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Arsenic in Drinking Water

Thematic Overview Paper 17

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Table of Contents

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1. Introduction

The acute toxicity of arsenic at high concentrations has been known about for centuries. It was only relatively recently that a strong adverse effect on health was discovered to be associated with long-term exposure to even very low arsenic concentrations. Drinking water is now recognised as the major source of human intake of arsenic in its most toxic (inorganic) forms.

The presence of arsenic, even at high concentrations, is not accompanied by any change in taste, odour or visible appearance of water. The presence of arsenic in drinking water is therefore difficult to detect without complex analytical techniques.

Alarming information has emerged in recent decades about the widespread presence of arsenic in groundwater used to supply drinking water in many countries on all continents. Hundreds of millions of people, mostly in developing countries, daily use drinking water with arsenic concentrations several times higher than the World Health Organization (WHO) recommended limit of 10 millionths of a gram per litre of water (10 µg/L). The full extent of the problem and related consequences are at present unclear, given the long time it takes for visible symptoms of arsenic related diseases to develop and the similarity of symptoms with those of other diseases. However, the effects of arsenicosis are serious and ultimately life-threatening, especially as the long term ingestion of arsenic in water can lead to several forms of cancer.

Arsenic in drinking water is a global problem affecting countries on all five continents. The most serious damage to health has taken place in Bangladesh and West Bengal, India. In the 1970s and 1980s, UNICEF and other international agencies helped to install more than four million hand-pumped wells in Bangladesh to give communities access to clean drinking water and to reduce diarrhoea and infant mortality. Cases of arsenicosis were seen in West Bengal and then in Bangladesh in the 1980s. By 1993 arsenic from the water in wells was discovered to be responsible. In 2000, a WHO report (Smith *et al.* 2000) described the situation in Bangladesh as: “the largest mass poisoning of a population in history … beyond the accidents at Bhopal, India, in 1984, and Chernobyl, Ukraine, in 1986.”

In 2006, UNICEF reported that 4.7 million (55%) of the 8.6 million wells in Bangladesh had been tested for arsenic of which 1.4 million (30% of those tested) had been painted red, showing them to be unsafe for drinking water: defined in this case as more than 50 parts per billion (UNICEF 2006). Although many people have switched to using arsenic free water, in a third of cases where arsenic had been identified, no action had yet been taken.

UNICEF estimates that 12 million people in Bangladesh were drinking arsenic contaminated water in 2006, and the number of people showing symptoms of arsenicosis was 40,000, but could rise to one million (UNICEF 2006). Other estimates are higher still.

The only ways to counteract the effects of arsenic contaminated water are to switch to unpolluted sources or to remove the arsenic before water is consumed. Use of alternative deep ground or surface water sources is expensive and not a solution in the short term for the most affected populations in rural areas. Rainwater harvesting has high investment costs, brings its own potential water quality problems and is of doubtful suitability in countries, such as Bangladesh, where rainfall is seasonal. Sustainable production of arsenic free water from a raw water source that contains arsenic is very difficult due to the limited efficiency of conventional water treatment technologies, the high cost and complexity of advanced treatment and the generation of large volumes of waste streams that contain arsenic. The situation is most difficult in rural areas in developing countries where arsenic contaminated groundwater is the only drinking water source. In such areas, where centralised systems usually do not exist, arsenic removal technologies suitable for centralised water supply systems are not applicable. Efforts are being made to develop effective household treatment systems, but these too have proved problematic, both technically and operationally.

The scale of the arsenic problem, in the absence of viable treatment approaches, has resulted in unprecedented interest from the scientific community, governmental organisations in affected countries and the commercial segment of the water sector, as well as from international donors and NGOs and from agencies such as the World Health Organization (WHO) and UNICEF. However, despite enormous efforts and funds being put into the search for solutions, millions of people worldwide are still exposed daily to arsenic in their drinking water.

This TOP provides an up-to-date overview covering the extent of the problem of arsenic in drinking water, related health and social problems, arsenic chemistry, analysis and standards, arsenic removal processes and systems, and social and institutional issues associated with mitigation of the problem. Two case studies are introduced: on arsenic removal at household level in rural Bangladesh, and on an arsenic removal pilot project in Hungary. Finally, an overview of relevant resources including publications and web sites, organisations, conferences, courses and arsenic mitigation projects and research programmes is provided.

2. Health and social problems with arsenic in drinking water

Human exposure to arsenic can take place through ingestion, inhalation or skin adsorption; however, ingestion is the predominant form of arsenic intake. High doses of arsenic can cause acute toxic effects including gastrointestinal symptoms (poor appetite, vomiting, diarrhoea, etc.), disturbance of cardiovascular and nervous systems functions (e.g. muscle cramps, heart complains) or death (National Research Council 2000; Abernathy and Morgan 2001; Quamruzzaman et al 2003).

Arsenic toxicity strongly depends on the form in which arsenic is present. Inorganic arsenic forms, typical in drinking water, are much more toxic than organic ones that are present in sea food. Inorganic arsenic compounds in which arsenic is present in trivalent form are known to be the most toxic. The acute toxicity of a number of arsenic compounds is given in Table 1 (Chappell et al, 1999). Toxicity is expressed as the number of milligrams of the compound per kilogram of body weight that will result within a few days in the death of half of those who ingest it in a single dose. This concentration is known as LD50. Table 1 shows the amount of various arsenic compounds per kilogram of body weight required to reach LD50 (the higher the number, the less toxic the compound.)

Table 1. Acute toxicity for different arsenic compounds

Arsenic form	**Oral LD50** (mg/kg body weight**)**
Sodium Arsenite	15- 40
Arsenic Trioxide	34
Calcium arsenate	20-800
Arsenobetane	>10,000

Exposure to such high levels of acute arsenic poisoning is very unlikely. However, long-term exposure to very low arsenic concentrations in drinking water is also a health hazard. Numerous references review the effect of long-term exposure to arsenic on people's health (National Research Council 2000; UN 2001; WHO 2001; Ahmed F.M. 2003; UNICEF 2006).

The first visible symptoms caused by exposure to low arsenic concentrations in drinking water are abnormal black-brown skin pigmentation known as *melanosis* and hardening of palms and soles known as *keratosis*. If the arsenic intake continues, skin de-pigmentation develops resulting in white spots that looks like raindrops (medically described as *leuko-melanosis*). In a clinical study conducted in West Bengal on a population exposed to high levels of arsenic in drinking water, 94% had such "raindrop" pigmentation (Guha et al, 1998). Palms and soles further thicken and painful cracks emerge. These symptoms are described as *hyperkeratosis* and can lead on to skin cancer (WHO 2001). Other cancers are also caused by long-term exposure to arsenic in drinking water.

Arsenic may attack internal organs without causing any visible external symptoms, making arsenic poisoning difficult to recognise. Elevated concentrations in hair, nails, urine and blood can be an indicator of human exposure to arsenic before visible external symptoms (Rasmussen and Andersen 2002).

The disease symptoms caused by chronic arsenic ingestion are called *arsenicosis* and develop when arsenic contaminated water is consumed for several years. However, there is no universal definition of the disease caused by arsenic, and no way of knowing which cases of cancer were caused by drinking arsenic affected water. Estimates therefore vary widely. Symptoms may develop only after more than ten years of exposure to arsenic, while it may take 20 years of exposure for some cancers to develop.

Long-term ingestion of arsenic in water can first lead to problems with kidney and liver function, and then to damage to the internal organs including lungs, kidney, liver and bladder. Arsenic can disrupt the peripheral vascular system leading to gangrene in the legs, known in some areas as black foot disease. This was one of the first reported symptoms of chronic arsenic poisoning observed in China (province of Taiwan) in the first half of twentieth century. A correlation between hypertension and arsenic in drinking water has also been established in a number of studies.

The International Agency for Research on Cancer has concluded that: "There is sufficient evidence in humans that arsenic in drinking-water causes cancers of the urinary bladder, lung and skin" (IARC, 2004). The U.S. Environmental Protection Agency has estimated that that the lifetime risk of skin cancer for individuals who consumed 2 litres of water a day at 50 µg/L could be as high as 2 in 1,000 (Morales *et al.*, 2000). Studies also report increased mortality from cancers of the lung, bladder and kidney in populations exposed to elevated arsenic concentrations in drinking water. Significantly higher levels of mortality from internal cancers have been reported in Taiwan (Chen *et al.* 1985; Chen et al. 1992) and Chile (Smith 1998).

While UNICEF reported 40,000 confirmed cases of arsenicosis in Bangladesh (UNICEF 2006), other estimates indicate that at least 100,000 cases of skin lesions have been caused by arsenic, and that one in ten people who drink water with very high levels of arsenic (500 mg/l or more) over the long term may die from arsenic related cancers (Smith et al. 2000).

How quickly symptoms develop depends on water quality and especially on arsenic, iron and manganese concentrations, levels of water intake and on nutrition. Higher arsenic concentrations speed up the development of arsenicosis while the presence of iron and manganese in water can reduce exposure to arsenic through adsorption and precipitation into iron and manganese precipitates before the water is consumed. Lowering drinking water intake and consuming food rich in proteins and vitamins can delay the development of symptoms.

There is no medical treatment for this disease and the only prevention is to stop ingesting arsenic, in most cases by using arsenic-free drinking water. If this is done at an early stage, symptoms can be reversed. At a later stage the disease becomes irreversible but the use of arsenic-free water can still bring some relief. It should be noted that, although mining and industrial emissions may constitute a health risk from arsenic, drinking water is by far the greatest risk to public health. Hand-washing, bathing, laundry etc. with arsenic contaminated water do not pose a risk to human health.

In addition to the direct health effects, people affected by arsenic poisoning, especially women in rural areas in developing countries, can face social exclusion due to the visible symptoms and a misconception that the disease is contagious.

3. Guidelines and standards

Because of the proven and widespread negative health effects on humans, in 1993, the WHO lowered the health-based provisional guideline for a “safe” limit for arsenic concentration in drinking water from 50 μg/L to 10 μg/L (i.e. from 0.05 mg/l to 0.01 mg/l). WHO retained this provisional guideline level in the latest edition of its standards (WHO 1993; WHO 2004).

The guideline value for arsenic is provisional because there is clear evidence of hazard but uncertainty about the actual risk from long-term exposure to very low arsenic concentrations (WHO 1993; WHO 2004). The value of 10 μg/ was set as realistic limit taking into account practical problems associated with arsenic removal to lower levels.

The WHO provisional guideline of 10 μg/L has been adopted as a national standard by most countries, including Japan, Jordan, Laos, Mongolia, Namibia, Syria and the USA, and by the European Union (EU). Some countries that recently joined the EU will have serious problems in meeting the EU regulations. For example, in Hungary more than a million consumers use drinking water with arsenic concentration in excess of the WHO guideline. These countries will get additional time and support to harmonise their national standards with EU regulations.

Implementation of the new WHO guideline value of 10 μg/L is not currently feasible for a number of countries strongly affected by the arsenic problem, including Bangladesh and India, which retain the 50μg/L limit. Other countries have not updated their drinking water standards recently and retain the older WHO guideline of 50 μg/L (UN 2001). These include Bahrain, Bolivia, China, Egypt, Indonesia, Oman, Philippines, Saudi Arabia, Sri Lanka, Vietnam and Zimbabwe. The most stringent standard currently set for acceptable arsenic concentration in drinking water is by Australia, which has a national standard of 7 μg/L.

4. Worldwide extent of arsenic problem

Inorganic arsenic found in groundwater is in most cases of geological origin. Typical arsenic concentrations in groundwater are very low and in most cases below 10 µg/L. Elevated arsenic concentrations up to 5,000 µg/L are typically found in areas with active volcanism, geothermal waters, sedimentary rocks and in soils with a high concentration of sulphides (e.g. arsenopyrite). Arsenic can be also introduced into groundwater by mining activities. Arsenic is highly soluble and mobile in water (WHO 2004). Groundwater contamination with arsenic is consequently widespread.

Arsenic concentrations above accepted standards for drinking water have been demonstrated in many countries on all continents and this should therefore be regarded as a global issue. Arsenic has been reported in groundwater in the following countries, among others:

Asia	Bangladesh, Cambodia, China (including provinces of Taiwan and Inner Mongolia), India, Iran, Japan, Myanmar, Nepal, Pakistan, Thailand, Vietnam
Americas	Alaska, Argentina, Chile, Dominica, El Salvador, Honduras, Mexico, Nicaragua, Peru, United States of America
Europe	Austria, Croatia, Finland, France, Germany, Greece, Hungary, Italy, Romania, Russia, Serbia, United Kingdom
Africa	Ghana, South Africa, Zimbabwe,
Pacific	Australia, New Zealand

The scale of the arsenic problem is most serious in the alluvial and deltaic aquifer of Bangladesh and West Bengal, where millions of people drink water with high levels of arsenic.

A detailed inventory of groundwater quality in Bangladesh, conducted in 1998/1999 by the British Geological Survey (BGS), demonstrated that in 46% of shallow wells (up to 150 metres), arsenic concentrations exceed the WHO guideline of 10 µg/L. Up to 57 million people were daily exposed to arsenic levels in drinking water that exceeded 10 µg/L, in some cases as high as 2,500 µg/L (BGS 2001). UNICEF reported in 2006 that 1.6 million (32%) of the 5 million tube wells so far tested were found to contain arsenic above 50 µg/L (UNICEF, 2006). The Water and Sanitation Program South Asia office (WSP-SA) cites estimates of 20-40 million people in Bangladesh ingesting unsafe levels of arsenic in their water (WSP-SA 2000).

An additional six million people in West Bengal (India) are believed to be exposed to arsenic levels of between 50 and 3,200 µg/L. (BGS 2001b; WHO 2004). Most of the affected population in Bangladesh and West Bengal live in rural areas characterised by an absence of centralised water supply systems. While definitive figures are hard to establish, many millions of people in this region are drinking arsenic affected water daily, thousands have already been identified with arsenic related symptoms, and the fear is that their numbers could grow exponentially.

In Europe, the arsenic problem is most alarming in Hungary, Serbia and Croatia. An inventory of groundwater quality conducted in Hungary (Csalagovits 1999) demonstrated that drinking water for almost 400 towns and villages in the Great Hungarian Plain has arsenic concentrations several times higher the WHO and EC guidelines. Recent legislation directs water supply companies in Hungary to meet the EC Drinking Water Directives, including ensuring that arsenic concentration is below 10 µg/L, by 2009. Fulfilling this requirement will be a major challenge for the water supply companies in this country. It was relatively recently recognised that a large part of northern Serbia contains an unacceptably high arsenic concentration in drinking water supplied to consumers, probably affecting more than half a million people (Wikipedia; Personal communication). The full extent of the problem in Serbia is not yet known.

Mexico, United States, Chile and Argentina are most affected by the arsenic problem in the Americas. It has been estimated that at least four million people are exposed to arsenic level > 50 µg/L in Latin America alone (Bundschuh et al 2006). Extremely high arsenic concentrations in order of milligrams per litre were found in some wells in Latin America, including Bolivia and Peru. Levels as high as 5,000 µg/L have been recorded in Argentina (Bundschuh et al., 2006), reaching as high as 11,500 µg/L in some wells in Cordoba Province (BGS 2001b).

Figure 1. Countries where arsenic has been reported in ground or surface waters

The pattern of arsenic presence in different wells, especially in the sedimentary aquifer with elevated arsenic concentrations (e.g. Bangladesh and Hungary) can be very irregular. Two nearby wells with similar depths can show a large variation in arsenic concentrations presumably due to a difference in sedimentary characteristics. It has also been found that arsenic concentration in a well can strongly increase within a few years of groundwater abstraction beginning, suggesting that arsenic concentrations in abstracted water should be analysed regularly.

Before the recent alarm over arsenic contamination of groundwater in Bangladesh, arsenic was not routinely analysed when groundwater was used as a drinking water source. At the same time, standards for an acceptable arsenic level in drinking water have become more stringent. It is therefore expected that arsenic in drinking water will be increasing problem in coming years, and that new countries will be identified as having an arsenic problem.

5. Sources and basic chemistry of arsenic in water

5.1 Sources of arsenic in drinking water

Arsenic is the twentieth most abundant element in the earth's crust. Arsenic occurs in the environment in rocks, soil, water, air, and in biota. Arsenic is introduced into water through the dissolution of minerals and ores; concentration in groundwater in some areas is elevated as a result of erosion from local rocks. Industrial effluents also contribute arsenic to water in some areas. Arsenic is also used commercially, e.g. in alloying agents and wood preservatives. Combustion of fossil fuels is a source of arsenic in the environment through atmospheric deposition. The greatest threat to public health arises from arsenic in drinking water. Exposure at work, mining and industrial emissions may also be significant locally (WHO 2001).

Arsenic is introduced into the aquatic environment from both natural and man-made sources. Typically, however, arsenic occurrence in water is caused by the weathering and dissolution of arsenic-bearing rocks, minerals and ores. Arsenic occurs as a major constituent in more than 200 minerals, including elemental arsenic, arsenides, sulphides, oxides, arsenates and arsenites. Although arsenic exists in both organic and inorganic forms, the inorganic forms are more prevalent in water and are considered more toxic.

5.2 Arsenic chemistry and speciation

Arsenic is a metalloid with the atomic number 33, atomic weight 74.9216, symbol As and placed in the group Va of the periodic table of elements together with nitrogen, phosphorus, antimony and bismuth. Arsenic is a redox-sensitive element, meaning that it can change its form through reduction (gain of an electron) or oxidation (loss of an electron). Its occurrence, distribution, mobility, and forms rely on the interplay of several geochemical factors, such as pH conditions, reduction-oxidation reactions, distribution of other ionic species, aquatic chemistry and microbial activity (Shih 2005).

Total arsenic is the sum of both particulate arsenic, which can be removed by a 0.45-micron filter, and soluble arsenic. Soluble arsenic occurs in two primary forms: inorganic and organic. Inorganic arsenic can occur in the environment in several forms and valencies, but in natural waters, and thus in drinking-water, it is mostly found as trivalent arsenite (As (III)) or pentavalent arsenate (As (V)). Organic arsenic species are abundant in seafood, and include such forms as monomethyl arsenic acid (MMAA), dimethyl arsenic acid (DMAA), and arseno-sugars. They are very much less harmful to health, and are readily eliminated by the body.

Arsenic is perhaps unique among the heavy metalloids and oxyanion-forming elements (e.g. arsenic, selenium, antimony, molybdenum, vanadium, chromium, uranium, rhenium) in its sensitivity to mobilisation at the pH values typically found in groundwater (pH 6.5–8.5) and under both oxidising and reducing conditions. The valency and species of inorganic arsenic are dependent on the redox conditions and the pH of the water. In general, arsenite, the reduced trivalent form [As(III)], is normally found in groundwater (assuming anaerobic conditions) and arsenate, the oxidised pentavalent form [As(V)], is found in surface water (assuming aerobic conditions), although the rule does not always hold true for groundwater. Some groundwaters have been found to have only As(III), others only As(V), while in some others both forms have been found in the same water source (Ferguson and Gavis 1972; Korte and Fernando 1991; Cheng *et al.* 1994; Hering and Chiu 2000). As(V) exists in four forms in aqueous solution based on pH: H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{2-}$, and AsO_4^{3-}. Similarly, As(III) exists in five forms: $H_4AsO_3^+$, H_3AsO_3, $H_2AsO_3^-$, $HAsO_3^{2-}$, and AsO_3^{3-}. The ionic forms of As(V) dominate at pH >3, and As(III) is neutral at pH <9 and ionic at pH >9. Conventional treatment technologies used for arsenic removal, such as iron removal by aeration followed by rapid sand filtration rely on adsorption and co-precipitation of arsenic to metal hydroxides. Therefore, the valency and species of soluble arsenic have significant effect on arsenic removal (Edwards *et al.* 1998).

The toxicity and mobility of arsenic varies with its valency state and chemical form. As(III) is generally more toxic to humans and four to ten times more soluble in water than As(V) (USEPA. 1997; USOSHA, 2001).

Chemical speciation is a critical element for the removal of arsenic. Negative surface charges facilitate removal by adsorption, anion exchange, and co-precipitation processes. Since the net charge of As(III) is neutral at natural pH levels (6-9), this form is not easily removed. However, the net molecular charge of As(V) is negative (-1 or -2) at natural pH levels, enabling it to be removed with greater efficiency. Conversion of As(III) to As(V) is a critical element of any arsenic treatment process. This conversion can be accomplished by adding an oxidising agent such as chlorine or permanganate.

6. Analysis of arsenic

Determination of the speciation and concentration of arsenic in water is the first step in the assessment of the extent and severity of arsenic contamination in any given area. Arsenic in water can be measured in the laboratory or in the field using one of several field test kits.

6.1 Field analysis (test kits)

Field test kits have been used extensively to test for arsenic in groundwater, and in many cases, this is the only assay applied. The current baseline methodology involves a variety of technologies, all variations on the "Gutzeit" method. These involve treating the water sample with a reducing agent (e.g. zinc) that separates the arsenic by transforming arsenic compounds in the water into arsenic trihydride (arsine gas AsH_3). Arsenic trihydride diffuses out of the sample where it is exposed to a paper impregnated with mercuric bromide. Reaction with the paper produces a highly coloured compound. By comparing the colour of the test strip to a colour scale provided with the kit, the amount of arsenic in a sample can be estimated (USEPA 2004). Some newer test kits provide a photometer with an electronic display to measure the colour on the paper more accurately.

Several field test kits for the measurement of arsenic in water are available on the market. The range of measurement, accuracy, time required for measurement and costs vary widely. Some commonly used arsenic measurement test kits are listed in Table 2.

Table 2. Commonly used arsenic test kits

Test Kit	**Range of measurement** (μg/L)
1. MERCK (Germany)	5 – 500
2. HACH (USA)	10 - 500
3. Quick (USA)	10 - 1000
4. AIIH&PH Kit (India)	Yes/No
5. NIPSOM (Bangladesh)	10 - 700
6. GPL (Bangladesh)	10 - 2500
7. Arsenator (UK)	<10 - 500

Test kits are relatively inexpensive, portable and effective for indicating the presence of arsenic. Their main limitation is that many chemical reactions in raw water samples may be masked by other reactions (by other ions) occurring in the same solution. Secondly, the field test kits are subject to fluctuations in sensitivity and accuracy depending on the model. Moreover, individual differences are inevitable when many field workers are involved, especially since reading the colour chart is to some extent subjective. Furthermore, arsenic's propensity to switch valency states means that As(III) is more likely to be indicated by test results, while the presence of As(V) may not be identified because it reacts more slowly. Test kits, therefore, commonly under-evaluate total arsenic presence (AusAID 2004).

Field-test kits can detect the presence of arsenic at high concentrations, and can therefore be useful. However, test kits are generally inaccurate for detecting lower concentrations that are still of concern for human health (WHO 2001). Many of the test kits claim accuracy down to 0.01 mg/L, but independent tests have shown that most kits are unlikely to meet this standard in practice (Jadavapur University 1999; Rahman *et al*. 2002; Erickson 2003).

6.2 Laboratory analysis

Accurate measurement of arsenic in drinking water at levels relevant to health requires laboratory analysis, using sophisticated and expensive techniques and facilities as well as trained staff not easily available or affordable in many parts of the world (WHO, 2001).

Several methods are available for the determination of arsenic in water. The most common of these methods include:

(i) Atomic absorption spectroscopic method – (a) hydride generation atomic absorption (AAS – HG) and (b) electrothermal atomic absorption (AAS – GF)

(ii) Silver diethyldithiocarbamate method (SDDC)

(iii) Inductively coupled plasma (ICP) method – (a) mass spectrometry (ICP-MS) and (b) atomic emission spectrometry (ICP-AES)

(iv) Anodic stripping voltammetry (ASV)

The hydride generation-atomic absorption method, which converts arsenic compound to their hydrides that subsequently are decomposed in an argon hydrogen flame, is the method of choice, although the electro-thermal method (direct injection of sample into the graphite tube) is simpler in the absence of interferences. The silver diethyldithiocarbamate method, in which arsine is generated by sodium borohydride in acidic solution, is applicable to the determination of total inorganic arsenic when interferences are absent and the sample contains no methyl arsenic compounds. The diethyldithiocarbamate method is also used for identifying and quantifying two arsenic species (arsenite and arsenate). The ICP method is useful at higher concentrations (greater than 50 μg/L). ASV is useful to quantify free, dissolved arsenic in aqueous samples. The chief advantage is that this technique does not require expensive instrumentation and is therefore useful for field analysis. Details of these methods and their detection levels can be found in Standard Methods for the Examination of Water and Wastewater (1995) and in USEPA (1999).

Analytical methods currently approved by US Environmental Protection Agency (USEPA) for analysis of arsenic in drinking water and detection limits are summarised in Table 3.

Table 3. Analytical methods approved by USEPA for analysis of arsenic in drinking water

Method		**Technique**	**Lowest limit of detection** (μg/L)
Multi-analyte methods	EPA 200.8	ICP – MS	1.4
	EPA 200.7	ICP – AES	8
	SM 3120 B	ICP - AES	50
Single-analyte methods	EPA 200.9	AAS - GF	0.5
	SM 3113 B	AAS - GF	1
	ASTM D 2972-93 Test method C	AAS - GF	5
	SM 3114 B	AAS - HG	0.5
	ASTM D 2972-93 Test method C	AAS - HG	1

Adapted from USEPA (1999)

The accurate speciation of inorganic arsenic species [As(III) and As (V)] present in groundwater is very useful, given their different toxicity and response to treatment. However, transport of field water samples to laboratory and their storage could result in changes in arsenic speciation over time. AWWA Research Foundation and USEPA recently developed a reliable field speciation and preservation method (Clifford et al. 2005).

7. Arsenic removal technologies

7.1 Introduction

Several treatment technologies have been adopted to remove arsenic from drinking water under both laboratory and field conditions. The major mode of removing arsenic from water is by physical-chemical treatment. Technologies for removing arsenic from drinking water include:

- Precipitation processes, including coagulation/filtration, direct filtration, coagulation assisted microfiltration, enhanced coagulation, lime softening, and enhanced lime softening
- Adsorptive processes, including adsorption onto activated alumina, activated carbon and iron/manganese oxide based or coated filter media
- Ion exchange processes, specifically anion exchange
- Membrane filtration, including nano-filtration, reverse osmosis and electrodialysis reversal
- Alternative treatment processes, especially greensand filtration
- In situ (sub-surface) arsenic removal (Jacks et al. 2001; Appelo and de Vet 2003)
- Biological arsenic removal (Katsoyiannis and Zouboulis 2004)

Some of these technologies are traditional treatment processes (coagulation/filtration, lime softening, iron/manganese oxidation, and membrane filtration), which have been tailored to improve removal of arsenic from drinking water in water treatment plants. Technologies such as ion exchange, manganese greensand filtration and adsorption on activated alumina have been employed in small and domestic systems. Innovative technologies, such as permeable reactive barriers, biological treatment, phytoremediation (using plants), and electrokinetic treatment, are also used to treat arsenic-contaminated water. However, many of these techniques are at the experimental stage and some have not been demonstrated at full-scale. Also, although some of these processes may be technically feasible, their cost may be prohibitive (USEPA 2000a; USEPA 2002). For these reasons, only the most common methods used for arsenic removal are elaborated here.

7.2 Precipitation processes

Precipitation processes involving coagulation/ filtration have been studied extensively for the removal of arsenic from water. Adsorption co-precipitation with hydrolysing metals such as Al^{3+} and Fe^{3+} is the most commonly used treatment technique for removing arsenic from water (Hering *et al.* 1997; Madiec *et al.* 1999; Chwrika *et al.* 2000; Gregor 2001; Mamtaz and Bach 2001; Meng *et al.* 2001). The precipitate formed after coagulation or in situ oxidation of iron and manganese present in water could be removed by sedimentation followed by rapid sand filtration or direct filtration or microfiltration (Ghurye et al. 2004). Coagulation with iron and aluminium salts and lime softening has been considered the most effective treatment process for removing arsenic from water to meet the interim primary drinking water regulations standard. Oxidation of As(III) to As(V) and removal using one of the processes described above has been recommended (USEPA 2000a & b). Atmospheric oxygen, hypochlorite and permanganate are commonly used for oxidation of As(III) to As(V). However, oxidation with air (atmospheric oxygen) is very slow.

Precipitation/co-precipitation is frequently capable of successfully treating a wide range of arsenic-contaminated influent concentrations to achieve or surpass drinking water standards. The effectiveness of this technology is less likely than other treatments to be reduced by characteristics and contaminants other than arsenic. It is also capable of treating water characteristics or contaminants other than arsenic, such as hardness or heavy metals. Systems using this technology generally require skilled operators: for this reason, precipitation/co-precipitation is more cost-effective at large scale where labour costs are spread over a larger quantity of treated water.

7.3 Adsorption processes

Adsorption involves the use of granular adsorptive media for the selective removal of arsenic from water with or without pH adjustment and with or without spent media regeneration. Several granular adsorptive filter media have shown high effectiveness in arsenic removal from water. These include activated alumina, activated carbon, iron oxide coated or based filter media including some commercial media like Aqua-Bind MP, ArsenX, Bayoxide E33 ferric oxide, Granular Ferrichydroxide (GFH), MEDIA G2, manganese greensand etc. These technologies are consistently capable of removing arsenic to below the required standard level (Huang and Fu 1984; Huang and Vane 1989; Driehaus et al. 1998; Petrusevski et al. 2000 and 2002; USEPA 2000b; Selvin et al. 2001; USEPA 2002).

The effectiveness of adsorption for arsenic treatment is more likely than precipitation processes to be affected by characteristics and contaminants other than arsenic. Small capacity systems using these technologies tend to have lower operating and maintenance costs and require less operator expertise. Adsorption and ion exchange therefore tend to be used more often when arsenic is the only contaminant to be treated, for relatively smaller systems, and as an auxiliary process for treating effluent from larger systems.

7.4 Ion exchange

Small-scale systems and point-of-entry (POE) systems (treating water as it enters the home or building) often use ion exchange (IX) for arsenic removal because of ease of handling and sludge-free operation. However, treatment costs are higher than for conventional treatment in large-scale systems (USEPA, 2000b).

Ion exchange does not remove As(III) because As(III) occurs predominantly as an uncharged ion (H_3AsO_3) in water with a pH value of less than 9.0 (Clifford, 1999). The predominant species of As(V), $H_2AsO_4^-$ and $HAsO_4^{2-}$, are negatively charged, and thus are removable by IX. If As(III) is present, it is necessary to oxidise As(III) to As(V) before removal by IX (Clifford and Lin 1991).

7.5 Membrane filtration

Membrane processes can remove arsenic through filtration, electric repulsion, and adsorption of arsenic-bearing compounds. The viability of microfiltration and ultrafiltration as a technique for arsenic removal is highly dependent on the size distribution of arsenic-bearing particles in the source water. Nano-filtration membranes are capable of removing significant portions of the dissolved arsenic compounds in natural waters. Reverse Osmosis (RO) is a technology proven through several bench- and pilot-scale studies, and is very effective in removing dissolved constituents. Since arsenic in groundwater is typically 80- 90% dissolved, RO is a suitable technology for arsenic removal in groundwater (Chang et al. 1994; Waypa et al. 1997; Amy 2000; Shih 2005). Membrane filtration is effective in removing both As(III) and As(V) species. However, efficiency in removing As(V) is higher than for As(III).

The effectiveness of membrane filtration for arsenic removal is sensitive to a variety of untreated water contaminants and characteristics (Bowler et al. 1998). It also produces a larger volume of residuals and tends to be more expensive than other arsenic treatment technologies. It is therefore used less frequently than precipitation/co-precipitation, adsorption, and ion exchange (USEPA 2002).

8. Arsenic removal systems

The arsenic removal technologies outlined in section 7 can be employed either in centralised treatment systems or in household point-of-use (POU) systems. Centralised treatment systems that provide drinking water for a city, community, or several communities are usually attached to a distribution system (Ahsan 2002). Household point-of-use systems are for use with on-site sources such as tubewells which provide water to one or several households close to the facility.

8.1. Centralised arsenic removal systems

The most commonly used arsenic removal systems in both developed and developing countries are based on conventional coagulation-separation and adsorption. Although treatment systems based on membrane filtration (reverse osmosis and nano-filtration) are effective in removing arsenic, their practical application is very limited due to high treatment costs and the generation of large volumes of waste water with very high arsenic concentrations. (At least 20% of raw groundwater is rejected by an RO membrane, resulting in a stream of concentrate or brine containing concentrated arsenic and other impurities). A membrane filtration system would be economically more attractive in circumstances where the drinking water source is brackish groundwater that not only contains arsenic but also other impurities that cannot be effectively removed through conventional or adsorptive treatment. Besides effectively removing arsenic, it is also important that treatment does not negatively affect the taste and colour of the water and affect user acceptability.

Coagulation-separation arsenic removal systems

Conventional coagulation based arsenic removal systems are the most common. Such systems comprise the addition of a coagulant (aluminium or iron based salts) followed by flocculation and floc separation unit(s), usually using sedimentation and rapid sand filtration. An example of a compact conventional coagulation based treatment unit attached to a tube well is given in Figure 2.

Parameters that commonly control coagulation process such as coagulant type and dosage, pH and interference by other impurities (e.g. organics, PO_4^+, etc.) have an effect on arsenic removal efficiency. Appropriate coagulant type and dosage and coagulation pH can be established through relatively simple jar-test experiments. In general, coagulant dosages need to be higher than for conventional coagulation of surface water. It should be noted, however, that the overall efficiency of arsenic removal is not only determined by the coagulation but also by the efficiency of the subsequent separation process.

Treatment can be simplified by applying direct filtration (without sedimentation and, in some cases, without flocculation units) when relatively low coagulant dosages (a few mg/L) are sufficient for efficient arsenic removal. Careful selection of filter media (e.g. coarse deep bed or dual media) is of critical importance for direct filtration.

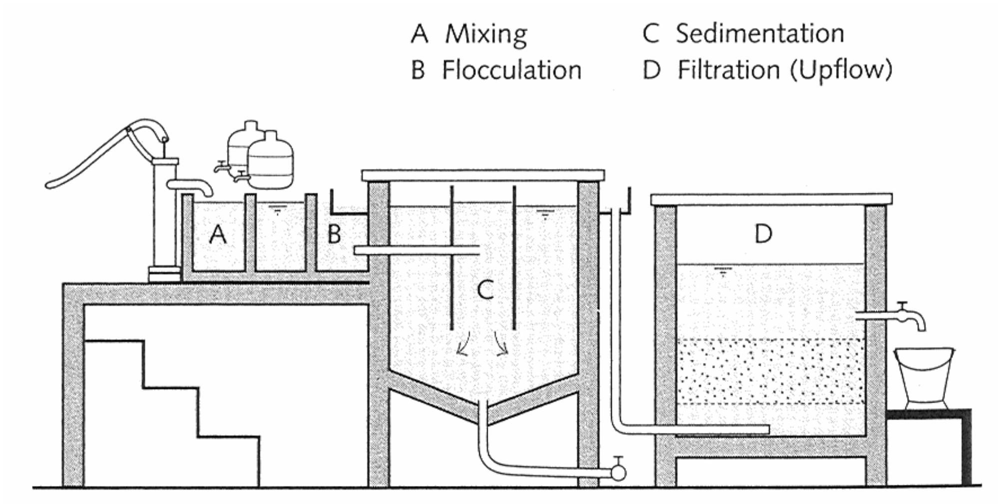

Figure 2. Conventional coagulation based treatment unit attached to a tube well (Ahsan 2002)

When groundwater that contains arsenic is being treated, an aeration step (cascade, plate aerator, aeration tower, etc.) normally precedes the addition of a coagulant. Aeration is essential to introduce oxygen into anoxic groundwater and to remove impurities such as methane that could cause serious problems during filtration. Oxygen introduced during aeration oxidises dissolved iron, commonly present in ground water, and results in the formation of ferric hydroxide flocs, comparable to the flocs formed when a coagulant is added. This means that the coagulant dosage can be reduced or, when groundwater has high iron concentrations, completely avoided. Conventional removal of iron from groundwater based on aeration and filtration will always result in the removal of some arsenic, although the efficiency of this process depends on the nature of the groundwater (iron and arsenic concentrations, arsenic speciation, pH) and process conditions (e.g. filter design and contact time available for iron precipitation). An example of a conventional iron removal system that will also result in (partial) arsenic removal is given in Figure 3.

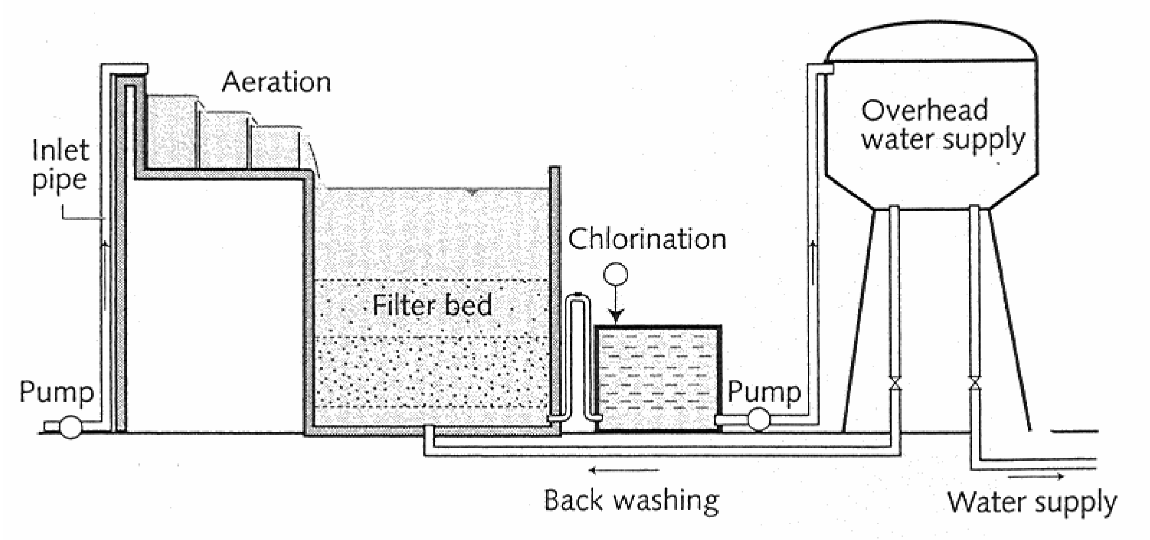

Figure 3. Conventional iron removal treatment unit (Ahsan 2002)

The use of aeration-rapid sand filtration is a promising system for arsenic removal in Bangladesh where 65% of groundwater contains iron in excess of 2 mg/l (Ahmed 2003).

An additional chemical pre-oxidation (e.g. chlorination or ozonation) may be required when a significant proportion of the arsenic in groundwater is present in As(III) form. Use of chemical oxidation increases treatment costs and the need for skilled personnel. There are also problems associated with the possible formation of oxidation by-products and these need to be addressed.

One serious drawback associated with coagulation based arsenic removal is the generation of a large volume of toxic liquid waste. Options for treatment and disposal of this waste and the related costs should be carefully taken into account when coagulation based treatment is considered as a means of treating water containing arsenic.

Different configurations of hybrid arsenic removal treatment system based on combination of coagulation and micro- or ultrafiltration have been extensively tested in pilot projects in recent years. Such systems could combine the advantages of both coagulation and membrane filtration. However, the wider application of hybrid coagulation-membrane filtration systems is doubtful in developing countries because of the high overall treatment costs.

Adsorption based arsenic removal systems

In the past, centralised systems using activated alumina (AA) as an adsorbent have been the most widely used. AA is widely available and, at 0.85-1.70 Euro/Kg, cheaper than other commercially available arsenic adsorbents. AA is effective at removing As(V) but its efficiency in removing As(III) is strongly affected by pH. In general, Empty Bed Contact Time (EBCT) in excess of 5 minutes and pH<7 are recommended. Arsenic adsorption capacity of AA is limited to a few thousands bed volumes (Driehaus 2005; Amy et al.

2005). If the water has a high salinity or other competing ions (e.g. fluoride or sulphate) present, the capacity of AA arsenic adsorption can be significantly reduced. Partial recovery of AA adsorption capacity is possible by rinsing the exhausted media with diluted caustic soda. However, the number of regeneration cycles is limited and regeneration results in arsenic-rich liquid waste that has to be dealt with.

Centralised arsenic removal systems using iron based adsorbents are increasingly being introduced, due to the growing availability of commercial adsorbents with high adsorption capacity and simplicity of operation. Such systems typically comprise one or a series of adsorptive filters without need for chemical addition. Most iron based and commercially available arsenic adsorbents for these systems (e.g. GFH, E-33, MetSorb G) are supplied as non-regenerative media with a typical arsenic adsorption capacity of 0.5-1.0 mg/g, at an equilibrium concentration of 10 μg/L and an absence of other interfering ions. An indicative price for these adsorbents is 5-10 Euro/Kg. (Amy et al. 2005). Assessment of the suitability of a specific adsorbent for particular application requires long, time consuming and expensive laboratory and field filter runs. A procedure for rapid small-scale assessment of arsenic adsorbents was recently proposed by AWWA Research Foundation and USEPA (AWWARF & USEPA 2005).

EBCT and filtration rate (hydraulic loading) are the main design parameters. A wide range of values for EBCT (3-20 minutes) is suggested in the literature (End 2004; Amy et al. 2005). An optimal EBCT should be established for each specific system, taking into account locally applicable investment and operational costs over the lifetime of the plant. A detailed overview of commercially available arsenic adsorbents, including detailed laboratory testing, has been conducted by AWWA Research foundations (Amy et al. 2005). This resource also includes a CD containing software that could help in conceptual design and cost estimate of adsorptive arsenic removal treatment based on use of various commercially available adsorbents.

An innovative alternative to commercially available and relatively expensive arsenic adsorbents is the use of iron oxide coated sand (IOCS) that originates from groundwater treatment plants. Groundwater treatment plants in The Netherlands, and possibly other countries, typically replace filter media after 3-10 years of operation due to the formation of a thick layer of iron oxides on virgin sand media. The discarded filter-media with the iron oxide provides a by-product with high arsenic adsorption capacity, comparable to the capacity of commercially available adsorbents. Arsenic removal is highly effective irrespective of arsenic speciation (Petrusevski et al 2000). Because IOCS has a less porous structure, arsenic removal requires longer contact time (>30 min) and lower filtration rates (e.g. 5 $m^3/m^2/h$).

Arsenic in groundwater is commonly a part of complex quality matrix that includes other impurities like ammonia, methane, iron, manganese, phosphate, silica, etc. As a result, this water probably requires an additional pre- or post-treatment (e.g. aeration or rapid sand filtration) in addition to adsorptive arsenic removal production, to make it fit for drinking.

8.2 Household level point-of-use (POU) treatment systems

Household level point-of-use arsenic removal systems can make an important contribution to safe drinking water, especially for rural populations in developing countries. Where centralised water supply systems are unavailable, a household level arsenic removal system is the only feasible short-term solution. Affordable POU removal systems seem relatively easy to implement given the availability of millions of tube wells and the fact that people are accustomed to using them.

The health hazards from using arsenic-contaminated water are linked only to drinking and food preparation, which account for only 2%-3% of total daily water consumption. This emphasises the potential for using household level systems, especially in rural areas.

However, household level systems have to be properly used and maintained and so there is a need to train families in their use and maintenance, to ensure that they work for sufficiently long periods and that filter material is changed appropriately.

Several POU arsenic removal technologies have been tried by various agencies with limited success, especially in Bangladesh. Household level arsenic removal systems are commonly based on adsorptive filtration (using an Alcan enhanced activated alumina, BUET activated alumina filter, Apyron Arsenic Treatment Unit, Read-F Arsenic Removal Unit, etc.) or coagulation (e.g.DPHE-Danida Bucket treatment unit, Garnet filter, Stevens Institute Technology system), ion exchange treatment (e.g. Tetrahedron) or combination of coagulation and adsorption (Sono 3-Kalshi filter). Some of the household level systems include an oxidation step (addition of chlorine tablets or potassium permanganate) in order to improve As(III) removal efficiency. All these household arsenic removal technologies have some advantages and disadvantages (WaterAid 2001a; WaterAid 2001b; Ahmed 2003; Akter 2004).

WaterAid has made a comprehensive survey of POU arsenic removal systems carrying out a short-term performance analysis in terms of flow rate, storage capacity, breakthrough time (after which arsenic is no longer effectively removed by the filter), bacteriological performance, chemical use, costs (investment and operation and maintenance), and user acceptability (WaterAid 2001a; WaterAid 2001b).

Five of the nine systems comfortably passed the arsenic removal test that required arsenic concentration in treated water to be below the Bangladeshi standard of 50 µg/L (Alcan enhanced activated alumina, BUET activated alumina, Sono 3-kolshi, Stevens Institute technology and the Tetrahedron). Two others (DPHE-Danida 2-bucket system and Garnet) passed the test under certain conditions, while two (Ardash filter and passive sedimentation) failed. However, the testers point out that: “The sustainability of these technologies is not just a function of the inherent robustness of the technology and of the treatment process used, but a function of the infrastructure and support services provided in support of the users of the technologies” (Sutherland *et al.* 2001).

Technologies were also tested for user acceptability and for their ability to keep the water clear of bacteriological contamination. The main reasons why some technologies were not acceptable to the users were the amount of work needed to operate and maintain them, the time that users had to wait for water and the daily volume of water available. The volume of water produced in 12 hours varied from 13 litres (Garnet), which is not enough even for one family, to 3,600 litres (Alcan), enough for more than 100 families. Some technologies were too expensive for family use, while almost all needed modification to improve the bacteriological quality of the water. However, these represented early models and improvements in design could be expected (Sutherland *et al.* 2001).Longer field testing will however be required.

Recently, the Government of Bangladesh approved four technologies for commercial sale in Bangladesh, namely Alcan, Sidko (a granular ferric hydroxide filer system), READ-F and Sono. Two of these are illustrated in Figure 4. It is estimated that 100,000 household arsenic removal systems are in use in Bangladesh, but the results have been very mixed. It appears that good back-up is essential, as are accepted methods of disposing of sludge (Arsenic Project 2006).

Since 1999, UNESCO-IHE has been developing POU technology for arsenic removal using iron oxide coated sand (IOCS) as an adsorbent. As explained in 8.1 above, this by-product of water treatment plants designed to remove iron from groundwater, is a very effective adsorbent for arsenic, and is therefore potentially very attractive for use in affordable point-of-use systems. The IHE 'family filter' is a simple, easy-to-use, adsorptive filter and does not require any chemicals. Like the other household systems described above it operates under gravity and does not require a power supply. 14 IHE arsenic removal family filters have been operating in rural Bangladesh continuously since early 2004, producing arsenic free-water (see section 10.1).

Figure 4. An Alcan filter (left) under testing in Azimpur village, Manikgonj district, Bangladesh, and a Sono arsenic removal filter (right)

9. Mitigating the arsenic problem: social and institutional aspects

9.1 Awareness

Because arsenic contamination is largely a natural phenomenon, and no preventive measures can usually be taken, there is a danger that communities feel helpless when an arsenic problem arises. It is important that communities are engaged and active in taking local action and pressing for support to mitigate the effects of arsenic contamination of water supplies. As Dr. M.I.Zuberi, a campaigner from the Rajshahi University in Bangladesh, has put it: “There should be thorough mitigation action through community involvement. This is important to restore hope to those who are affected and save the community from rapid degradation of society” (Source News 2003).

Public awareness campaigns will be needed where the problem is not already familiar to communities. The mass media may need accurate information and facilitation to publicise problem and solutions, and to generate action rather than alarm. Radio and television especially can play an important role in public information and education. While mass media is critical to generating political will and public awareness within countries, it tends to have less penetration and influence in rural areas. Local popular media, such as folk theatre, can make a difference especially when this is linked to group discussion and participatory groups.

Any public awareness campaign, national, regional or local, should reflect the different roles and responsibilities that women and men have in the provision of good domestic water to the home and take into account differences in access to various media. Special efforts may be needed to reach women and very poor people who do not have regular access to media.

Meetings to raise awareness and plan local action may be needed, and in some areas these may need to be planned so that women and men are seated separately (with equal access to the meeting), or separate meetings may need to be arranged for women and men. Participants can be encouraged to map the causes and effects of arsenic poisoning. During a group discussion about the symptoms of the disease, its presence, cause and impacts, a literate group member can note the interrelations (Figure 5). Such meetings are very effective in generating active community demand for measures to remove arsenic from the water.

Figure 5. A group producing a cause and effect diagram related to arsenic contaminated water

One useful tool to help groups to trace the impact of arsenic contaminated water is shown in Figure 6. At the back of some of the pictures there is a mark indicating that a person is suffering from arsenicosis. Group members first discuss who is represented and, after turning over the pictures, discuss why these members have contracted the disease and what the effects might be. When each group has completed an internal discussion, they share their findings and conclusions so that a common understanding is reached on the need for and urgency of local action (Breslin and Sawyer 1999). These silhouettes were originally developed for group discussions around HIV and AIDS. They should be redrawn, if necessary, so that the silhouettes are appropriate for the culture in which they are being used.

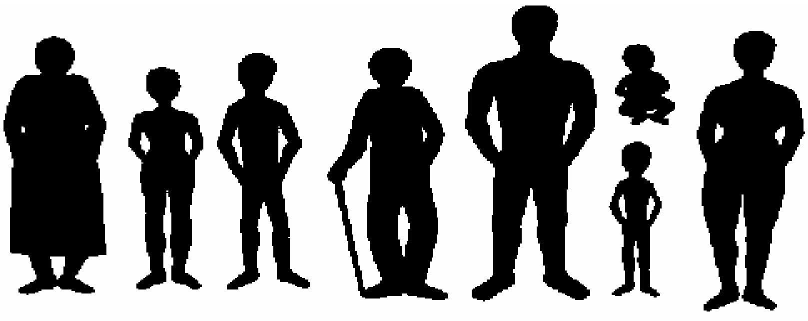

Figure 6. Silhouettes of a typical family, used to consider the effects of arsenic on people in a community

Once people are convinced that the disease is contracted through drinking contaminated water and can be countered by switching to arsenic-free water, the next step is for them to familiarise themselves with options for addressing the issue. Basically, there are three options: sharing sources that are still arsenic free, each household adopting a point-of-use removal system, or a neighbourhood adopting a community-based removal system.

9.2 Sharing arsenic-free point sources

Due to differences in sedimentary characteristics, not every drinking water source is affected. Since only water for drinking and cooking has to come from an unaffected source, it is in principle possible to share an arsenic-free point source (usually a handpump well). However, sharing a source is less simple than it sounds, due to socio-cultural and economic constraints. First, there is the issue of the number of users and the distance to be travelled for water collection. When there are only a few arsenic-free handpump wells and a large number of people, the pressure may simply be too great to make sharing a feasible option. This may also be the case when women and children, the usual water carriers, have to haul water over long distances.

Second, there is the willingness of the owners of the arsenic-free source to share their water, and how. Sharing calls not only for solidarity with the people who have been less fortunate in their water source, but also for communally agreed rules of use, for the amount that can be drawn, who can collect water, the hours when they may do so, and the sharing of handpump maintenance and replacement costs. Gender, ethnicity and class issues all need to be addressed. In many cultures, water drawing is done by men only if they are water vendors. There may be problems when a source is to be shared by people from different ethnicity, class or caste. In such situations, participatory tools and techniques and the choice of a mediator in case of problems, are very helpful in reaching satisfactory arrangements. Tools may include social mapping as shown in Figure 7, silhouette pictures as shown in Figure 6, and the depiction of tasks and the costs involved in maintenance, repair and replacement.

Solutions based on sharing may prove only temporary. An arsenic-free source may become contaminated, while population growth may put unsustainable pressure on unpolluted sources.

9.3 Arsenic removal at household level

A second option is the removal of arsenic at household level. Communities and households need to know about the different types of equipment that may be on the market, at what price, and how long each can be expected to last. This information needs to be available to both women and men. Demonstrations should be arranged to show operation and maintenance tasks, such as filter cleaning, and to demonstrate the effectiveness of treatment and the colour and taste of the water. Once equipment has been installed, training in operation and maintenance will have to be given with follow up until proper use becomes routine.

Even if subsidies are available, the cost of equipment will be beyond most poor families. Where poverty prevents people from acquiring the equipment in one go, arrangements for credit and saving through banks and/or credit and savings groups will be needed. Although banks do not easily give loans to low-income individuals, there are promising experiences with microcredit (Fonseca, 2006).

9.4 Communal plant

The third option that the people can consider is to have a treatment plant installed at community level. A community-level solution has the advantage of being able to deliver arsenic free water to a large number of households. However, there are financial costs for a (part time) operator, and costs in time for a management committee and for regular meetings. A successful communal system depends on the operator, management committee and implementing agency interacting well together and functioning effectively. A communal plant is therefore best installed when there is a clear sense of community and experience with community processes and services.

Drawings of various options should be provided so that groups can discuss the pros and cons of individual household filters versus a community plant.

9.5 Institutional aspects

Informed choice implies good quality information, communication and decision-making processes. In the early stages, there is a need for experienced facilitators who know how to work with different user groups using participatory techniques in an equitable manner. Facilitators also need to be well-versed in the technology so that they can explain the processes and answer any questions that may arise in group discussions. Within many cultures, it is important to have male and female facilitators, and for a woman to train the women in operational skills and for a man to train the men.

When a communal system is going to be installed, users have to choose a local management committee. To make an informed choice, it is important that the tasks and required skills of the different committee members and operator are laid out first. Drawings of a committee with male and female members and drawings or real life symbols representing the different tasks (e.g. a spanner, a notebook, some local money, etc.) help participants to visualise what work needs to be done and what kinds of people they should select. It is important to assess how much work will be involved – what are the different tasks, how long may they take and how often they need to be performed. Visualising different workloads with the help of coins, seeds or matchsticks for the number of hours of work per day, per week and per month can help participants make good decisions on who can best do the work, whether anyone needs to be paid, and if so, how much. Community members can also discuss which groups different committee members will represent, and to whom they will report about which aspects of the work. Guided and informed decisions make it more likely that a committee comprises men and women who represent the different groups in a community and that members are held accountable.

When operators are appointed, it is important to check whether they may sometimes pass on work to other family members. It has happened that in multi-stage filtration treatment systems, a male part-time operator who is away from home has passed on his duties to his wife or daughter, who had not been trained. It may be better to choose a couple and train both, so that the work is always done well. Salary and credits will then go to the couple rather than to one individual.

Implementation and training can start when the operators, committee members and other functionaries have been chosen and roles and remuneration have been decided. Decisions over the design and installation of the plant and distribution net will include the location of facilities, such as a well, treatment plant, storage tank, and the distribution net to shared or individual household taps. The committee plays a central role in communicating the proposal to user groups, locating proposed sites and discussing their acceptability. Sites should be marked on a social, community-made map in which all houses, roads and key geographic features are depicted, not necessarily to scale. The location of water supply components and outlets are marked on the map and can also be marked on the ground, so that everyone can understand the new system, including ease of access to any shared distribution points.

The social map can also assist in setting contributions towards construction and/or operation and maintenance costs. Participants draw a typical better off family, a middle income family and a poorer family in their community. Subsequently, they determine whether each house in the community falls into the better, worse or in-between category and mark these houses on the map, using different colours or shapes (Figure 7).

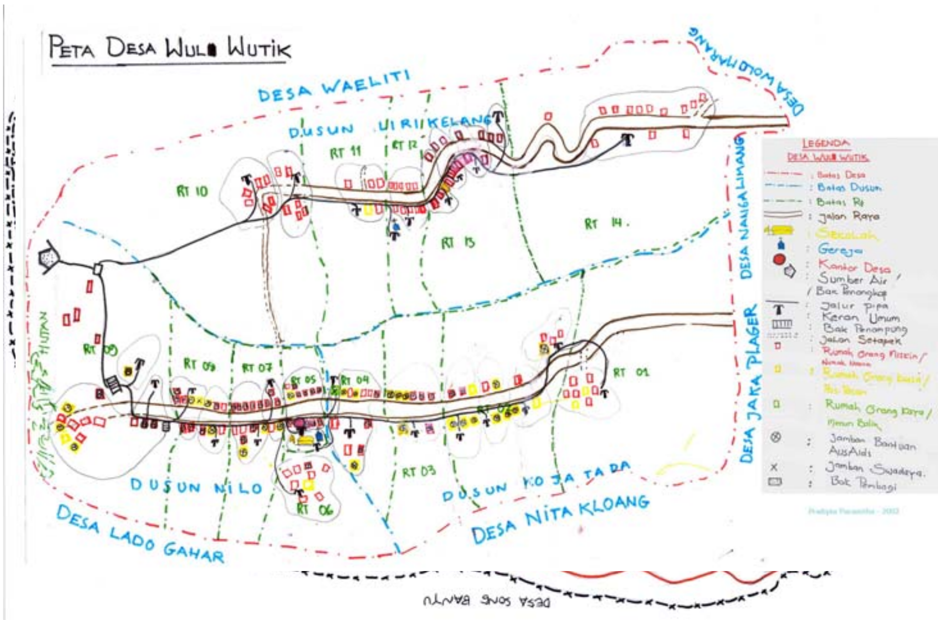

Figure 7. Example of a social map with houses in green, yellow and red depicting better-off, middle income and poorer households (courtesy Pradipta Paramitha, Jakarta)

Once decisions have been made, the committee will guide the implementation process. This will include organising self-help activities, such as digging trenches, checking depth and smoothness and backfilling and the curing of concrete at standpoints. After completion, the committee will supervise operation, maintenance and simpler repairs, organise more complex repairs, and exercise financial management, ensuring regular accounting to users for the management of the scheme and the accounts. This requires a sufficient amount of training on management and administration. It will be necessary to determine a training venue in consultation with community members, to ensure that it is accessible. It may, for example, be practically and culturally difficult for women to go to a different location and/or to be away for some time. Training on the job can facilitate access for all members.

The facilitating roles with communities and households are central. As women are often more effective and better accepted in communicating with women, and men more effective and better accepted with men, this implies that facilitators of both sexes are needed. If this has not been possible, working with local intermediaries, such as female teachers, may be effective and acceptable. Skills and attitudes for participatory work are only to a certain extent acquired through training – more important is an inherent capacity to observe, respect poor people and be good communicators. This is essential, for example, when urban, educated facilitators are working with semi or non-literate community members.

Communities should never left on their own after training. Individuals may leave their posts or become demotivated, technical problems may change or other pressures on communities may destabilise arrangements. A long-term arrangement for periodic back-up is needed to assist with technical and administrative tasks to keep systems operational, financially secure and in use.

10. Case studies

10.1 Point-of-use arsenic removal project in Bangladesh

Point-of-use arsenic removal systems represent the only feasible short-term approach for arsenic removal in rural Bangladesh and other countries where there is no piped water supply and/or centralised treatment facilities. Several POU systems have been tested and developed in Bangladesh and some have become commercially available (see 8.2 above). Some have shown promising results, but testing of effectiveness and sustainability has been relatively short-term.

For several years UNESCO-IHE (IHE Delft) has been developing an adsorbent-based POU system (the IHE family filter) to remove arsenic from groundwater at household level (Shahidullah 2000; Petrusevski et al. 2000, Omeroglu 2001, Petrusevski et al. 2002). The results of preliminary field-testing of this technology conducted in 2001 and 2002 in rural Bangladesh were very promising (Hossain 2002). To speed-up development IHE Delft together with a number of other organisations obtained funding from Partners for Water, an agency of the Dutch Government to develop the family filter at demonstration scale in Bangladesh. The first phase took place from May 2003-June 2004. The other organisations were Vitens (the largest Dutch Water Supply Company), IRC International Water and Sanitation Centre, Norit Filtrix (Leading Dutch supplier of water treatment equipment) and Christian Service Society (CSS) NGO in Bangladesh).

The family filters consisted of a PVC filter column (90-100 mm in diameter), feed and treated water buckets, connecting tubes and an orifice as a flow control device. The capacity of the filter was approximately 40 l/day, sufficient to provide water for drinking and cooking purposes for a typical family in a rural Bangladesh. Each filter was filled with iron oxide coated sand (IOCS) [size 1.0-4.0 mm; iron content 354 mg Fe/g sand] originating from a Dutch groundwater treatment plant, placed on a supporting layer of coarse material (sand or pumice). As outlined in section 8.1, IOCS has a high arsenic adsorption capacity (Petrusevski et al. 2000; Petrusevski et al. 2002). The filters were operated in an up-flow mode at a filtration rate of 0.20-0.25 m/h. The filters were regularly cleaned under gravity by opening the drain valve at the bottom of the filter. The frequency of filter cleaning varied from once in four days to once in two weeks based on the iron concentration in the groundwater. The feed buckets were regularly cleaned to remove iron flocs.

Based on the findings of the first field study in Bangladesh (Hossain, 2002), the design of the IHE family filter was further improved and 2nd generation prototypes were installed and operated in four different houses in the Rajbari district of Bangladesh (Begum, 2003). In a 75-day test, the family filter confirmed under field conditions its ability to consistently produce arsenic free water (<10 μg/L) from highly arsenic contaminated groundwater.

Some of the shortcomings of this prototype family filter included a high concentration of arsenic and iron in the filtrate for some time after the filter had been drained, the development of air locks that could block the flow after feed bucket washing, and a requirement for occasional cleaning of the tubes.

Building on the experience of the previous two field studies and short missions, an improved prototype IHE family filter was developed and field-tested at 12 different sites in Rajbari, Kushtia and Khulna districts of Bangladesh (Khan, 2004). Shortcomings experienced with the previous prototype were solved and the capacity of the filter was increased to 100 L/day.

Arsenic concentrations in groundwater at the 12 test-sites ranged from 180 µg/L to 544 µg/L. All the 12 filters removed arsenic consistently to a level below the Bangladesh standard of 50 µg/L for a testing period in excess of 450 days (Figure 8). Ten filters out of 12 removed arsenic to a level below the detection limit of AAS-GF (4 µg/L), which is much lower than the WHO standard of 10 µg/L. Iron concentration in groundwater at the 12 sites ranged from 3.95 mg/L to 20.5 mg/L. All 12 filters removed iron consistently to a level below the Bangladesh standard of 1 mg/L for the whole testing period of four months.

The operation of the family filter is very simple and easy. An operational and maintenance guideline was prepared for the users in Bengali and, following a short training period, they were able to follow operational procedures. The family filter prototypes tested in this study were well accepted and highly appreciated by the families in rural Bangladesh and their neighbours. Water from the filter was very attractive mainly due to its crystal clear appearance (removal of iron) and the taste of the product water was also considered pleasant. Users expressed their willingness to pay to keep the family filter after the field-testing was complete. The filters are still in operation in these households with the operation periodically supervised by the local NGO, CSS.

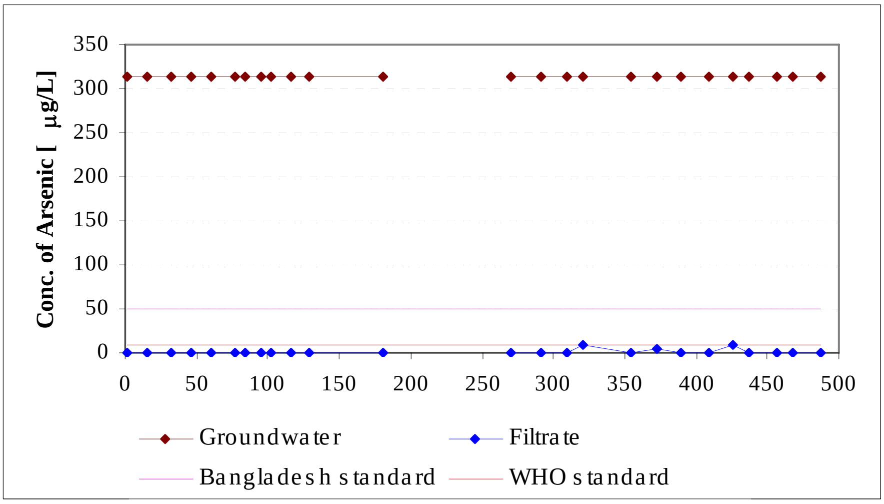

Figure 8. Arsenic removal achieved with IHE family filter installed in Tilok, Khulna, Bangladesh. The top line represents the original levels of arsenic in the water and the bottom line represents arsenic levels following filtration. The characteristics of the groundwater were Fe = 16.5 mg/l; NH4 =3.6 mg/l; pH = 6.9

One of the M.Sc studies conducted under this project also compared the performance of the IHE family filter with three other POU arsenic removal systems namely Alcan Filter, Shapla Filter and Star Filter, in rural Bangladesh (Akter, 2004). The IHE Family Filter and Alcan Filter consistently removed arsenic and iron below the WHO guideline values of 10 µg/l and 0.3 mg/l respectively during the field-testing. The Shapla filter also removed arsenic below the Bangladeshi standard of 50 µg/l but it was not effective in iron removal. Most of the time iron concentrations in the filtrate were higher than the WHO guideline value of 0.3 mg/l and frequently more than Bangladeshi standard of 1.0 mg/l. The Star filter was not so effective. Initially it showed some arsenic removal, but after 110 days of operation, arsenic was observed to completely break through the filter. Iron concentrations in the filtrate were also often more than 1 mg/l.

Figure 9. IHE arsenic removal filter in use in rural Bangladesh

10.2 Arsenic removal pilot project in Hungary

Within the European Union Hungary is the country most seriously affected by arsenic in groundwater, with approximately 20% of all groundwater exceeding EU norm of 10 μg/L. Groundwater is the main source for drinking water production in this country, and since current groundwater treatment technologies in Hungary are ineffective for arsenic removal, there is an unacceptably high arsenic presence in drinking water. The magnitude of the problem was recognised only recently when it emerged that approximately 400 towns and villages in Hungary have arsenic levels several times higher than the EU norm and WHO guidelines (Csalagovits 1999). Under recent legislation, all water supply companies in Hungary will have to fulfil European Union legislation, including arsenic concentration, by 2009. This will be a major challenge.

Drinking water in the Makó region is exclusively produced from groundwater that is frequently contaminated with arsenic. Out of 50 production wells, six have already been taken out of production due to very high arsenic concentrations (up to 30 times higher than the EU standard). A further 30 wells have elevated arsenic concentrations that several times exceed drinking water guidelines. These wells are still in production because they are required in order to provide required sufficient drinking water for the population. In addition to arsenic, groundwater used for drinking water production in this region also contains ammonia, methane, hydrogen sulphate iron and manganese.

There has been an urgent need to improve the situation by providing groundwater treatment systems in the Makó area. No experience of such complex water treatment was available in the region, and commercially available arsenic removal systems are complex and expensive. Water supply systems confront very similar situations in other counties of South and Southeast Hungary where thousands of consumers are at high risk from arsenic in their drinking water.

Since 2003, UNESCO-IHE Institute for Water Education, in co-operation with SELOR (a Dutch technology group) and Vitens, the Dutch drinking water supply company, have been conducting field experiments in the Makó region with demonstration scale pilot plants treating arsenic contaminated groundwater (arsenic concentrations up to 260 μg/L) from several different wells. These pilots plants make use of an innovative arsenic removal technology developed by UNESCO-IHE based on adsorption on IOCS (the same material originating from Dutch groundwater treatment plants and used in the POU family filters described in 10.1). In order to prolong the lifetime of the adsorbent, a simple procedure for in-situ regeneration of exhausted adsorbent was developed and successfully tested in the field. Two adsorptive arsenic removal filters were placed in series and pre-treatment (aeration- rapid sand filtration) was introduced to remove other impurities that could interfere with arsenic removal. The plant scheme is outlined in Figure 10.

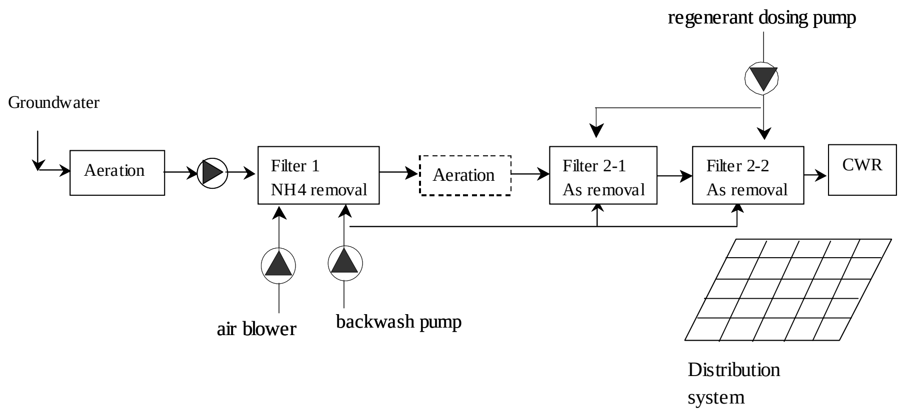

Figure 10. Process scheme of the demonstration scale groundwater treatment plant installed in Makó, Hungary

Extensive water quality analysis during several months of continuous operation of pilot plants in Makó area confirmed the ability of this treatment technology to consistently produce water with arsenic < 10 µg/l throughout the whole testing period, irrespective of the raw water arsenic concentration and speciation (Figure 11). In addition, very efficient and consistent removal of methane, ammonia, iron and manganese was achieved (Petrusevski et. al 2005, UNESCO-IHE 2006).

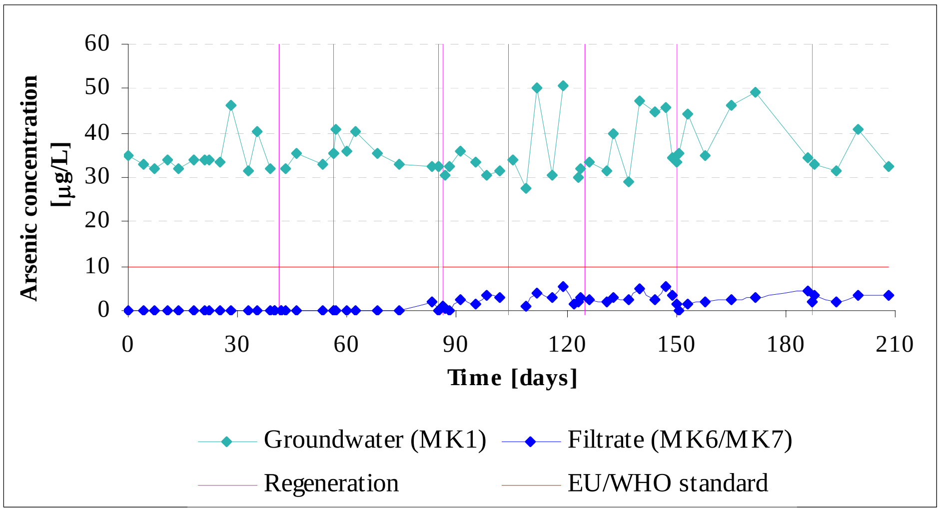

Figure 11. Arsenic concentration in influent and in filtrate of the demonstration scale groundwater treatment pilot plant in Makó, Hungary

This feasibility study, financially supported by EVD, an agency of the Dutch Ministry of Economic Affairs, included a detailed life cycle cost analysis that took into account all investment, financing and operational costs and the disposal of waste, and showed that overall treatment costs will be approximately 0.10 Euro/m3. This arsenic removal technology obtained a licence in 2006 for its application in Hungary.

Glossary and acronyms

Glossary of some scientific terms used in this TOP

Adsorption	Process of accumulation of a substance (gas, liquid, or dissolved substance) on a surface
Anion	Ion with negative charge (an excess of electrons)
Arsenic (sensitivity to) mobilisation	Arsenic present in soil in rocks and minerals can be dissolved in ground water under both aerobic and anaerobic conditions
Bed volumes	Volume of filtrate (water passing through a filter) in comparison to the volume of the filter bed.
Chemical speciation	Distribution of an element amongst defined chemical species or forms in a system
Empty Bed Contact Time	The ratio of length of filter bed (in metres) to filtration rate (in metres per hour; calculated as flow (m^3/h) over filter surface area (in m^2)
Equilibrium concentration	Concentration of a solute in a given adsorption system at which there is no change in concentration over time
Flocculation	The process of bringing small particles (flocs) together to form bigger particles/flocs, making it easier to remove.
Ion	An electrically charged atom or group of atoms
Jar-test experiment	A bench-scale experiment to determine and optimise the amount of coagulant needed under given conditions
LD50	Toxicity expressed as number of milligrams of a compound per kilo body-weight that results in death of half of those who ingest it
(Negative) surface charge	The electrical charge present at an interface for instance on surface of arsenic compounds dissolved in water
pH	Measure of acidity or alkalinity of water (hydrogen ion concentration in water)
Phytoremediation	The use of plants and trees to remove or neutralise contaminants, as in polluted soil or water
Redox-sensitive	Sensitive to the process of reduction (gain of electron) or oxidation (loss of electron); substances which are oxidised or reduced relatively easily
Valency	The relative combining capacity of an atom or a group of atoms compared with that of the standard hydrogen atom. Arsenic is mainly found in water in two forms: trivalent (As (iii)) or pentavalent arsenic (As (v))
Microfiltration, ultrafiltration, nano-filtration.	Membrane filtration processes with smaller pore sizes from micro- to ultra- to nano-filtration enabling smaller particles (impurities) to filter water

Acronyms

AA	Activated alumina
AAS – GF	Atomic absorption spectroscopic method (electrothermal)
AAS – HG	Atomic absorption spectroscopic method (hydride generation)
AIIH&PH	All India Institute of Hygiene and Public Health
As (III)	Trivalent arsenite
As (V)	Pentavalent arsenate
ASV	Anodic stripping voltammetry
AusAID	Australian Agency for International Development
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
BGS	British Geological Survey
BUET	Bangladesh University of Engineering and Technology
CSS	Christian Service Society
DMAA	Dimethyl arsenic acid
DPHE	Bangladesh Department of Public Health Engineering
EBCT	Empty Bed Contact Time
EVD	Agency for International Business and Cooperation, the Netherlands
GFH	Granular Ferrichydroxide
GPL	General Pharmaceuticals Ltd. (Bangladesh)
HIV	Human immunodeficiency virus (the cause of AIDS)
IARC	International Agency for Research on Cancer
ICP	Inductively coupled plasma
ICP-AES	Inductively coupled plasma atomic emission spectrometry
ICP-MS	Inductively coupled plasma mass spectrometry
IOCS	Iron oxide coated sand
IRC	IRC International Water and Sanitation Centre, Delft, the Netherlands
IX	Ion exchange
Mg/L	Milligrams (thousands of a gram) per litre
μg/L	Micrograms (millionths of a gram) per litre
MMAA	Monomethyl arsenic acid
NGO	Non-governmental organisation
NIPSOM	National Institute of Preventive & Social Medicine
POE	Point of Entry
POU	Point-of-use
PVC	Polyvinyl chloride
RO	Reverse osmosis
SDDC	Silver diethyldithiocarbamate detection method
UNICEF	United Nations Children's Fund
USEPA	U.S. Environmental Protection Agency
USOSHA	U.S. Occupational Safety and Health Administration
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNESCO-IHE	Institute for Water Education, Delft, Netherlands
WHO	World Health Organization
WSP	Water and Sanitation Program
WSP-SA	Water and Sanitation Program South Asia

TOP books, articles, papers

Aquatic Arsenic Toxicity and Treatment
Editors: Murphy, T. and Guo, J., Environment Canada; 2003
This book reviews arsenic toxicity in the worst sites in Asia and in Latin America. The arsenic levels found at these sites contrast sharply with the new the proposed USA EPA standard of 10 µg/L. Fear of cancer has driven most efforts to remove arsenic from water. However, some studies in Taiwan indicate that there may be a threshold that is critical when setting standards and performing any risk analysis. There are also important regional differences in the response to arsenic that are not understood. This book reviews various technologies that can remove arsenic from water or contain arsenic contamination at the source. Management of arsenic contamination must reflect the culture of the country but use global scientific and engineering principles.

Arsenic and Arsenic Compounds
WHO, Environmental Health Criteria Series, No. 224, 521 pages; 2001
This book evaluates the risks to human health and the environment posed by arsenic and arsenic compounds. Arsenic is widely distributed in the earth's crust and is emitted into the atmosphere by coal-fired power generation plants and volcanic activity. Inorganic arsenic of geological origin is found in groundwater in several parts of the world, e.g., Bangladesh. In these areas, drinking water is the main source of arsenic intake, but elsewhere food is the principal source.

Arsenic Awareness in Six Bangladesh Towns
Authors: Suzanne Hanchett, Qumrun Nahar; Astrid van Agthoven, Cindy Geers, and Md. Ferdous Jamil Rezvi; Publisher: Royal Netherlands Embassy; Dhaka, 2000
This report focuses on the general public’s reaction to the news about arsenic, their specific concern and their water use practices. It also examines the effectiveness of communication strategies and whether people at different economic levels respond differently.

Arsenic Contamination: Bangladeshi Perspective
Editor M. Feroze Ahmed. Published by ITN-Bangladesh; 2003
Collection of papers covering different aspects of arsenic contamination, focused on Bangladesh.

Arsenic Contribution from Dietary Sources
Authors: E Pellizzari, J Raymer, C Clayton, R Fernando, L Milstein; 2004
AWWARF Report Series
This study provides important findings about arsenic in the diet and drinking water that will enhance scientific risk assessment. This study presents results from cooking studies, a market basket survey and a diary analysis. The relationships between environmental and biological media presented here may be used in scenario-based models to predict arsenic

exposure, allowing regulators, utility managers, and consumers to obtain risk assessments based on science.

Arsenic in Drinking Water

Published by Subcommittee on Arsenic in Drinking Water, National Research Council, USA, 330 pages; 2001 (Updated)

Arsenic in Drinking Water evaluates epidemiological data on the carcinogenic and non-carcinogenic health effects of arsenic exposure on Taiwanese populations and compares these with the effects of arsenic exposure in other countries including the United States. The book also reviews data on toxicokinetics, metabolism, and mechanism and mode of action of arsenic to ascertain how these data could assist in assessing human health risks from arsenic exposures

Arsenic in Drinking-water

The World Health Organization (WHO); 2006

This publication is prepared under the auspices of WHO in collaboration with the World Bank and UNICEF under the authority of the Administrative Committee on Water Resources (ACCSCWR). *Arsenic in Drinking-water* provides a synthesis of current knowledge of a key concern of global drinking-water safety. It has been prepared as part of the UN coordinated action in response to the serious health problems caused by arsenic in drinking water. It will be a valuable source of reference for all those concerned with drinking water including planners, research and development staff, government officials, and development aid agencies at national and regional levels.

Arsenic in the Environment, Cycling and Characterization (Advances in Environmental Science and Technology)

Editor: Jerome O. Nriagu: 448 pages; 1994

The first of two volumes (see also below) covering both the chemistry and effects of arsenic, and aimed at chemists and environmental engineers. It explores the history, chemical composition and characteristics of arsenic and examines its behaviour in the environment, and the analytical techniques used to measure it. Some specific topics are mobilisation and bioavailability in soil, its removal from drinking water, and the environmental effects of using arsenic in aquatic weed control.

Arsenic in the Environment, Human Health and Ecosystem Effects (Advances in Environmental Science and Technology)

Editor: Jerome O. Nriagu: 320 pages; 1994

This is the second part of the comprehensive, study of arsenic (see entry above) that examines arsenic's complex and potentially deadly chemistry, and its effect on human health and the surrounding ecosystem. It features original research on the health effects of environmental arsenic; toxicity and metabolism of inorganic and methylated arsenicals; the effects of arsenic on DNA synthesis of human lymphocytes; estimations of human exposure to and uptake of arsenic found in drinking water; and arsenic hazards to plants and animals.

Arsenic Exposure and Health Effects
Editors: W.R. Chappell, C.O. Abernathy, R.L. Calderon and D.J. Thomas
These proceedings (2003) of the Fifth International Conference on Arsenic Exposure and Health Effects,14-18 July 2002, San Diego, California, contains several papers on arsenic contamination of water and its toxicological effects, specifically on human health.
Note that the proceedings of the earlier third international conference are also a valuable resource – see next entry.

Arsenic Exposure and Health Effects
Editors: W.R. Chappell, C.O. Abernathy, R.L. and Calderon
These proceedings (1999) of the Third International Conference on Arsenic Exposure and Health Effects,12-15 July 1998, San Diego, California, contains several papers on arsenic contamination of water and its toxicological effects, specifically on human health, and the treatment of victims of chronic arsenic poisoning. This is a valuable reference in addition to the proceedings of the fifth international conference (see entry above).

Arsenic in Groundwater: Geochemistry and Occurrence
Editors: Welch, A. H.; Stollenwerk, K. G.; 488 pages; Springer Publications, 2003
This book consolidates much of what is known about the geochemistry of arsenic and provides information on relationships between high concentrations of arsenic in groundwater and geochemical environments. The subject matter of this book ranges from molecular-scale geochemical processes that affect the mobility of arsenic in ground water, to arsenic contaminated ground water at the national scale. Chapters were contributed by an international group of research scientists from a broad range of backgrounds. Information includes reviews of existing thermodynamic data for arsenic-containing mineral phases and aqueous arsenic species, factors that affect adsorption of arsenic in common ground water environments, and spectroscopic techniques used to determine the chemical reactions controlling arsenic partitioning between solid and liquid phases at particle-water interfaces.

Arsenic Poisoning - A Medical Dictionary, Bibliography, and Annotated Research Guide To Internet Ref (US Edition)
Icon Health Publications; 84 Pages; 2004
This is a 3-in-1 reference book. It gives a complete medical dictionary covering hundreds of terms and expressions relating to arsenic poisoning. It also gives extensive lists of bibliographic citations. Finally, it provides information to users on how to update their knowledge using various Internet resources. The book is designed for physicians, medical students preparing for Board examinations, medical researchers, and patients who want to become familiar with research dedicated to arsenic poisoning.

Arsenic Contamination of Ground Water in Bangladesh: Cause, Effect and Remedy
Published by Dhaka Community Hospital (DVH), Bangladesh with Support from Ministry of Environment and Forest (MoEF) and Sustainable Environmental Management Programme (SEMP); 2003

These proceedings of the fourth international conference on arsenic in Bangladesh (12-13 January 2002) collect 38 papers on different aspects of arsenic contamination of groundwater in Bangladesh including epidemiology, toxicology, socio-cultural impacts and remedial measures.

Arsenic Contamination: A Bangladesh Perspective
Editor: M. Feroze Ahmed. ITN-Bangladesh; Published by ITN, Civil Engineering Building, BUET, Dhaka-1000, Bangladesh; 2003
An edited volume with very useful information for serious students or researchers of arsenic contamination of drinking water in Bangladesh.

Arsenic Poisoning in Bangladesh: End of a Civilization?
Author: Jamal Anwar; 321 pages; Palash Media Publisher, Dhaka Bangladesh; 2000
This book deals with arsenic source, processes and toxicology. It makes a critique of the surveys of British Geological Survey, present arsenic mitigation projects, arsenic in agrochemical, arsenic purification methods and importance of surface water irrigation in Bangladesh.

Arsenic Removal From Drinking Water (UK Edition)
Author: Bianchelli, Tatiana; 150 pages; Nova Science Publishers, Inc; 2004
Reviews research in the US into the incidence of high arsenic levels, the removal of arsenic from groundwater and the effect of low doses of arsenic on humans.

Arsenic Removal by Enhanced Coagulation and Membrane Processes
Authors: Hering, J.G. and Elimelech, M., 217 pages; 2001
Published by AWWA and AWWARF
This research report of AWWA and AWWARF provides an overview of arsenic removal by the processes of enhanced coagulation with and without membrane filtration processes, elaborating on process conditions (pH, coagulant dose, arsenic species, presence of other ions) and the removal of the particulate formed by micro and ultra-filtration.

Arsenic: Environment and Health Aspects with Special Attention to Groundwater in SE Asia
Editors: Chakraborti, D., Hussam, A. and Alauddin, M.; 2003
This is a special issue of the Journal Environmental Science and Health (Mercel Dekker, USA) Volume 38, No 1 (2003) and contains information on arsenic problems in India, Nepal, Bangladesh, Taiwan, Australia and some articles on health aspects.

Chemistry and Treatment of Arsenic in Drinking Water
Authors: Narasimhan, R., Thomson, B. and Chwrika, J.; 550 pages, American Water Works Association; 2005
The USEPA promulgated a new drinking water arsenic regulation in 2001 that required more than 4,000 water systems to install treatment or other mitigation measures by January 2006. This is the first comprehensive treatment and design handbook to address the necessary implementation and operational activities. Designed to increase

understanding of arsenic treatment and provide guidance to utility managers, engineers, consultants, operators, and state regulators in implementing compliant measures.

Demonstration of Emerging Technologies for Arsenic Removal, Vol. 1: Bench-Scale Testing
Published by: American Water Works Association (AWWA) and AWWA Research Foundation; 119 pages; 2004.
A comprehensive evaluation of most currently available arsenic removal technologies. It can assist water utilities, especially small systems, in planning, process selection, system design, operation, and maintenance. The methodologies in the report also provide useful guidance on pilot testing and full-scale implementation.

Disposal of Waste Resulting from Arsenic Removal Processes
Authors: Cornwell, D., MacPhee, M., Mutter, R., Novak, J. and Edwards, M.; American Water Works Association Research Foundation; 2003
It is essential for utilities that are in the process of selecting an arsenic removal treatment technology for drinking water to also identify the types of residuals that would be generated, their expected arsenic concentrations, and pre-treatment strategies that would be required prior to final disposal. This document provides utility guidelines for disposal of residuals containing elevated concentrations of arsenic.

Environmental Chemistry of Arsenic
Editor: William T., Jr. Frankenberger, 410 pages, Marcel Dekker; 1st edition; 2001
This book contains contributions from international scientists on topics related to toxicity of arsenic, analytical methods for determination of arsenic compounds in the environment, health and risk exposure of arsenic, biogeochemical controls of arsenic, treatment of arsenic-contaminated water, and microbial transformations of arsenic that may be useful in bioremediation.

Fate of Arsenic in the Environment
Editors: Feroze Ahmed, M. Ashraf Ali, Zafar Adeel; 2003
A compilation of papers presented at the International Symposium on Fate of Arsenic in the Environment (5-6 February 2003 Dhaka, Bangladesh) organised by Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh and The United Nations University, Tokyo, Japan with assistance from ITN Centre, Bangladesh.
Available online at http://www.unu.edu/env/Arsenic/BUETSymposiumProc.htm

Field Measurement Methods For Arsenic In Drinking Water (US Edition)
Author: Laurie McNeill, Ryan Anderson, Marc Edwards, Siyuan Morton; 92 pages, American Water Works Association; 2004
With the lowering of the arsenic levels by the EPA, smaller utilities face a challenge to efficiently and cost-effectively monitor arsenic concentration. This project sought to develop a fast, safe easy-to-use and relatively inexpensive field method as existing and newly introduced kits were found lacking in various ways. The new field method developed by this project is based on a standard hydride generation protocol. While field-testing did

not prove as accurate as laboratory tests it still has some value. Also discussed are the arsine gas detector modification potential, methods to provide automated "on-line" monitoring and utilisation for arsenic removal.

Speciation of Arsenic in Water and Biological Matrices

Author: X. Chris Le; 145 pages; Publisher: AWWA Research Foundation and American Water Works Association; 2001

This report presents the conclusions of a study on the speciation of arsenite (As(III)), arsenate (As(V)), monomethylarsonic acid (MMA), and dimethylarsinic acid (DMA) in water and biological matrices. Several analytic methods were employed to identify trace levels of individual arsenic species, with an eye toward current concerns over human exposure and more stringent environmental regulations. Chapters discuss HPLC with HGAFS detection, the use of disposable cartridges, stability and preservation in water and urine, molecular fluorescence detection, and the application of urinary arsenic speciation techniques. Appendixes describe protocols for arsenic speciation in urine and water.

Natural Arsenic in Groundwater: Occurrence, Remediation and Management

Editors: Bundschuh, J., Bhattacharya, P. and Chandrashekharam, D.; A.A. Balkema Publishers Taylor & Francis Group plc, London, UK; 2005

This publication is based on the papers presented at the Pre-Congress Workshop "Natural Arsenic in Groundwater" during the 32nd International Geological Congress at Florence, 18-19 August 2004.

Venomous Earth: How Arsenic Caused The World's Worst Mass Poisoning

Andrew Meharg, 208 pages, Publisher: Palgrave Macmillan; 2005

Venomous Earth describes arsenic contamination as the worst chemical disaster in human history. It explores the geology, politics and biology of why tens thousands of people are dying, hundreds of thousands developing cancer and tens of millions of people are at risk in Bangladesh, India and beyond, from arsenic-contaminated water. Venomous Earth looks at how the arsenic crisis is to be tackled and highlights new challenges.

TOP websites on arsenic

This TOP does not include a separate list of contacts. The websites mentioned below will help you to find experts on the topic.

Asia Arsenic Network (AAN)
http://www.asia-arsenic.net/index-e.htm
The AAN website provides information on Asia's arsenic problems, some test kits used in Asia, removal technologies and a newsletter.

British Geological Survey
http://www.bgs.ac.uk/arsenic/home.html
The arsenic page of British Geological Survey provides links to their reports on "Groundwater studies for arsenic contamination in Bangladesh" (Phase 1 and 2) including maps and data. Additionally there is some information on arsenic contamination of groundwater in Ghana.

Dhaka Community Hospital, Bangladesh
http://www.dchtrust.org/arsenic_problem.htm
Dhaka Community Hospital played the pioneering role in bringing the arsenic crisis in Bangladesh issue into limelight. The website provides information on arsenic contamination in Bangladesh and other countries in the world, social problems and health effect of arsenic, and efforts for its prevention and remedy.

EAWAG, SANDEC, Switzerland
http://www.eawag.ch/news_e/arsenic/e_index.html
This website contains information on SANDEC/EAWAG research on arsenic in drinking water including Solar Oxidation and Removal of Arsenic (SORAS) Technology.

Engconsult Limited, Toronto, Canada
http://www.eng-consult.com/arsen.htm
This website dedicated to the rural poor of Bangladesh contains information and links to statistics, arsenic removal technologies, arsenic references and online articles, organisation involved

Groundwater Arsenic Research Group (GARG), Royal Institute of Technology, Sweden
http://www.lwr.kth.se/Personal/personer/bhattacharya_prosun/Garg/index.htm
GARG, Sweden is involved in research on hydro-geochemistry of the high-arsenic groundwaters, together with sediment geochemistry to enhance the understanding of the geochemical processes at the sediment-water interface responsible for arsenic mobilisation in the sedimentary aquifers. This web site contains information and publications on different studies on geochemistry of arsenic and low-cost arsenic removal technologies.

Harvard University Arsenic Project
http://phys4.harvard.edu/~wilson/arsenic/countries/arsenic_project_countries.html
This very comprehensive and rich website contains information on arsenic contamination in different countries (with the link to references), health effects, books, conferences and remediation technologies

International Groundwater Resources Assessment Centre (IGRAC), The Netherlands
http://igrac.nitg.tno.nl/ggis_map/start.html
The Global Groundwater Information System (GGIS) at the website of IGRAC provides the information and maps of groundwater quality and quality in different countries and regions around the world, including arsenic concentration in groundwater.

Lehigh University, USA
http://www.lehigh.edu/~aks0/arsenic.html
The arsenic page of Lehigh University website provides information on arsenic crisis in Indian subcontinent and details of the well head arsenic removal unit developed by the university and field-tested in India.

Massachusetts Institute of Technology (MIT), USA
http://web.mit.edu/watsan/arsenic_tech.htm
This website provides information on different arsenic removal technologies and links to different field works and theses completed by MIT students on arsenic removal in Nepal. It also provides link to “Murcott Arsenic Remediation Technologies - Online Information Database” which is a very good database on technologies used for arsenic removal worldwide at laboratory, pilot of full-scale.

National Arsenic Mitigation Information Centre (NAMIC)
http://www.bwspp.org/photo_albam.html
The Government of Bangladesh (GOB), with assistance from the World Bank and Swiss Development Cooperation, initiated a national programme to address the arsenic problem under the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP). A National Arsenic Mitigation Information Centre (NAMIC) within the project aims to bank all arsenic related information collected or generated by stakeholders and integrates, analyses, stores and disseminates the information.

NGO Forum on Drinking Water Supply and Sanitation, Bangladesh
http://www.ngoforum-bd.org/
This website provides information on activities of NGO Forum related in arsenic mitigation in Bangladesh. NGO forum also provides an information window on arsenic, called NGOs Arsenic Information and Support Unit (NAISU).

Seven Trent Services
http://www.severntrentservices.com/water_purification/filtration_products/arsenic.jsp

This web site of Seven Trent Services provides information about their SORB 33 arsenic removal system which employs the granular ferric oxide (Bayoxide E33) media for arsenic removal.

SOS Arsenic Network
http://www.sos-arsenic.net
This web site provides information on arsenic contamination in groundwater of Bangladesh, its associated health and social problems, removal technologies and ongoing projects in four languages (English, French, German and Spanish). Also contains information about arsenic contamination in Nepal and Inner Mongolia and links to case studies and pictures of the sufferers.

Sustainable Development Networking Programme, Bangladesh
http://www.sdnbd.org/sdi/issues/arsenic/index.htm
This web provides link to information on workshops, articles and reports on arsenic, arsenic removal technologies and organizations involved in arsenic removal in Bangladesh. Several papers and reports are available to download.

The Arsenic Site
http://thearsenicsite.net/1/
The arsenic site is a forum for discussing cost-effective solutions for the international water-borne arsenic crisis. The goal of is to build a community of responsible individuals with accurate perspectives on the matter of reducing arsenic levels in drinking water.

The National Academies Press (NAP), USA
http://books.nap.edu/catalog/6444.html
This website provides online access to *Arsenic in Drinking Water* published by National Research Council of USA.

UN Synthesis Report on Arsenic in Drinking Water
http://www.who.int/water_sanitation_health/dwq/arsenic3/en/
This report has been prepared in cooperation with other UN agencies under the auspices of an inter-agency coordinating body (the Administrative Committee on Coordination's Sub-committee on Water Resources. It provides a synthesis of available information on chemical, toxicological, medical, epidemiological, nutritional and public health issues; develops a basic strategy to cope with the problem and advises on removal technologies and on water quality management.

UNICEF
http://www.unicef.org/bangladesh/wes_420.htm
This web site of UNICEF provides information on arsenic problem in Bangladesh, arsenicosis and activities of UNICEF assisted Arsenic measurement and mitigation project.

United Nations University, Japan (UNU)
http://www.unu.edu/env/Arsenic/Index.htm

The website contains information on arsenic contamination in the Asian regions including proceedings of the different conferences, workshops and meeting on fate of arsenic in water and removal technologies.

United States Environmental Protection Agency (US EPA)
http://www.epa.gov/safewater/arsenic.html
A resource-rich website with information on arsenic occurrence, health effects and risks. Analysis (measurement) techniques, removal technologies and costs, waste disposal.

United States Geological Survey (USGS)
http://water.usgs.gov/nawqa/trace/arsenic/
This website provides detailed information on arsenic contamination of groundwater in the United States and links to documents and sites on arsenic.

US Filter - Arsenic Removal with GFH Media
http://www.usfilter.com/water/Business+Centers/General_Filter_Products/General_Filter_Products/general_filter_gfh.htm
This web site provides information about the arsenic removal system of US filter using GFH Media.

WaterAid, UK
http://www.wateraid.org.uk/international/what_we_do/where_we_work/bangladesh/2546.asp
This site contains useful and informative online reports on arsenic namely (i) Arsenic 2002 - An overview of Arsenic Issues and Mitigation Initiatives in Bangladesh. and (ii) The Rapid Assessment of Household Level Arsenic Removal Technologies (Phase I and II). The web site also contains facts sheet on Groundwater in Bangladesh, Ghana and Nepal.

West Bengal India and Bangladesh Arsenic Crisis Information Centre (ACIC)
http://bicn.com/acic/
Online focal point for the environmental health disaster in Bangladesh and West Bengal, India, where millions of people are drinking ground water heavily contaminated with arsenic. Site includes infobank of news articles, scientific papers, comprehensive links to other relevant sites, online forum, email newsletter, and local site search.

World Health Organisation (WHO)
http://www.who.int/mediacentre/factsheets/fs210/en/
WHO arsenic page contains comprehensive information on arsenic contamination of drinking water worldwide, its sources, health effect and guidelines. It also has links to other websites related to arsenic.

Water Supply Program, The World Bank
http://www.wsp.org/08_Region_output.asp?Region=South+Asia
A number of reports on arsenic contamination of drinking water in Bangladesh and ongoing mitigation activities are available at this web site.

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About IRC

IRC facilitates the sharing, promotion and use of knowledge so that governments, professionals and organisations can better support poor men, women and children in developing countries to obtain water and sanitation services they will use and maintain. It does this by improving the information and knowledge base of the sector and by strengthening sector resource centres in the South.

As a gateway to quality information, the IRC maintains a Documentation Unit and a web site with a weekly news service, and produces publications in English, French, Spanish and Portuguese both in print and electronically. It also offers training and experience-based learning activities, advisory and evaluation services, applied research and learning projects in Asia, Africa and Latin America; and conducts advocacy activities for the sector as a whole. Topics include community management, gender and equity, institutional development, integrated water resources management, school sanitation, and hygiene promotion.

IRC staff work as facilitators in helping people make their own decisions; are equal partners with sector professionals from the South; stimulate dialogue among all parties to create trust and promote change; and create a learning environment to develop better alternatives.

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