
23 Technologies for arsenic removal from groundwater

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23.1 Occurrence of arsenic in groundwater

Arsenic is the twentieth most abundant element in the earth's crust. It is normally found dissolved in surface and ground water in the order of magnitude of micrograms per litre ($\mu\text{g/L}$). It is a highly toxic element, but when dissolved in water it is colourless, odourless and tasteless and cannot be easily detected. Arsenic concentration above the drinking water supply standard has been found in groundwater from large parts of Argentina, Chile, Taiwan, Inner Mongolia, Mexico and the western USA. However, the worst situations are in Bangladesh and in the State of West Bengal in India. In Bangladesh, out of approximately 8 million tubewells, about 3 million are contaminated with arsenic above the acceptable limit, and 20 million people are potentially at risk. WHO has described this crisis as the largest mass poisoning in the world. In West Bengal another 5 million people are at risk.

In 1993 WHO lowered its guideline value for arsenic in drinking water from 50 to 10 $\mu\text{g/L}$. Several countries have also lowered their standard to match. However, many developing countries, including Bangladesh and India, still have 50 $\mu\text{g/L}$ as their standard.

Until recently arsenic was not an element for routine measurement in groundwater supply or quality assessment programmes, particularly in developing countries. However, the recent discovery of widespread arsenic contamination in Bangladesh and India has made it necessary to investigate this parameter in other hydro-geological environments. Mining-related arsenic contamination is often locally confined and it does not tend to disperse far beyond the mining areas because of its sorption onto mineral surfaces, particularly ferric hydroxide. The wide contamination of aquifers outside mining areas is due to natural geo-chemical processes over thousands of years. The exact mechanism of arsenic release and its mobility into the groundwater is not yet known. There are two hypotheses for the developments in Bangladesh and West Bengal:

- Arsenic occurs in sedimentary pyrite and arsenopyrite and is released by oxidation as the water table is lowered in response to groundwater pumping.
- Arsenic occurs adsorbed onto iron and manganese oxyhydroxides, which are carried in the suspended load of rivers, and is released by natural reductive processes accompanying burial of the sediments.

Arsenic is harmful only when it is consumed internally, i.e. it is used for drinking and cooking. No adverse affect had been reported for external usage like washing and bathing. Boiling does not remove arsenic from water.

23.2 Arsenic-related health problems

After fluoride, arsenic is the naturally occurring chemical constituent of groundwater that causes the most health-related problems. Arsenic-related diseases occur when arsenic-contaminated water is consumed over a long period of time (years). The severity of illness depends on the contamination level, the period of consumption, and the nutrition level of the person concerned. It also differs from person to person. A clear explanation for this variation is not yet known.

The symptoms of arsenic-related diseases are both visible and invisible (sub-clinical). Both are equally harmful. The main visible symptoms in the first stage of arsenic related disease are the darkening of the skin and the appearance of black spots (melanosis), and the hardening of palms and soles of feet (keratosis). In the second stage, raindrop-like white spots appear on the skin (leuko-melanosis), palms of hands and soles of feet grow hard, growths and cracks appear and they become very painful (hyper-keratosis). Other symptoms are the swelling of the feet and complications in kidney and liver functions. The third stage is damage of internal organs like lungs, kidney, liver, bladder, etc, and in extreme cases gangrene and cancer. As internal damage can occur without showing any visible symptoms, it is difficult to identify all arsenic affected patients.



Fig. 23.1. Visible symptoms of hard growths and cracks in the sole of arsenic affected patients.

23.3 Cure for arsenic-related diseases

Arsenic toxicity has no known effective medicine for treatment. **The only cure for arsenic-related disease is consuming arsenic-free water.** During the early stages of the disease it can be reversed by drinking arsenic-free water, which flushes the toxicity out of the body. But at a later stage the disease becomes irreversible and when the vital organs are damaged the patient often suffers a painful death. As for medical care, sometimes multi-vitamins are recommended to assist the body's immune system and ointments are applied in cracked hands and soles to prevent secondary infection.

23.4 Arsenic testing

Arsenic contamination in water can be tested in laboratories. Field test kits are available commercially and can detect arsenic contamination down to 50 µg/l with an acceptable accuracy. New generation field test kits claim to detect down to 10 µg/l. However, they have not been widely tested as yet. Handpump tubewells in villages can be tested with the field test kits. In Bangladesh, when the arsenic concentration is found to be above the allowable limit, the handpump is painted red, indicating that it is not suitable for drinking and cooking. Otherwise it is painted green, showing that it can be used for all purposes.



Fig. 23.2. Testing of tubewell water by a field test kit (left) and a contaminated handpump being painted red indicating that it should not to be used for drinking and cooking (right).

If the handpump used by a group of people has been painted red, there must be another water source nearby that gives water with an acceptable arsenic content suitable for drinking and food preparation. That can be a green-painted handpump, a rainwater tank, or any other safe source. That also means that more people will go to the “safe” water sources to get their drinking and cooking water there. Often, it will be necessary to make sharing arrangements with the families that are already using these sources. Some form of agreement has to be reached between new and old user families. This may relate to the maximum number of new users and the exclusive purpose of use of the safe water (for drinking and cooking), because the yield of the source may be limited. But also issues such as the times of collection and the realistic contribution for the O&M cost because of the extra wear and tear, need to be agreed. Here, a facilitator with skills in participatory planning tools such as social maps and time diagrams helps to work out locally feasible arrangements.

23.5 Physical-chemical processes for arsenic removal

The technologies for removal of arsenic are based on one or a combination of several physical-chemical processes. The five common types of treatment are summarised below:

Oxidation: Arsenic in groundwater may occur as arsenite, As(III), and arsenate, As(V), in different proportions. Most arsenic treatment technologies are very effective in removing the pentavalent form of arsenic (arsenate), but the removal efficiency of the trivalent form (arsenite) is very low. Therefore, many treatment technologies include oxidation as a pre-treatment step to convert As(III) to As(V).

Atmospheric oxygen, hypochlorite and permanganate are most commonly used for oxidation process of arsenic in developing countries.



Other chemicals that are used include gaseous chlorine, ozone and other oxidising agents. Natural oxidation of arsenic by air is very slow and can take several weeks, but the above chemicals can oxidise rapidly.

Adsorption and co-precipitation: Conventional water treatment through coagulation is also effective for arsenic removal. For this method a coagulant (e.g. alum or ferric chloride) is added and rapidly mixed for about one minute. Aluminium or ferric hydroxide micro-flocs are formed (coagulation). The water is then gently stirred for a few minutes (flocculation) and the majority of the micro-flocs agglomerate into larger settleable flocs. During the coagulation-flocculation process many micro-particles and negatively charged ions are attached onto the flocs. Arsenic also attaches to the flocs (adsorption). Subsequently sedimentation and filtration (co-precipitation) are used to separate the flocs, together with the adsorbed arsenic.

Commonly used coagulants are alum, $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$; ferric chloride, FeCl_3 ; and ferric sulphate, $\text{Fe}_2(\text{SO}_4)_3 \cdot 7\text{H}_2\text{O}$. Ferric salts are comparatively more effective on a weight basis and operate over a wider pH range (6.0 – 8.5). Alum is effective over a narrow range of pH (7.2 – 7.5). In both cases, As(III) is not effectively removed, but As(V) is. Pre-oxidation is highly recommended.

Removal of naturally occurring iron: In many areas, including Bangladesh and West Bengal, arsenic in groundwater is often found together with high levels of iron and manganese. The conventional iron (and manganese) removal method of aeration,

flocculation (optional), sedimentation (optional) and filtration can also significantly remove arsenic. This process is basically similar to the adsorption and co-precipitation process except that no coagulant is added. During aeration and flocculation, iron hydroxide flocs are created. Arsenic is attached onto these flocs, and separated by sedimentation and filtration. Some remaining arsenic in the solution can also be removed by adsorbing onto the iron coating formed over the filter sand grains.

The efficiency of this process is low if the water contains a low amount of iron or if the proportion of As(III) is low. In these cases, the removal efficiency can be increased by addition of coagulants (e.g. alum or ferric chloride) and oxidants (e.g. chlorine) respectively.

Sorption on filter media: When arsenic-contaminated water is passed through a sorption media bed, its media can remove arsenic. The commonly used media are activated alumina, activated carbon, iron and manganese coated sand, activated carbon, kaolinite clay, and hydrated ferric oxide. The efficiency and the total amount of water treated depend on the media and the water composition, as different contaminants and components of water compete for the available sites on the media. In most of the cases arsenic removal is very effective if oxidation is carried out before sorption.

Ion exchange: Synthetic ion exchange resins are a special kind of sorption media. They are used in water treatment to remove undesirable ions by replacing ions attached to the resins. With the continuing use of the resins their removal capacity is exhausted and they need regeneration.

The arsenic exchange equation can be represented as follows where **R** represents ion exchange resins and Cl⁻ is an ion attached to the resin.



The regeneration equation using common salt as regeneration agent is



Ion exchange is very effective when the form of arsenic in water is predominantly As(V). Otherwise a pre-oxidation step is necessary. Various anion exchange resins that can remove arsenic (arsenate) concentration below 1 µg/L are commercially available. Conventional sulphate-selective and nitrate-selective resins are suitable for arsenic removal. The arsenic removal capacity depends on the sulphate and nitrate contents of the raw water as they are exchanged prior to arsenic.

23.6 Technologies for arsenic removal

For large central treatment plants several technologies are available for removing arsenic. These technologies are based on one or more of the processes already described. Many of the technologies can also be scaled down to a smaller version for small towns and rural areas. The large-scale contamination of groundwater with arsenic was detected only in recent years. Several small version technologies have been installed on a pilot basis and others are emerging. So far experience with these technologies is low. Smaller version technologies can be classified according to their production capacity and number of users. Some promising technologies are discussed below. A summary of the processes and technologies is presented in table 23.1.

23.7 Community-scale treatment plants

Community-scale treatment plants are designed for small urban settlements or villages. The plants are operated in a continuous-flow mode and treated water is distributed through small-diameter pipelines.

Conventional plants: the treatment methods used in a conventional water treatment plant, i.e. application of coagulants (e.g. alum, ferric chloride), coagulation-flocculation, sedimentation and finally filtration, are also effective in arsenic removal. A small capacity conventional plant may be used for community level treatment. Normally groundwater is first aerated and other processes then follow. If groundwater contains a higher proportion of As(III), oxidation by air alone is not sufficient to oxidize As(III) to As(V) for effective arsenic removal. In that case after aeration an additional chemical oxidation step (e.g. chlorine) is recommended.

Iron removal plants: When groundwater contains an excessive amount of iron (and/or manganese), plants designed for iron removal treatment can at the same time remove arsenic. Depending on the proportion of As(III) in the water, a chemical oxidation step may be required. Many iron removal plants do not use flocculation and sedimentation; the flocs formed as a result of the presence of natural coagulants or added coagulants are removed in the direct filtration step. Figure 23.3 shows a direct filtration process of iron and arsenic removal.

Other methods that can be used in small communities are arsenic-specific filter units (like activated alumina filters) and ion exchange resin beds. These units may need a coarse sand pre-filter unit to remove excessive iron so that iron hydroxide flocs formed do not clog the subsequent filter units. Again a chemical oxidation step may be necessary depending on the proportion of As(III).

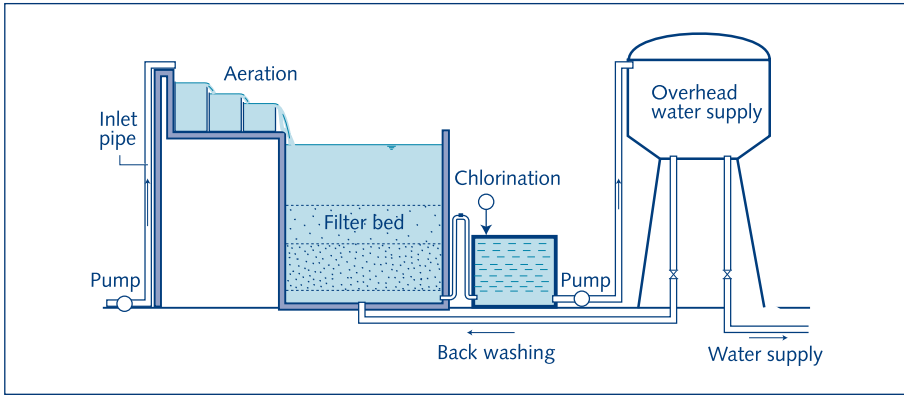


Fig. 23.3. Schematic diagram of iron and arsenic removal plant in Bangladesh

23.8 Arsenic removal units attached to tubewells

Handpump tubewells are widely used for rural water supply in many developing countries. However, many of the tubewells in Bangladesh and West Bengal, which were believed to be safe for drinking, are now found to be arsenic contaminated. Attempts have been made to develop treatment units attached to these tubewells. The units normally operate in intermittent flow mode and the treated water is carried manually in containers (such as pitchers, buckets and cans). Tubewell-attached units can be used by a number of families in the neighbourhood. Three types of units are described below.

Compact conventional treatment unit: In villages of West Bengal, India, compact conventional treatment units for arsenic removal are attached to contaminated handpump tubewells. Figure 23.4 shows a typical unit. In this case the treatment processes include chemical oxidation by sodium hypochloride, addition of alum as coagulant, mixing, coagulation-flocculation, sedimentation and upflow filtration.

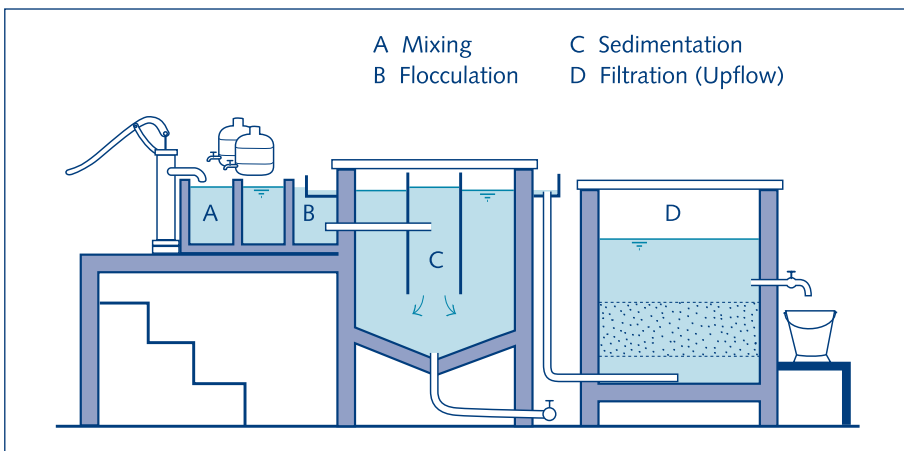


Fig. 23.4. A compact conventional treatment unit attached to a tubewell

Iron removal unit: This is a small version of an iron removal plant and is attached to a handpump tubewell. It is used where groundwater contains an excessive amount of iron. Figure 23.5 shows a typical design of a unit with a cube with side dimensions of about 1 m. The treatment method consists of aeration, sedimentation, flocculation and sedimentation in a roughing filter and final filtration. The water from the handpump tubewell is passed through a slotted horizontal PVC pipe and falls into the cubical structure. The structure consists of three chambers. Water from the slotted pipe falls into the first chamber and aeration occurs. Here partial sedimentation also takes place. Water from the first chamber then enters the bottom of the second chamber, which is an upflow roughing filter with coarse aggregates (20-30 mm). Here, flocculation-sedimentation occurs and iron hydroxide micro-flocs grow in size with most of them settling onto the coarse aggregates. The partially filtered water then overflows into the third chamber, consisting of a bed of coarse sand or small aggregates, and a final downflow filtration takes place. The filtered water is delivered through an underlying compartment and pipes. During the iron removal process arsenic is removed by adsorption and co-precipitation.

The iron removal units require regular washing to maintain them in a proper working condition. Where the iron concentration is over 10 mg/l, partial cleaning is required every seven to ten days. Partial cleaning is done by scraping the top layer of the smaller grain filter media in the third chamber, opening all washouts and pouring two to three buckets of water over each chamber. The scraped filter media is cleaned and replaced in position. Complete washing is required once a month. This is a laborious process that takes at least one person-day. It involves taking out all the filter materials, thoroughly washing and replacing them.

Sorption media filters: A filter unit consisting of sorption media can also be attached to a handpump tubewell. If the water contains a high amount of iron, a pre-filter unit of coarse sand is often required. The pre-filter unit must be washed periodically. Units with activated alumina on the sorption media are installed in many places in Bangladesh and West Bengal on a pilot basis. These units have a coarse sand pre-filter unit. The arsenic removal efficiency of activated alumina is high (> 95 %) and both arsenite and arsenate can be removed. Activated alumina can be used for months before breakthrough and then it needs to be replaced or regenerated.

Other sorption media like filters with ion exchange resins can also be attached to tubewells. If needed the water can be oxidised by adding potassium permanganate in a pre-treatment step.

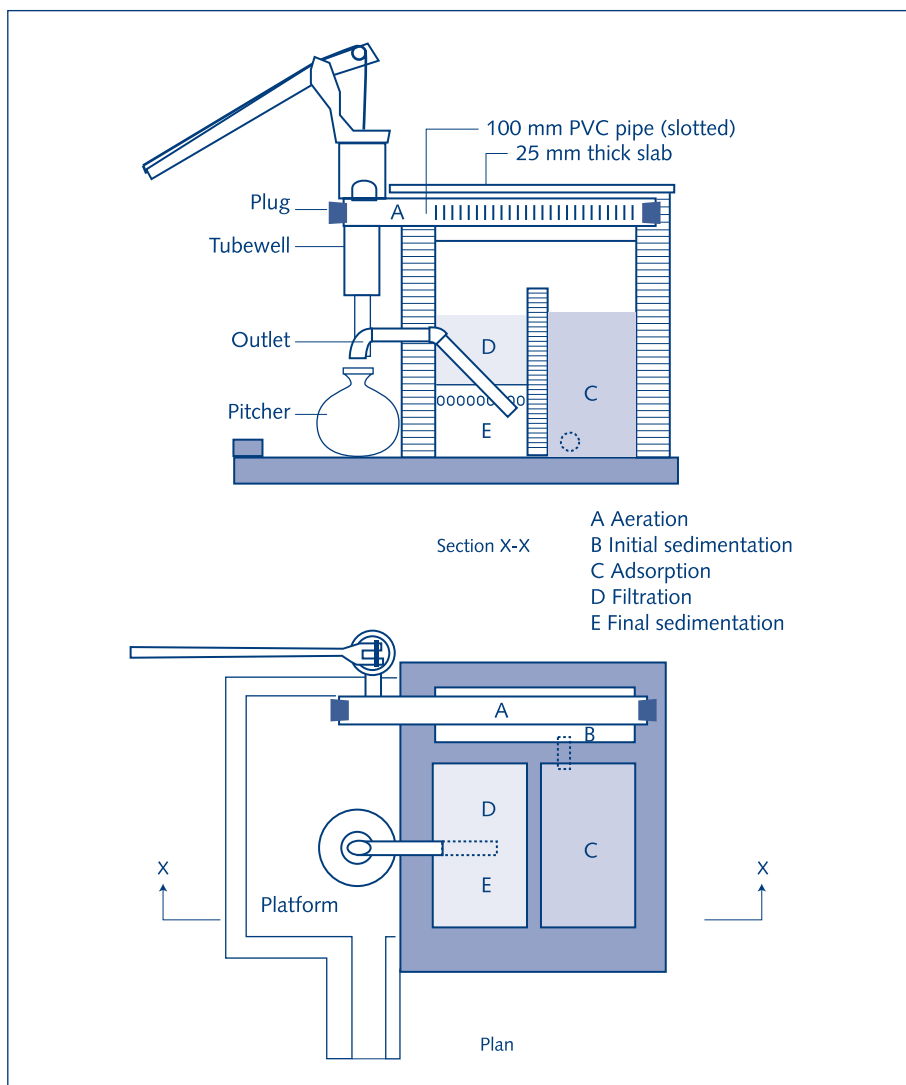


Fig. 23.5. A tubewell attached iron and arsenic removal unit

23.9 Household treatment units

Household units are basically meant to provide safe drinking and cooking water for a family. About 5 litres of water per capita per day is required. Several household treatment units are currently being proposed and others are under development. Normally, water from an arsenic affected source tubewell is collected and manually poured into the units. These units operate in batch flow mode. So far there is not much experience with the long-term effectiveness of household treatment units. Some promising ones are described below.

Two-bucket treatment unit: This method is based on the co-precipitation process. The unit consists of two buckets, each with a capacity of about 20 litres. Normally they are placed one above the other. Arsenic-contaminated water is poured in the top bucket. Chemicals are then added and vigorously stirred with a stick for about one to two minutes. Thereafter the water is gently stirred for flocculation for another two to three minutes. The mixed water is allowed to settle for about two hours. The chemicals added are a mixture of coagulant (e.g. alum, ferric chloride or sulphate) and oxidant (potassium permanganate, calcium hypochloride) in crushed powder form. They are normally supplied in single dose packages.

After settling, the top two thirds of the supernatant water from the first bucket is poured gently (or flows by plastic pipe) into the second bucket. The second bucket is half filled with filter sand and has a perforated underdrain pipe connected to an external tap. When the tap is opened the settled water passes through the filter sand, which removes the remaining micro-flocs. A schematic diagram of the two-bucket system is shown in figure 23.6.

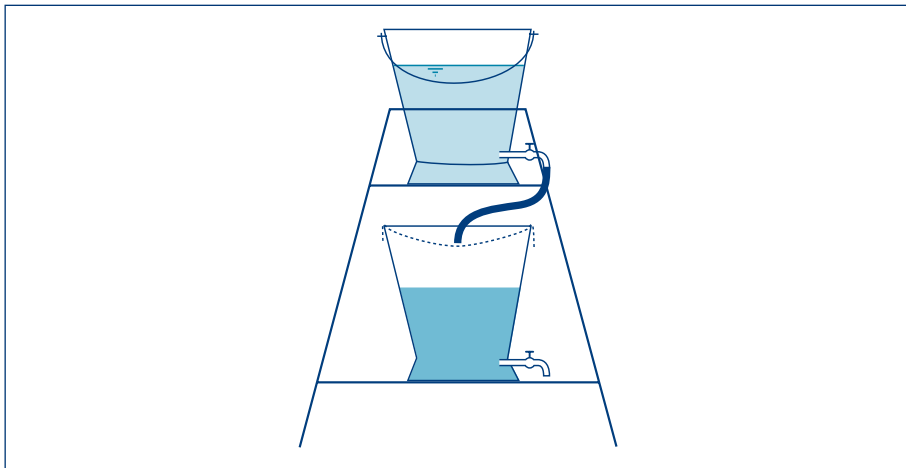


Fig. 23.6. Schematic diagram of a typical two-bucket household unit

The filter sand in the second bucket needs to be manually cleaned once or twice a week. Usually the women heads of households operate the filter. They need training in how to operate the system and to prevent bacteriological contamination of the water. Having women trainers facilitates communication and recognises women's water management roles.

Normally the two-bucket units can lower the arsenic concentration of effluent water to below the developing country standard of 50 µg/L. The performance varies with operation and maintenance skills and with the water quality parameters, especially pH. The use of ferric salts has been found to be most effective in arsenic removal.

Three-pitcher method: The three-pitcher filter consists of three 20-liter clay pitchers stacked in a frame. A schematic diagram of a typical three-pitcher filter is shown in figure 23.7. The top first pitcher contains 2 kg of coarse sand covered with 3 kg of iron filings. The second pitcher contains 2 kg of coarse sand with 1 kg of charcoal above it. The third pitcher collects the filtered water.

The three-pitcher filter has been found to be very effective in arsenic removal for the first four to six weeks. After that, the removal efficiency starts to decline. The flow rate of effluent is slow, about 1-2 litres per hour. Normally the three-pitcher filter needs to be replaced after three to four months as the efficiency declines and the iron filings in the first filter become clogged and hardened and cannot be removed. Although this method is effective in arsenic removal, the bacteriological contamination in effluent water is sometimes high as the open filter media harbour growth of micro-organisms.

Several household filter units have been developed that use different kinds of filter media. Some of the promising ones are iron coated sand filters, iron coated granular activated carbon filters, activated alumina and resin filters (see references). Research is also under way on a technology using solar energy – SORAS¹.

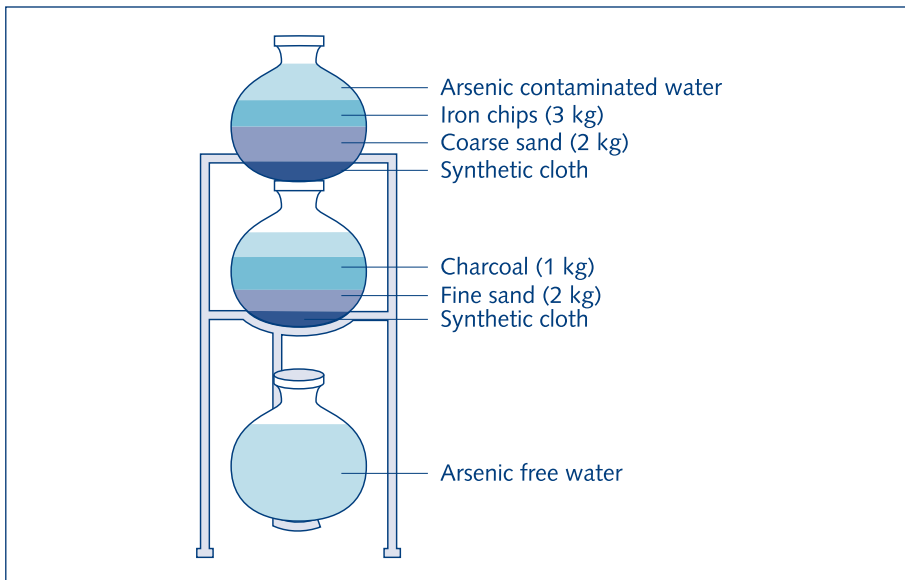


Fig. 23.7. Construction details of a three-pitcher filter

1 For SORAS (Solar Oxidation and Removal of Arsenic) see website:
<http://www.eawag.ch/research/arsen/d-index.htm>

23.10 Uncertainties and considerations for arsenic removal technology

There are several uncertainties and considerations related to the arsenic problem in drinking water supply. Often there is no systematic pattern in spatial distribution of arsenic contamination. In a village one tubewell may have arsenic concentration above the allowable limit whereas the neighbouring one may have no contamination. Therefore, all the existing tubewells need to be tested for their arsenic contamination level. Although research and investigation is going on, the exact mechanism of arsenic release into the groundwater and its mobility remain unclear, so there is an uncertainty in further spreading of arsenic.

Several technical and social uncertainties prevail in selecting an appropriate technology. Many technologies are being piloted and have promising results. They need to be properly tested over time and validated before large-scale replication. These technologies have to be socially acceptable and user friendly. And the filter materials (such as sand and iron chips) and chemicals packed for household use need to be available and affordable, otherwise their sustained operation and use will remain questionable.

The effect of arsenic on human health and the acceptable standard for drinking water are being debated globally and in specific countries. Several developing countries still have the standard as 50 µg/L but in the near future it may be reduced to the WHO recommended level of 10 µg/L. In that case many of the presently suggested technologies may become obsolete or will require modification.

The safe disposal of arsenic sludge is an environmental issue. The standards and methods are yet to be determined.

Finding an acceptable water source is an important issue. There are two main options: find a new arsenic-free water source or use the existing arsenic-contaminated water source and treat that water. In either case, the supplied drinking water has to be free from arsenic contamination, i.e. below the acceptable limit as well as free from bacteriological and other chemical contamination.

The new source may be surface water but that water needs to be treated. Rainwater harvesting is feasible in some areas. The new water source may also be groundwater that is arsenic safe and located in a different aquifer (e.g. a deep aquifer that appears to have water with no or low arsenic levels) or come from a suitable aquifer in a nearby location. In some areas dug wells with depths up to 10 metres are found to be free of arsenic contamination. Locating an arsenic-safe aquifer that will remain arsenic free in the long run requires substantial hydrogeological investigations.

When designing the production capacity of a treatment unit a decision has to be made about whether the amount of treated water is to be enough for all purposes or only for drinking and cooking. The plant type and the number of people using a unit have to be determined, i.e. will it be a community, a neighbourhood or a household level technology? In many instances, a central village level treatment unit and piped distribution system is preferred. This is because people like to have a higher, or at least equal, level of service compared with the existing contaminated one. Other advantages are that water quality monitoring can be done in one place instead of several and that the per capita costs can be comparable to other options. If a better technology emerges, or if water quality deteriorates, or the water quality standard is made more stringent in future, then the technology replacement or modifications can be conveniently done in one place. The private sector can be involved through the treatment and sale of the treated water in larger containers.

Hence, all the considerations, including possible future developments, have to be carefully weighed and discussed with the users; only then can they make a well-informed and balanced decision on the most suitable technology for their specific conditions. On the other hand, immediate supply of arsenic-free water is needed in arsenic-affected areas to prevent further spreading of arsenic-related diseases. Governments may make a decision to provide arsenic-safe water immediately by applying a proven technology. In parallel, field tests need to be carried out in search for the best long-term sustainable technologies.

Table 23.1 Summary of processes for arsenic removal

Physical-chemical processes	Removal efficiency		Experience with different scale of operation and remarks
	As (III)	As (V)	
Oxidation	n.a.	n.a.	This is not a removal process, but converts As(III) to As(V) for subsequent efficient removal. Oxidation by air is very slow and as such chemical oxidation is preferred. Chemical oxidation is a proven technology and requires moderate skill. Moderately expensive.
Adsorption and co-precipitation - using iron salts	++	+++	Well proven at central level, piloted at community and household levels. Phosphate and silicate may reduce arsenic removal rates. Generates arsenic-rich sludge. Relatively inexpensive.
Adsorption and co-precipitation - using alum	-	+++	Proven at central level, piloted at household levels. Phosphate and silicate may reduce arsenic removal rates. Optimal over a relatively narrow pH range. Generates arsenic-rich sludge. Relatively inexpensive.

Physical-chemical processes	Removal efficiency		Experience with different scale of operation and remarks
	As (III)	As (V)	
Naturally occurring Fe removal	?	+/ + +/ + + +	Little application in central systems, limited studies at community and household levels. More research is needed on which hydrochemical conditions are conducive for good arsenic removal. Inexpensive.
Sorption on filter media – activated alumina	+/ + +	+ + +	Tested in a pilot scale in community and household systems, in industrialised and developing countries. Can remove both forms of arsenic. In most areas chemical oxidation is not required. Regeneration requires strong acid and base and produces arsenic-rich waste. the long-term performance of regenerated media needs documentation. Water rich in iron and manganese may require pre-treatment to prevent media clogging. Moderately expensive.
Sorption on filter media - ion exchange resins	-	+ + +	Tested on a pilot scale in central and household systems, mostly in industrialised countries. Interference from sulphate and high TDS. High adsorption capacity, but long-term performance of regenerated media needs documentation. Water rich in iron and manganese may require pre-treatment to prevent media clogging. Chemical oxidation required for water with high As(III) proportion. Moderately expensive. Regeneration produces arsenic-rich brine.
Sorption on filter media – other media	+/ + +	+ +/ + + +	Has been shown to be effective in laboratory studies in industrialised and developing countries. Needs to be evaluated under different environmental conditions, and in field settings. Sometimes chemical oxidation required. Simple media are inexpensive, advanced media can be relatively expensive.

+++	Consistently > 90% removal
++	Generally 60-90% removal
+	Generally 30-60% removal
-	< 30% removal
?	Insufficient information
n.a.	not applicable

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Web sites

Bangladesh Arsenic Mitigation Water Supply Project <http://www.bamwsp.org>

WaterAid reports: <http://www.wateraid.org.uk/research/BangladeshA.htm>

SANDEC on SORAS technology: <http://www.eawag.ch/news/arsen/d-index.htm>

British Geological Survey: http://www.bgs.ac.uk/arsenic/bphase1/b_intro.htm

WHO: <http://www.who.int/inf-fs/en/fact210.html>

http://www.who.int/water_sanitation_health/Arsenic/ArsenicUNReptoc.htm

WELL: <http://www.lboro.ac.uk/well/resources/fact-sheets-htm/aidw.htm>

Environmental Protection Agency (USA): <http://www.epa.gov/safewater/arsenic.html>

