection of arsenic in Bangladesh, it has become quite clear that technologies may work abroad, but give very erratic results in Bangladesh, or may work in one part of Bangladesh but not another. The varied chemical matrix of groundwaters in Bangladesh has shown that local testing of arsenic removal technologies is essential to ensure adequate performance.

The Government of Bangladesh has decided to allow introduction of an arsenic mitigation technology when three steps have been satisfactorily completed:

- the proponent or manufacturer should make available for scrutiny certified test results from the country of origin of the technology;
- the technology should be re-tested and its technological performance verified by a competent scientific institute in Bangladesh. Evaluation will be limited to technical issues (e.g. removal of arsenic, effects of water quality, power requirements, etc....);
- Field testing should be conducted through the dissemination of 10-20 plants or 100-200 domestic solutions in 3-4 locations in Bangladesh, and performance should be tested and monitored for 1-6 months. Evaluation includes both technical and non-technical issues (e.g. socio-economic, cultural considerations).

In order to apply these principles, and to regulate the introduction of arsenic removal and reduction technologies, the Government of Bangladesh recently started a process of Environmental Technology Verification for Arsenic Mitigation (ETV-AM). The Canadian International Development Agency and the UK Department for International Development are assisting the Government through OCETA and WS Atkins/WaterAid respectively in a fast track preliminary verification of nine traditional and commercially developed technologies, based on coagulation and filtration, activated alumina, and ion exchange resins.

The fast track approach involves a first phase, in which the dozens of potential candidates for evaluation are screened using a protocol similar to that developed in these pages. The most promising technologies move on to a second phase, and undergo a rigorous evaluation similar to

the ETV programmes being used in Canada and the US. Technologies that pass this evaluation will be awarded a Verification Certificate by the government. CIDA is also financing a longer term (three year) programme that will allow for the development of a full indigenous ETV testing programme including the testing of further technologies as they become available. Results are expected throughout 2001. END BOX

6.5 Case study: application of evaluation protocol in Bangladesh

The protocol developed in the previous section makes use of a number of technical and non-technical parameters for use in evaluation of various safe water supply options in a given socioeconomic and cultural setting. As an example, this section will document the application of this protocol to a number of water supply options that are available in the seriously arsenic-affected areas of Bangladesh.

Six safe water technologies that hold promise for application in Bangladesh are described in comparative detail, and evaluated as far as possible in terms of the parameters described in the previous section. Each technology is rated for each parameter with a score ranging from 1 to 5, with the higher marks indicating greater acceptability. Scoring is necessarily somewhat subjective, but does allow the various strengths and weaknesses of a particular technology to be clearly seen and weighed.

6.5.1 Water supply and treatment options for consideration

As described in **Chapter 1**, the shallow aquifer in parts of Bangladesh is heavily contaminated with arsenic. Arsenic contaminated tubewells are found in almost all parts of the country, but are strongly concentrated in the south-west and south-east regions and the north-west Sylhet basin. While there is high spatial variability, in the south-east in particular there are extensive areas where more than 90% of the wells are contaminated (DPHE/BGS/MML, 1999).

In some arsenic affected areas, only a small number of wells are contaminated, and users of these wells can relatively easily find safe water by sharing water from a well that has been tested and found safe, or installing another well at a different depth. In areas of more intense contamination, however, alternative water supplies are required; either in the form of an arsenic-free, bacteriologically safe water source, or of an arsenic removal system. In most communities at least some tubewell water will be arsenic-free, and community members can be encouraged to share this valuable resource (See **Chapter 7**).

The traditional sources of drinking water in Bangladesh have been surface water and shallow dug wells. Because of the heavy fecal contamination of both of these sources, groundwater was heavily promoted, and readily accepted by the private sector. It is estimated that some 70-80% of the country's 4-6 million shallow tubewells are privately owned. In certain areas of the country, the shallow aquifer is either saline or unproductive, and alternate sources of drinking water have been promoted, such as deep tubewells, protected shallow dug wells, slow sand filtration, and rainwater collection. This section will apply the evaluation protocol presented in **Section 6.4** to these four technologies, as well as to two novel alternatives being tested in Bangladesh: SODIS and arsenic removal through coagulation and filtration. These should not be considered as the only options available for safe water supply in Bangladesh, but they represent the most promising technologies at the time of preparation of this document, for which at least preliminary results are available.

Disinfection of surface water is not commonly practiced in Bangladesh, except in larger townships. Use of decentralized small-scale hypochlorite production units has been considered but not implemented. Reverse osmosis and ion-exchange or adsorption media also hold promise for arsenic removal, but very little field experience exists at this time.

Deep tubewells

Below a depth of 150-200 m groundwater in Bangladesh is generally arsenic-free. The drilling technology used for deep tubewell (DTW) installation in Bangladesh is unique, and reflects the special geological setting. In much of the country, the first several hundred meters of subsurface consists of loose, unconsolidated sands, silts, and clays, with occasional gravel but rare rocky layers. Accordingly, drilling can be done without the use of a rig, using instead a rotary jetting method with a pump operated by a donkey, or a team of men. This method is efficient, cost effective and suited to local geology. Depths of 300-400 m are routinely drilled, rapidly and at low cost. At the ground level a concrete apron around the borehole with a drainage outlet prevents surface water from seeping down the sides of the well and contaminating the water supply.

In arsenic-affected areas, it is critical to ensure that the drilling process itself does not introduce arsenic into the deep aquifer by providing a hydraulic connection with contaminated shallow sediments. Deep tubewells should therefore have a seal between the upper and lower aquifers. This can be done by injecting clay or grouting into the annular space between the borehole and aquifer sediments. However, this is reportedly difficult to accomplish with the donkey drilling method. Drillers and water supply engineers in Bangladesh claim that after completion of a deep borehole, the annular space around the borehole collapses onto the rising main, forming a natural seal. More data is required to determine to what extent this takes place and hence the efficacy of such a naturally formed seal as opposed to grouting. One indication that cross-contamination is not occurring is the continued ability of deep tubewells in the coastal zone to produce fresh water, even after decades of pumping in areas where the shallow aquifer is saline. The use of deep groundwater has been the subject of debate for some time in Bangladesh. An international workshop held in August 2000 by DPHE concluded that water abstracted below the deep confining unit (at 150-250 m) would remain safe from arsenic. No quantitative or qualitative problems were anticipated in exploiting this resource for drinking water purposes.

Since the piezometric surface of the deep aquifer is generally close to the ground, water can usually be abstracted with simple handpumps. The most common DTW configuration in Bangladesh is a 4-inch diameter well, mounted with a suction-mode handpump (No. 6). In areas where the piezometric surface is naturally lower, or where seasonal abstraction for irrigation lowers the piezometric surface below the range of a suction pump, force-mode pumps such as the Tara are sometimes used.

In areas of particularly high population density, such as peri-urban communities and urban areas not reached by municipal water systems, it may be more effective to install one deep tubewell and deliver water to several standposts through a small reticulation system. In this case a motorized pump is required, and the well should be larger in diameter (6 to 8 inches), with a 4-inch diameter screen and a submersible pump. The well can feed water into an overhead storage tank, which provides the pressure to distribute the water to households or public standposts through a small pipe network. Public standposts don't require users to pump, and can be designed with multiple taps and good flow rates. Thus, more people can be served at a time than would be possible at a handpump. An additional advantage is that if any water treatment is required (e.g. to remove iron), it can be done at one central location.

It is further assumed here that the water taken is used for drinking and cooking. An appropriate management system needs to be put in place to ensure that the costs of water production are covered by sales and other income. A lease contract and a system of (subsidized) tokens for water collection at the standpost can be considered. If sufficient water can be produced at a reasonable cost, a distribution network can offer different levels of service: those willing to pay higher prices can have household connections, while those with less money can make use of communal

standposts. Disadvantages of reticulated systems include higher capital costs, and the need for more attention to sustainable operation and maintenance.

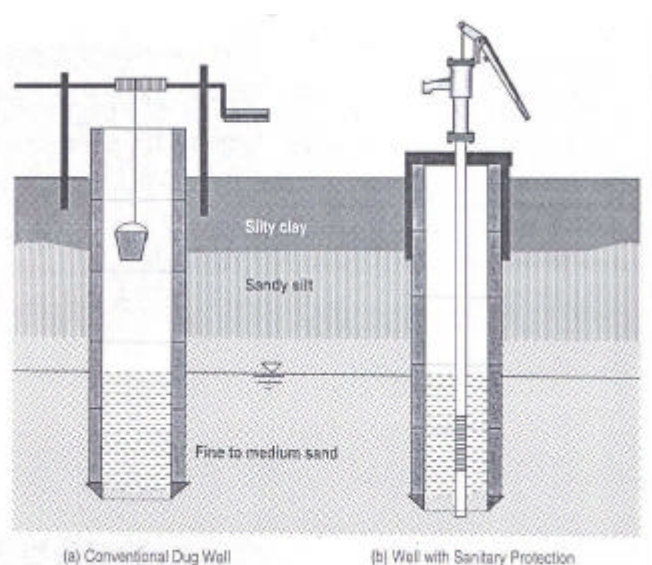
Protected shallow dug wells

Hand dug wells are an old technology, which has been largely replaced in Bangladesh by handpump-mounted shallow tubewells. Shallow tubewells can be cheaply and rapidly constructed using manual drilling methods, and most importantly, are less susceptible to surface water bacteriological contamination. Nonetheless, in some areas of the country where the shallow aquifer is rocky or unproductive, hand dug wells, or ringwells, continue to be an important source of drinking water. The dug wells in use in Bangladesh generally provide water with arsenic concentrations within the Bangladesh limit.

Dug wells are typically less than 10 meters deep, and from 1 to 3 meters in diameter. During construction, dug wells are lined with concrete rings, bricks, or porous masonry, to prevent the collapse of the walls. Most commonly in Bangladesh, concrete rings are used, and the dugwells known as ringwells.

Traditional ringwells are open at the surface, and water is drawn by hand with buckets. This system is inexpensive but very prone to bacterial contamination. This risk can be minimized by extending the well lining at least 0.5 m above the ground, forming a 'head wall'. A concrete apron can be constructed on the ground surface around the head wall. Ideally, the top of the head wall will also be sealed with a watertight lid, and mounted with a handpump for raising water.

Figure 6.15: Dug wells



Slow sand filtration – the Pond Sand Filter

Ponds of various sizes (most commonly one to two hundred square meters) are ubiquitous in Bangladesh. These ponds formerly served as the major source of drinking water, but since the advent of shallow tubewells both rural and urban families have switched drinking water sources. Over the past three decades a massive drilling program, initially supported by foreign aid agencies, but then taken up by private enterprise, has resulted in the installation of 4-8 million shallow tubewells fitted with inexpensive handpumps.

Today, pond water remains the most frequent source of water for cooking and bathing in rural areas. In coastal areas of the country, where the shallow aquifer is saline, slow sand filtration of pond water has been promoted as a safe drinking water source. The Bangladesh Department of Public Health Engineering has standardized a design for a 'Pond Sand Filter', which can serve approximately 100-300 users.

Following widespread concern about arsenic in groundwater, there have been numerous calls for a return to surface water as a drinking source, and there is strong political will to promote pond water, treated through Pond Sand Filters, as an alternate source of safe drinking water.

Rainwater Collection

Bangladesh receives an immense amount of rainfall every year, but very few Bangladeshis collect rainwater as a primary source of drinking water, perhaps because of the ubiquitous surface and groundwater resources. Many families informally practice rainwater collection from rooftops, using a variety of different size containers. In the 1970s rooftop rainwater collection became a formally recognized rural water supply technique, and designs for large ferrocement storage jars, based on Thai designs, were standardized. These jars range from 1 to 3.2 cubic meters, and serve individual households or small clusters of homes. The jars have a sealed lid, and a tap near the base for water collection, to minimize the possibility of bacterial contamination.

Recently, as part of a joint DPHE/UNICEF/BRAC arsenic project, smaller storage tanks have been built using the widely available concrete rings used for pit latrines. Five hundred-liter tanks can be constructed easily at significantly lower cost, and can store enough water to provide a good level of service during the rainy season and drinking water for a few weeks into the dry period.

Corrugated iron roofs are present in about 50% of households in Bangladesh, and are clearly the most suitable collection surface, although tiled and asbestos-sheet roofs can also be used. Roof run-off is fed through gutters into aboveground ferrocement storage containers. Some private users have used other materials such as brick, and have constructed tanks of various sizes both above and below ground.

Solar Disinfection

The solar disinfection system promoted as SODIS, described in **Section 6.2**, has recently been introduced into Bangladesh as a large field-scale project. This technology is unfamiliar to Bangladeshis, and one of the biggest difficulties has been convincing water users, community leaders, and local government officials of the safety of treated water. Nonetheless, initial results are encouraging, and show both that conditions in Bangladesh are favorable for SODIS, and that with proper education and motivation, water users can become enthusiastic converts. SODIS can be used effectively in conjunction with rainwater harvesting. When stored rainwater runs out, the household can secure safe drinking water from nearby ponds by applying SODIS for the remainder of the dry season.

Arsenic Removal

Arsenic elimination techniques are described in detail in **Section 6.3**, and in recent years many systems have been tried out in Bangladesh, mostly as small pilot studies. The most commonly used technology has been coagulation and filtration, most likely because these processes are relatively well documented, have been applied successfully in other arsenic-affected areas, and the materials required are available locally. This section will consider a generic system in which

an oxidant (chlorine or permanganate) is added to contaminated water, followed by a coagulant, either ferric chloride or alum.

6.5.2 Technical Criteria

Water Quality

Drinking water sources must be free from unsafe levels of arsenic, but also from undue microbiological contamination, and other chemical contaminants. Since the arsenic problem in Bangladesh has been largely restricted to shallow tubewells, it has been suggested to abandon the contaminated wells – and even seal them – and return to surface water. Cholera and typhoid once devastated millions in Bangladesh because of lack of safe water. In the last two decades diarrhoeal diseases have been brought under control through bacteriologically safe drinking water, better hygiene and household based case management through oral rehydration therapy. Diarrhea-linked illness and death have been reduced to a large extent. Now, as it turns out that groundwater is contaminated another change of direction is necessary, but one that should build on earlier achievements in water, health and hygiene, rather than forcing households back in time. It is critical that any alternate source of drinking water should be free from microbiological contamination, as well as arsenic.

Deep tubewells probably offer the highest water quality of the various options under consideration. Deep groundwater is not only low in arsenic, but also free from the high levels of iron and manganese that make much of the shallow groundwater unpalatable. A properly constructed deep tube well provides excellent protection against anthropogenic microbiological contamination.

In contrast, the shallow aquifer is highly contaminated with arsenic in some areas. Nonetheless, researchers from Jadavpur University (West Bengal) have tested over 100 dug wells in arsenic-affected areas of West Bengal and Bangladesh, and in all cases arsenic levels were below 50 µg/L. This is thought to be due to the fact that during storage in the dug well, water is exposed to oxygen, and dissolved iron in the groundwater is able to precipitate as ferric hydroxide, removing any arsenic from solution in the process (Chakraborti, 1999). Dug well water may also contain a higher proportion of recent rainwater than other groundwater sources. Dug wells are, however, very susceptible to microbiological contamination, unless they are protected with head walls and rope or hand pumps for raising water.

Ponds in Bangladesh generally contain safe levels of arsenic, though arsenic levels of over 150 µg/L have been found in some areas (Islam et al., 2000). Therefore, pond water should be tested for arsenic before installation of pond sand filters. Many large ponds in rural areas are privately owned, and used for raising of fish. Owners dose the ponds with pesticides to kill predator fish before they introduce fingerlings. Large amounts of fertilizers are applied as well. The use of these ponds for fish-rearing has made it difficult to find suitable ponds for construction of community pond sand filter systems. Agricultural runoff can also contaminate ponds, though most ponds are surrounded by berms that normally keep out the bulk of external surface water.

Ponds are also used for washing of clothing, dishes and livestock, and for bathing. In too many cases, hanging latrines drain directly into ponds. Recent studies by the NGO BRAC indicate that the initial high bacterial pollution load is difficult, but not impossible, to eliminate. Once a Pond Sand Filter has been constructed by the side of a pond, there is some evidence that communities may become more disciplined in protecting the pond from various types of contamination.

Collected rainwater in Bangladesh has been examined and found to have low to negligible levels of coliform bacteria, and no detectable arsenic. Further research on other parameters, especially

pH, zinc, and lead, has yet to be conducted. Storage tanks should be designed with screens to prevent the entry of small animals and the breeding of mosquitoes.

Field studies have demonstrated that SODIS can effectively eliminate microbiological contamination from surface waters in Bangladesh. However, any chemical contaminants in the source (typically pond water) will not be removed by solar disinfection. Water users often like the taste of the water, and if bottles are stored on a rooftop through an afternoon and overnight, cool, safe water is available the following morning.

Arsenic removal systems applied in Bangladesh have been able to reduce even highly contaminated levels of arsenic down to 10-30 µg/L, well below the national standard. Iron and manganese are also effectively removed. Potential water quality problems include lowered pH, residual aluminum if alum is used as the coagulant, and microbiological quality of stored water. Limited data suggest that none of these water quality parameters pose a problem in waters treated in well-designed systems. In fact, drinking water collected from traditional sources, including tubewells, often becomes highly contaminated with fecal pathogens during household storage, and a well-designed household arsenic removal system significantly reduces this risk.

Water Supply Option	Score	Water Quality
Deep tubewell	5	Excellent inorganic and biological water quality.
Dug well	3	Arsenic-free, but relatively high risk of chemical or biological contamination from surface water.
Pond sand filter	3	Can provide excellent pathogen removal, but users will not be aware if system fails and pathogens break through. Potential for contamination from agricultural chemicals.
Rainwater collection	4	Excellent inorganic quality, low levels of coliform contamination. More information needed on pH and trace metals.
SODIS	4	Excellent microbiological quality, some risk of contamination from agricultural chemicals.
Arsenic removal	5	Adequate, though incomplete arsenic removal. Appropriate design can minimize pathogen contamination during household storage.

Water Quantity

Since one person needs from seven to ten liters of water per day, a family of six will need about 1200-1800 liters of water monthly for drinking and cooking purposes. Safe water technologies should be able to meet this need throughout the year, either on their own or in combination with other safe sources.

The piezometric surface of the deep aquifer in Bangladesh undergoes some seasonal fluctuation, but on a much smaller scale than the shallow aquifer, and in most areas suction-mode handpumps are able to abstract water throughout the year. Recharge mechanisms and rates are not well understood, and a sudden change to large-scale abstraction might stress deep aquifer resources. While the amount of water needed for drinking water alone would not likely have much of an impact, water abstracted for large-scale irrigation might. Handpump-mounted DTWs can serve from fifty to over three hundred users, whereas a reticulated system with a half-kilometer radius

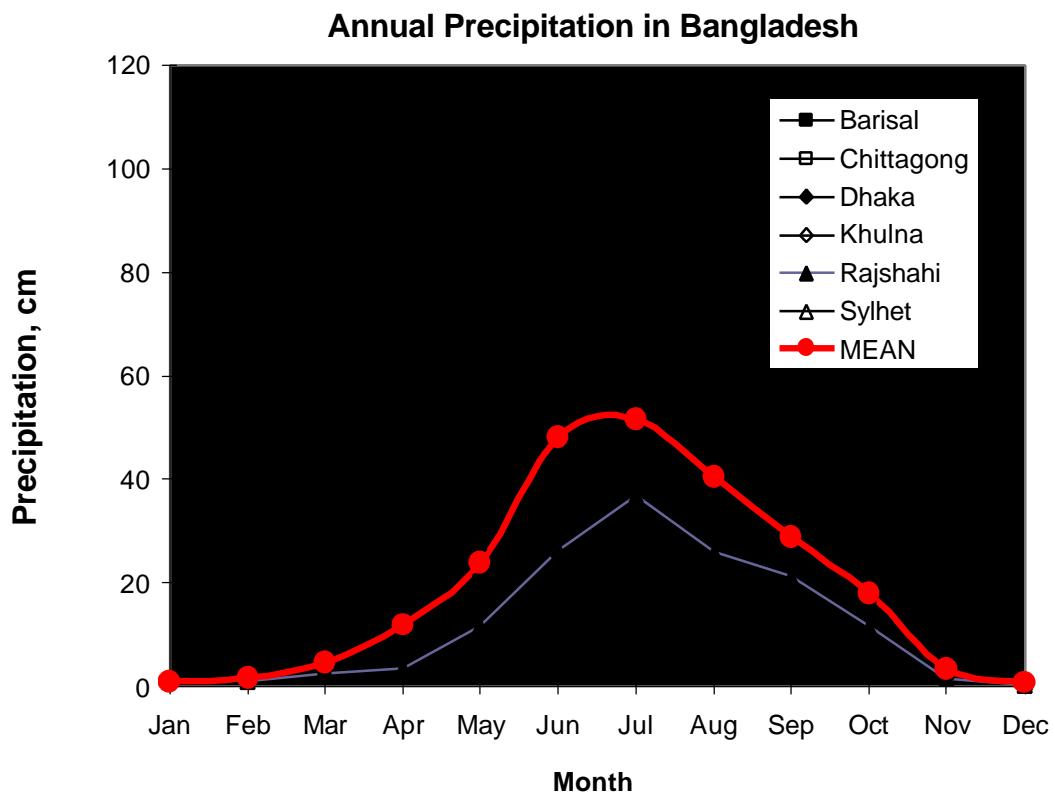
and five standposts could serve a population of two to three thousand in built-up areas such as peri-urban fringes, small towns and sub-district headquarters.

Dug wells and Pond Sand Filters both rely on near-surface water resources, which are prone to running dry during the dry season, especially in the west of the country. For both systems, local climatic conditions, along with the size and depth of the pond or well, will determine the effective season for water supply. In coastal areas and in the northeast, these systems are often able to provide water through most of the year. If ponds are adequately full, one Pond Sand Filter can produce water for two to three hundred users, whereas a dug well is adequate for about fifty users.

SODIS and arsenic removal can produce drinking water in whatever quantity is required, as long as the water source (surface water or contaminated shallow groundwater) remains available. SODIS users generally only treat water needed for drinking purposes, since cooking destroys pathogens effectively.

Rainfall in Bangladesh is highly seasonal, with over 80 percent of rain falling between May and September. The quantity of rainfall varies significantly throughout the country, with the rainiest area (Sylhet) receiving nearly three times as much precipitation as the driest area (Rajshahi). However, the seasonal nature of precipitation is fairly consistent, with a dry season ranging from December through March.

Figure 6.16: Annual precipitation in Bangladesh (Rashid, 1991)



A small dwelling with a corrugated iron roof measuring five by eight meters will be able to collect approximately 32 liters per millimeter of precipitation, assuming an 80% collection

efficiency to account for evaporation, lost water, and the first flush. On average, then, such a rooftop collection system in Bangladesh could collect nearly 75 cubic meters of water annually, enough to meet the needs of over 35 people. However, because of the extreme seasonality of precipitation, water availability is not constant. With the above five by eight meter rooftop, and a very small (200-500 L) storage tank, rainwater collection could meet the drinking water needs of six family members for about nine months. If larger storage tanks, or larger catchment areas were used, rainfall could meet needs for longer periods. With the above catchment, a tank of about two cubic meters could provide enough storage to get completely through the dry season. In Rajshahi, however, at least three cubic meters of storage would be required, because of the later onset of the rainy season.

Water Supply Option	Score	Water Quantity
Deep tubewell	5	Should be able to provide sufficient water. Handpump-mounted systems can serve up to 300, reticulated systems from 2000-3000.
Dug well	3	Vulnerable to drying up during dry season, slow to refill. 50 users served.
Pond sand filter	3-4	Depending on size and local climate, may dry up or become unusable during dry season. 200-300 users served.
Rainwater collection	4	With storage, the dry season can be partly or completely bridged.
SODIS	3-4	Depends on access to source waters during dry season.
Arsenic removal	3-4	Depends on access to source waters during dry season.

Reliability and robustness

Handpump-mounted deep tubewells are fairly reliable, but do break down on occasion. Sometimes newly installed wells become clogged with fine sediments and must be purged or abandoned. Deep tubewells with motorized pumps attached to storage tanks and reticulation networks must be installed professionally, and require more frequent maintenance. Due to the large number of people such systems serve, system breakdowns can have quite serious impacts in the absence of spares and a capable maintenance crew.

One drawback of Pond Sand Filters is that pathogens can break through without any visible change in water quality, so users do not know when the filter has failed. Chlorination after filtration as a safety measure could guard against this danger, but ensuring a correct and continuous dose can be difficult and the PSF designs used in Bangladesh have omitted this step.

Dug wells and rainwater collection are unlikely to break down and regular maintenance and repair generally lies within the ability of the users. Arsenic removal efficiency, however, relies heavily on user inputs, and if chemicals are added wrongly or the system is operated incorrectly, arsenic might break through into the treated water. The reliability of SODIS in Bangladesh is under evaluation, but in other countries has proved robust even during periods of cloudy weather and relatively low temperatures.

Water Supply Option	Score	Robustness
Deep tubewell	4	Possible breakdown, clogging, risk of failure in reticulated system.
Dug well	5	Low maintenance
Pond sand filter	3	Frequent maintenance, possibility of failure without warning
Rainwater collection	4	Minor maintenance and repairs required periodically.
SODIS	?	Testing in Bangladesh underway.
Arsenic removal	3	Significant opportunity for user error to prevent effective removal.

Operational Safety

Among the technologies considered, only arsenic removal involves the addition of chemicals. Both of the oxidants commonly used in Bangladesh, permanganate and bleaching powder, are corrosive, caustic skin irritants that are toxic if ingested directly. Special care is required during application and storage of these chemicals to prevent exposure to household members, particularly children.

Water Supply Option	Score	Operational safety
Deep tubewell	5	No operational risks to users.
Dug well	5	No operational risks to users.
Pond sand filter	5	No operational risks to users.
Rainwater collection	5	No operational risks to users, except for falling off roof during cleaning.
SODIS	5	No operational risks to users.
Arsenic removal	4	Possible exposure of users to hazardous chemicals.

Environment

Deep tubewell abstraction for drinking water alone likely would have no significant impact on the environment. The amount of water needed for drinking and cooking purposes is relatively small, and should not put undue pressure on deep groundwater resources, except possibly in large municipal settings.

Dug wells and rainwater collection have no significant environmental impacts. When Pond Sand Filters are installed, communities typically take steps to improve the environmental conditions around the pond, producing improved environmental conditions. Likewise, SODIS actually has a slight positive impact, in that it converts ubiquitous plastic bottles from annoying rubbish into useful tools.

Arsenic removal can have a slight negative impact on the environment, especially when applied at the household level, because arsenic-rich sludge will need to be disposed of safely. However, this impact is minor since arsenic adsorbed onto sludge is fairly stable (see **Section 6.3.6**). Furthermore, only that water required for drinking and cooking need be treated, so the amount of arsenic sequestered into the sludge will be small compared to the amount in water pumped for non-drinking purposes, especially irrigation.

Water Supply Option	Score	Environment
Deep tubewell	4	No impact, unless irrigation led to unsustainable withdrawal
Dug well	4	No impact
Pond sand filter	5	Slight positive impact through pond protection
Rainwater collection	4	No impact
SODIS	5	Slight positive impact through conversion of plastic bottles to valued commodity
Arsenic removal	3	Slight negative impact from arsenic-rich wastes.

6.5.3 Socioeconomic criteria

Economic considerations

The economic costs will often determine which technically viable technologies can be implemented. These costs include not only the start-up costs, but also the costs of operation and periodic maintenance and repair.

In Bangladesh it is generally accepted that users contribute to the investment and operational cost of water supply. Presently 97% of the population has access to pathogen-safe drinking water, and it is estimated that at least 75% of water supply points have been constructed by the private sector, without direct government support. This achievement bears out the willingness and ability of the population to invest in water supply, and shows the capacity of the private sector and the social banks to support development.

Bangladesh is a poor country and many households are economically overstretched. The Government of Bangladesh and many NGOs assist the poor in obtaining access to good water, mainly through water points equipped with a handpump. Government subsidization rates vary according to the technology, with users contributing about 10% of the capital costs of shallow tubewells, dug wells, and pond sand filters. The more expensive deep tubewells are slightly more heavily subsidized, with cost recovery rates of 6-9%. All cost recovery rates are somewhat dependent on local economic conditions. Users are trained to operate and maintain these sources, and are responsible for recurring economic costs such as replacement of parts. Government tubewell mechanics are available for more serious repairs.

Typically, a deep tubewell (250 m) fitted with a handpump will cost from \$800 to \$1000⁶, but in rocky areas costs could be much higher. When a submersible pump, diesel generator, storage tank and reticulation network are added, capital costs rise considerably, but the population served also increases significantly. The major factor determining costs is the walking distance from household to supply point, which in turn dictates the length of the reticulation network. With a network of five standposts and a radius of 500 meters, a reticulated deep tubewell system could cost approximately \$12,000. Operation and maintenance costs would also be significantly higher.

The cost of a protected dug well, lined to a depth of ten meters with concrete rings and including a properly constructed apron and all fittings for a handpump, is approximately US\$160.

⁶ All price calculations in this section are based on the simplifying assumptions of an average household size of six and an exchange rate of USD\$1 = Taka50. The actual exchange rate as of January 2001 was 53.81, and in recent years has been slowly increasing.

Operating and maintenance costs are low, and consist of periodic cleanings and minor repairs to the handpump.

Pond sand filters are slightly less expensive than handpump-fitted deep tubewells, with startup costs of approximately \$800. Maintenance costs are relatively high, since the filter must be cleaned monthly, and new sand periodically added to replace lost volume.

The costs of rainwater collection depend largely on the storage tank size. Large 3.2 m³ ferrocement tanks can be built for about \$110, but smaller 500-liter tanks can be easily constructed from the ubiquitous concrete rings used for pit latrine construction for under \$25. Existing rooftops are usually used, but guttering and downpipes are required, adding approximately \$10 per unit. While the use of larger tanks permits some bridging of the dry season, increasing the catchment area can have the same effect, often at lower costs.

SODIS costs are very low, since appropriate plastic drinking water bottles are ubiquitous in Bangladesh. A small amount of money must be spent in painting one side of the bottles black, and in occasional replacement of bottles. A family of six will require at least twelve bottles, to meet drinking water needs alone, which would cost approximately \$6.

The cost of arsenic removal systems will vary somewhat, most systems in Bangladesh require two or three water containers, some type of filter, and a water tap. All of the required materials are locally available, and should cost from five to ten dollars. Chemicals must regularly be procured, but the costs are relatively low.

Water Supply Option (households served)	Score	Economic Considerations	
		Startup costs per household	Annual costs per household
Deep tubewell w/handpump (15-50)	2-3	\$20-\$65	\$1 to \$2
Reticulated deep tubewell (350-500)	3-4	\$25-\$35	\$5 to \$8
Dug well (10)	4	\$15	\$1 to \$2
Pond sand filter (40-50)	4	\$15-\$20	\$2 to \$3
Rainwater collection w/3200 L tank (2)	3	\$55	< \$1
Rainwater collection w/500 L tank (1)	4	\$25	< \$1
SODIS (1)	5	\$5	< \$1
Arsenic removal (1)	5	\$5 to \$10	\$2 to \$4

Scoring system: 5 = < \$10; 4 = \$10-\$30; 3 = \$30-\$60; 2 = \$60-\$100; 1 = > \$100

Institutional Considerations

Deep tubewells, either with or without reticulation systems, are admirably suited for private sector involvement. A vibrant economy exists in the installation of shallow tubewells, and this trained workforce could easily adapt to the installation of deep tubewells. With motorized systems, there is a danger of power loss, either if the local grid goes down, the diesel generator should become broken, or generator operators are unable (or unwilling) to procure fuel. A relatively skilled team of operators and monitors is required to ensure success.

Dug wells, pond sand filters and rainwater collection systems can also be easily installed by local masons, once they are given some training from enabling institutions such as government or

NGOs. There is opportunity for the use of community labor to reduce costs and to assume responsibility for most operation and maintenance tasks.

SODIS and arsenic removal systems are more alien to water users, and to the network of civil servants involved in public health and water supply. Considerable training will be required to ensure that these technologies are applied correctly, especially for arsenic removal. Continued monitoring of water quality will be essential, and will require sophisticated management. However, all of the operations and maintenance can eventually be done by the water users themselves. Arsenic removal systems also require an established mechanism for supply of reagents.

Water Supply Option	Score	Institutional Considerations
Deep tubewell	4	Private sector already heavily involved in tubewell installation. High startup costs mean that credit will probably be required.
Dug well	5	Private sector familiar with technology, all materials locally available
Pond sand filter	4	Private sector has skills required for this technology, but will require some training
Rainwater collection	4	Private sector has skills required for this technology, but will require some training. All materials locally available
SODIS	4	Main institutional needs are for promotion, training, and some water quality monitoring. Material needs are minimal.
Arsenic removal	3	Training required, as well as supply network and regular water quality monitoring

Gender considerations

The most direct impact of water technology on women will be the amount of time and effort required for water collection and/or treatment. The further the water source is from the house, the more physically burdensome the new technology will be. In Bangladesh, women's social mobility is more limited than that of men, and it may be socially unacceptable for women to travel outside of their neighborhood, or *bari*, to collect water. Therefore, the gender criteria ranking closely parallels that discussed under 'convenience'. It is important, however, to recognize that the inconvenience of water collection falls mainly on the shoulders of women, who already have heavy work burdens in the household. An optimal system would impose no greater additional burden on women than on men, and would favor sharing of the water workload between women and men. However, as practiced currently in Bangladesh all of the technologies under consideration rely almost exclusively on women's labor. Therefore, in the following table, none of the technologies are given high marks.

Water Supply Option	Score	Gender consideration
Deep tubewell	2-3	Handpump-mounted DTW, depending on distance and population served.
	4	DTW with reticulation network, source is close and no pumping required.
Dug well	3	Nearby, some pumping involved.
Pond sand filter	3	Medium distance, pumping required.
Rainwater collection	4	In-house access, no pumping or queues involved.
SODIS	3	Water must be collected, each bottle filled individually.
Arsenic removal	3	Water must be collected from nearby source, and is then treated within the household.

Convenience

Deep tubewells mounted with handpumps can be relatively inconvenient, as collectors (women and children) must walk to the site, which may be several hundreds of meters away. If large populations are served, long queues may form at the wellhead. Reticulated systems could greatly improve the convenience of this option, by bringing water to standposts much closer to users, or even directly into households. These systems require a motorized pump, which would further reduce the work burden of water collectors.

Deep tubewells fitted with handpumps require periodic maintenance and repair from professional mechanics and/or trained tubewell caretakers within the community. When motorized pumps are used, much more regular maintenance is required. Annually, the pump should be overhauled, the inlet screen cleaned and the valves inspected. Occasional maintenance and repair of the pump house, storage tanks, reticulation system and standposts will also be required.

Since dug wells serve a relatively small population, they are usually located fairly conveniently, close to water users. Maintenance needs are minimal. At the end of the dry season the well can be cleaned, checked, if yield is low well can be deepened and lining extended. Occasionally there may be a need to disinfect the well with chlorine.

Pond Sand Filters serve larger communities, and sometimes queues form during hours of peak use. Some community members must regularly clean the sand filter, which requires several hours of manual labor.

During the raining seasons rainwater harvesting provides a very good level of service, while in the period after the end of the rainy season water security remains high. Household rainwater collection is extremely convenient – water is readily available from on-site storage containers. This system is also more convenient than many other options in that no pumping is required, unless underground storage tanks are used. Maintenance is important, but consists mostly of keeping the catchment, gutters and tank clean.

SODIS requires more active work on the part of household water managers: water must be collected from a reasonably clean source, and poured into plastic bottles, which must be placed in a dedicated spot, typically on corrugated roofing. Water is not instantly available, so water managers must plan their water needs at least a day in advance. However, once households are accustomed to a SODIS routine, the added work burden would not be terribly onerous.

Household arsenic removal using oxidation and coagulation requires systematic, sustained input from water users. Water can be collected from nearby tubewells, but for each batch of water

treated, chemicals must be added in the correct dose, stirred for the appropriate amount of time (ten to fifteen minutes is recommended for optimal floc formation), and allowed to settle for a fixed period of time. As with SODIS, water is not immediately available for consumption, so water planning is required. Once a routine is established, however, water users have the convenience of safe water on tap, within the household. It should be noted that other arsenic removal systems require less intensive user input, but have not yet been as extensively tested in Bangladesh, and are not considered in this section.

Water Supply Option	Score	Convenience
Deep tubewell	3-4	Handpump-mounted DTW, depending on distance and population served.
	5	DTW with reticulation network, source is close and no pumping required.
Dug well	4	Nearby, some pumping involved.
Pond sand filter	3-4	Medium distance, pumping required. Regular cleaning required.
Rainwater collection	5	In house access, no pumping or queues involved. Water on tap.
SODIS	3	Water must be collected, each bottle filled individually.
Arsenic removal	2	Users must treat each batch of water, stir for several minutes, and allow floc to settle before use.

Communication

Communities in arsenic-affected areas need information about arsenic contamination in their homes, and about safe options available to them. Familiar, accepted technologies will always be easier to promote than unfamiliar systems. It is more difficult to promote options that contradict or conflict with community beliefs regarding safe water.

For the past three decades, water supply communication activities have tried to convince people that pond water is unclean and unsafe, and that groundwater represents the only appropriate drinking water source. Dug wells have been seen as something of a 'next-best' alternate in areas where tubewells are not feasible. It will be a major challenge to encourage behavioral change towards sources that were recently discouraged (e.g. ponds) or towards sources that are unfamiliar to people.

Regarding arsenic removal, users are sometimes understandably reluctant to add 'chemicals' to drinking water. Some of the reagents suitable for arsenic removal, notably potassium permanganate and alum, are locally available and accepted as safe. Alum, in particular, is already used to remove suspended solids from pond water for cooking and household uses (though not for drinking purposes).

Water Supply Option	Score	Communication
Deep tubewell	5	Familiar and popular technology.
Dug well	4	Familiar technology, seen as older and less safe than groundwater.
Pond sand filter	3	Pond water is a familiar source, though filters are novel. Users understand the concept that the filter is required for water purification.
Rainwater collection	3	Not widely practiced, public concerns remain.
SODIS	2	Completely novel, runs against previous messages that surface water must be boiled before drinking.
Arsenic removal	2	Completely novel, requires detailed training

Social acceptability

The most socially acceptable options will be those that have scored well in previous categories: that provide what is perceived as sufficient water of high quality, that are convenient and familiar. Affordability often does not enter into user's consideration of acceptability, since users expect government to provide the source for free or at very low cost.

In Bangladesh, by far the most socially acceptable source of drinking water is the tubewell. Older technologies such as pond water treatment and dug wells are seen as inferior alternates, only to be resorted to when tubewells are impossible. The new technologies being tested in Bangladesh, SODIS and various types of arsenic removal systems, have been very popular among communities, but it remains to be seen whether such enthusiasm will outlast the pilot trials.

Water Supply Option	Score	Social acceptability
Deep tubewell	5	Tubewell water is the most widely accepted form of drinking water, and is considered interchangeable with 'safe water'. Users like the prospect of having piped water.
Dug well	3	A traditional technology, but users are aware of some hazards.
Pond sand filter	3	Users are reluctant to return to surface water, pond water is visibly impure, and ponds can no longer be used for fish culture
Rainwater collection	3	Users are not convinced that water quality is high, especially for stored water.
SODIS	4	Users appreciate the low cost and ease of this system
Arsenic removal	4	Water on tap in the home, which often tastes better than local groundwater, makes this technology appealing to users.

6.5.4 Conclusions

The following table summarizes scores given to each technology in the preceding discussion:

Table 6.7: Summary of protocol scores

	Deep tubewell	Dug Well	Pond Sand Filter	Rainwater Collection	SODIS	Arsenic Removal
Technical Criteria						
Water quality	5	3	3	4	4	5
Water quantity	5	3	3-4	4	3-4	3-4
Reliability/robustness	4	5	3	4	?	3
Operational safety	5	5	5	5	5	4
Environment	4	4	5	4	5	3
Socio-cultural considerations						
Economic	2-3	3-4	4	3-4	5	5
Institutional	4	5	4	4	4	3
Gender	2-4	3	3	4	3	3
Convenience	3-5	4	3-4	5	3	2
Communication	5	4	3	3	2	2
Social acceptability	5	3	3	3	4	4

The various criteria summarized above are not all of equal importance, and an overall score should not be calculated simply by summing all of the scores. For example, shallow tubewells in intensely arsenic-affected areas would score very highly in all categories except for water quality, but obviously would not be the appropriate mitigation choice.

In an ideal hydrological and hydrogeological setting, one of the above technologies should be the method of choice. But as is to be expected, there is no single universal technology solution for a specific area. Local geography, geology, climate, soil characteristics, population density, community willingness to pay for a particular technology, and community acceptance, all play important roles in technology selection. The question of household versus community level technology is a function of community acceptance, cost and technical parameters.

It is perhaps not surprising that the most acceptable technologies in terms of many of the technical criteria are also the more expensive options. Further work is needed to make these options more affordable, the development of small, inexpensive rainwater storage tanks using pit latrine rings is a good example.

Of the more established water supply options considered in this section, rainwater harvesting and the deep tubewell emerge as superior to the dug well and the pond sand filter. The chief difference between these two options is essentially scale of application: the deep tubewell is optimally suitable for small to medium-sized communities, and is most cost-effective when large numbers of users are served, whereas rainwater harvesting is presently best suited to the individual household.

There are many aspects of the deep tubewell option that call for caution and further research: key questions exist regarding over-pumping and saline intrusion near the coastal areas; the availability and productivity of the deep aquifer outside of coastal zones; how to deal with major breakdowns in rural settings; the absolute need for meticulous operation and maintenance and relatively highly trained mechanics (for reticulated systems); and most importantly a significant community revenue contribution.

The novel technologies of SODIS and arsenic removal achieve comparable scores to deep tubewells and rainwater collection, and are economically much more feasible. These technologies should be considered as viable alternatives. Because of their novelty, both will require more extensive promotion and communication efforts. Both of these technologies might best be used as complements to other systems that are only viable seasonally, especially rainwater collection.

6.6 Application of safe drinking water supply technologies in arsenic-affected areas

Previous sections have shown that there are technically viable technologies for removal of arsenic from drinking water, at least to the 50 µg/L level. Some of the technical processes may be more difficult to operate in developing countries, or may be prohibitively expensive. However, in many cases, technical challenges may be small compared to logistical and institutional difficulties. Different institutional structures and approaches will be required for arsenic removal at municipal, community, and household levels.

6.6.1 Municipal level

Most large-scale experience with arsenic removal to date has been conducted in urban settings, where governments have been able to install arsenic removal systems. These experiences have shown that publicly operated, centralized treatment can effectively provide arsenic-free water to urban populations.

Plants generally involve large engineered production/treatment facilities, which are often custom-designed, and a large piped distribution network. This type of system requires trained professional operators, and rigorous quality assurance and quality control. The design parameters of such plants are well beyond the scope of this review, but all arsenic removal plants will make use of the physical and chemical processes discussed in **Section 6.3**. For more information on design and operation of municipal water treatment plants the reader is referred to standard texts (e.g. Twort et al., 1985; Viessman and Hammer, 1985; ASCE/AWWA, 1990; Salvato, 1992).

Not all of the water supply technologies used in industrialized nations are appropriate for conditions in developing countries. Some of the technology is too difficult to operate, maintain and repair, due to a lack of spare parts, supplier support, and trained staff. Some technologies will also be prohibitively expensive in poorer countries. It is important, therefore to choose an appropriate technology that can be understood by local operators, and can be readily maintained and repaired.

Water supply utilities are responsible for ensuring the quality of water produced and delivered. Water quality should be monitored periodically, according to national drinking water regulations. Parameters to be sampled and sampling frequency are usually determined by the regulatory agency in order to ensure compliance, though plant operators may need to monitor certain parameters more closely in order to better control plant operation and quality of produced water.

Most experience with municipal arsenic mitigation has been in relatively industrialized countries and regions such as Chile, Taiwan, and Hungary, where a mix of source substitution and arsenic removal has been practiced. In all of these places, and in the US and Europe, coagulation with

iron salts has been chosen as the most appropriate technology for arsenic removal in large centralized water supply plants. Alternate and emerging technologies for arsenic removal have not yet been applied in large-scale plants, though some of the advanced technologies will likely become necessary where drinking water standards are well below 50 µg/L.

Centralized treatment for arsenic removal offers certain economies of scale, and in areas of high population density, capital costs can be distributed over a large number of consumers, so per capita costs need not be high. One disadvantage of centralized arsenic removal systems is that all of the water produced must be treated, even though only a small fraction will eventually be consumed through drinking or cooking. It is also possible to design a centralized system with two distribution networks, one for highly treated water for consumption and one with less treated water for other uses. Distribution costs would necessarily be higher, but treatment costs would decrease, and in some instances this dual distribution networks might be appropriate.

Another disadvantage of central plants is that they generate significant amounts of arsenic-rich wastes. Proper plant operation and handling of chemical supplies and wastes is crucial in any country, but water utilities in industrialized nations typically have more experience in compliance with environmental regulations. In developing countries, special consideration should be given to monitoring of plant operations, to quality control assurance, and to ensuring that arsenic-rich wastes are disposed of appropriately, in accordance with national regulations.

There is typically little or no community involvement in design and operation of central arsenic removal plants, though beneficiaries may contribute to the costs of arsenic removal through taxes or water fees.

Box 6.12: Source substitution and arsenic removal in Hungary

In the early 1980s, arsenic was found in deep groundwater of five counties of southern Hungary, with concentrations ranging up to 220 µg/L in municipal water works. Some 400,000 people were exposed to drinking water over the national standard of 50 µg/L. The first steps taken were to close the most affected municipal production wells, and to modify mixing ratios with the remaining wells, to reduce arsenic levels by about 50%. However, most of the water supplies still remained above the national standard. For a short period bottled water was supplied for children under 14 (two liters per day), but this proved expensive and ineffective. Hydrogeological investigations were conducted to find arsenic-free aquifers, and in some parts of the country new, deeper wells were installed. In one area a safe aquifer was identified 20-30 km from the affected region, and a new regional water works was established to transport water to the affected settlements.

In some affected areas, no safe aquifer could be found, and the government commissioned several arsenic removal plants, using the standard technology of oxidation, coagulation with ferric chloride, and filtration. These plants were able to reduce arsenic levels by 80-90%, to 20-40 µg/L, bringing communities into compliance. Experiments were also made with various adsorption and ion exchange technologies, but coagulation proved more practical.

By 1998, due to the combination of source substitution and arsenic removal, only about 10,000 people were drinking water slightly over the national limit. However, as Hungary joins the European Union, it is compelled to adopt the lower EU standard of 10 µg/L for arsenic in drinking water. Since source substitution and standard coagulation have already been used, Hungary faces a serious challenge in lowering arsenic levels even further, by an additional 50-80%. Water quality engineers are examining new strategies, including modification of the coagulation process; adsorption or ion exchange; membrane technologies; and *in situ* immobilization. It seems likely that the costs of compliance with the new standard will be significantly higher than the initial costs of reducing arsenic levels to under 50 µg/L. END BOX

Box 6.13: Arsenic removal plants in Taiwan and Chile

In both Taiwan and Chile, drinking water was found to be contaminated with arsenic in the 1960s. Although the water sources were very different (groundwater in Taiwan, surface water in Chile), in both cases the majority of the exposed populations was concentrated in urban areas served by a piped water supply. Accordingly, after laboratory experiments and pilot testing, full-scale arsenic removal at a central location was chosen in both cases. Both the Taiwan and Chile plants used chlorine to oxidize arsenite (1.0 mg/L in Chile, 12 mg/L in Taiwan), then added ferric chloride (30 mg/L in Chile, 32 mg/L in Taiwan), and removed the resulting HFO through sedimentation and filtration. In Taiwan, arsenic levels were reduced from 600-800 µg/L to below 50 µg/L, while in Chile concentrations were reduced from 350-500 µg/L to 40-50 µg/L. Sources: (Shen, 1973; Sancha and Ruiz, 1984; Sancha et al., 1998; Sancha, 1999). END BOX

6.6.2 Community level

In most small towns and rural communities, water supply conditions are very different from in urban settings. The population served is smaller, often infrastructure such as reticulation systems are missing, and there is a shortage of trained personnel to operate plants. Rural populations tend to be poorer than urban ones, and less accustomed to considering water as an economic good.

Small piped water supply systems tend to have relatively high startup costs, particularly regarding the establishment of a reticulation network. Piped systems also require trained operators, who have the technical skills not only to keep the system in operation, but to make repairs in the case of system failure. For these reasons, piped water supply systems are the norm in urban water supply, but are less common in rural, developing contexts. In certain socioeconomic and geographical contexts, however, small reticulated systems can be an economically feasible option. An excellent manual for technical planning and implementation of community piped water supply systems is given by (Okun and Ernst, 1987). In some piped water systems, rather than establishing connections at individual households, communal collection points, sometimes with a storage tank, are established. These 'standposts' are described in detail in (IRC, 1979).

In some cases, rather than distribute water through a piped system, a 'point source' of drinking water is established, where community members come to the water source to collect safe water as needed. Most commonly, wells are used in this way, though surface water treatment (e.g. slow sand filtration) or rainwater collection can also serve as community water supply points. Two good resources on the use of tubewells in community water supply systems developed during the International Drinking Water Supply and Sanitation Decade are (Arlosoroff et al., 1987) and (IRC, 1988).

In arsenic-affected areas, any of the technologies for source substitution or arsenic removal discussed in **Sections 6.2 and 6.3** could be applied, in theory. In practice, some of these technologies will not be appropriate in a rural setting, because of high capital costs, the need for highly trained operators and repair technicians, and other infrastructure needs that may be absent. Technologies best suited for application at the community level will be those that are robust, operate well under a range of environmental conditions, and can be effectively operated and maintained by people without extensive technical training (See **Section 6.4**). A useful collection of articles covering community level sources of water, abstraction, pumping and distribution, and training and maintenance is given in (Kerr, 1989). UNICEF, WHO and the IRC have all produced important documents describing water supply in small communities (IRC, 1981; WHO, 1997b; UNICEF, 1999b).

The past twenty years have seen the gradual evolution of consensus that greater participation of community members in supply, construction, financing, and operation of water supply systems is crucial for sustainable rural water supply. In theory, increased community participation can

generate a greater sense of involvement and ownership among the beneficiaries, and lead to a more sustainable water supply system. Communities acquire new management and organization skills, and develop into self-reliant, informed consumers, rather than passive beneficiaries of government largesse.

Increased community participation has fundamental implications for the role of central governments – decision-making power, and financial responsibility, must be decentralized to locally composed bodies, either in the form of local government institutions or community groups. This paradigm shift was endorsed at the 1990 New Delhi meeting that marked the end of the International Drinking Water Supply and Sanitation Decade. Participants agreed on a resolution that “a changing role of government is envisaged, from that of provider to that of promoter and facilitator, enabling local public, private and community institutions to deliver services.”

Much has been written about the challenges of truly involving community members, including sections of the community which are typically excluded from decision-making such as women and the poor, in planning and implementing water and sanitation supply projects. Some particularly valuable documents for those interested in enabling community participation have been produced by various UN agencies (Whyte, 1986; Srinivasan, 1990; WHO, 1997b; UNICEF, 1999b); the IRC (IRC, 1981); and the German agency for overseas aid (GTZ, 1989). Two IRC papers focus particularly on the participation of women in water supply: (van Wijk-Sijbesma, 1985; van Wijk-Sijbesma, 1988)

One of the most important issues in community participation is the role of community members in operation and maintenance of water supply systems. In most developing countries, an estimated one quarter of rural water supply systems are out of order (Cairncross and Feacham, 1993). Often the problem is simple, but goes unattended due to a lack of an effective structure for maintenance and repair. Many governments, unable to mobilize civil servants to maintain decentralized community water supplies, have sought greater community involvement in operation and repair of rural water supply systems.

In practice, this type of self-help has proved difficult to implement, and there are at least as many examples of failure as of success. In numerous cases, governments have promised to provide technical support and matching funds, if communities were able to raise money (typically 50% of capital costs) and contribute labor. Often, communities have risen to the challenge, but governments have found themselves unable to make good on promises of support. Even when water supply systems are constructed with community participation, communities are often less involved with operation and maintenance. Consistent maintenance can be much more difficult than construction, and poor maintenance cannot always be blamed on insufficient motivation and skills among community members (Cairncross and Feacham, 1993).

Several IRC documents directly address community management of water and sanitation systems (Appelton and Evans, 1993; IRC, 1993; Kurup, 1996). Good reviews are also provided by the UNDP/World Bank Water and Sanitation Program (McCommon et al., 1990) and the USAID-funded WASH project (Yacoob and Rosensweig, 1992).

Only a few examples of arsenic removal at the community level have been documented. Most of these are preliminary or pilot level experiments, in Bangladesh, India, China and Argentina, where large rural populations are exposed to arsenic in drinking water.

Maintenance of most arsenic removal systems involves periodic tasks that can easily be done by unskilled laborers, such as backwashing and cleaning of porous media beds and scrubbing of tanks. Community members can also be responsible for collection and disposal of arsenic-rich wastes, though external support may be necessary, depending on the type of waste. Tasks that

involve hazardous chemicals, such as chlorine dosing or regeneration of spent media, will require detailed training, but it may be possible to designate a responsible community member for these tasks, particularly if they are given some financial compensation.

When making community-level interventions, consideration must be given to logistic concerns such as supply of fresh chemicals and disposal of wastes. Appropriate institutions will need to be identified that can procure and distribute chemicals, and collect arsenic-rich wastes, if necessary (see **Section 6.3.7**, above). This role could be played by government agencies, NGOs, or the private sector. Any of these groups might require external support during the design and start-up phases.

Box 6.14: Community level arsenic removal with ferric chloride in Argentina

A well containing 270 µg/L arsenic was selected for a pilot wellhead filter in Rufino, Argentina. The filter consists of a cylindrical tank nearly 4 m high. Sulfuric acid is added to lower the pH from 8.5 to 6.5, followed by sodium hypochlorite to oxidize arsenite, and the coagulant, ferric chloride (30 mg/L). Treated water is then filtered through a bed of anthracite (1 m, 1.3 mm diameter) and sand (50 cm, 0.5 mm diameter). HFO forms in the tank and in the anthracite bed, and is removed in the anthracite and sand beds. The anthracite and sand beds are periodically cleaned with air blowing and caudal rinsing, using raw water from the well. Arsenic levels in the treated water are low, ranging from 20 to 40 µg/L. Iron levels were also dramatically reduced, though after 8 hours of operation, iron levels rose in the treated water. Source: (Madeic et al., 1999) END BOX

Box 6.15: Community level arsenic removal with activated alumina in India

The Bengal Engineering College (Deemed University) of Howrah, West Bengal (India), has developed a rural, community-level arsenic removal unit using domestically produced activated alumina. Contaminated groundwater is manually pumped directly into a column containing about 100 liters of activated alumina. The unit treats about 2500-4000 liters of water per day, and removes influent arsenic (a mix of arsenite and arsenate in nearly equal proportion) from about 500 µg/L to less than 50 µg/L. Several pilot units, each serving 800-1000 people, have been installed with support from the US NGO, *Water For People*, and one has been in operation since 1998, and has treated 12,000 bed volumes without regeneration as of January 2000. The influent water is high in iron (8-10 mg/L), which precipitates out and slows flow rates. However, periodic backwashing clears the filter and restores adequate flow rates. A village water use committee is responsible for maintaining the system, and charges users a small fee for access. These funds are kept in a bank account, and used for the regeneration and eventual replacement of exhausted media. Local contractors are trained to regenerate saturated activated alumina and to immobilize the resulting arsenic wastes in cement blocks. Source: (Gupta et al., 2000) END BOX

Box 6.16: Small private arsenic removal plants in the United States

Activated alumina and ion exchange resins have been the methods of choice for arsenic removal in small systems in the United States. A review of two activated alumina and two ion exchange small treatment plants, serving two schools, a medical facility and an industrial facility, showed that arsenic levels can be reduced from 50-80 µg/L to under 5 µg/L. All of the plants included an oxidation step, either with chlorine or a solid manganese-based oxidant. The activated alumina plants both backwashed tanks every 4-6 months. Both of these plants use activated alumina on a throw-away basis, replacing half of the media every 1.5 years. The ion exchange resin plants regenerate media automatically, including backwashing and rinse steps. One system regenerated every six days and had excellent effluent quality. The other system regenerated every three months, and effluent water showed periodic spikes of arsenic, sometimes at higher levels than the

influent. It was recommended that this system regenerate more frequently to prevent arsenic peaking. Source: (Sorg and Wang, 2000) END BOX

6.6.3 Household level arsenic removal

Arsenic removal at central or community levels is generally cost-efficient, because of economies of scale. Large capital costs are made bearable when shared by a large number of users. In contrast, household systems have a small number of beneficiaries, and can be relatively expensive.

However, household systems have several advantages over larger systems. Small systems will have smaller capital costs (even if per capita costs are higher). There is no ambiguity about who is responsible for operating and maintenance, and there is less chance of ‘freeloaders’ who enjoy the benefits of arsenic-free water but do not contribute to the costs of obtaining it. Experience from decades of water supply and sanitation projects has shown that families are better at maintaining household systems correctly than community members are at managing larger systems. Another key advantage is that in household systems, only the water that is required for drinking and cooking need be treated. In the case of a system breakdown, only a small number of users are affected.

In industrialized countries, household treatment, often called Point-Of-Use (POU) treatment is sometimes the most cost-effective option, especially in rural settings. POU systems are typically installed and monitored with support from local government agencies. In developing countries, governments may not have the capacity to provide support to household level arsenic removal systems, especially if a large number of households are affected. Private sector and NGO groups are more likely to have the grass-roots networks necessary to disseminate information and supply materials at the local level, though government and multinational agencies can play an important role in providing technical assistance to these groups.

Box 6.17: Point-of-use arsenic removal in the Southwestern US

San Ysidro is a small rural community of 200 people in central New Mexico. The local water supply draws on groundwater which contains leachate from geothermal waters, and exceeds maximum contaminant levels (MCLs) for arsenic, fluoride, iron, manganese, chloride, and total dissolved solids. When the water quality problem was discovered, source substitution was attempted, but deeper tubewells were also contaminated. Central treatment of water was not considered feasible for many reasons. After reviewing available treatment technologies, water supply engineers determined that reverse osmosis would be the most appropriate for the community. Accordingly, the village passed an ordinance which made the use of village water contingent upon installation of the reverse osmosis unit in the home, and 70 units were installed. Arsenic removal has been good, and other advantages have included easy installation, overall improvements in water quality, and relatively low cost. Disadvantages have included high sampling costs, training for new members of the community, and do-it-yourself plumbers. Source: (Rogers, 1988) END BOX

POU technologies in industrialized countries have focused on technologies that require little or no operator input for extended periods of time: activated alumina, ion exchange resin, and membrane filtration. Coagulation and filtration have not traditionally been considered for household use, because the procedures require handling of hazardous chemicals. However, in developing countries advanced technologies may not be available, while materials required for coagulation (e.g. chlorine, permanganate, alum, ferric salts) are often locally available and inexpensive. Alum, particularly, is very inexpensive and is widely used in rural communities for water clarification. This last point is important, because people are often reluctant to add chemicals to

drinking water – if the coagulant is locally known and accepted, this problem can be avoided. Because of these concerns, most household arsenic removal systems in developing countries have been based on coagulation and filtration. If coagulation and filtration are to be practiced at the household level for arsenic removal, system operators must be given solid training in chemical dosing and maintenance. Where alum is the coagulant of choice, an oxidation step will be necessary if arsenic is present in the form of arsenite. One major difficulty is ensuring the correct dosage: for small volumes of water, only trace amounts of the oxidant will be needed, and over- or under-dosing will have serious effects. It may be possible to minimize this risk by pre-packaging reagents.

Box 6.18: Household arsenic removal in Bangladesh (1)

A simple household removal system has been developed by the Bangladesh government with Danish support that relies on high doses (200 mg/L) of locally available alum as a coagulant. Potassium permanganate, also locally available, is used as an oxidant (1.5 mg/L). The two chemicals are mixed in powder form, and supplied to users, who add a fixed amount of the mixture to a 20-L plastic bucket full of water. The user stirs the mixture vigorously, and allows the water to settle for at least 4 hours. Water is then decanted into a second bucket, which is fitted with a coarse sand filter and tap. This system has been tested in affected households for over two years, and consistently reduces arsenic to less than 20 µg/L, even from influents of over 1000 µg/L. Over 400 households in the pilot area now use this system regularly. This system has the added benefit of removing iron and manganese from the groundwater, making the treated water aesthetically appealing to users. One challenge identified has been that users don't always stir the coagulants as briskly or as long as recommended, resulting in relatively poor floc formation. END BOX

Box 6.19: Household arsenic removal in Argentina

The Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS) has developed a system for arsenic removal at the household level. CEPIS engineers have evaluated the efficiency of mixtures based on alum (called Alufloc) and ferric chloride (Ferrifloc). The mixtures also contain chlorine, to oxidize arsenite, and activated clays, which increase the surface area of the floc, allowing more area for sorption and coprecipitation of arsenic. The mixture is added to arsenic-rich water, stirred rapidly for one minute and slowly for fifteen minutes, and then allowed to settle for one hour. In laboratories, both materials have achieved from 95-98% removal of arsenic. Field testing of both mixtures was done in Salta, Argentina, on groundwater containing 300 µg/L arsenic. One important finding has been that when alum is used as the coagulant, filtration greatly improves arsenic removal.

Table 6.8: Field testing of Alufloc and Ferrifloc in Salta, Argentina

	Composition (mg/L)			% Arsenic removal	
	Activated Clay	Coagulant	Oxidant (Ca(OCl) ₂)	Without filtration	After filtration
Alufloc	500	50	5	70	97
Ferrifloc	1000	60	5	94	94

CEPIS engineers found that when arsenic levels are below 1000 µg/L, Alufloc and Ferrifloc perform equally well. For more contaminated waters, Ferrifloc is more efficient. At lower concentrations, Alufloc is slightly preferable, since the mixture is less expensive, and more stable

(Ferrifloc absorbs water from the atmosphere). Residual aluminum levels in waters treated with Alufloc were below the WHO guideline value (based on aesthetic concerns) of 0.2 mg/L.

Both mixtures come in double-compartment sachets, since it was found that when stored in single compartments, chlorine would react with clay and lose its strength rapidly. The double-compartment sachets remain stable for at least a year and a half. Each set of sachets can treat 20 liters of water, and costs US\$0.22, though unit costs could decline to US\$0.15 if produced in quantity. Alufloc is currently being pilot tested in three communities in rural Argentina. Source: (Castro de Esparza and Wong de Medina, 1998) END BOX

Box 6.20: Household arsenic removal in Bangladesh (2)

In Bangladesh, researchers at Rajshahi University have taken advantage of the fact that HFO can adsorb both arsenite and arsenate. They have fitted a simple 100-L plastic tank with a tap a few inches from the bottom, and added pre-formed HFO (200 mg/L as FeCl_3). The tank is filled with contaminated water (~800 $\mu\text{g/L}$, mostly as arsenite) in the evening, settled overnight, and filtered through a coarse sand filter. The HFO can treat over a dozen batches before residual arsenic exceeds the drinking water standard of 50 $\mu\text{g/L}$. University workers visit the filters every two weeks to provide fresh HFO, and regenerate the spent HFO in laboratories. END BOX

6.7 Conclusions and continuing needs

In both developing and industrialized countries that have faced arsenic contamination of drinking water resources, source substitution, where possible, has been the preferred alternative. However, in some areas, arsenic removal may be a more practical, economically feasible strategy, at least for short-term supply of safe drinking water. Contaminated sources can still be safely used for purposes other than drinking and cooking, and should not be sealed unless safe water is conveniently available in the quantities required for all purposes.

Conventional systems for drinking water supply are well-documented, and those striving to develop safe sources of drinking water in areas affected by arsenic can turn to a rich library of manuals, texts, and journal articles, a selection of which are referenced above. Locally, research may be needed to determine what water resources are available, but once inventoried, conventional systems for water supply are relatively well understood.

The situation is slightly different regarding arsenic removal technologies. Some systems are fairly well documented. Conventional coagulation, notably, has been extensively reviewed in the literature in recent years. Arsenic removal under varying geochemical conditions has been investigated, and the effects of coagulant dose, influent arsenic concentration, pH, and the presence of competing co-solutes have been described in some detail. While some details, such as the mechanisms of arsenite adsorption onto HFO and effects of competition from phosphate, are not yet quantitatively documented, enough is known about the mechanisms of arsenic removal through coagulation to design effective removal systems, at least to reduce arsenic levels below 50 $\mu\text{g/L}$.

For the newly emerging technologies, such as semi-permeable membranes and various sorptive media, less is known about the effects of dose and pH, and even less about the effects of competing solutes. Global interest in improved methods of arsenic removal has led to a rich period of experimentation, in which novel sorbents have been essayed, and existing technologies for arsenic removal modified and/or combined to yield substantially different systems. These novel systems have typically been evaluated only by a handful of researchers, under a narrow range of environmental conditions, for short periods of time. In many cases advances in removal of arsenic, particularly of arsenite, has been demonstrated, but mechanisms are still poorly understood. Much more research needs to be conducted to identify those technologies that can

effectively remove arsenic under real-world conditions, and consistently do so for extended periods of time.

Especially with regard to arsenic removal in rural settings, more research needs to be done on the safe handling and disposal of arsenic-rich wastes. Experiments in the US have shown that coagulant sludge is generally safe for disposal in municipal landfills. However, in developing countries sanitary landfills are usually nonexistent, and solid waste often ends up simply dumped into rubbish heaps. The stability of arsenic waste streams under such environmental conditions has not been investigated. Simple burial, biomethylation, and stabilization of wastes into cement or brick have all been proposed, but not thoroughly researched.

Numerous technical questions remain unanswered. Nonetheless, based on the technology available, it is certainly possible to design arsenic removal systems that can reduce even highly contaminated influents to below 50 µg/L. Centralized arsenic removal plants in various countries have proven that such plants can be effective under a wide range of environmental and economic conditions. However, the great majority of people exposed to arsenic in drinking water globally live in rural, generally poor areas, where centralized arsenic removal is not practicable. Arsenic mitigation interventions in these areas must make use of source substitution, decentralized arsenic removal, or a combination of both.

Experiences with decentralized arsenic mitigation remain scarce, and are generally limited to a handful of pilot studies that are heavily donor-dependent. Accordingly, there is a great need for operations research, to determine how the technologies (both conventional water supply and arsenic removal) described above can be effectively applied as arsenic mitigation interventions in rural settings. The limited experiences available indicate that effecting change in water use practices in arsenic-affected areas requires much more than telling users not to use a specific source. Affected communities are often ignorant both of the threat posed by arsenic in their water supply, and of potential sources of arsenic-free water. Until water users understand the problem of arsenic contamination and its impact on their health, and have reliable information about safe alternatives, they will be unwilling and unable to make an informed choice to change their water use patterns. The biggest challenges ahead lie in adapting the technologies described in this chapter for application in poor, rural settings, and in enabling those communities to choose safe sources of water for drinking and cooking.

6.8 References

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