

Technological Options for the Removal of Arsenic with Special Reference to South East Asia

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INTRODUCTION

Arsenic contamination in ground water, used for drinking purpose, has been envisaged as a problem of global concern. It gets introduced in ground water through dissolution of minerals and ores and through erosion from natural resources. Arsenic is generally concentrated in magnetic sulphides and iron ores. The most important ores of arsenic include arsenic pyrites or mispickel, realgar and orpiment. Anthropogenic activities resulting in discharge of untreated industrial effluents from metallurgical operations, ceramic, dye and pesticides manufacturing industries, petroleum refinery etc. into water sources has resulted in increased arsenic levels in surface and ground waters.

In natural water, and thus in drinking water, arsenic is mostly found in trivalent [As(III)] or pentavalent [As(V)] states. The concentration of arsenic in natural waters depends on the geological composition and varies widely depending on the redox conditions in the geological environment. Over the past several years, numerous toxicological and epidemiological studies have been conducted to ascertain health risks associated with low-level exposure to arsenic ingestion. Ingestion of inorganic arsenic can result in both cancer and non-cancer health effects. Arsenic interferes with a number of essential physiological activities, including the actions of enzymes, essential cations and transcriptional events in cells. The USEPA has classified arsenic as a Class A human carcinogen. Chronic exposure to low arsenic levels has been linked to health complications, including cancer of the skin, kidney, lung and bladder, as well as other diseases of the skin, neurological and cardiovascular system.

Drinking water poses the greatest threat to public health from arsenic. Arsenic dissolved in water is acutely toxic and can lead to a number of health problems. Usually arsenic is built up in the body through drinking water and food contaminated with arsenic and causes increased risks of cancer in the skin, lungs, liver, kidney and bladder. Consumption of arsenic also leads to disturbance of the cardiovascular and nervous system functions and eventually leads to death. People drinking arsenic contaminated water with concentrations equal to or greater than 50 µg/L are prone to increased risks of lung and bladder cancer and of arsenic-associated skin lesions. The US Environmental Protection Agency in 2001 adopted a new standard for arsenic in drinking water at 10 µg/L replacing the old standard of 50 µg/L.

The world's five biggest cases of ground water arsenic contamination and the worst sufferings of the people have been reported from Asia. In order of magnitude these are Bangladesh, West Bengal in India, Inner Mongolia and Xin-Xiang Provinces of People's Republic of China and Taiwan. In all these countries, more and more ground water withdrawal is taking place because of agricultural irrigation. Most arsenic affected areas are located in South East Asia, Bangladesh and West Bengal-India. More than 130 million people in Bangladesh and

India are at risk. Nine districts in West Bengal-India and 47 districts in Bangladesh have arsenic level in ground water above the maximum permissible limit of 50 µg/L. The WHO guideline for arsenic in drinking water is 10 µg/L.

Rahman et al. (2001) has reported that in the combined areas of West Bengal-India and Bangladesh, around 150 million people are at risk from arsenic-contaminated ground water. Recent estimates suggest that the number of affected villages in West Bengal increased to 3417 in 111 blocks in twelve districts including Kolkata. The overall study indicates that more than 9 million people from 9 affected districts (population ~ 50 million) of 18 total districts (total population ~ 80 million) are drinking water containing > 10µg/L arsenic. More detailed information about arsenic contamination in ground water of West Bengal can be found in various reports (Bhattacharya, et al., 1997; Chowdhury, TR et al., 1997; Chowdhury, UK et al., 2000a,b; Chakraborti et al., 2002, 2003, 2004). Despite years of research in West Bengal and Bangladesh, additional affected villages are identified by virtually every new survey. It has been further reported that the present research efforts may be only the tip of the iceberg representing the full extent of arsenic contamination. The presence of natural elevated levels of arsenic in ground water has also been reported from other Indian States, namely Chattisgarh (earlier it was a part of Madhya Pradesh) (Chakraborti et al., 1999). Bihar (Chakraborti et al., 2003, 2004), Jharkhand (Chakraborti et al., 2004) and Uttar Pradesh (Chakraborti et al., 2004; Ahamed et al., 2006; Tripathi, 2006). However, the extent of the problem in these states is not fully known.

Singh (2004) reported arsenic contamination in ground water of north eastern states like Assam, Tripura, Manipur, Arunachal Pradesh and Nagaland. Arsenic was detected in parts of Assam (20 districts out of 23 districts) and some plain areas of Tripura (three districts), Manipur (one district), Arunachal Pradesh and Nagaland (one district each). More than 300µg/L of arsenic was found in many places. Maximum arsenic concentration was observed in Jorhat, Dhemaji, Golaghat and Lakhimpur in the State of Assam; West Tripura, Dhalai and North Tripura Districts in the State of Tripura; Thuobal in Manipur; Dibang Valley in Arunachal Pradesh and Mokochung and Mon Districts in the State of Nagaland. This alarming picture of the arsenic contamination in ground water in the region and continuous consumption of this water has the potential of posing serious health hazard to the local population. A thorough survey is therefore needed to assess the magnitude of the problem in these states and to take appropriate measures like generating awareness about health problems associated with arsenic and providing safe drinking water to the affected population.

In this study an attempt has been made to update the technological development in arsenic removal technologies, understand the problems, prospects and limitations of different treatment processes and delineate the areas of further improvement for successful implementation and adaptation of technologies to the society.

ARSENIC MITIGATION STRATEGIES

Arsenic toxicity has no known effective medicine for treatment, but drinking of arsenic free water can help the arsenic affected people to get rid of the symptoms of arsenic toxicity. Hence, provision of arsenic free water is urgently needed to mitigate arsenic toxicity and protection of health and well being of people living in acute arsenic problem areas. The basic objective of mitigation of arsenic problem is to supply safe water to the community. The technological options for safe water supply in the arsenic affected areas could be one of the

following:

- a) Removal of arsenic from ground water;
- b) Supply of surface water by using conventional treatment system through piped network;
- c) Upgrading surface water sources like ponds through the application of HRF-SSF technology;
- d) Rainwater harvesting;
- e) Tapping alternative safe aquifer for arsenic free ground water

The alternative options available for water supply in the arsenic affected areas include arsenic avoidance and treatment of arsenic contaminated ground water. Treatment of surface waters by low-cost methods, rain water harvesting and water from deep aquifers would be potential sources of water supply to avoid arsenic ingestion through shallow tube well water. However, the use of alternative sources will require a major technological shift in water supply. On the other hand, treatment of arsenic contaminated well water is an alternative option to make use of a huge number of tube wells likely to be declared abandoned for yielding water with high arsenic content.

Problematic arsenic levels in drinking water can be mitigated in several different ways.

- i) Abandonment - The total abandonment of the problematic source(s) and subsequent switching to other source(s).
- ii) Seasonal Use - Switching the problematic source(s) from full-time used to seasonal use only with subsequent blending with other full-time source(s).
- iii) Blending - The combination of multiple water sources to produce water with an arsenic concentration below the permissible limits.
- iv) Sidestream Treatment - The treatment of a portion of the high arsenic water and subsequent blending back with the untreated portion of the water to produce water that meets the permissible limits.
- v) Treatment - The processing of all or part of a water system to reduce the arsenic concentration to below the permissible limits. This can be achieved through wellhead treatment, centralized treatment or point-of-use treatment.

The selection of the most appropriate mitigation strategy should be based on feasibility, sustainability, system constraints and costs.

CONVENTIONAL TREATMENT TECHNOLOGIES

Various technologies available for removal of arsenic from contaminated water are based mainly on four principles:

- i) Oxidation and Co-precipitation: Oxidation of As(III) to As(V) by adding suitable oxidizing agent followed by coagulation, sedimentation and filtration (co-precipitation).
- ii) Adsorption: Activated Alumina, Iron filings (zero valent iron) and hydrated iron oxide.
- iii) Ion exchange through suitable cation and anion exchange resins.
- iv) Membrane Technology: Reverse osmosis, nanofiltration and electro dialysis.

The most treatment methods available for removal of arsenic from water are effective in removing arsenic in pentavalent form, so a pretreatment step of oxidation of trivalent to pentavalent arsenic is required.

Pretreatment Step (Pre-Oxidation)

Arsenic is normally present in ground water in As(III) and As(V) states in different proportions. Most treatment methods are effective in removing arsenic in pentavalent state and hence include an oxidation step as pretreatment to convert As(III) to As(V). Following oxidizing agents can be used for conversion of arsenite to arsenate:

- Oxygen (process is very slow);
- Powdered active carbon and dissolved oxygen (catalytic oxidation);
- UV irradiation;
- Chemicals (free chlorine, hypochlorite, bleaching powder, ozone, permanganate, hydrogen peroxide etc.);
- Sunlight.

Although, arsenite can be oxidized to arsenate by oxygen, catalytic oxidation, UV irradiation, chemicals (free chlorine, hypochlorite, bleaching powder, ozone, permanganate, hydrogen peroxide etc.) and sun light but air oxidation of arsenic is very slow and can take weeks for oxidation. Chlorine dioxide and monochloramine are ineffective in oxidizing As(III). Ultraviolet (UV) light, by itself, is also ineffective. However, if the water is spiked with sulfite, UV photo-oxidation shows promise for As(III) conversion. Based on these considerations, only chlorine, permanganate and ozone are effective oxidizing agents for oxidizing As(III) to As(V) over wide range of working condition. Table 1 provides a summary of the benefits and drawbacks associated with the use of several oxidizing agents.

Oxidation and Filtration

Oxidation/filtration normally refers to processes that are designed to remove naturally occurring iron and manganese from water. The processes involve the oxidation of the soluble forms of iron and manganese to their insoluble forms and then removal by filtration. If arsenic is present in the water, it can be removed via two primary mechanisms: adsorption and co-precipitation. First, soluble iron and As(III) are oxidized. The As(V) then adsorbs onto the iron hydroxide precipitates that are ultimately filtered out of solution.

Although some arsenic may be removed by adsorption/co-precipitation with manganese, iron is much more efficient for arsenic removal. The arsenic removal efficiency is strongly dependent on the initial iron concentration and the ratio of iron to arsenic. In general, the Fe:As mass ratio should be at least 20:1. These conditions customarily result in an arsenic removal efficiency of 80-95%. In some cases, it may be appropriate to add ferric coagulant in the beginning of the iron removal process to optimize arsenic removal.

The common iron/manganese methods consist of (i) air oxidation or chemical oxidation followed by media filtration and (ii) potassium permanganate oxidation followed by a greensand media filter. The latter process is commonly referred to as the greensand process. The greensand process can be operated on an intermittent regeneration basis or on a continuous feed basis. With

intermittent regeneration operational procedure, the greensand filter is periodically regenerated with potassium permanganate following the back washing of the filter. In the continuous feed mode, permanganate or chlorine is continuously added to the feed water ahead of greensand filter. In the air/chemical oxidation filtration iron removal process, the iron is oxidized with either air (aeration tower) or with an oxidizing chemical, usually chlorine. Because of the limitations of air to oxidize As(III), chlorine is normally used in order for the process to be effective for arsenic removal. Once the water is oxidized, it is filtered with a granular media to remove the iron hydroxide precipitates that contain the adsorbed arsenic. The effectiveness of the granular media is important because any iron particles that manage to get through the filter media will contain some arsenic.

The greensand process is a special case of pressurized granular-media filtration where the granular media, greensand, catalyzes the oxidation and precipitation of iron and manganese. In the greensand process, operated on intermittent regeneration basis, the water is passed through a column of greensand media, which adsorbs and catalyzes the oxidation of the iron and manganese. In order for greensand to retain its adsorption and catalytic oxidation capabilities, the media must be regenerated with permanganate or chlorine. When operated on an intermittent regeneration basis, the greensand filter column is taken off line and the media is soaked in a solution of permanganate. In the continuous feed mode, permanganate or chlorine is continuously added to the feed water ahead of greensand filter where they provide continuous oxidation of the iron and As(III) and regeneration of the greensand. If the arsenic in the ground water is not already oxidized to As(V), it is recommended that continuous feed process using chlorine or permanganate be used to provide continuous oxidation of the iron, manganese and As(III).

In all oxidation/filtration processes, the filter media must be periodically backwashed to dislodge solids and restore hydraulic capacity. The specific amount of solids will depend on several factors, including raw water iron levels, coagulant addition (if any), filter run length and background solids concentration.

Table 1. Comparison of oxidizing agents

Oxidant	Benefits	Drawbacks
Chlorine	<ul style="list-style-type: none"> -Low relative cost -Primary disinfection capability -Secondary disinfectant residual -MnO₂ media regenerant -Oxidizes arsenic in less than 1 minute 	<ul style="list-style-type: none"> -Formation of disinfection by-products -Membrane fouling -Special handling and storage requirements
Permanganate	<ul style="list-style-type: none"> -Unreactive with membranes -No formation of disinfection by-products -MnO₂ media regenerant? -Oxidizes arsenic in less than 1 minute 	<ul style="list-style-type: none"> -High relative cost -No primary disinfection capability -Formation of MnO₂ particulates -Pink Water -Difficult to handle -An additional oxidant may be required for secondary disinfection
Ozone	<ul style="list-style-type: none"> -No chemical storage or handling required -Primary disinfection capability -No chemical by-products left in water -Oxidizes arsenic in less than 1 minute in the absence of interfering reductants 	<ul style="list-style-type: none"> -Sulfide and TOC interfere with conversion and increase the required contact time and ozone dose for oxidation -An additional oxidant may be required for secondary disinfection

Co-precipitation

Co-precipitation has been the most frequently used method to treat arsenic contaminated water, including ground water, surface water, drinking water and wastewater in numerous pilot- and full-scale applications. In order to remove arsenic by co-precipitation, a coagulant is to be added. Water treatment with coagulants such as alum [$\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$], ferric chloride [FeCl_3] and ferric sulfate [$\text{Fe}_2(\text{SO}_4)_3 \cdot 7\text{H}_2\text{O}$] are effective in removing arsenic from water. Ferric salts have been found to be more effective in removing arsenic than alum on a weight basis and effective over a wider range of pH. In both cases pentavalent arsenic can be more effectively removed than trivalent arsenic. The following steps are involved in the co-precipitation process for removal of arsenic:

- Addition of bleaching powder / hypochlorite,
- Addition of alum / ferric sulphate,
- Rapid mixing of chemical followed by slow mixing,
- Sedimentation, and
- Filtration.

In the coagulation-flocculation process, aluminium sulfate or ferric chloride or ferric sulfate is added and dissolved in water under efficient stirring for few minutes. The water is then gently stirred for few minutes for agglomeration of micro-flocs into larger easily settleable flocs. During this flocculation process all kinds of micro-particles and negatively charged ions are attached to the flocs by electrostatic attachment. As trivalent arsenic occurs in non-ionized form, it is not subject to significant removal. Oxidation of As(III) to As(V) is thus required as a pretreatment for efficient removal. This can be achieved by addition of bleaching powder (chlorine) or potassium permanganate. The co-precipitation technique for removal of arsenic can be applied for following system:

- Central Arsenic Removal Plant (ARP) attached with tube wells for piped water supply,
- Arsenic Removal Plant (ARP) attached with Hand Pump, and
- Domestic Arsenic Removal Units using Earthen Pots, Plastic Buckets, Bucket Treatment Units, Modified BTUs, Stevens Institute Technology, Fill and Draw Units, Naturally Occurring Iron, Chemical Packages, etc.)

Adsorption

Adsorption is the most prospective technology for removal of arsenic. Adsorption technology has been widely used to treat ground water and drinking water containing arsenic. Its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. In adsorption technology, solutes (contaminants) concentrate at the surface of a sorbent, thereby reducing their concentration in the bulk liquid phase. The adsorption media is usually packed into a column. As the contaminated water is passed through the column, contaminants are adsorbed. When adsorption sites become filled, the column must be regenerated or disposed of and replaced with new media.

Several adsorbents are available for removal of arsenic from water, viz., activated alumina, activated carbon, iron and manganese coated sand, kaolinite clay, hydrated ferric oxide,

activated bauxite, titanium oxide, silicium oxide and many natural and synthetic adsorbents. The efficiency of sorptive media depends on the use of oxidizing agent as aids to sorption of arsenic. Saturation of media by different contaminants and components of water takes place at different times of operation depending on the specific sorption affinity of the medium to the given component.

Adsorption technology largely depends on capital cost, operation and maintenance cost, operational procedure and user-friendliness. The following media may be used for removal of arsenic through adsorption technique:

- Activated alumina (AA),
- Activated Carbon (AC)
- Iron Based Sorbents (Granular Ferric Hydroxide, Iron Coated Sand, etc.),
- Indigenous Filters, and
- Cartridge Filters.

Several constituents can interfere with the adsorption process, either by competing for adsorption sites or clogging the media with particulate matter. The presence of suspended solids in the feed water could gradually clog the media and therefore pre-filtration is recommended for sources where the turbidity exceeds 0.3 NTU.

Activated alumina is a low cost chemical (Rs. 100/- to Rs. 110/- per kg.) and it can be regenerated by washing with acid and alkali. Activated alumina has a useful life expectancy and after which fresh activated alumina will replace the exhausted alumina. The technologies and market for alumina-based adsorptive media is continuously expanding. There are several emerging proprietary media, commonly referred to as modified AA, which contain alumina in a mixture with other substances such as iron and sulfur. In some instances, these media have greater overall adsorptive capacities, enhanced selectivity towards arsenic, and/or greater overall operational flexibility than conventional AA, thus making them more cost-effective.

Ion exchange

Ion exchange is a physical-chemical process in which ions are swapped between a solution phase and solid resin phase. The solid resin is typically an elastic three-dimensional hydrocarbon network containing a large number of ionizable groups electrostatically bound to the resin. These groups are exchanged for ions of similar charge in solution that have a stronger exchange affinity (i.e., selectivity) for the resin. In drinking water treatment, this technology is commonly used for softening and nitrate removal. The technology typically can reduce arsenic concentrations to less than 50 $\mu\text{g/L}$ and in some cases to below 10 $\mu\text{g/L}$. Its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It is used less frequently than precipitation/ coprecipitation and is most commonly used to treat ground water and drinking water. Arsenic removal is accomplished by continuously passing water under pressure through one or more columns packed with exchange resin.

Different categories of synthetic resins can be used for arsenic removal. The process is similar to that of adsorption; just the medium is a synthetic resin of more well defined ion exchange capacity. However, the resins need to be replenished after use and renewal interval is dependent on the quantity of arsenic in water.

Membrane technology

Membrane technology can remove a wide range of contaminants from water. This technology typically can reduce arsenic concentrations to less than 50 µg/L and in some cases to below 10 µg/L. However, its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It also produces a larger volume of residuals and tends to be more expensive than other arsenic treatment technologies. Therefore, it is used less frequently than precipitation/coprecipitation, adsorption and ion exchange.

Membrane techniques are capable of removing all kinds of dissolved solids including arsenic from water. They can address numerous water quality problems while maintaining simplicity and ease of operation. In this process, water is allowed to pass through special filter media which physically retain the impurities present in water. The water, for treatment by membrane techniques, should be free from suspended solids and the arsenic in water shall be in pentavalent form. Most membranes, however, can not withstand oxidizing agent.

There are four types of membrane processes: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). All the four processes are pressure-driven and are categorized by the size of the particles that can pass through the membranes or by the molecular weight cut off (i.e., pore size) of the membrane. The force required to drive fluid across the membrane depends on the pore size; NF and RO require a relatively high pressure (50 to 150 psi), while MF and UF require lower pressure (5 to 100 psi). The low pressure processes primarily remove contaminants through physical sieving and the high pressure processes through chemical diffusion across the permeable membrane.

Because arsenic species dissolved in water tend to have relatively low molecular weights, only NF and RO membrane processes are likely to effectively treat dissolved arsenic. MF has been used with precipitation/coprecipitation to remove solids containing arsenic. MF generates two treatment residuals from the influent waste stream: a treated effluent (permeate) and a rejected waste stream of concentrated contaminants (reject).

RO is a high pressure process that primarily removes smaller ions typically associated with total dissolved solids. The molecular weight cut off for RO membranes ranges from 1 to 20,000, which is a significantly lower cut off than for NF membranes. The molecular weight cut off for NF membranes ranges from approximately 150 to 20,000. NF is a high pressure process that primarily removes larger divalent ions associated with hardness but not monovalent salts. NF is slightly less efficient than RO in removing dissolved arsenic from water. Reverse Osmosis (RO) units can be used as stand-alone arsenic treatment under most water quality conditions.

INNOVATIVE TECHNOLOGIES

Innovative technologies, such as permeable reactive barriers, phytoremediation, biological treatment and electrokinetic treatment, are also being used to treat arsenic-contaminated water, waste water and soil. However, only a few applications of these technologies at full scale are available in the literature and additional treatment data are needed to determine their applicability and effectiveness in field condition. These technologies may be developed at full scale to treat arsenic more frequently in the future. A brief description of these technologies is given below.

Permeable Reactive Barriers (PRBs)

PRBs are walls containing reactive media that are installed across the path of a contaminated ground water plume to intercept the plume. The barrier allows water to pass through while the media remove the contaminants by precipitation, degradation, adsorption or ion exchange. PRBs are used to treat ground water in-situ. This technology tends to have lower operation and maintenance costs than ex-situ (pump and treat) technologies, and typically requires a treatment time of many years.

PRBs are being used to treat arsenic in ground water at full scale at only few sites. Although many materials for the reactive portion of the barrier have been tested at bench scale, only zero valent iron and limestone have been used at full scale. The installation techniques for PRBs are established for depths less than 30 feet, and require innovative installation techniques for deeper installations. The following chemicals and reactive media are used in PRBs to treat arsenic:

- Zero valent iron (ZVI)
- Limestone
- Basic oxygen furnace slag
- Surfactant modified zeolite
- Ion exchange resin

Phytoremediation

Phytoremediation is an in-situ technology applicable to contaminated soil and ground water. It is designed to use plants to degrade, extract, contain or immobilize contaminants in soil, sediment or ground water (Zhang et al., 2001). Typically, trees with deep roots are applied to ground water and other plants are used for shallow soil contamination. This technology tends to have low capital, operating and maintenance costs relative to other arsenic treatment technologies because it relies on the activity and growth of plants.

The mechanisms of phytoremediation include phytoextraction (also known as phytoaccumulation, the uptake of contaminants by plant roots and the translocation/accumulation of contaminants into plant shoots and leaves), enhanced rhizosphere biodegradation (takes place in soil or ground water immediately surrounding plant roots), phytodegradation (metabolism of contaminants within plant tissues), and phytostabilization (production of chemical compounds by plants to immobilize contaminants at the interface of roots and soil). Most applications of phytoremediation for arsenic removal include phytoextraction and phytostabilization.

Experimental research into identifying appropriate plant species for phytoremediation is ongoing. It is generally applicable only to shallow soil or relatively shallow ground water that can be reached by plant roots. In addition, the phytoremediating plants may accumulate high levels of arsenic during the phytoremediation process, and may require additional treatment prior to disposal.

The selection of the phytoremediating species depends upon the species ability to treat the contaminants and the depth of contamination. Plants with shallow roots (for example, grasses, corn) are appropriate only for contamination near the surface, typically in shallow soil.

Plants with deeper roots, (for example, trees) may be capable of remediating deeper contaminants in soil or ground water plumes.

Biological Treatment

Although biological treatments have usually been applied to the degradation of organic contaminants, some innovative techniques have applied biological remediation to the treatment of arsenic. This technology involves biological activity or micro-organisms that promote precipitation/coprecipitation of arsenic from water and leaching of arsenic in soil. Biological precipitation/coprecipitation processes for water create ambient conditions intended to cause arsenic to precipitate/coprecipitate or act directly on arsenic species to transform them into species that are more amenable to precipitation/coprecipitation. The microbes may be suspended in the water or attached to a submerged solid substrate.

An adequate nutrient supply should be available to the microbes to enhance and stimulate growth. If the initial solution is nutrient deficient, nutrient addition may be necessary. Iron or hydrogen sulfide may also be added. For biologically enhanced iron precipitation, iron must be present in the water to be treated. The optimal iron level depends primarily on the arsenic concentration.

Biological treatment for arsenic is used primarily to treat water above-ground in processes that use microorganisms to enhance precipitation/coprecipitation. This technology may require pretreatment or addition of nutrients and other treatment agents to encourage the growth of key microorganisms. The leachate from bioleaching requires additional treatment for arsenic prior to disposal.

Electrokinetic Treatment

Electrokinetic treatment is an emerging remediation technology designed to remove heavy metal contaminants from soil and ground water. It is an in-situ treatment technology and therefore does not require excavation of contaminated soil or pumping of contaminated ground water. Fine-grained soils are more amenable to electrokinetic treatment due to their large surface area, which provides numerous sites for reactions necessary for electrokinetic processes (Acar and Gale, 1995; Evanko and Dzomback, 1997). However, its effectiveness may be limited by a variety of contaminants and soil and water characteristics. In addition, its treatment depth is limited by the depth to which the electrodes can be placed. The technology has limited number of applications for arsenic.

Electrokinetic remediation is based on the theory that a low density current will mobilize contaminants 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 (Will, 1995). Contaminants 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.

The chemicals used in electrokinetic process for arsenic removal include sulfuric acid, phosphoric acid and oxalic acid. In situ electrokinetic treatment of arsenic uses the natural conductivity of the soil (created by pore water and dissolved salts) to affect movement of water,

ions and particulates through the soil (Will, 1995). Water and/or chemical solutions can also be added to enhance the recovery of metals by electrokinetics. Positively charged metal or metalloid cations, such as As (V) and As (III) migrate to the negatively-charged electrode (cathode), while metal or metalloid anions migrate to the positively charged electrode (anode). Extraction may occur at the electrodes or in an external fluid cycling/extraction system. Alternately, the metals can be stabilized in situ by injecting stabilizing agents that react with and immobilize the contaminants. Arsenic has been removed from soils treated by electrokinetics using an external fluid cycling/extraction system.

WASTE DISPOSAL / SLUDGE MANAGEMENT

Waste disposal is an important consideration in the treatment selection process. Arsenic removal technologies produce several different types of waste, including sludges, brine streams, backwash slurries and spent media. These wastes have the potential for being classified as hazardous and can pose disposal problems. The arsenic-rich sludge should be disposed in a controlled manner. According to the study conducted by AIHH&PH, arsenic rich sludge may be disposed by the following method:

- i) Disposal in on-site sanitation pits;
- ii) Mixing with concrete in a controlled ratio;
- iii) Mixing with clay for burning for brick manufacturing.

The adsorbed media rich in arsenic can also be mixed with concrete as an additional aggregate but in a controlled proportion.

Liquid wastes must have lower concentrations than the toxicity characteristic in order for the waste to be classified as non-hazardous. The arsenic toxicity characteristic is 5.0 mg/L. Those liquid wastes that contain more than 5.0 mg/L of arsenic would therefore be classified as a hazardous waste. Many of the arsenic removal technologies also remove other constituents (e.g., chromium). The liquid waste must also be analyzed for other substances that may be present in concentrations above their respective toxicity characteristics. Because of the cost implications, on-site treatment or off-site disposal of hazardous waste is likely to be infeasible for small water systems. Indirect discharge through sewer to treatment plants may be viable option for waste disposal. There are five realistic methods for the disposal of arsenic wastes.

- Landfill Disposal
- Direct Discharge to Surface Waters
- Indirect Discharge
- Land Application
- On-Site Sewerage

CONCLUSION

A remarkable technological development in arsenic removal processes has taken place during last few years. One should also realize that arsenic mitigation strategy should be location specific. A method suitable for a specific area should not be generalized for the other affected regions due to i) geographical and geomorphological variations, and ii) different socio-economic and literacy conditions of people.

All the technologies described in this paper have their own merits and demerits and should be refined to make them suitable for a particular situation. The modifications should be based on the pilot-scale implementation of the technologies with the objectives to:

- Improve effectiveness in arsenic removal,
- Reduce the capital and operation cost of the system,
- Make the technology user friendly,
- Overcome maintenance problems, and
- Resolve sludge and arsenic concentrates management problems.

Arsenic removal technologies have to compete with other technologies in which cost appears to be a major determinant in the selection of a treatment option by the users. The rural people habituated in drinking tube well water may find arsenic removal from tube well water as a suitable option for water supply. In many arsenic affected areas, arsenic removal may be the only option in the absence of an alternative safe source of water supply.

The arsenic calamity of Bangladesh and West Bengal-India, which have been claimed as the biggest in the World, should not be neglected any more. There is a need to combat with the situation by providing an alternative source of water for drinking purposes. West Bengal-India and Bangladesh are lands of rivers. The average annual rainfall in these two areas is 2000 mm. West Bengal has about 7,000 m³ and Bangladesh has 11,000 m³ of available surface water per capita. Besides this, West Bengal has about 4000 km² of wetland and vast river basin is flooded almost every year, but due to the negligence most of these water goes as waste. There is an urgent need for a proper watershed management so that the vast surface and rain water resource could be used to combat with the situation. A proper watershed management approach with active participation from the people can solve the problem of arsenic contamination in ground water by providing alternative surface and rain water as a source of safe drinking water to the affected population. Its high time to make use of vast surface and rainwater resources of West Bengal and Bangladesh as an alternate source of safe drinking water to combat with the situation and reduce ground water extraction.

REFERENCES

- Acar, Y. B. and Gale, R.J. (1995). Electrokinetic remediation: Basics and technology status, *Journal of Hazardous Materials*, 40, 117-137.
- Ahamed, S., Sengupta, M.K., Mukherjee, A., Hossain, M.A., Das, B., Nayak, B., Pal, A., Mukherjee, S.C., Pati, S., Dutta, R.N., Chatterjee, C., Mukherjee, A., Srivastava, R. and Chakraborti, D. (2006). Arsenic ground water contamination and its health effects in the state of Uttar Pradesh (UP) in upper and middle Ganga plain, India: A severe danger, *Science of the Total Environment*, 370, 310-322.
- Bhattacharya, P., Chatterjee, D. and Jacks, G. (1997). Occurrence of arsenic contaminated groundwater in alluvial aquifers from Delta Plains, Eastern India: Options for safe drinking water supply, *International Journal of Water Resources Development*, 13, 79-92.
- Chakraborti, D. Mukherjee, S.C., Pati, S., Sengupta, M.K., Rahman, M.M., Chowdhury, U.K., Lodh, D., Chanda, C.R., Chakraborti, A.K. and Basu, G. K. (2003). Arsenic groundwater contamination in Middle Ganga Plain, Bihar, India: a future danger? *Environ, Health Perspective*, 111, 1194-1201.

- Chakraborti, D., Sengupta, M.K., Rahman, M.M., Ahamed, S., Chowdhury, U.K., Hossain, M.A., Mukherjee, S.C., Pati, S., Saha, K.C., Dutta, R.N. and Quamruzzaman, Q. (2004). Groundwater arsenic contamination and its health effects in the Ganga–Meghna–Brahmaputra plain, *J. Environ. Monit.*, 6, 74N–83N.
- Chakraborti, D., Rahman, M.M., Paul, K., Chowdhury, U.K., Sengupta, M.K., Lodh, D., Chanda, C.R., Saha, K.C. and Mukherjee, S.C. (2002). Arsenic calamity in the Indian subcontinent: What lessons have been learned?, *Talanta*, 58, 3–22.
- Chowdhury, T.R., Mandal, B.K., Samanta, G., Basu, G.K., Chowdhury, P.P., Chanda, C.R. (1997). Arsenic in groundwater in six districts of West Bengal, India, the biggest arsenic calamity in the world: the status report up to August 1995. In: *Arsenic: Exposure and Health Effects* (Eds. C.O. Abernathy, R.L. Calderon and W.R. Chappel), London, Chapman & Hall, pp. 91–111.
- Evanko, C.R. and Dzomback, D.A. (1997). Remediation of Metals-Contaminated Soils and Groundwater, Prepared for the Ground-Water Remediation Technologies Analysis Center, Technology Evaluation Report TE-97-01, October 1997. <http://www.gwrtac.org/pdf/metals.pdf>
- Chowdhury, U.K., Biswas, B.K., Chowdhury, T.R., Samanta, G., Mandal, B.K., Basu, G.C., Chanda, C.R., Lodh, D., Saha, K.C., Mukherjee, S.K., Roy, S., Kabir, S., Quamruzzaman, Q. and Chakraborti, D. (2000a). Groundwater arsenic contamination in Bangladesh and West Bengal, India, *Environ. Health Perspective*, 108, 393-397.
- Chowdhury, U.K., Biswas, B.K., Chowdhury, T.R., Mandal, B.K., Samanta, G., Basu, G.K. (2000b). Arsenic groundwater contamination and sufferings of people in West Bengal, India and Bangladesh. In: *Trace Elements in Man and Animals* (Eds. A.M. Roussel, R.A. Anderson and A.E. Favier), New York, Plenum Press, pp. 645–650.
- Nikolaidis, N. P. and Lackovic, J. (1998). Arsenic remediation technology -AsRT, International Conference on Arsenic Pollution of Ground Water in Bangladesh: Causes, Effect and Remedies, Dhaka, 8-12 February 1998.
- Rahman, M.M., Chowdhury, U.K., Mukherjee, S.C., Mondal, B.K., Paul, K., Lodh, D. (2001). Chronic arsenic toxicity in Bangladesh and West Bengal, India - a review and commentary, *J. Toxicol. Clin. Toxicol.*, 39, 683–700.
- Singh, A.K. (2004). Arsenic contamination in groundwater of Northeastern India. In: *Water Quality Monitoring, Modelling and Prediction* (Eds. C. K. Jain, R. C. Trivedi and K. D. Sharma), Allied Publishers Pvt. Ltd., New Delhi, pp. 255–262.
- Tripathi, P., Ranjan, R.K., Ramanathan, A.L. and Bhattacharya, P. (2006). Groundwater arsenic in the Central Gangetic Plain in Ballia District of Uttar Pradesh, India: A future concern (Abstract), In: *International Conference on Groundwater for Sustainable Development: Problems, Perspectives and Challenges (IGC-2006)* (Eds. A.L. Ramanathan et al.), New Delhi, 1-4 February 2006.
- Will, F. (1995). Removing toxic substances from soil using electrochemistry, *Chemistry and Industry*, 376-379.
- Zhang, W., Cai, Y., Tu, C. and Ma, L.Q. (2001). Speciation and distribution of arsenic in an arsenic hyperaccumulating plant, *Biogeochemistry of Environmentally Important Elements. Symposia, Papers Presented Before the Division of Environmental Chemistry, American Chemical Society, San Diego, CA, April 1-5, 2001.*

