PRACTICAL ACTION
Technology challenging poverty

REMOVING ARSENIC FROM WATER

This brief outlines the different arsenic removal methods and technologies that are available for use with small-scale supplies in developing countries.

Introduction

Arsenic is a chemical element which exists in a number of forms and exhibits characteristics of both metals and non-metals. Arsenic has no taste, odour or colour, and long-term health risks. It is considered toxic to humans and long term exposure above the can result in skin thickening and pigmentation known as hyperkeratosis and cancer of the lungs, bladder and kidneys with a predicted 200,000 future cancer-related deaths. In addition cardiovascular and neurological diseases have been found to be linked to arsenic ingestion. The World Health Organization – WHO designated guideline for safe drinking water is not more than 10 micrograms per litre (µg/l) although many developing countries still use the older WHO level of 50 µg/l as their standard. Testing for arsenic is done in laboratories but field test kits are available commercially that commonly detect arsenic contamination down to 50 µg/l while newer field test kits claim to detect down to 10 µg/l. On its own the arsenic element is not very soluble in water but its compounds (HAsO42-(aq) and H2AsO4- (aq)) are very soluble.

Figure 1: An arsenic poisoned well in Bangladesh. When arsenic is found to be above the limit the well is painted red to indicate it is not suitable for drinking. Wells that are safe are painted green. Photo: Practical Action / Zul Mukhida.

Groundwater has often been proposed as a safe alternative drinking water supply to surface water, due to the low risk of contamination with harmful bacteria, thus reducing diarrhoeal disease. However, in many parts of the world including Ghana, Argentina, Chile, China, India, and the United States but most severely in Bengal and Bangladesh, this groundwater is contaminated with arsenic that occurs naturally within the rocks or in some cases introduced through industrial activities (i.e. gold mining in Ghana). Arsenic from mining tends to be more locally confined while naturally occurring arsenic can be widespread.

If arsenic levels are high it is necessary to either find an alternative water source or to treat the water and remove the arsenic. Surface water options such as rainwater harvesting, river sand filters or pond sand filters are again being promoted as an alternative to contaminated groundwater although the success of promoting groundwater has meant that people can be reluctant to use surface water options.

See Rainwater Harvesting documents for more information on this subject. And in many cases there is no safe alternative supply or the contaminated groundwater already replaces a microbiologically unsafe supply, so treatment is the only option.

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Arsenic removal is routinely carried out in large-scale water supplies in centralised plants by processes such as reverse osmosis, membrane filtration and ion exchange, but these are not appropriate for use with small-scale supplies in developing countries. For many, households the options for arsenic treatment are limited to simple technologies that can be done near to or at home.

Boiling water does not remove arsenic while passive sedimentation, that is storing water in pitchers, does reduce arsenic concentration in water to some extent but not always to a sufficiently low level. Storing water in this way is common practice in certain areas and allows time for oxidation and sedimentation to take place.

Small-scale Technologies

A number of arsenic removal technologies appropriate for small-scale supplies at a domestic or community level in developing countries that are currently available or under development are: outlined below.

- Arsenic and Iron Removal Plant (AIRP)
- Solar Oxidation and Removal of Arsenic (SORAS)
- Filtration
  - Arsenic Bio-sand Filter (ABF)
  - SONO filter
- Activated alumina filters
  - Magc-Alcan Filter
  - Nirmal Filter
- Coagulation and flocculation
  - Conventional coagulation based treatment unit
  - 2-Kolshi Filter
  - The Bucket Treatment Unit – BTU
- Ion-exchange resins
  - READ-F
- Absorbers
  - Granular Ferric Hydroxide AbsorpAs
  - Shapla Filter
  - Ceramic absorbers of nano-scale iron oxide particles on porous alumina tubes
- Subsurface aerated water injection
- Arsenic Removal Using Bottom Ash
- Electro-Chemical Arsenic Remediation (ECR)

These technologies and methods are discussed further below.

Arsenic and Iron Removal Plant (AIRP)

This very simple approach works on the principle of aeration where oxidation of arsenic and iron takes place transforming the contaminates into an insoluble form which can be trapped in filters.

The structure comprises 4 chambers connected with pipes that water can pass through. Water is introduced into the first chamber through a perforated inlet which increases the amount of oxygen contained in the water. This oxygen reacts with the iron and arsenic in the water, transforming them into their insoluble compounds which will then precipitate out. The water containing the precipitated compounds passes through

Figure 2: The larger AIRP structure for community use. Photo: Practical Action Bangladesh.

the next two chambers which are filled with different types and sizes of filter medium such as graded brick chips, stone chips, gravel and course sand. These filter medium absorbs and filters the iron and arsenic precipitates. The final chamber contains water that has a 70-75% reduction in arsenic compared to the untreated water.

This technology has been used by Practical Action in Bangladesh See http://practicalaction.org/a-small-scale-arsenic-and-iron-removal-plant for more details.

Iron content within the system must be maintained at a suitable level for reactions to take place so if there is not much iron within the water it needs to be added as nails or other small pieces within the plant.

The filter medium needs to be maintained in good condition and after the filter medium cleaning process is done, the effectiveness of the system may be reduced for a couple of days before the system starts to work properly again.

Solar Oxidation and Removal of Arsenic (SORAS)

SORAS use sunlight to trigger the photochemical oxidation of arsenic. Ultraviolet radiation catalyses the oxidation process. Containers need to be PET- or other UV-A transparent bottles.

The contaminants then precipitate out from the water as solid particles that sink to the base of the container, where they can either be filtered or the clear water above can be decanted off from the top.

As with the AIRP process there needs to be some iron for the reaction to work. Arsenic (III) converts to arsenic (V) and is absorbed into iron III.

See SORAS (Solar Oxidation and Removal of Arsenic from Drinking Water) http://wedc.lboro.ac.uk/resources/conference/26/wegelin-soras.pdf

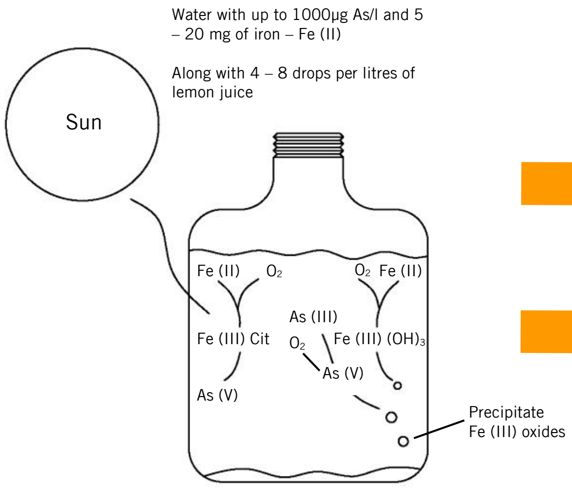

Figure 3: Solar Oxidation and Removal of Arsenic. Illustration: Practical Action / Neil Noble.

The actual process is as follows:

1. A container is partially filled with the untreated water and citrate or lemon juice is added. This will enhance the oxidation of arsenic and also maintain the presence of the oxidated iron III compound at a neutral pH7.
2. The container is then shaken for 40 seconds before being filled to 90% capacity before being left vertically in strong sunlight for approximately 3 hours. During this time the iron III hydroxides and absorbed arsenic V will precipitate.
3. The water is then left overnight for the precipitate to settle following which it can be filtered through a fine material.

The main disadvantage of this method is that it relies upon the presence of iron in water and is not effective otherwise. Trials in the Ashanti region of Ghana where iron wasn't naturally present in groundwater only showed an 8% reduction in arsenic levels while trials in Bangladesh showed an average reduction of around two thirds.

Also see SODIS - Solar Water Disinfection

Filtration

Arsenic *Bio-sand Filter (ABF)* is an adaptation of the bio-sand filter, designed to remove arsenic as well as improve the microbiological quality. The system works on a similar principle to the bio-sand filter (see Practical Answers Technical Brief on Bio-sand water filters) and is constructed from plastic or concrete, filled with layers of sieved and washed sand and gravel and with the addition of a diffuser basin or container in the top filled with non-galvanised nails to react with the arsenic. Water is poured intermittently into the diffuser basin and a layer or bricks prevent the iron nails from moving. The rust that forms on the outside of the nails reacts with the arsenic in the water, with a proven reduction of 85-95% from tests carried out in the field. To aid the development and maintenance of a biolayer called a schmutzedecke, the key pathogen removal component of the system, the water level should be kept approximately 5 cm above the top sand layer. The schmutzedecke takes up to 30 days to form but water can be removed before this time providing it is thoroughly disinfected.

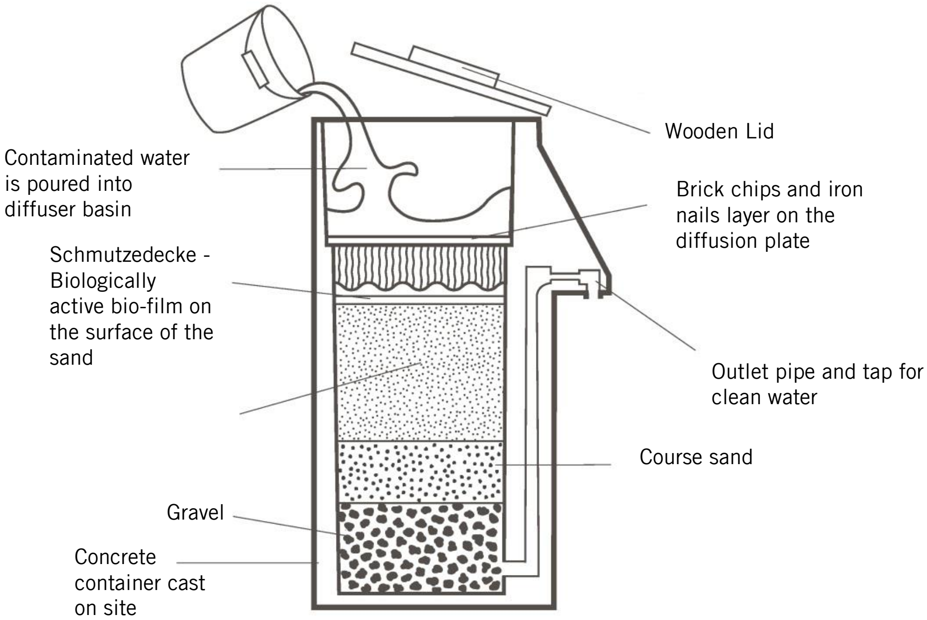

Figure 4: An arsenic bio-sand filter (ABF). Illustration: Practical Action.

In terms of maintaining the arsenic removal part of the system, only the nails would need to be replaced every 2-3 years to ensure the system remains efficient.

Also see http://web.mit.edu/watsan/tech_hwts_chemical_kanchanarsenicfilter.html

The *SONO filter* is small-scale point-of-use filter which uses locally available materials used for most of its construction with the exception of the composite iron matrix (CIM).

Its advantages include its low maintenance and locally sourced materials while its main disadvantage is that it uses a proprietary process in the preparation of the composite iron matrix.

The SONO filter is made from two buckets, one above the other. The upper bucket contains layers of coarse river sand, a composite iron matrix and brick chips. The water passes through these layers and then passes onto the lower bucket where it passes through layers of coarse sand, wood charcoal and fine sand. The water can then be collected from the lower bucket through a tap at the bottom of the bucket.

These are a low cost technology and can be made locally in terms of the Bangladesh situation, they are reliable and have a five year warranty although this is not always effective.

The disadvantages from a user's point of view, is that they have a slow rate of delivery and they are heavy and can be damaged in transit.

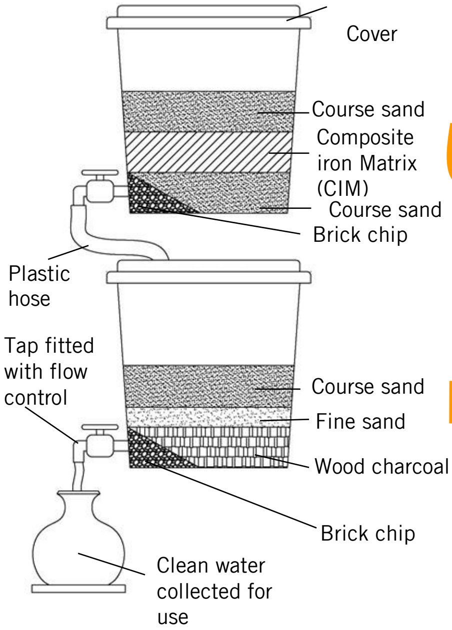

Figure 5: The Sono filter (stand not show). Illustration: Practical Action / Neil Noble.

Activated Alumina Filters

Phosphate, sulphate, chromate and fluoride are also removed by activated alumina, but nitrate is not. Saturated activated alumina can be regenerated with flushing with strong base followed by strong acid. Regenerated media loses some volume and eventually must be replaced. Like ion-exchange resins, activated alumina beds can be clogged by precipitation of iron.

The process will be more effective if air is mixed into the contaminated water at the start to introduce some oxygen.

The *Magc-Alcan Filter* design is a two bucket filter commercial product for household use. They are small and convenient to use but are more expensive than some other options in the Bangladesh market.

A porous activated alumina media is used in both of the buckets packed in beds that absorb the arsenic. Contaminated water is poured into the top bucket and allowed to pass through the activated alumina media and then to the lower bucket and again the water passes through the media and then it can be collected in a separate container ready for drinking once it has passed through both containers

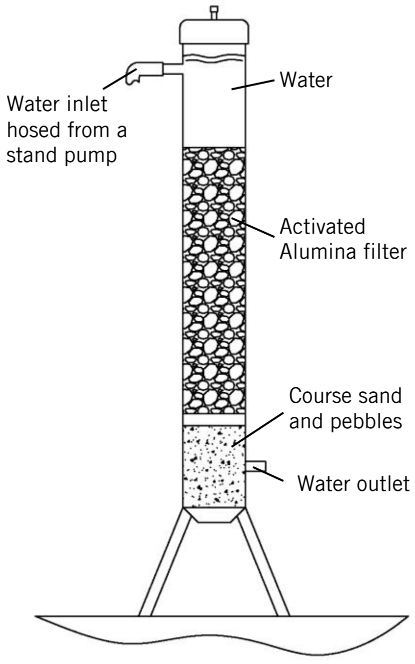

Figure 6: Activated Alumina Filters. Illustration: Practical Action / Neil Noble.

The Magc-Alcan Filter was developed by MAGC Technologies and Alcanof US by thermal dehydration (at 250-1150˚C) of an aluminium hydroxide and is sold in Bangladesh. Other issues that have arisen are that it does not have a reservoir which means people need to supply a separate vessel to contain treated water. And it can have a bad smell in its initial stage of use.

A similar activated alumina design, the *Nirmal Filter*", is available in India. It has a secondary filtration stage through a ceramic candle and is less expensive but it needs to be regenerated every 6 months.

Removal rates are sensitive to pH levels, activated alumina works best in slightly acidic waters (pH 5.5 to 6) but above pH 7 removal efficiency drops sharply. Additional equipment can be used to control pH levels. The main factors controlling bed run length are pH and arsenic concentration. Concentrations of other solutes have a relatively small effect. Typically several tens of thousands of beds can be treated before arsenic breakthrough.

Generally the process of filters and media make these products too expensive for poorer households.

Coagulation and flocculation

Coagulation is a treatment process that uses the addition of chemical coagulants such as iron sulphate or iron chloride to combine with the arsenic within the water to produce a solid precipitate that can then be filtered out and allowed to settle out from the water.

For the *2-Kolshi Filter* arrangement the coagulant is added to the water in a separate bucket. A specific amount of iron sulphate and sodium hypochlorite is mixed into the water creating a chlorine odour. Mixing with water adds oxygen converting As(III) to As(V) co-precipitates As^{5+} while iron chloride and ash brings the precipitated flocs together into bigger clumps making them easier to filter out.

After the water has settled for an hour it is then added to the first ceramic pot where it is filtered and passes into the lower pot. It produces 3-5 litres an hour and reduces microbial and arsenic contamination.

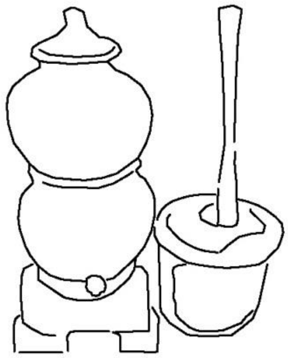

Figure 7: 2-Kolshi Filters with separate mixing bucket.
Illustration: Practical Action / Neil Noble.

The initial cost of the ceramic pots filter is around $10 but coagulant will cost around $15 to $20 per year.

The Bucket Treatment Unit – BTU has been developed within the DPHE-Danida project. It starts off with air being mixed into the water to provide some oxygen (loss of electrons of As(III) to form As(V)) and coagulation processes using potassium permanganate and aluminium sulphate. The water is then filtered through cloth into a second bucket that contains a sand filter.

The BTU can be constructed from locally available materials. The unit comprises 2 buckets stacked vertically. After the initial mixing the arsenic contaminated water is introduced into the top bucket which contains a number of iron rods placed upon a layer of fine sand. The oxygen in the water reacts with the iron rods to form iron III which precipitates as particles of iron oxyhydroxide ($Fe(OH)_3$). This $Fe(OH)_3$ which will absorb arsenic and settle on the base of the top bucket. The fine sand filters out this precipitate and prevents it from entering the second or middle bucket.

The bucket also contains a layer of wood charcoal weighted down with non-reactive materials such as rocks which serves to remove any organic impurities present in the water over a layer of fine sand which serves as a secondary filter to ensure any leftover particles of arsenic are removed and clean water enters the final or bottom bucket.

The main advantage of this system is that it doesn't rely on the presence of iron in water and although it isn't a quick method with every litre of water filtered it took 1 hour to collect the filtrate during trials in the Ashanti region of Ghana, it is shown to be highly effective in the removal of arsenic, with a 68-90% reduction noted.

The disadvantages are that the filter will easily clog in turbid water and this system isn't appropriate if the water contains large amounts of organic material. There is also some uncertainty as to whether the water's long residence time in the system encourages bacterial growth.

Ion-Exchange Resins

The *READ-F* exists as a community treatment unit and as a household treatment unit. It uses a proprietary resin bed of ethylene-vinyl alcohol copolymer-borne hydrous cerium oxide in which hydrous cerium oxide ($CeO_2.nH_2O$) is the absorbent filter developed by the Japanese company Shin Nihon Salt Co. Ltd. and Brota Services International of Bangladesh.

The units need iron removal by sand filtration to avoid clogging of the resin bed by iron flocs. In the household unit both the sand and resin beds have been arranged in one container while the community unit sand and resin beds are placed in separate containers.

It is effective at removing arsenic (95+%)absorbing arsenic ions in both arsenite and arsenate forms. A separate oxidation stage is not required and pH levels of the water does not have an impact on the treatment process.

READ-F can be regenerated by adding sodium hydroxide and then sodium hypochloride and finally washing with water. The regenerated READ-F needs neutralization by hydrochloric acid and washing with water for reuse.

The resin bed of household version has a long lifespan of over 3 years but is more costly than some other household units at around $50-70.

Absorbers

Ferric Hydroxide reactors are fixed bed absorbers operating like conventional filters with a downward water flow. The basic reaction is Water and Ferric Chloride reacts to produce Ferric Hydroxide and Hydrocloric acid outlined as....

$$3H_2O + FeCl_3 \longrightarrow Fe(OH)_3 + 3HCL$$

Ferric Hydroxide is a strong absorbent of Arsenate As(V).

Granular Ferric Hydroxide AbsorpAs® developed by SIDKO, a commercial company based in Bangladesh, is a community scale water treatment technology that has been used in Bangladesh. As a community based technology its throughput and cost are higher than individual household technologies, costing something in the region of $4,300 along with its running costs and it requires electricity to operate.

The system is self-operating although there is need for suitable maintenance and repair to keep the system working effectively. Therefore it is important to ensure that there is adequate technical knowledge available after installation. There is potential for the land owner or caretaker to "privatise" the supply but the community based approach tended to work quite well overall and can reduce the number of social conflicts.

Although it is intended to serve more than 50 households some serve a smaller number and so are not being made best use of so careful planning is required before implementing such systems. This also applies to the technical issues.

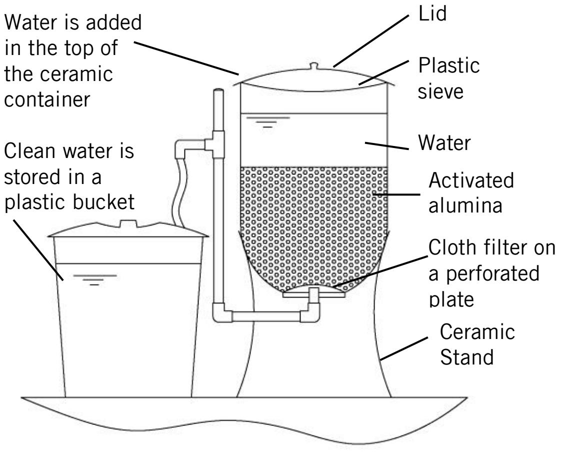

Figure 8: Activated Alumina Filters. Illustration: Practical Action / Neil Noble.

Social acceptance is dependent on how the plant is established and the quality of its management.

The *Shapla filter* is an earthen household arsenic removal technology developed by International Development Enterprises (IDE), Bangladesh. It is based on absorption of the arsenic to the iron on the coated brick chips, which works as well as iron coated sand. The bricks are coated by treatment with a ferrous sulphate solution (Ahmed, 2005). The filter can hold up to 30 litres of water.

As water passes through the filter, arsenic from the water is rapidly absorbed by the iron on the brick chips. The media (20 kg) filters 4,000 litres of arsenic-contaminated water reducing arsenic concentrations to undetectable levels and supplying an average family with 25-32 litres of safe drinking water per day.

Pour the water into the filter and allow it to pass through the filter medium.

The used filter media is non-toxic and can be disposed of safely without danger to the environment or human health. The media container is re-useable and easily maintained.

The *Ceramic absorbers of nanoscale iron oxide particles on porous alumina tubes* approach uses nano-scale iron oxide particles coated onto porous alumina (Aluminium oxide Al_2O_3) ceramic tubes that can absorb the reacted arsenic.

A filtration cell containing the arsenic contaminated water is connected to the ceramic tube and the water is driven into the tube via supply of air to the filtration cell. The water permeates through the tube and the arsenic contained absorbs onto the iron oxide particles.

Although the production of the iron oxide coated tubes is quite sophisticated the application of the technology is relatively simple and low cost. The process works at low pressure and does not require pumping.

This system is suitable for small-scale supplies but can also be adapted for use in a large scale system such a municipal water treatment plant. Additionally it does not create any liquid wastes.

Read more: http://www.lenntech.com/abstracts/217/iron-oxide-absorbers-for-arsenic-removal-a-low-cost-treatment-for-rural-areas.html#ixzz2pMgpmBFU

Subsurface aerated water injection

In this method aerated water is pumped into the saturated zone of an aquifer, either through an abstraction point or an adjacent purpose-built well.

The aerated water reacts with iron and manganese contained within the subsurface water to produce an oxidation zone, in which the oxidised forms of iron and manganese are precipitated onto soil grains within the aquifer. In the case of iron it is oxidised to Fe III which is strongly absorbing. When water is abstracted through the well it flows through this oxidation zone and arsenic contained in the groundwater will be absorbed onto the Fe III and thus removed.

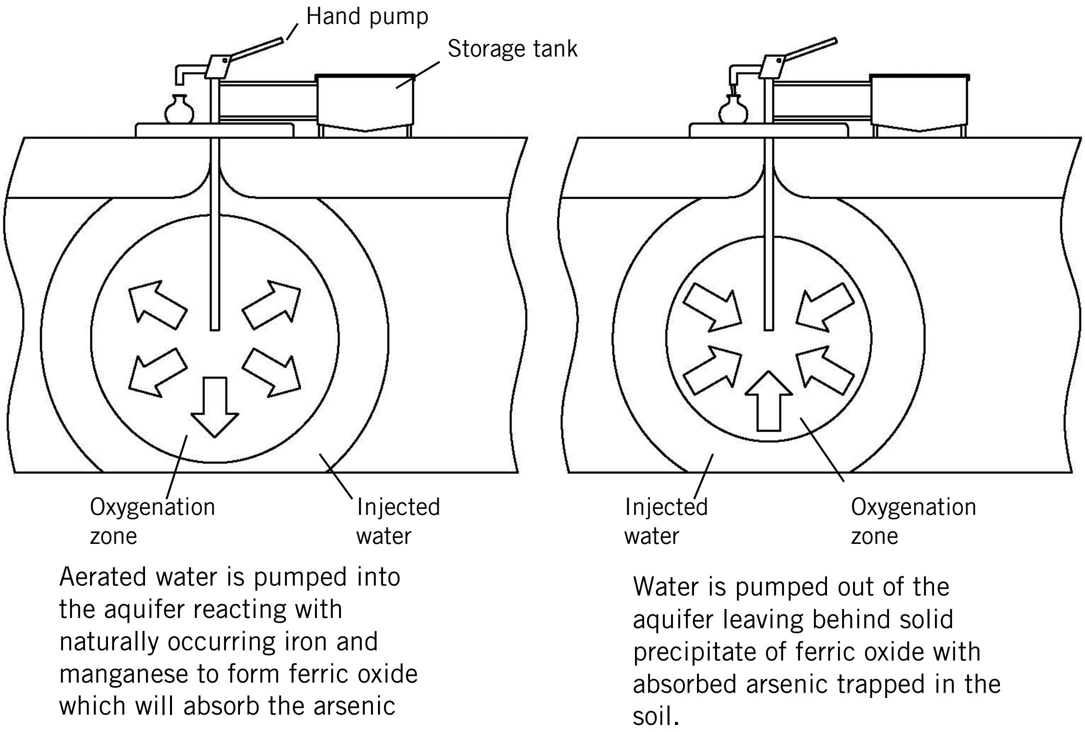

Figure 9: Subsurface arsenic removal. Illustration: Practical Action / Neil Noble.

This method can be carried out as a single, double or 4-well design.

The single-well design may be more practical for the household level but as water is injected into the abstraction well it will be non-operational for approximately 12 hours whilst the oxidation zone 'settles'.

Double-well designs have the advantage that the 2 wells can be used alternately for abstraction and injection, with the switch made when arsenic is removed from the extraction well.

This system is more suitable for multiple households. The 4-well design comprises a central extraction well surrounded by 3 injection wells, through which either large volumes of water are added intermittently or smaller volumes are added continuously. The disadvantage of adding water intermittently is that the system must be shut down for approximately 12 hours during injection, whilst there remain doubts that injecting smaller volumes continuously will sufficiently develop the oxidation zone upon which this arsenic removal system relies. In any case the 4-well design is suitable for large groups of people due to the large volumes of water involved.

Uncertainties exist in relation to arsenic remobilisation and the required groundwater properties which include the arsenic/iron ratio, effect of varying pH and interference in the process by other competing compounds such as phosphorous. Furthermore, it is not known if specific well dimensions may affect the creation of a sufficient oxygen supply, vital to the functioning of this method. Experiments on Hand-pump Subsurface Arsenic Removal carried out in rural Bangladesh, with small injection volumes of less than 1 m^3, found that it did not provide drinking water below the WHO arsenic guideline of 10 µg/l from the injection of oxygen rich water or from higher iron to arsenic rations nor from multiple injection-abstraction cycles. However, it was successful when the abstraction-injection ratio was increased to Va/Vi = 2.

See [Artificial Aquifer Tube-wells]
See http://subsurfacearsenicremoval.org/principle.html

Arsenic Removal Using Bottom Ash (ARUBA)

Waste material such as coal ash particles are coated with ferric hydroxide which the arsenic will bind with and then can be filtered out as a dark red solid.

The powder is sold to households at an affordable price for low income villagers. The powder is manufactured in factories and then distributed through a commercial network. This approach has been developed at Berkeley Lab and is licenced to companies who apply for exclusive rights for their particular location. This method has been tested in Bangladesh and Cambodia.

See http://eetd.lbl.gov/l2m2/arsenic.html

Electro-Chemical Arsenic Remediation (ECAR)

This approach uses a small electrical charge through an iron electrode to produce ferric hydroxides, oxyhydroxides, and oxides, a form of rust. The rust reacts with the arsenic in the water which is then filtered or allowed to settle out of the water.

The normal reaction of natural rusting is slow and consequently there have been efforts by Berkeley Lab to improve the speed at which rust is produced through the application of an electrical current. If not enough rust is generated then not all of the arsenic will be able to react and the water will remain contaminated.

The advantage of this approach is that it does not require continuous supplies of a treatment material from a centralised producer. The electrodes are self-cleaning when the current is reversed which can be done once a day.

The disadvantages include its complicated set up, the availability of the equipment, and its need for an electricity supply.

ECAR treatment is similar to another treatment process called electro-coagulation, which has been used to treat wastewater containing arsenic, but has an additional post electrical mixing stage with allows more time for the arsenic to react increasing the reduction in arsenic levels in the water.

ECAR can be applied to point of use applications or to larger community based systems.

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Saraban Tahura, S M Shahidullah, Tofizur Rahman and Abul Hasnat Milton, Rejuan Hossain Bhuiyan **"Evaluation of an Arsenic Removal Household Device: Bucket Treatment Unit (BTU)"** ***Technologies for Arsenic Removal from Drinking Water***
NGO Forum for Drinking Water Supply and Sanitation & The Department of Geography and Environment, Dhaka University

Suzanne Hanchett, Richard Johnston, Mohidul Hoque Khan ***Arsenic Removal Filters in Bangladesh*** UNC Water and Health Conference, October 5, 2011, EAWAG

Branislav Petrusevski, Saroj Sharma, Jan C. Schippers (UNESCO-IHE), and Kathleen Shordt (IRC) (2007) ***Arsenic in Drinking Water Thematic Overview Paper 17***
IRC International Water and Sanitation Centre

Other resources

Akvopedia, the open water and sanitation resource that anyone can edit, available at: http://akvopedia.org/wiki/Water_Portal

CAWST (Centre for Affordable Water and Sanitation Technology), available at: http://www.cawst.org/

SOS-Arsenic.net
http://www.sos-arsenic.net/english/mitigation/update_miti.html

Arsenic, UNICEF
http://www.unicef.org/bangladesh/Arsenic.pdf

A Safe and Simple Arsenic Detector
Researchers have built a bacteria-based device that sniffs out the toxic chemical.
By Jennifer Chu on January 25, 2007
http://www.technologyreview.com/news/407222/a-safe-and-simple-arsenic-detector/

An Overview of Arsenic Removal Technologies in Bangladesh and India
http://archive.unu.edu/env/Arsenic/Ahmed.pdf

Arsenic Removal Filters in Bangladesh
http://www.eawag.ch/forschung/sandec/publikationen/ws/dl/Hanchett_2011.pdf

Arsenic Project Remediation Technology
http://users.physics.harvard.edu/~wilson/arsenic/remediation/arsenic_project_remediation_technology.html

The summary of an updated International Programme on Chemical Safety Environmental Health Criteria Document on Arsenic published by WHO is available at http://www.who.int/pcs/ehc/summaries/ehc_224.htm#English.

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