

Design of A Low-cost Purification System for the Removal of Arsenic from Tubewell water in Bangladesh and India

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Abstract

A low-cost purification system has been designed which incorporates air/light oxidation, a sediment trap and a bed of adsorbent chemicals in a brick-tank which can be placed next to a tube well. The brick-tank (5.5 m long, 2.0 m wide and 1.5-2.0 m high) comprises a reservoir for arsenic-contaminated water, a tap for flow control, spreader troughs from which water drips (in order to expose a large water surface to air), a series of baffles which forces water repeatedly to the surface (in order to expose it to air and light), a series of sediment traps (to remove arsenic-contaminated iron hydroxide, calcium carbonate and other sparingly soluble salts), an adsorbent bed to remove remaining arsenic species, a water lock so that the system can not run dry, and a reservoir for purified water. Baffles are low brick walls with every second half-brick removed in the base row of every second wall. Sediment traps are layers of crushed brick with particles of increasing size (2 to 10 mm), placed at the bottom of the baffles. Layers of crushed brick of decreasing particle size are placed above and below the adsorbent bed in order to prevent mechanical disturbance during the percolation of water. The adsorbent bed comprises a mixture of charcoal and ash to which is added spent brine, followed by a suspension of fine rust particles. Charcoal is obtained by heating rice husks or coconut husks in the absence of air in a modified brick kiln. Ash is obtained from the fuel used in the brick kiln. Spent brine, rich in magnesium salts, is the liquid remaining from the crystallization of salt from seawater. Rust particles are obtained by placing scrap iron in water. In the adsorbent bed, potassium carbonate from the ash reacts with magnesium salts from the brine to form magnesium hydroxy-carbonate as a gelatinous precipitate which coats the charcoal and ash particles and serves to retain the

fine particles of rust. Considerable oxidation of arsenite to arsenate ions occurs in the baffles due to the action of light and oxygen, perhaps assisted by microbial activity. Most arsenic(V) and some arsenic(III) species precipitate with iron(III) hydroxide and are retained in the crushed brick of the sediment trap. Remaining arsenic is retained as magnesium arsenate, iron(III) arsenite and iron(III) arsenate in the adsorbent bed. The adsorbent bed does not clog with particles, since iron and calcium salts have already been removed. The design allows treatment of 750 L of water each day, with long residence time (~10 days) and low linear flow rates, in order to maximize air/light oxidation, sedimentation and adsorption processes.

INTRODUCTION

Arsenic in water from tube wells in Bangladesh^{1,2,3} and West Bengal^{4,5,6} is currently poisoning around 20 million people^{7,8,9,10,11,12,13}. Symptoms of arsenic poisoning have already reached epidemic proportions and cataclysmic effects are predicted if the majority of people in affected areas are not soon provided with safe drinking water¹⁴.

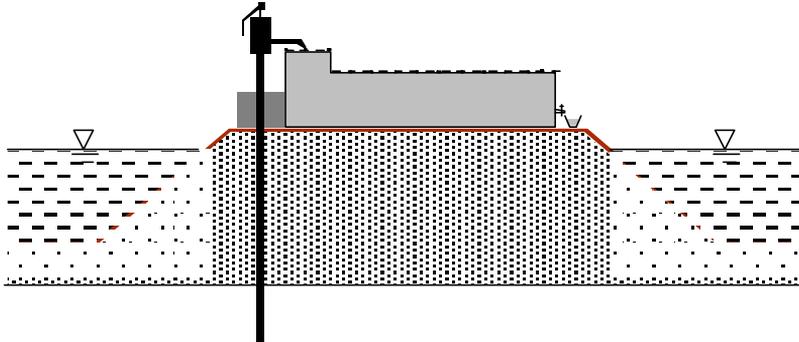
Water purification techniques using membrane systems, coagulation-flocculation^{15,16} and other advanced systems¹⁷ may find use in large-scale water treatment for towns and cities but are not appropriate to the treatment needs of the majority of the population, who live in small villages or on farms. Small-scale systems for purifying the water for a single household have been demonstrated^{18,19}, but these systems have two disadvantages. They are time-consuming, reducing time available for family care and education, especially for women. Secondly, they are expensive by the standards of the region, especially for initial purchase of equipment. Due to the widespread poverty amongst the affected people, arsenic removal from groundwater must be accomplished at very low cost, using materials that are either widely available or capable of being produced with only minor modifications to existing production techniques. Materials that can be made using few resources other than human labor are favored. A second consideration is that water treatment should be accomplished on a scale that allows sharing of duties by several families and hence minimum time-wasting activities. The purification system described in this paper is designed to meet these objectives.

The design has two components: the physical design of a water treatment tank that can be constructed next to a tube well, and the chemical design of an adsorbent bed of harmless low-cost chemicals which can trap and remove arsenic species from the water. The design allows 750 L volumes of water to be treated each day, sufficient for several families, who could share costs of construction and maintenance.

COMPONENTS OF THE PURIFICATION SYSTEM

Water Treatment Tank

The water treatment tank (Figures 1 and 2) is constructed in stages as follows:



Figures 1 : Water treatment system.

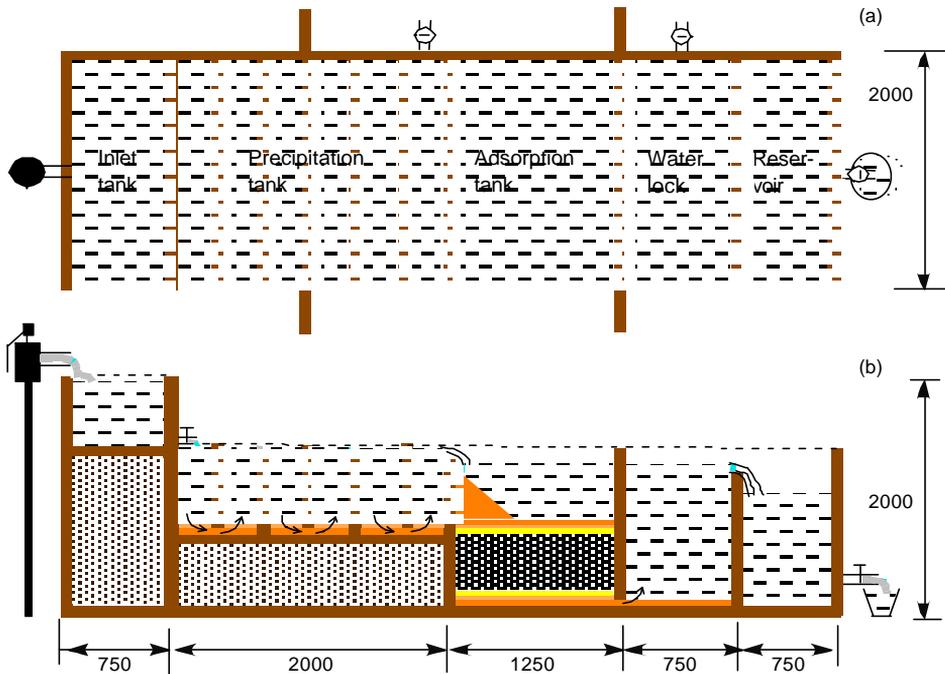


Figure 2 : Water treatment system in plan view (a) and cross-sectional view

All Dimension\$ are in mm.

Mound

Since Bangladesh and West Bengal are subject to regular flooding and clean water supplies are critical during times of inundation, the water treatment tank should be built on a mound of earth, the top of which is comfortably above the maximum flood level recorded in the area. It is likely that global climate change is occurring and that flooding will become more severe in the future. Since the mound will be subject to frequent human traffic and will be prone to erosion in times of flood, the mound should preferably be paved with brick. The top of the mound should be flat, to accommodate the treatment tank (5.5 m x 2.0 m) and should allow a sufficient walkway (minimum 2 m) around the tank for traffic and maintenance. The soil in the mound should be allowed to compact fully before further construction (Figure 1).

Tube Well

A tube well should be sunk at one end of the mound, so that there is space for the treatment tank next to it (Figure 1). The tube well should terminate with its outlet 2.2 m above the top of the mound. Since it is necessary to manually operate the pump in the top of the tube well, a brick platform and a set of steps should be constructed to allow easy access for pumping. Even during times of flood, no surface water should enter the tube well due to the compacted earth around it.

Outer Structure

The tank should be constructed from double brick, in order to provide strength. Bricks with low porosity and grout containing a large proportion of cement should be used in order to reduce water permeability. Sealing of the structure need not be perfect, but low permeability will make the system more efficient and longer lasting.

The tank is rectangular in shape, 2.0 m x 5.5 m, with walls 1.5 m high, rising to 2.0 m at the inlet tank (Figures 1 and 2). Construction begins by cementing together a base layer of bricks (or using an area of the paving bricks), and then adding another layer of bricks with grout between them. It may be desirable to incorporate a sheet of plastic into the base of the structure as a sealant, since leaks would be difficult to detect at the bottom of the tank. The walls are then constructed on the base, taking care to seal the joints. It is desirable to buttress the outer walls with tapering brick supports at right angles to the walls, especially in the center of the larger tanks.

Internal Structure

The internal walls are constructed at the same time as the outer walls, so that the fresh cement will bind all components together. The only exceptions are the internal baffles of the precipitation tank. Four internal walls are required to provide the inlet reservoir, the precipitation tank, the absorption tank, the water lock and the reservoir for purified water (Figure 2). The minimum width for an internal structure of full height is 0.75 m, to allow access for maintenance.

The inlet reservoir is filled with dirt until only 0.5 m depth remains, the dirt is compacted and a brick floor cemented into place. The precipitation tank is filled to half its depth with compacted dirt and a brick floor similarly constructed, followed by a series of five vertical baffles. Gaps are left at the bases of odd-numbered baffles by omitting each second half-brick in the bottom brick layer. This allows water to alternately pass through the base and over the top of successive baffles.

Drip Troughs

The spout from the tube well delivers water to a trough, which extends across the 2-m width of the inlet tank and is shaped so that water dips evenly off its entire width. This ensures maximum absorption of oxygen from the atmosphere. Similar drip troughs are constructed beneath the tap from the inlet tank and at the end of the precipitation tank.

Sediment Trap

The precipitation tank is filled to a depth of 0.25 m with layers of crushed brick, the bottom layer being 10-mm diameter and the top 2 mm diameter. This allows free migration of liquid in the lowest layer, while maintaining adequate particle trapping in the top layer.

Taps

A brass tap with a washer, seat and handle is used to set the flow rate of water through the system at the bottom of the inlet tank. A tap, in the simplest form, comprising a short length of plastic tubing with a stopper, is required in the wall of the purified water reservoir, and two others should be inserted near mound level in the precipitation tank and the water lock, to allow draining of the system for maintenance.

Covering

In order to prevent insects and other animals entering the tank, timber structures supporting mosquito netting should be kept on top of the tanks at all times. A durable covering (Figures 1 and 2) would be provided by five timber frames,

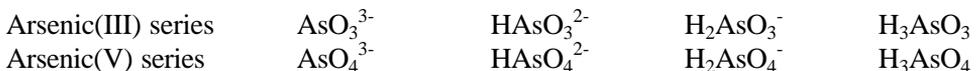
each 2 m wide and the length of each tank, with cross supports at approximately 0.5 m intervals. To each is fixed a layer of mosquito netting between two layers of wire gauze (e.g. chicken wire). Metal hooks could be inserted in the brickwork of the tank during construction to provide anchor points for ropes which hold the covering in place during high winds. The covering should be carefully maintained in order to prevent spread of water-borne diseases or use of the tank by disease vectors such as mosquitoes. Birds and other animals will be attracted to the treatment tank and may defecate on the mesh screen. The cover for the last section, containing purified water, must be continuous and totally animal-proof. Tube wells are typically housed in a roofed structures, but this would greatly reduce ultraviolet radiation intensity and should be avoided.

Adsorbent bed for Arsenic Removal

The adsorbent bed (Figure 2b) is inserted into the treatment tank after the cement of the latter has thoroughly set and all other components are in place. There must be as little disturbance as possible to the adsorbent bed after it has been installed. The following sections describe the design for a low-cost adsorption bed based on available materials. Other adsorbents, such as iron filings, finely-chopped tin cans, aluminum oxide and treated clays, could be substituted, if available. The bed should not clog with particles (largely iron(III) hydroxide and calcium carbonate) as has occurred with other adsorption systems tested in the region, since reactions with the atmosphere should have proceeded almost to completion in the precipitation tank. A large proportion of the arsenic species in the water should also have been removed with the sediment forming in the precipitation tank, reducing the load on the adsorption bed.

AQUEOUS CHEMISTRY OF ARSENIC

Arsenic occurs in groundwater in two forms: arsenite (AsO_3^{3-}) and arsenate (AsO_4^{3-}) ions, often referred to as arsenic(III) and arsenic(V) species due to the oxidation number of the central arsenic atom²⁰. The chemistry is complicated²¹ by the fact that each ion can acquire from water one or more protons, depending on the acidity, to yield a series of chemical species:



At the acidity of drinking water, the dominant arsenic(III) species is the neutral compound H_3AsO_3 and the dominant arsenic(V) species are the ions HAsO_4^{2-} and H_2AsO_4^- . However, all arsenic(III) species coexist and rapidly interconvert, as is the case for arsenic(V) species. The arsenic(III) and arsenic(V) series can also interconvert. This is more difficult since oxidation or reduction processes are

required, but conversion occurs slowly in rocks, groundwaters and surface waters due to the influence of minerals²², microorganisms and atmospheric oxygen²³. Arsenic(III) compounds are more toxic than arsenic(V) compounds²⁴, by a factor of about ten. The proportion of arsenic(III) in well water typically ranges between 50 and 90%.

The idea of using harmless metal ions, such as iron^{4,25,26,27,28,29}, copper²⁴, manganese^{30,31,32} or aluminum³³, to trap and remove arsenic species from drinking water as their insoluble salts is attractive since the chemicals required are inexpensive. Other metals with somewhat more soluble arsenic salts, such as magnesium and calcium, are also worthy of examination. Metal salts have been used for large-scale treatment of wastewaters for arsenic removal, for example, in the mining industry. The problem is that the metal salts of arsenic(III) and arsenic(V) have widely different solubilities^{34, 35} and it is necessary to choose metals carefully. Arsenic(V) salts (metal arsenates) are generally less soluble than arsenic(III) salts (metal arsenites)³⁶. It is vital, however, that arsenic(III) compounds be removed since they are the more dangerous.

Sparingly soluble metal arsenites and arsenates in equilibrium with water near neutral pH, generally yield concentrations of dissolved arsenic species greater than those acceptable in drinking water (currently 50 µg/L; proposed 20, 10 and 5 µg/L). On the other hand, binding of arsenic species to solid surfaces by adsorption may be extremely strong, since adsorption processes are not limited by the thermodynamics of solubility products, and adsorption is frequently better for reducing the concentration of dissolved arsenic species than precipitation.

Many ions in natural waters, particularly phosphate, may interfere with adsorption processes involving arsenic species. Even chloride and sulfate may influence adsorption. Sufficient excess adsorption capacity must be available or selective adsorbents used. Growth of algae in sections of the treatment system may be beneficial for removing phosphate ions.

Calcium ions and hydrogen-carbonate ions are abundant in well waters. When a well water is exposed to the air, carbon dioxide is lost and calcium carbonate precipitates. Iron(II) ions, also abundant in well waters, are slowly oxidized by oxygen in the air, especially in the presence of light, forming iron(III) hydroxide which precipitates with the calcium carbonate. Large amounts of aqueous arsenic species are adsorbed by iron(III) hydroxide/calcium carbonate mixtures as they precipitate. Typically, half the arsenic(III) and nearly all the arsenic(V) species are removed.

DESIGN AND CONSTRUCTION OF ADSORBANT BED

Chemicals for the Adsorbent Bed

In most areas of Bangladesh and India, no money is available for the purchase of imported chemicals or treatment devices. It is essential to use chemicals that can be made locally, from materials that are free or widely available at little cost, e.g. agricultural wastes. The chemicals chosen for construction of the adsorbant bed are:

- *Charcoal*, from heating coconut or rice husks in an oven the absence of air,
- *Ash*, from combustion of coconut or rice husks in air,
- *Magnesium salts*, from the brine left after the recovery of salt from sea water, and
- *Rust*, from clean scrap iron placed in water and exposed to the air.

Charcoal is a well-known adsorbent for organic compounds and may weakly adsorb arsenic species. Its main value is as a porous material to provide a large surface area on which to deposit other chemicals. Ash contains several percent by weight of potassium carbonate, a chemical critical for construction of the proposed adsorbent bed. Mineral particles, such as silica, will help to provide bulk and surface area for the adsorption bed. A brick kiln could be modified to produce charcoal and ash, using available agricultural wastes. Rice husks, for instance, could be burnt beneath the kiln to produce ash and heat for pyrolysis of other rice husks in the kiln chamber to produce charcoal.

Magnesium ions occur in seawater at a concentration of 1.27 g per litre³⁶. After salt has been crystallized from seawater, the remaining liquid is greatly enriched in magnesium salts, principally magnesium chloride. The liquid is usually discarded to the sea, but could be inexpensively dried in the sun to yield a damp solid (magnesium chloride, the principal salt absorbs moisture from the air) and transported throughout the region. Production of magnesium chloride would provide additional income for impoverished salt workers.

Rust can be prepared by heating scrap iron in a fire (perhaps with rice husks in a modified brick kiln) to burn off paint, oil or metal plating, and then the clean iron can be placed in water in a shallow container to allow easy access by atmospheric oxygen. Addition of small amounts of acidic materials such as lemon juice may promote more rapid rusting. The slurry of rust particles settling to the bottom is collected and used. Lumps of clean scrap iron could be reused until they had corroded completely.

Construction of the Adsorbent Bed

The adsorbent bed (Figure 2b) is constructed by mixing together charcoal and ash, then moistening the mixture with water to dissolve the potassium carbonate in the ash and allow it to soak into the pore spaces in the charcoal particles. A concentrated solution of magnesium ions, prepared by mixing impure magnesium chloride with a little water, is then added to the wet charcoal/ash and the combined materials further mixed. At this stage, magnesium ions and carbonate ions will react to form magnesium hydroxy-carbonate³⁷, which will deposit on and within the charcoal particles. The reaction conditions must be optimized to obtain the maximum surface area of magnesium hydroxy-carbonate, a white gelatinous solid.

The base of the adsorption tank must now be prepared to receive the adsorbent bed. The problem is that the adsorbent is in the form of fine particles and will wash away unless the particles are anchored in some manner. Rock, gravel and sand are not available in most areas due to the abundance of deltaic silt deposits; however, bricks are made from clay silts and are a common building material. Bricks can be crushed and sieved to yield fractions with different particle-size ranges. Anchoring the bed can be achieved by means of layers of crushed brick. A layer of coarsely crushed brick (~10 mm particle diameter; 50 mm thickness) is placed in the bottom of the treatment tank, extending through the holes at the bottom of the wall separating the water lock. On top of this is placed a layer of medium crushed brick (~3 mm particle diameter; 50 mm thickness) and a third layer of fine crushed brick (~1 mm particle diameter; 50 mm thickness). It is important that the layers be level, uniform in thickness and continuous. If there are any gaps or other defects, water and particles of adsorbent will channel through them, reducing the efficiency of the bed.

The magnesium-treated mixture of charcoal and ash is now poured on top of the fine layer of crushed brick in the treatment tank. Water is carefully added so that the surface of the bed is not disturbed and the tank is filled with water to the top of the charcoal/ash bed.

The next stage is to incorporate particles of rust (hydrated iron oxide) into the bed. A slurry of rust particles in water is now added carefully to the bed. The rust particles will percolate part of the way through the bed and be retained by the charcoal and magnesium hydroxy-carbonate. The bed should be allowed to stand for several days to compact.

Fine, medium and coarse particles of brick, in that order, are now added to the bed as successive layers, to form a mirror image of the layers below (Figure 2b). The purpose is to stabilize the top of the bed and prevent erosion and channeling, both of which would reduce efficiency. Finally a heap of coarse brick is placed next to the wall from which water enters the tank, in order to spread the inflow of water and prevent damage to the adsorbent bed.

Chemistry of the Adsorbent Bed

The chemistry will involve principally the magnesium hydroxy-carbonate and the hydrated iron oxide. Arsenic(V) ions are expected to exchange with carbonate and hydroxide ions at the particle surfaces, becoming trapped as highly-insoluble magnesium arsenate, and releasing harmless ions in their place. However, magnesium arsenite is slightly soluble and it is likely that only a small amount of arsenic(III) will be retained as magnesium salts. It is the task of the rust particles to retain most of the arsenic(III) species, principally by adsorption³⁸. Iron(III) arsenite is highly insoluble in water and surfaces containing iron(III) species should be readily available in the rust particles embedded in a matrix of magnesium hydroxy-carbonate. In areas where well waters are already rich in iron, there may be no need to add particles of rust.

Oxidation of arsenic(III) to arsenic(V) species will occur between the baffles in the precipitation tank due to the direct action of sunlight and oxygen from the air, or as a result of trace quantities of hydrogen peroxide and other oxidized species generated. Oxidation reactions are catalyzed by particle surfaces containing iron(III) species.

Algae and bacteria are expected to grow in all chambers of the treatment tank, forming a layer on top of the crushed bricks and the tank walls. Provided air is available, biological activity is likely to stimulate oxidation processes and may contribute to the conversion of arsenic(III) to less-toxic arsenic(V) compounds which can be more easily removed. Removal of excess algae may be a major maintenance task.

OPERATION OF THE SYSTEM

The inlet tank (750 L) is filled with water from the tube well. The flow of water from the tank is set by the tap at the base to approximately 1.5 L/min, so that the entire volume flows into the system during the most brightly-lit hours of the day, say from 8 a.m. until 4 p.m.. Purified water is available soon after the day's treatment begins.

The water volumes in the sections of the treatment system are: inlet tank (0.75 m³), precipitation tank (~2.25 m³), adsorption tank (~2.75 m³), water lock (1.5 m³) and reservoir (0.75 m³), making a total volume of approximately 8 m³. If 0.75 m³ of water are passed into and out of the system each day, the residence time is approximately 10 days. If smaller volumes of water are required, the flow rate can be reduced, so that greater residence time is available in the system, leading to more efficient operation.

It is expected that most of the arsenic(V) and around half of the arsenic(III) in the well water will precipitate with the iron hydroxide in the precipitation tank.

The greater the extent of oxidation of arsenic(III), the greater the removal efficiency. The role of the adsorption tank is to eliminate virtually all of the remaining arsenic(III) and any traces of arsenic(V) species.

If the tap for purified water is left open accidentally, the water level will drop to the level of the tap but will not cause the treatment tank to dry out. If the adsorbent bed in the treatment tank should dry out, it would probably channel and lose efficiency. Provided the tank is in daily use and checked regularly, the adsorption bed should never dry out.

It is important that the purified water be free from suspended particles of iron hydroxide or other minerals, since arsenic species may be adsorbed on mineral surfaces and may dissolve in the hydrochloric acid in the human stomach following ingestion. Arsenic species which have been removed from solution as insoluble material could be remobilized in the human body.

CONCLUSION

The design described in this paper attempts to extract maximum benefits from air, ultraviolet radiation, natural iron(II) ions and time, allowing spontaneous reactions to go virtually to completion, then eliminating remaining traces of arsenic by means of simple adsorbents.

Construction of a treatment tank will be time consuming and will require a high level of practical skills in bricklaying and manipulating powdered materials. However, skilled human labour should be available and necessary crafts could be learned. The cost of materials for a treatment tank is modest, especially if shared between a community of users. Most materials should be available locally or able to be manufactured locally. Once skilled workers develop the necessary techniques, rapid construction of treatment tanks should be possible. Only a fraction of the tube wells in affected areas require treatment tanks to be fitted: those for providing drinking water. Contaminated wells can be used for washing and other purposes.

A scale model of the treatment system described in this paper is currently being constructed and will be tested with simulated well waters. The adsorbent properties of magnesium hydroxy-carbonate and rust particles are also being evaluated. The treatment tank should be able to accommodate any type of adsorbent bed, and its development is independent of the final composition of the adsorbent. The retention times required in the precipitation tank for waters with different iron(II), calcium and hydrogen-carbonate ion concentrations are not known. The efficiency and long-term performance of the adsorbent bed also must be assessed. Extensive practical testing of the design will be needed to identify optimum components and the best manner for combining them.

ACKNOWLEDGEMENTS

The authors would like to thank Prof. M. Feroze Ahmed (BUET, Dhaka), Prof. Bob Robbins and Prof. Tam Tran (UNSW, Sydney) and Prof. Pritam Singh (Murdoch University, Perth) for their helpful comments.

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