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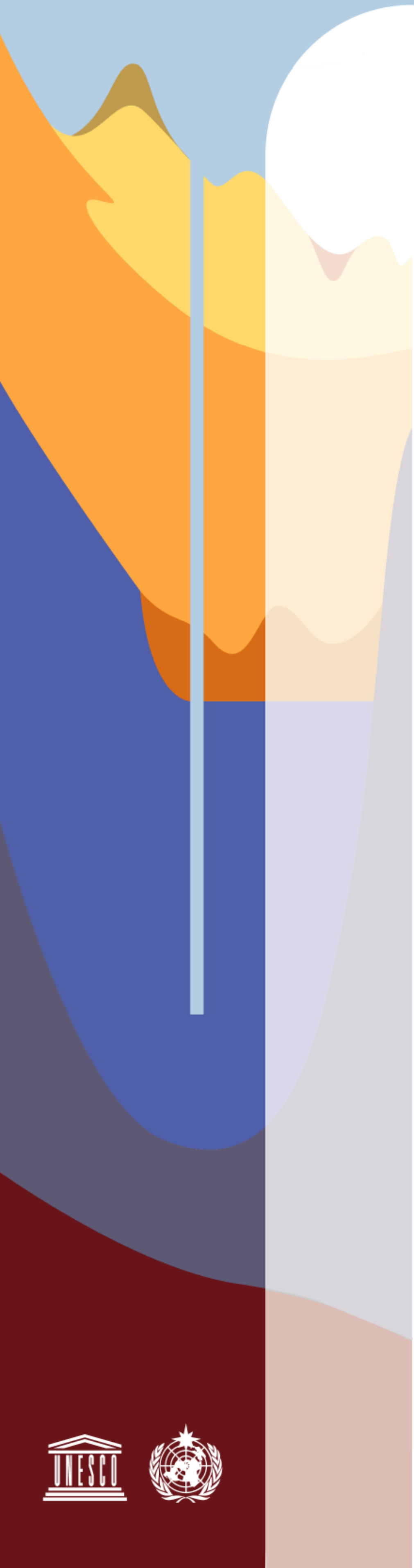

Arsenic in groundwater:
Overview and evaluation of removal methods

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Summary

In this report information is given about methods for the removal of arsenic from groundwater. The methods can be used by domestic well owners and communal water suppliers. Based on available information, a matrix is composed to give an idea about the applicability of the methods for some given situations.

Arsenic removal methods

Methods	domestic + low costs	community + low costs	domestic + high As removal	community + high As removal	domestic + brackish water	community + brackish water
alum coagulation	🟩	🟩	🟩	🟩	🟥	🟥
Iron coagulation	🟩	🟩	🟩	🟩	🟥	🟥
Enhanced coagulation (EC)	🟩	🟩	🟩	🟩	🟩	🟩
Activated alumina	🟧	🟧	🟩	🟩	🟥	🟥
Iron coated sand (IBS)	🟩	🟩	🟩	🟩	🟥	🟥
Ion exchange	🟧	🟧	🟩	🟩	🟥	🟥
membrane processes	🟥	🟥	🟩	🟩	🟩	🟩
conventional Fe-removal technique	🟩	🟩	🟥	🟥	🟥	🟥
memstill®	🟧	🟧	🟩	🟩	🟩	🟩
waterpyramid/solar dew	🟧	🟧	🟩	🟩	🟩	🟩
UNESCO-IHE IOCS	🟩	🟩	🟩	🟩	🟥	🟥
Alcan Activated Alumina	🟩	🟧	🟩	🟩	🟥	🟥
BUET Activated Alumina	🟩	🟥	🟩	🟥	🟥	🟥
Sono 3-kolski method	🟩	🟥	🟩	🟥	🟥	🟥
Stevens Institute Method	🟩	🟧	🟩	🟩	🟥	🟥
Tetrahedron	🟩	🟧	🟧	🟧	🟥	🟥
Two bucket System	🟩	🟥	🟧	🟥	🟥	🟥

The colours in the matrix correspond with the appropriateness of the method for the given situation:

- Green colour means that the method is very suitable
- Orange colour means average suitability
- Red colour means that the method is unattractive or not applicable for the given situation.

The methods marked in italic are household level arsenic removal methods, which have been tested by WaterAid in Bangladesh (WaterAid, 2001b). From the matrix it is evident that all the mentioned household methods are low cost methods. For community scale, iron and alum coagulation and Iron coated sand (IBS/IOCS) adsorption are low cost methods. A promising emerging technique is Enhanced Coagulation (EC). With this technique a very efficient removal of As(III) and As(V) is possible to below the recommended WHO-value of 10 µg/l. With EC also the removal of fluoride, humic substances and other harmful or toxic matters is realised (metal hydroxides). For groundwater with high iron content, also conventional iron removal techniques, like aeration and filtration, can be used to remove arsenic at low costs. However the efficiency of these techniques for As-removal is not very high.

In situations where high arsenic removal efficiency is necessary, several methods can be used. With the mentioned household methods an arsenic concentration reduction to well below 50 µg/l can be achieved. This concentration is still applied as a drinking water standard in many developing countries. It must be stressed that these household methods were tested under field conditions in rural

Bangladesh with no or limited monitoring involved. Under optimal conditions and with the required monitoring, a reduction of the arsenic concentration to below the WHO guideline value of 10 µg/l can be achieved by using advanced methods like membrane processes and adsorption[1].
Most of the methods do not remove arsenite (arsenic III) as efficient as arsenate (arsenic V). Therefore an oxidation of arsenite to arsenate is recommended.
For brackish water membrane processes like reverse osmosis and electrodialysis reversal are available. The emerging techniques Memstill® and the Water Pyramid®/Solar Dew are also suitable. Again, enhanced coagulation is a very promising technique for this application.

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[1] UNESCO-IHE reports that with the IHE-family filter also arsenic concentrations to below the WHO standard of 10 µg/l can be reached (Petrusevski et al., 2007)

1 Introduction

1.1 Special projects of IGRAC

The International Groundwater Resources Assessment Centre (IGRAC) aims to facilitate and promote world-wide exchange of groundwater knowledge. IGRAC focuses on activities that are prompted by the international groundwater community.

IGRAC's special projects intend to collect, analyse and display information on specific groundwater issues relevant to development of groundwater resources on various scales. Occurrence of hazardous compounds in groundwater is one of these issues. In 2004, IGRAC reviewed available information about groundwater contaminated with arsenic and displayed the probability occurrence of arsenic on continental maps (Brunt et al, 2004).
In this report, an overview is given of arsenic removal methods.

1.2 Occurrence of arsenic

Total arsenic is the sum of both particulate arsenic and soluble arsenic. Inorganic form of soluble arsenic in natural waters usually occurs as trivalent arsenite or pentavalent arsenate. Under anaerobic conditions, groundwater normally contains arsenite. Arsenite is readily oxidized to arsenate in aerobic water at pH values above 7.0. Conversely, arsenate can be reduced to arsenite at low pH values.

Natural sources of arsenic are related to various types of rocks and to geothermal activity. Industrial activities, especially mining, can also contribute to an increased arsenic concentration in groundwater. A review of the sources and behaviour of arsenic in natural waters is given by Smedley and Kinniburgh (2002).

Arsenic in drinking water is a global problem. Long-term exposure to arsenic can result in chronic arsenic poisoning. The most serious damage to health has taken place in Bangladesh and West Bengal, India. Arsenic concentrations in these areas can vary from 50 to more than 3000 μg/l (Petrusevski et al., 2007). The WHO guideline value for arsenic in drinking water was reduced from 50 μg/l to a provisional value of 10 μg/l in 1993 (WHO, 1993; WHO 2004). However, many affected countries still operate 50 μg/l standard due to lack of adequate testing facilities.

1.3 Outline of the report

In chapter 2 an overview is given of removal methods. The basic principles of common methods are summarized. The methods are intercompared in a table according to relevant criteria such as scale, removal efficiency, required skill, costs and advantages and disadvantages. Some emerging technologies are also outlined.

In chapter 3 examples are given of centralised treatment systems and household point-of-use systems.

An evaluation of the methods is given in chapter 4.

Chapter 5 deals with the selection process. To help water users by choosing the most appropriate methods for their situation, process selection decision trees were made for both large scale applications and small scale systems.

The electronic version of this report is available on the IGRAC web-site: www.igrac.nl .

2 Overview of removal methods

2.1 Introduction

In this chapter an overview is given of common arsenic removal methods and emerging methods.

On the website of the Massachusetts Institute of Technology (MIT, 2001), an online informational database of arsenic remediation technologies is given. Besides the database with a description of 46 different technologies, an overview of nine general categories of remediation processes for arsenic removal is given.

In EPA report Arsenic Treat Technologies for Soil, Waste and Water (EPA, 2002), an extended description, including cost figures and performance data, is given of the following techniques:

- precipitation
- membrane filtration
- adsorption
- ion exchange
- permeable reactive barriers

For more overviews and detailed technique descriptions please check the following references:

- Arsenic Treatment Technology Evaluation Handbook for Small Systems (EPA, 2003)
- Technologies and Costs for Removal of Arsenic from Drinking water (EPA, 2000)
- Arsenic in Drinking Water, Thematic Overview Papers of IRC (Petrusevski et al., 2007)

In the second mentioned report (EPA, 2000), detailed information is given about the costs of arsenic removal technologies. NAISU (2003) produced an overview of 10 household level Arsenic removal technologies which have been tested in Bangladesh.

2.2 Common methods

Detailed description of common methods for removing arsenic from drinking water is given by Petrusevski et al. (2007). These methods are based on the following processes:

- *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 processes*, including nano-filtration, reverse osmosis and electrodialysis.

Precipitation processes
Adsorption co-precipitation with hydrolysing metals such as Al^{3+} and Fe^{3+} is the most common treatment technique for removing arsenic from water. Sedimentation followed by rapid sand filtration or direct filtration or microfiltration is used to remove precipitate. Coagulation with iron and aluminium salts and lime softening is the most effective treatment process. To improve efficiency of this method, a priory oxidation of As(III) to As(V) is advisable. Hypochlorite and permanganate are commonly used for the oxidation. Atmospheric oxygen can also be used, but the reaction is very slow.

Adsorptive processes

Adsorptive processes involve the passage of water through a contact bed where arsenic is removed by surface chemical reactions. Activated alumina, activated carbon, iron oxide coated or based filter media are used for these processes.

Ion exchange processes

In these processes, ions held electrostatically on the surface of a solid phase are exchanged for ions of similar charge dissolved in water. Usually, a synthetic anion exchange resin is used as a solid. Ion exchange removes only negatively charged As(V) species. If As(III) is present, it is necessary to oxidise it.

Membrane processes

Microfiltration (MF), utrafiltration (UF), nano-filtration (NF), reverse osmosis (RO) and electrodialysis reversal (EDR) can remove arsenic through filtration, electric repulsion, and adsorption of arsenic-bearing compounds. The use of MF and UF membranes is dependent on the size distribution of arsenic bearing particles in water. To increase removal efficiency with a low percentage of particulate arsenic content, MF can be combined with coagulation processes. Coagulation assisted microfiltration is discussed in section 2.3. Nano-filtration membranes are capable of removing significant portions of the dissolved arsenic compounds in natural waters. Reverse Osmosis (RO) is very effective in removing dissolved arsenic. Electrodialysis reversal (EDR) can also be used for removal of arsenic. A water recovery of 85% is achievable. Reported arsenic removal varies from 28% to 86% (EPA, 2000). In general, membrane filtration is more effective for removal As(V) than for As(III).

In table 1 an overview is given of the traditional arsenic removal methods. This table indicates that the majority of low cost methods rely on precipitation or adsorption. 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 method is less likely than other treatments to be reduced by characteristics (pH, colour) and components other than arsenic. It is also capable of treating water characteristics or presence of solutes other than arsenic, such as hardness or heavy metals. Systems using this method 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. The effectiveness of adsorption for arsenic treatment is more likely than precipitation processes to be affected by components other than arsenic. Small capacity systems using these methods 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 component to be treated, for relatively smaller systems, and as a supplementary process for treating effluent from larger systems. The effectiveness of membrane processes for arsenic removal is sensitive to a variety of untreated water components and characteristics. It also produces a larger volume of residuals and tends to be more expensive than other arsenic treatment methods. It is therefore used less frequently than precipitation/co-precipitation, adsorption, and ion exchange.

Table 1: Removal methods for Arsenic from groundwater/drinking water (based on Johnston and Heijnen, 2001and Ahmed, 2001)

Techniques	Household	Community level	Removal As (III)	efficiency As (V)	Working pH	Interferences	Operator skill	Relative costs	Advantages	Disadvantages	Remarks
Oxidation/Precipitation											
Air oxidation	x	x	-	-					relative simple, low-cost	partial removal of arsenic slow process	
chemical oxidation	x	x	-	+					relative simple and rapid proces oxidizes other impurities and kills microbes		
Coagulation/Co-precipitation			-	+++		little		low	no monitoring of break through is requir low costs and simple chemicals	toxic sludge is produced operation requires training	most effective process to meet the regulations standard wide-range of arsenic contaminated influent concentrat
Alum coagulation	x	x	-	+++	6.0 - 8.0		medium	low	chemicals normaly available low capital costs	pre-oxidation is a must (low removal of As (III) produces toxic sludges	proven at central level piloted at community and household level silica and phosphate may reduce As removal
Iron coagulation	x	x	++	+++	< 8		medium	low	efficient at low costs simple operation common chemicals	medium removal of As (III) pre-oxidation may be required	well proven at all three levels. silica and phosphate may reduce As removal
Lime softening	x	x	+	+++	> 11,5		medium	low-medium	common chemicals	re-adjustment of pH is required large waste	proven in lab and pilot scale
Enhanced Coagulation	x	x	++	+++	5.0-9.0		meduim	low-medium	high removal efficiency of As also removal of organic matter and metal hydroxides	emerging technique, not proven on practical scale	
Sedimentation	x	x	-	-			low	low	simple	low reduction	relies on passive coagulation with iron
Oxidation/Filtration	x	x	-	++	5.5-8.5		medium	medium			
Adsorption			+	+++		average			no daily sludge problem	requires monitoring break through requires periodical regeneration or medium shift	
Activated Alumina	x	x	++	+++	5.5 - 6		low	medium	well known, commercially available very efficient removal low maintenance, no daily sludge	re-adjustment of pH required toxid solid waste monitoring is difficult	pilot scale in community and household level in indus. countries arsenite removal is poorly understood
Iron based Sorbents (IBS)	x	x	+	+++	6.0-8.5		low	low-medium	plenty possibilities well defined technique no regeneration	requires pH control requires replacement of media after exhausting reuqires regular testing to provide safe operation	

Table 1 cont.

Techniques	**Household**	**Community level**	**Removal efficiency**		**Working pH**	**Interferences**	**Operator skill**	**Relative costs**	**Advantages**	**Disadvantages**	**Remarks**
			As (III)	**As (V)**							
Ion exchange											
Anion resin	x	x	-	+++	6.5-9.0	many	high	medium	well defined medium no pH correction	only As (V) removal interference from sulfate, nitrate and TDS adding of salt monitoring is difficult high costs	pilot scale in central and household systems, mostly in indus. countries
Membrane/Reverse Osmosis								high	high removal efficiency no solid waste capable of removal of other contaminant	high running costs high tech operation and maintenance re-adjustment water quality is required	shown effective at lab scale in industrial countries pretreatment required research needed on removal of arsenite
Reverse osmosis	x	x	-/++	++			medium	high	easily monitoring no chemicals required no toxic wastes	removal of Arsenite (III) lower than Arsenate (V) removal high investment costst high tech operation/maintenance	
Electrodialysis		x	-/++	+-++			medium	high	removal of other contaminants	interference by oxidizing agents toxic waste water	
Nanofiltration			-/++	++			medium	high	well defined, high removal efficiency	very high capital and running costs	
CAMP (Coagulation Assisted Membrane Process)		x	-/+++	+++				high		pre-treatment required high costs	
Biological											
Other											
In-situ Oxidation/immobilizatio		x	++	+++				medium	no arsenic-rich wastes	possibility of aquifer clogging	very limited experience

*)
: +++ = > 90% removal
: ++ = 60 - 90% removal
: + = 30 - 60% removal
: - = < 30% removal

2.3 Emerging methods

Besides the methods mentioned in table 1 several new methods have been studied recently. Some interesting methods are shortly described below.

- Fe-Mn-Oxidation
- Green sand filtration
- Coagulation assisted Microfiltration
- In situ (sub-surface) arsenic immobilization
- Enhanced coagulation (aka electrocoagulation, electroflotation)
- Biological arsenic removal
- Phytoremediation
- Electrokinetic treatment
- IOCS (iron oxide coated sand (see also chapter 3.1)
- Memstill®
- Water Pyramid
- Solar Dew Collector

Fe-Mn Oxidation
Conventional iron and manganese removal can result in significant arsenic removal, through coprecipitation and sorption onto ferric or manganic hydroxides (Johnston, R. and Heijnen, H., 2001). Most low-cost methods for arsenic and manganese removal rely on aeration and filtration through porous media such as sand and gravel. Any method that effectively removes iron and manganese could be evaluated to see if arsenic is also removed effectively. See also chapter 3.1 and 3.2.

Manganese Greensand
Greensand is a granular material composed of the mineral glaucite, which has been coated with manganese oxide. It is a natural zeolite (microporous mineral), and has strong ion exchange properties, and will remove iron, manganese, arsenic, sulphide, and many other anions (Water & Wastes, 2003). Like manganese dioxide coated sand, greensand surface is strongly oxidizing, and is thus able to remove both arsenite and arsenate.

This method is especially interesting to utilities where Fe and Mn are already being removed using a manganese greensand filter. It is possible that a small pH adjustment from 8+ to 6.5 may be all that is required to bring the facility into compliance.

Coagulation assisted Microfiltration
In coagulation assisted microfiltration technology, microfiltration is used in a manner similar to a conventional gravity filter. The advantages of MF over conventional filtration are a more effective microorganism barrier, removal of smaller floc sizes and an increased plant capacity (EPA, 2000; Wachinski et al., 2006). The microfiltration membrane system works to remove arsenic from water by the addition of an iron-based coagulant, such as ferric chloride, to the water. The arsenic is adsorbed onto positively charged ferric hydroxide particles, which are then removed by microfiltration. In pilot studies, the removal of arsenic to below 2 µg/l is reported in waters with a pH between 6 and 7.

In situ (sub-surface) arsenic immobilization
When arsenic is mobilized in groundwater under reducing conditions, it is also possible to immobilize the arsenic by creating oxidized conditions in the subsurface. In Germany, in order to remediate an aquifer containing high arsenite, high ferrous iron, low-pH groundwater, potassium permanganate was injected directly into contaminated wells, oxidizing arsenite, which coprecipated with ferric oxides as ferric arsenate. Arsenic concentrations were reduced by over 99%, from 13,600 tot 60 µg/l. In another project atmospheric oxygen was used to reduce arsenic concentrations in situ from approximately 20

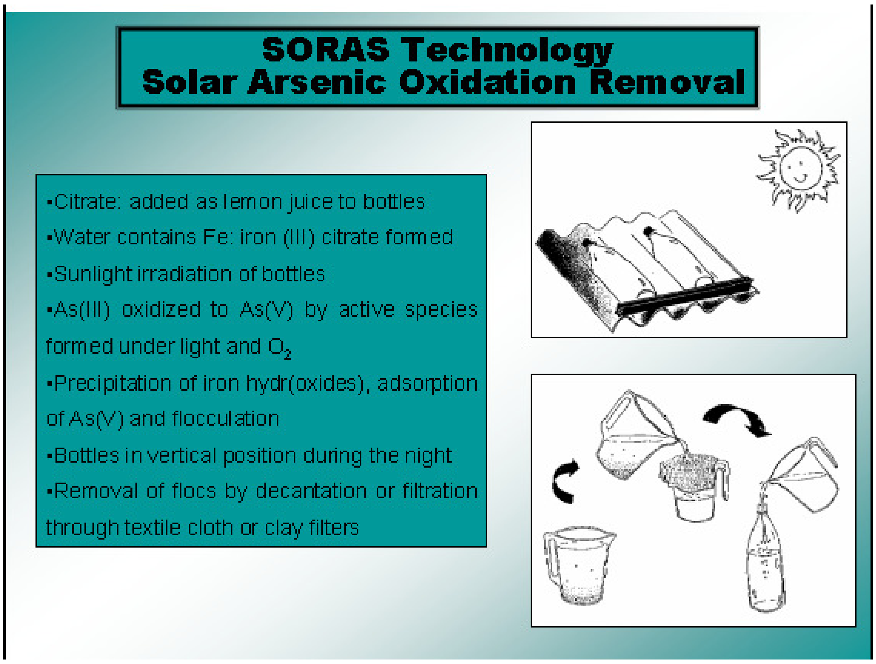
to 5 µg/l, while iron and manganese levels were also lowered (Johnston and Heijnen, 2001). However, this oxidation is a slow process. Under reducing conditions, and in the presence of sulphur, arsenic can precipitate out of solution and form relatively insoluble arsenic sulphides. However, arsenic sulphides like all metal sulphides are not stable when in contact with acidic conditions (low pH values). In situ immobilization has the great advantage of not producing any wastes that must be disposed of. However, experience is limited, and the technique should be considered with caution.

Enhanced coagulation (aka electrocoagulation, electroflotation)
With enhanced coagulation, aka electrocoagulation or electroflotation, soluble anodes made from iron or aluminium are used. Reported advantages mentioned in laboratory studies are the in-situ oxidation of As(III) tot As(V), and better removal efficiencies than with classical coagulation. Also organic arsenic, fluoride and dissolved metals are removed by this method. Final As concentrations in groundwater are below 10 µg/l, even with high initial concentrations (Kumar et al., 2004). An additional advantage of enhanced coagulation is the reported removal of natural organic matter (NOM). Recent studies showed two to three times better effects on the removal of humic substance (NOM) than required by US EPA (Perisic, 2006). The method has many advantages for purification of highly humic waters. It simply and efficiently neutralizes molecules to form flocs and coagulates. The coagulation evolves at a high specific reduction of the coagulant, which makes the method suitable from a techno-economic viewpoint and with respect to environmental aspects. The efficient floc separation allows a long safe operation of sand filter without washing.

Biological arsenic removal
Arsenic in water can be removed by microbiological processes (Rahman and Ravenscroft, 2003). Two main types of metal-microbe interactions can be potentially used for the removal of arsenic from ground water. They are (a) microbial oxidation of arsenic (III) to arsenic (V) to facilitate its removal by conventional arsenic removal processes, and (b) bioaccumulation of arsenic by microbial biomass.

The Biological Activated Carbon (BAC) system, developed by the Mainstream BMS Ltd.,Vanscoy, Saskatchewan and Davnor Water Treatment Technologies Ltd., Calgary, Alberta, is a biologically active filtration unit. In this system a granular activated carbon (GAC) filter is used, which are continuously aerated to enhance the growth of biological activity within the filter media. This system has been used in rural Saskatchewan on experimental basis for seven years with consistent arsenic removal exceeding 90% (Pokhrel et al., 2005). This system could also remove more than 99% of iron and also dissolved organic material.

Solar Oxidation and Removal of Arsenic (SORAS) is a simple method that uses irradiation of water with sunlight in PET or other UV transparent bottles to reduce arsenic level from drinking water. The process is developed by Swiss Federal Institute of Environmental Science and Technology, Switzerland (EAWAG) and Swiss Agency for Development and Cooperation (SDC) (Wegelin et al., 2001). The method is based on photochemical oxidation of As (III) followed by precipitation or filtration of As (V) adsorbed on Fe (III) oxides. Field tests in Bangladesh show removal efficiency between 45-78% with an average of 67%. Concerning the Bangladesh guideline value of 50 µg/l, SORAS can treat raw water having an arsenic concentration below 100 – 150 µg/l (Weling et al., 2001).



SORAS Technology
Solar Arsenic Oxidation Removal

- Citrate: added as lemon juice to bottles
- Water contains Fe: iron (III) citrate formed
- Sunlight irradiation of bottles
- As(III) oxidized to As(V) by active species formed under light and O_2
- Precipitation of iron hydr(oxides), adsorption of As(V) and flocculation
- Bottles in vertical position during the night
- Removal of flocs by decantation or filtration through textile cloth or clay filters

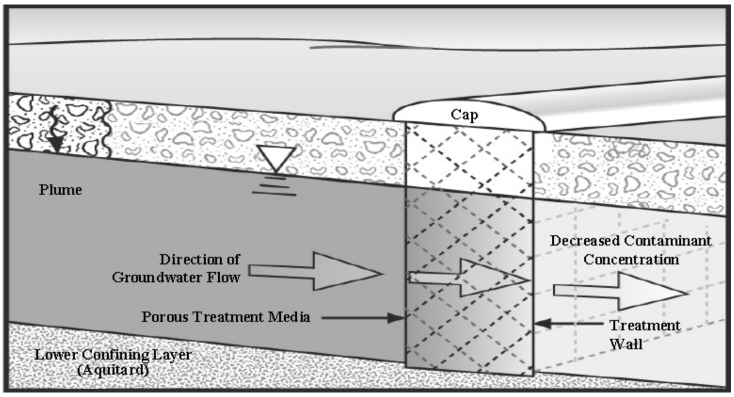
Source: D'Hiriat et al., 2006

Phytoremediation

Some aquatic plants have capacity to accumulate arsenic. Among these aquatic plants, Azolla and Spirodella (duckweed) species have the highest efficiency of arsenic absorption. A study on duckweed in removing arsenic from contaminated water was carried out by Dr. Abdul Aziz of the Department of Botany of Dhaka University (Rahman and Ravenscroft, 2003). This study revealed that Sirodella polyrhiza species was found to absorb arsenic very efficiently. The results indicated that a complete cover of Spirodella polyrhiza could accumulate about 175 g of arsenic from a pond of one hectare area per day.

Permeable reactive barriers

Permeable reactive barriers (PRBs) are used to treat groundwater in situ. This method tends to have lower operation and maintenance costs than ex situ (pump and treat) methods. On the other hand it typically requires a treatment time of many years. PRBs are already commercially available and are being used to treat groundwater containing arsenic at a full scale at two sites in the USA, although arsenic is not the primary target component for treatment by the method at either site (EPA, 2002). Permeable reactive barriers are walls containing reactive media that are installed across the path of a contaminated groundwater plume to intercept the plume. The barrier allows water to pass through while the media remove the components by precipitation, degradation, adsorption, or ion exchange (see picture below).



Model of a permeable reactive barrier *Source: EPA*

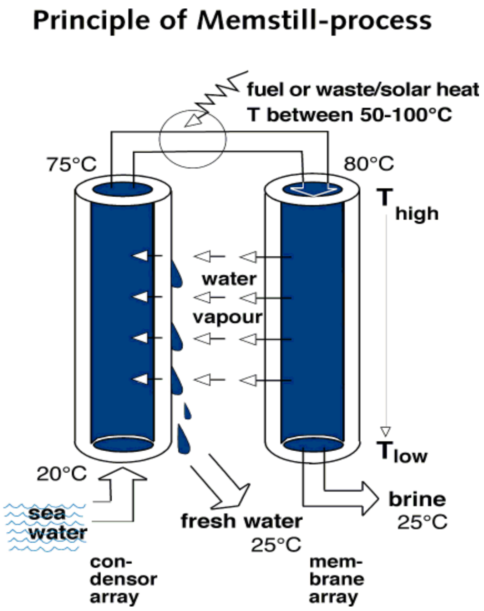
Electrokinetic treatment
Electrokinetic treatment is an emerging remediation method designed to remove heavy metal contaminants from soil and groundwater. The method is most applicable to soil with small particle sizes, such as clay. However, its effectiveness may be limited by a variety of components and soil and water characteristics. Electrokinetic remediation is based on the theory that a low current density will mobilize components in the form of charged species. A current passed between electrodes is intended to cause water, ions, and particulates to move through the soil, waste, and water. Components arriving at the electrodes can be removed by means of electroplating or electrodeposition, precipitation or coprecipitation, adsorption, complexing with ion exchange resins, or by pumping of water (or other fluid) near the electrode (EPA, 2002). Electrokinetic treatment is a method with relatively few applications for arsenic treatment. It is an in situ treatment method, and therefore does not require excavation of contaminated soil or pumping of contaminated groundwater. Its effectiveness may be limited by a variety of soil and contaminant characteristics. In addition, its treatment depth is limited by the depth to which the electrodes can be placed

Iron oxide coated sand (IOCS) (see also chapter 3.1 and 3.2)
UNESCO-IHE developed an arsenic removal method based on adsorption on iron oxide coated sand (IOCS). IOCS is a by-product from groundwater treatment plants and consequently very cheap. This technique is efficient for both As(III) and As(V). Different family scale removal filters were tested in Bangladesh (2004) and also a large scale centralized application was tested in Greece and Hungary (Petrusevski et al., 2007).

Arsenic removal ‘Family Filter’

Iron oxide coated sand *Source: UNESCO-IHE*

Memstill® technology
The Netherlands Organisation of Applied Scientific Research (TNO) has developed a membrane-based distillation concept which radically improves the economy and ecology of existing desalination technology for seawater and brackish water. This so-called "Memstill® technology" combines multi-stage flash and multi-effect distillation modes into one membrane module (Hanemaaijer et al., 2007).

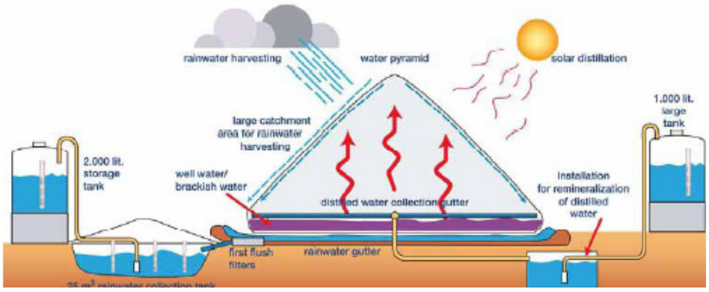


Memstill MD modules *Source: TNO*

Cold feed water takes up heat in the condenser channel through condensation of water vapour, after which a small amount of (waste) heat is added, and flows counter currently back via the membrane channel. Driven by the small added heat, water evaporates through the membrane, and is discharged as cold condensate. The cooled brine is disposed, or extra concentrated in a next module.
The Memstill® technology can produce (drinking)water at a cost well below that of existing methods like reverse osmosis and distillation.
With the Memstill® technology also anions like fluoride and arsenic are removed. It is expected that the Memstill® technology will also be developed for small scale applications using solar heat.

The WaterPyramid® solution
Aqua-Aero WaterSystems has developed the WaterPyramid® concept for tropical, rural areas (Aqua-Aero Watersystems, 2007). The WaterPyramid makes use of simple method to process clean drinking water out of salt, brackish or polluted water. One of the pollutants could be fluoride. Most of the energy needed to clean the water is derived from the sun.

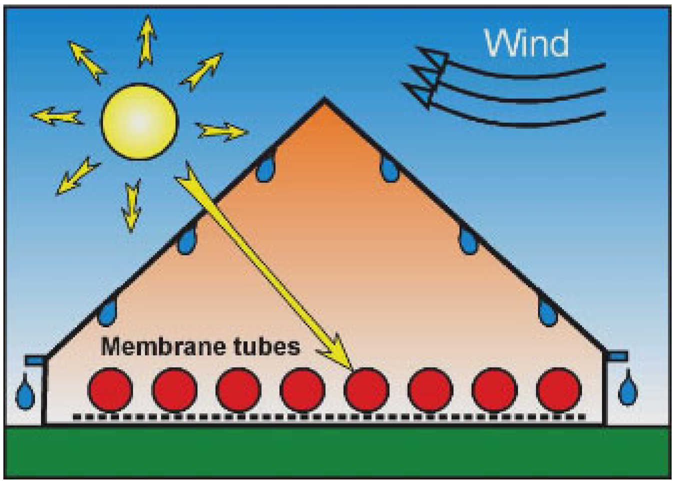
WaterPyramid® with a total area of 600 m^2 and situated under favourable tropical conditions, can produce up to 1.250 litres of fresh water a day. The production rate depends on site specific factors such as climate and temperature, cloudiness and wind activity. Desalination is driven by the sun and the energy needed for pressuring the WaterPyramid® is obtained using solar cells in combination with a battery back-up system. Intermittent peak demands in electricity, related to e.g. (borehole) pumping and maintenance, are covered using a small generator system.



Source: Aqua-Aero WaterSystems

The Solar Dew Collector system

Solar Dew purifies water uses a new porous membrane to purify water using solar energy (Solar Dew, 2007). The technique is similar to the WaterPyramid®. Water sweats through the membrane, evaporates on the membrane's surface and increases the air humidity in the evaporation chamber. Based on a temperature difference, pure water condenses on the cooler surfaces of the system.



Source: Solar Dew

The product water quality is very constant and similar to that of distilled water. The quantity depends on the intensity of the solar radiation. To avoid crystallization, the brine has to be drained periodically. The system is able to process: sea-, brackish or contaminated waste water (e.g. with heavy metals, oil residue, boron, fluoride) with an allowable pH range of 5-11.

3 Arsenic removal methods for centralised systems and household point-of-use systems

3.1 Introduction

The arsenic removal methods as described in chapter 2 can be used either in centralised treatment systems or in household point-of-use (POU) systems. Centralised urban and community treatment systems are usually attached to a distribution system. Household point-of-use systems are connected to domestic wells, which provide water to one or several households close to the facility.

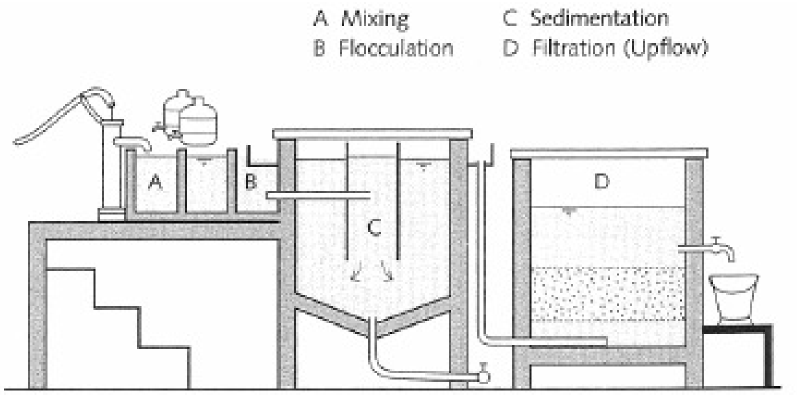
This chapter provides a summary of an overview published by IRC International Water and Sanitation Centre (Petrusevski, et al., 2007).

3.2 Centralised arsenic removal systems

Conventional coagulation-separation and adsorption are the most common methods used in centralised removal systems both in industrialised and developing countries.

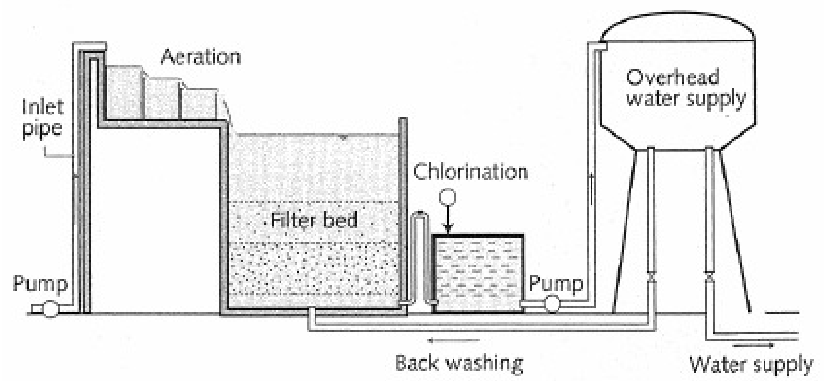
a. Coagulation-separation arsenic removal systems

In these systems, aluminium or iron based salts are used as a coagulant. After flocculation, flocs are separated in a floc separation unit, usually using sedimentation and rapid sand filtration. An example of a compact conventional coagulation based treatment unit is given in the figure below.



Conventional coagulation based treatment unit attached to a tube well (Source: IRC)

Aeration (cascade, plate aerator, aeration tower, etc.) can be used before adding the coagulant. In groundwater containing high iron concentrations, aeration can considerably reduce the coagulant dosage. Aeration and filtration used in a conventional iron removal system (see figure below) will always remove some arsenic.



Conventional iron removal treatment unit (Source IRC)

Aeration combined with rapid sand filtration is promising for iron-rich groundwater areas in Bangladesh. Chemical pre-oxidation (chlorination or ozonation) is required for removal of As(V). Production of a large volume of toxic liquid waste is the major disadvantage of the coagulation based systems.

b. Adsorption based arsenic removal systems
Traditionally, these systems use activated alumina (AA) as an adsorbent. This absorbent is cheap, but its efficiency strongly depends on pH, salinity and presence of competing ions (e.g. fluoride or sulphate).

Recently, iron based adsorbents are used. Commercial available adsorbents are relatively expensive but have high adsorption capacity. The systems using these adsorbents are simply to operate. Such systems typically comprise one or a series of adsorptive filters without need for chemical addition (BASF, 2007).

Iron oxide coated sand (IOCS) from groundwater treatment plants is an innovative and cheap alternative for commercially available adsorbents.

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

Household level arsenic removal systems use adsorptive filtration or coagulation, ion exchange treatment or combination of coagulation and adsorption. Oxidation is sometimes used to improve As(III) removal efficiency.

A comprehensive survey of POU arsenic removal systems based on a short-term performance test in terms of flow rate, storage capacity, breakthrough time, bacteriological performance, chemical use, costs, and user acceptability has been made by WaterAid. The results of this survey are presented in two reports (WaterAid, 2001a,b).

UNESCO-IHE has developed a POU filter for arsenic removal with iron oxide coated sand (IOCS) as an adsorbent. The filter is simple, easy-to-use and does not require any chemicals.

Alcan, Sidko (a granular ferric hydroxide filer system), READ-F and Sono are four commercial methods recently approved by the Government of Bangladesh for sale.. Good back-up and accepted methods for sludge disposal are essential for the operation of the POU systems (Arsenic project, 2007). Alcan and Sono filters are shown in figure below.

An Alcan filter (left) under testing in Azimpur village, Manikgonj district, Bangladesh, and a Sono arsenic removal filter (right) (Source: IRC)

4 Evaluation

Historically, the most common methods for arsenic removal have been coagulation with metal salts, lime softening, and iron/manganese removal. Since the WHO Guideline Value for arsenic in drinking water was lowered from 50 to 10 µg/L in 1993, several countries have lowered their drinking water standards; in some cases to 10 µg/L. Traditional coagulation processes are sometimes unable to efficiently remove arsenic to these low levels. As a result, various alternative methods have been developed or adapted that are capable of removing arsenic to trace levels. These advanced treatment options include ion exchange, activated alumina, enhanced coagulation and membrane technologies such as reverse osmosis and nanofiltration. While these methods have all been shown to be effective in lab or pilot studies, there is still relatively little experience with full-scale treatment. In addition, a number of novel removal methods are under development, some of which show great promise.
A comparison of the main arsenic removal processes is shown in Table 2.

Table 2: Overview of the main arsenic removal processes (based on Johnston and Heijnen, 2001 and Ahmed, 2001)

Technologies	**Removal Efficiency**		**Advantages**	**Disadvantages**	**Experience and issues**
	As (III)	As (V)			
Oxidation/Precipitation					
Air oxidation	-	-	relative simple low cost	slow process partly removal of As	
Chemical oxidation	-	+	simple and rapid process oxidizes other impurities		
Coagulation/coprecipitation					
Alum Coagulation	-	+++	rel. low capital costs rel. simple operation	toxic sludges low As (III) removal	proven at several levels phosphate and silicate do disturb
Iron Coagulation	++	+++	commen chemicals available inexpensive		proven at several levels phosphate and silicate do disturb
Sorption techniques					
Activated Alumina	++	+++	well known commercially available	toxic solid waste regeneration required	proven at several levels iron rich water needs pre-treatment
Iron Coated Sand	-	+++	well defined technique plenty possiblities	high tech operation and maintanance	?
Ion Exchange Resin	-	+++		rel. high costs	pilot scale, mostly in industrialized countires interference from sulfate and TDS
Membrane techniques					
Nanofiltration	-	++	well defined technique high removal efficiency	very high capital and running costs	research needed for arsenite removal
Reverse osmosis	-	++	no toxic solid wastes	high tech operation	pre-treatment required
Electrodialysis	-	++	capable of removal of other contaminants	toxic waste water	

All the methods, based on the processes listed in Table 2, have their merits and demerits and are being refined to be suitable under rural conditions. The modifications based on the pilot-scale implementation of the methods are in progress with the objectives to:

- improve effectiveness in arsenic removal
- reduce the capital and operation cost of the systems
- make the method user friendly
- overcome maintenance problems
- resolve sludge and arsenic concentrates management problems.

In table 3 an overview is given of tested arsenic removal methods. Most of them are small scale (household) methods practiced in rural areas.

Table 3: Overview of small scale (household) arsenic removal methods (based on WaterAid, 2001 and Rahman and Ravenscroft, 2003)

Technology	**Method**	**Removal Efficiency**		**Flow rate**	**Cost (US$)**	**User**	**Agency/promotor**
		As (III)	**As (V)**				
Passive sedimentation	sedimentation	-	0	20 litres in 12 hours	5 (20 litre aluminium kolhsi)	Household	DPHE
in-situ sedimentation	sedimentation	-	0			Community	DPHE/Danida
Ardasha Filter (AR)	sedimentation + adsorption			13 litres in 12 hours	11 (installation)	Household	CRS-Ardasha filter Ind., Chagalnaya, Feni
Solar Oxidation (SORAS)	oxidation	-	-	not adequate		Household	Swiss Federal Institute for Environmental Science and technology
UNESCO-IHE IOCS-technology	adsorption	++	+++	100 litres in 12 hours		Household (Fam. filter)	UNESCO-IHE, Vitens and Selor
UNESCO-IHE IOCS-technology	adsorption	++	+++	> 200 M3/day	0,25/m3 (total costs)	Large scale application	UNESCO-IHE, Vitens and Selor
Alcan Activated Alumina (AL)	adsorption			> 3600 litres in 12 hours	170 (installation)	Household/comm.	MAGC Technologies Ltd., Dhaka
BUET Activated Alumina	oxidation + adsorption		+++	100 litres in 12 hours	20 (installation)	Household	Department of Civil Engineering, BUET
Two Bucket System	coagulation + adsorption		++	43 litres in 12 hours	7 (installation)	Household	DPHE/Danida
GARNET-filter	coagulation		0	13 litres in 12 hours	12 (installation)	Household	GARNET
Sono 3-kolski method	coagulation + adsorption		+++	60 litres in 12 hours	6 (installation)	Household	Prof. Khan/University of Dhaka
Stevens Institute Method	coagulation + filtration		++	240 litres in 12 hours	40 (installation)	Household/community	Stevens Institute
Rice Husk Arsenic Unit	coagulation + flocculation	-	+	not adequate		household	DPHE/Danida
ARU (Arsenic Removal Unit)	adsorption	-	+	sufficient		Community	DPHE/Danida
Harbauer Technology	adsorption	0	+++	sufficient	low	Community	German-Sidko Ltd.
Safi filter	oxidation + filtration	-	+	not adequate		Household	Prof. Safiullah, Safiullah University
Tetrahedron	Ion exchange		+	1800 litres in 12 hours	250 (installation)	Household/comm.	Tetra hedron@prodigy.net
Bio-solution to Arsenic Problem	micro-biological		0	sufficient		Community	Prof. Aziz, Department of Botany Dhaka University
Microbiological process	micro-biological	0	0	not adequate		Community	Paknikar

5 Selection

For the selection of an appropriate arsenic removal method two process selection decision trees have been made.

A decision tree for large scale applications is shown if figure 1.

Process selection decision tree Centralised Arsenic removal systems-

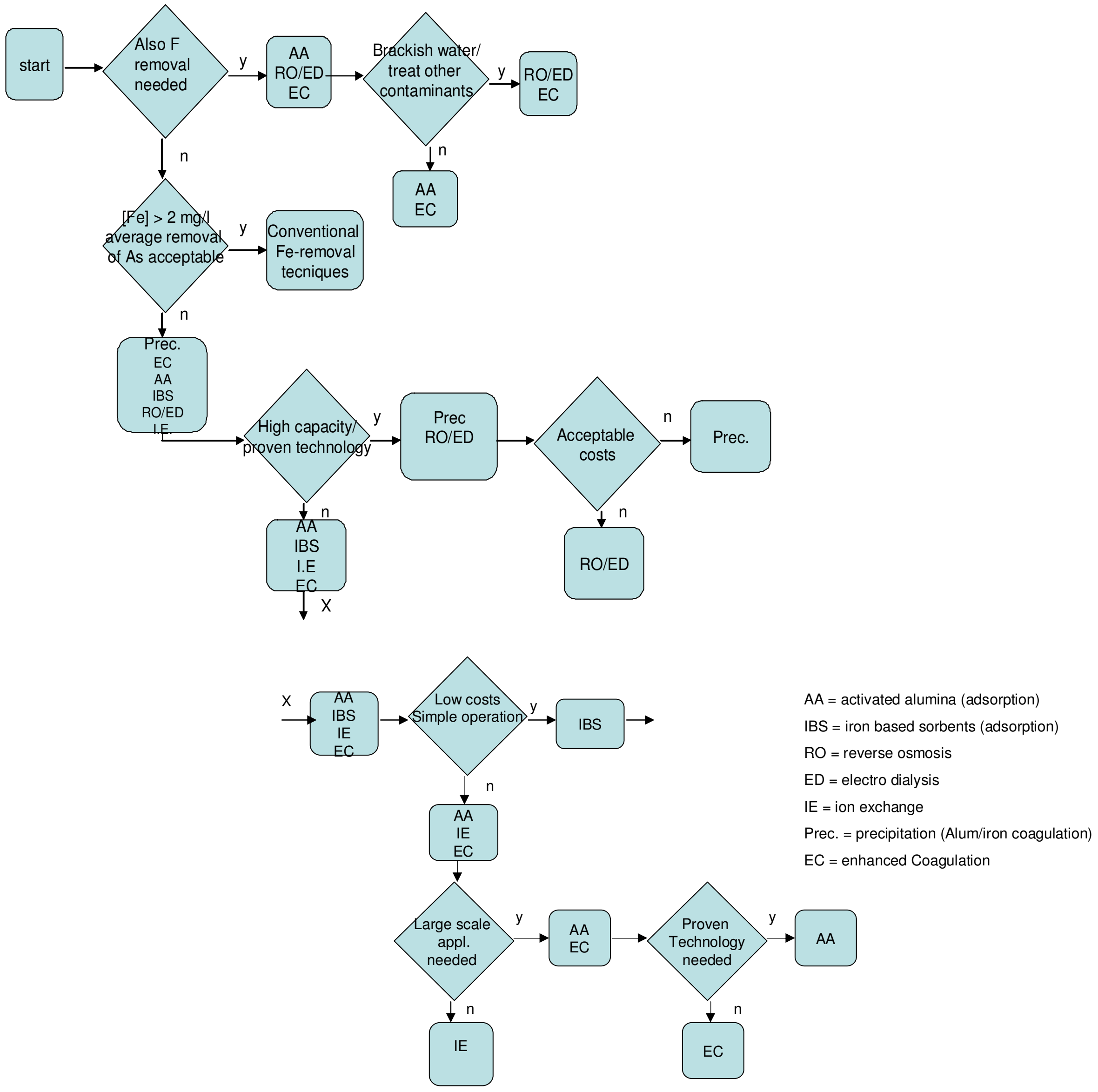
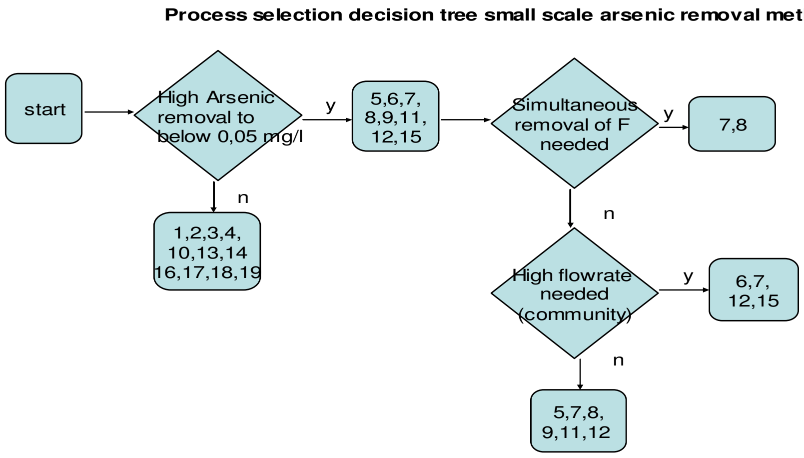


Figure 1: Decision tree for centralised arsenic removal systems

Above diagram indicates that precipitation techniques are most favorite techniques when a high capacity, proven method and acceptable costs are needed. Use of iron oxide coated sand (IOCS) that originates from groundwater treatment plants is an innovative method with low costs. IOCS is also used in household treatment systems. Membrane filtration systems are still too expensive for wide application. A promising emerging method with high advantages comparable with the standard arsenic removal techniques, is Enhanced Coagulation (EC). With this technique both As(III) and As(V) can be removed to WHO-level. Also fluoride, humic substances and metal hydroxides are being removed with EC. The method uses electricity and a soluble electrode to form iron arsenate flocs. A traditional battery can serve as a source for electricity. Initial tests show very promising results; the method should be demonstrated to gain full acceptance.

A decision tree for small scale (household/community) removal methods, which can be used in rural areas, is shown in figure 2.



Numbers referring to Table 3:
1 = passive sedimentation
2 = in-situ sedimentation
3 = Ardasha Filter (AR)
4 = Solar Oxidation (SORAS)
5 = Unesco-IHE IOCS-technology (household)
6 = Unesco-IHE IOCS-technology (lager scale)
7 = Alcan Activated Alumina
8 = BUET Activated Alumina
9 = Two Bucket System
10 = GARNET-filter
11= Sono 3-Kolski method
12 = Stevens Institute method
13 = Rice Husk Arsenic Unit
14 = ARU (Arsenic removal Unit)
15 = Harbauer Technology
16 = Safi Filter
17 = Tetrahedron
18 = Bio-solution to Arsenic problem
19 = Microbiological process

Figure 2: Decision tree for small scale arsenic removal methods

Because there are so many different methods known for removal of arsenic at household and community level, it is very difficult to make a selection for the best method for a given situation. Several methods can be used for one and the same case. So there is no best arsenic removal technique. Arsenic removal efficiency will vary according to many site-specific chemical, geographic and economic conditions. Because of the many factors that can affect arsenic removal efficiency, any method should be tested using the actual water to be treated, before implementation of arsenic removal systems in the field. The first step is to be sure that the system removes arsenic. Once this has been proven, then it is essential to identify ergonomics and other concerns of the uses and to modify design to address these concerns. Two of the main issues that need attention is reducing the risk of

bacteriological contamination and increasing the acceptability of the methods to users (WaterAid, 2001b).
Diagram for arsenic removal techniques for developing countries shows techniques are suitable for reaching an arsenic concentration below 50 µg/l. Also it can be seen which techniques can be used at house hold level and which can be used at community/family level.

As already mentioned in chapter 3, WaterAid tested several arsenic removal methods at the household level (WaterAid 2001b). After a first selection the following seven techniques were selected (for numbers see figure 2):

- Alcan (7)
- BUET (8)
- Two Bucket system (9)
- GARNET (10)
- Sono 3 (11)
- Stevens Institute method (12)
- Tetrahedron (17)

The Alcan (7), BUET (8) and Sono 3 (11) were the three most consistently effective methods for removing arsenic below 50 µg/l (Bangladesh drinking water standard). Institute method (12) and Tetrahedron (17) are also effective at reducing arsenic level to below 50 µg/l most of the time (between 80% and 95% of samples).

In EPA Report Arsenic Treatment Technology Evaluation Handbook for Small Systems (EPA, 2003), decision trees for selecting new treatment techniques are given for small water systems[2], based on the source water quality. Therefore, the water quality parameters must be measured. Important water quality parameters are:

- Total arsenic,
- Arsenate [As(V)]
- Arsenite [As(III)]
- Nitrate (NO_3^-)
- Orthophosphate (PO_4^{-3})
- pH
- Chloride
- Silica
- Fluoride
- Sulphate
- Iron
- Total Dissolved Solids (TDS)
- Manganese
- Total Organic Carbon (TOC)

In figure 3 a simplified and summarizing decision tree is given, based on the decision trees of (EPA, 2003).

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[2] In (EPA, 2003) a "small" system is defined as a system serving 10,000 or fewer people.

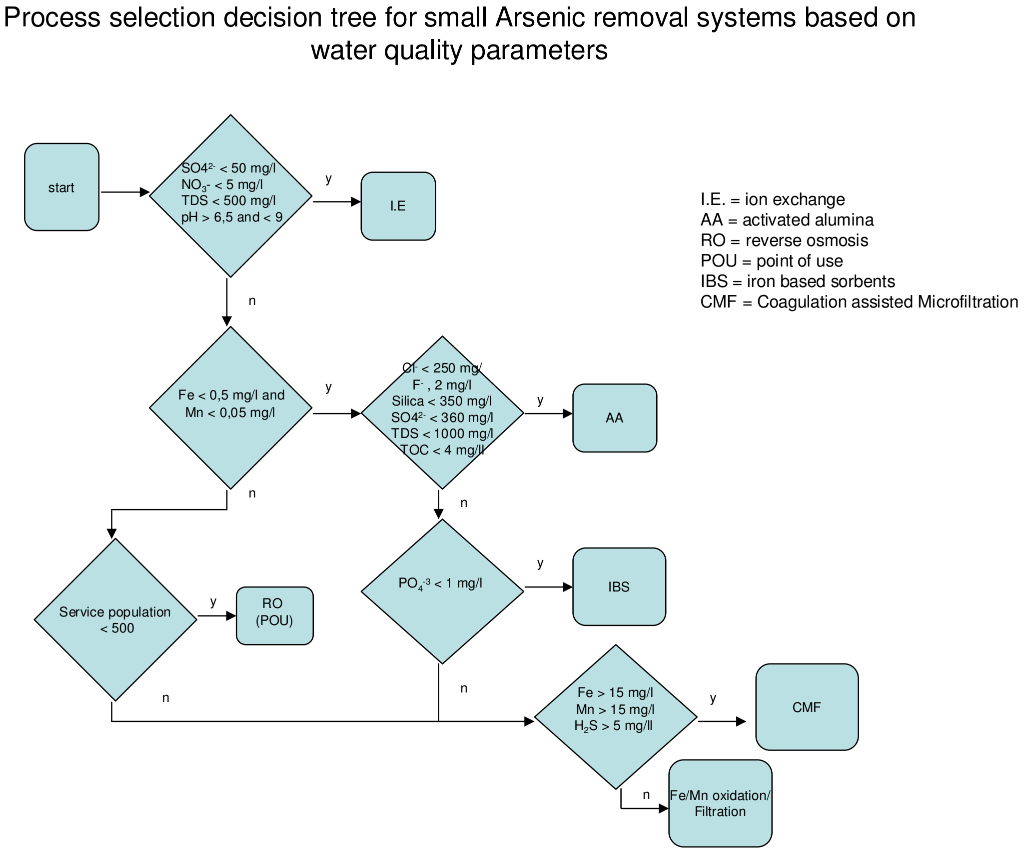

Figure 3: Decision tree for small scale arsenic removal systems, based on water quality parameters (after EPA, 2003)

Figure 3 shows that in case of low nitrate, sulphate and TDS concentrations, Ion Exchange is suitable. With medium concentrations of Cl, F, SO4, etc., and a low iron and manganese content, Activated Alumina is preferable. With higher concentrations of Fe, Mn and H_2S, Fe/Mn oxidation/filtration and coagulation assisted microfiltration (CMF) can be used. In case of low orthophosphate content also Iron Based Sorbents (IBS) can be used. For small applications RO is also advisable.

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