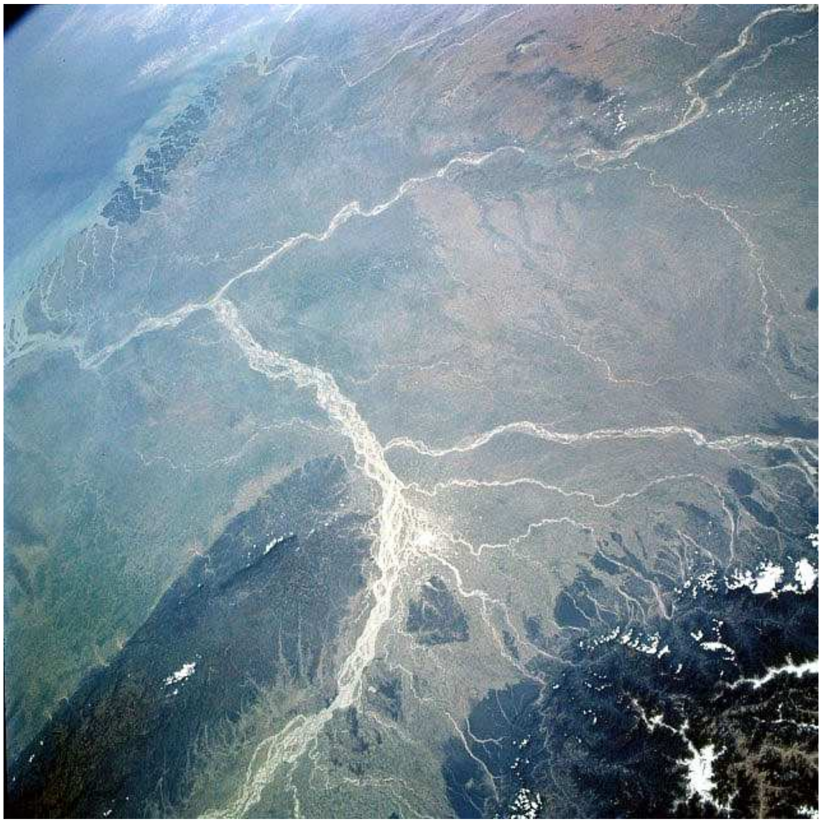
Advanced Chemical Engineering Design
ChE 4273 – Capstone

Development of an Arsenic Mitigation Strategy for Bangladesh



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Abstract

An activated alumina-based arsenic removal device has been developed and optimized for arsenic removal from well water in rural Bangladesh. The cost of implementing this plan is $4.79 per person, for each of the 80 million people affected. The cost over the ten year lifespan of the project is $383 million. The activated alumina device is designed to connect directly to the existing pumps used to draw water out of the wells, and to provide clean water at a spigot on the side of the device. The device has a diameter of 5.6 feet (1.7 m) and a height of 3.7 feet (1.13 m). The initial installation cost is $1140 per unit, and the annual maintenance cost is $30 per unit.

Bangladesh has a population of 140 million people. Since 1993, arsenic contamination has been discovered in the majority of Bangladesh's groundwater wells. The World Health Organization (WHO) standard for arsenic in drinking water is 10 ppb or less. Thirty million people in Bangladesh are currently drinking water with greater than 50 ppb arsenic, and 50 million people are drinking water with levels between 10 and 50 ppb.

A plan for country-wide arsenic mitigation is proposed, which prioritizes unit placement based on the level of arsenic contamination. Before this plan is implemented on a national level, it is proposed to carry out a pilot project in Gazipur Union, in the Haim Char Sub-District of the Chandpur District. This small region of 5,500 people is at high risk for arsenic poisoning. Both user feedback and performance data could be used to refine the design of the unit before wide scale implementation.

Activated alumina and reverse osmosis based designs are studied in this report. Prior to the arsenic removal step both designs use a slow sand filter to remove pathogens, as well as particulate matter that could clog the activated alumina granules or the reverse osmosis membrane. The activated alumina device minimizes cost per person and is easier to use, thus it was chosen to place at each arsenic-contaminated well head.

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BACKGROUND

UN Millennial Goals

Target 10 of the United Nations' Millennium Goals reads "[to] halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation." Furthermore, five of the first ten targets center around improving health, of which clean water is the most critical factor. Millions of people in many countries still do not have adequate access to safe drinking water. Of these countries, Bangladesh is one of the worst. Water is not only a key factor to the well-being of developed communities, but a critical factor to the numerous undeveloped communities in the world. Any effort made to advance water treatment technology is an effort towards not only the bettering of lives, but the saving of lives, and that is a worthy cause.[1]

Country Overview

Bangladesh is a low-lying country in southern Asia, located on the Bay of Bengal. Most of the country is on a delta formed by many rivers, which experience flooding during the annual monsoon season. It has a warm, temperate climate. With 144 million people and an area of 57 thousand square miles, it is one of the most densely populated countries in the world.[2] The average village in Bangladesh has 1,200 people,[3] with an average of 5.6 people per household.[4] Thus, the average village consists of 214 households.

The literacy rate in Bangladesh is only 44%, which presents a unique problem in communicating operating and maintenance instructions. The dominant (98%) ethnic group is the Bengalis, who speak Bengali as their primary language.

Sunni Muslim is the state religion, although there are small Buddhist, Christian, and animist religious communities.

Bangladesh has historically suffered from many waterborne viruses. In an attempt to curb these conditions, the government began drilling shallow tube wells in order to provide the cleaner ground water. It was not until 1993 that Bangladesh became painfully aware that the majority of their tube wells were laced with toxic concentrations of arsenic. Tube wells are wells created by constructing a hole in the earth, supported by a tube, to a depth that gives access to ground water. The source of the arsenic in these tube wells is believed to be of geological origin. Although the exact cause for such a high concentration has not been concluded, it is related to rock formations near water tables under the effected land regions. High arsenic levels manifest in these water resources due to particular natural formations of the earth in that area. Because of this, no effort has been made in regard to treat the water at the source, but instead the option of treating the water was suggested as more practical.

Ninety-seven percent of the nation relies on ground water from tube wells as its main source of water. There are over 10 million tube wells, with estimates as high as 85 million people being at risk of dangerous levels of arsenic exposure. Almost all 64 districts of the country are affected.[5] Estimates show that at least 26 million people are in danger of drinking water with arsenic concentrations higher than the national limit of 50 ppb. Though there are regions with higher amounts of contaminated tube wells, the locations of these tube wells does not manifest in any type of currently identifiable pattern, which adds to the complexity of well diagnosis and thus difficulty of response. The effects of arsenicosis (arsenic poisoning) are even social, causing some Bengalis to be removed from public institutions and decreasing others chances of marriage. The Bangladesh government has developed mitigation strategies and the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP) was formed at the turn of the century. BAMWSP has actively been screening tube wells, training health personnel and strengthening the capacity of local governments and communities to respond to the issue.[6] The sheer number of tube wells, combined with the fact that many have been drilled only within the last decade, led some to believe that the situation could be even worse, and symptoms simply have not yet been fully developed and diagnosed. There is currently a window of opportunity to address the arsenic contamination issue before more people reach advanced stages of arsenic poisoning. The situation is critical.

Arsenic Contamination and Water Quality

Figure 1 shows the average concentrations of arsenic in the tested tube wells in these areas. This map shows that the highest arsenic concentrations are on the east side of the Ganges River, near Chandpur district. Any area that is not green or white is an area with arsenic levels higher than the WHO standard.

Figure 2 is a map depicting at risk areas in Bangladesh. The highest risk areas appear in intense purple and represent a 70% or higher probability that tube well users in this location will be drinking water with toxic levels of arsenic.

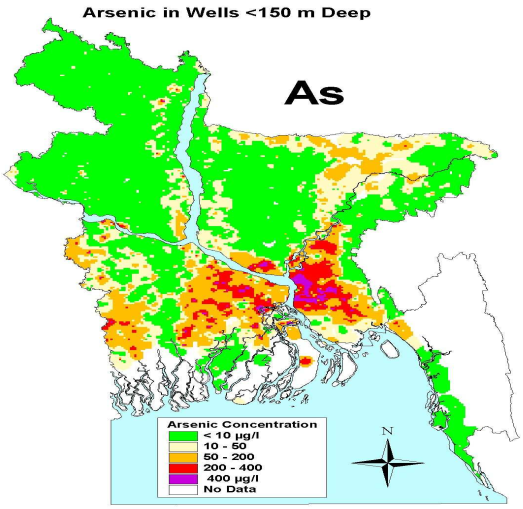

Figure 1:Geographical Arsenic Concentrations in Bangladesh

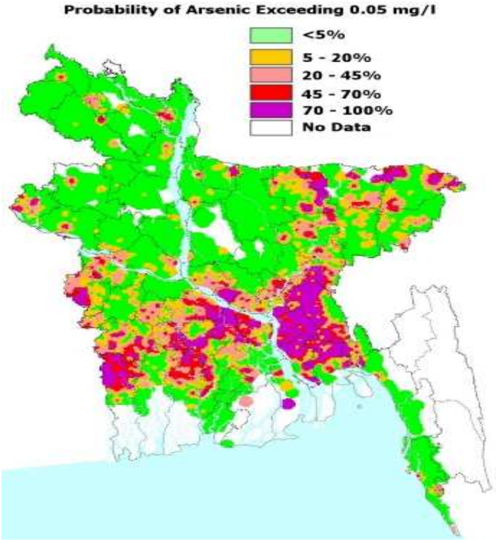

Figure 2: Geographical Percentages of Well Arsenic Contamination

Below, Tables 1 and 2 present data from the British Geological Survey's technical report, *Arsenic contamination of groundwater in Bangladesh*.[7] The first table presents the percentage of tube wells in Bangladesh with arsenic contamination in the specified range. The second table outlines other water constituents and their abundance in groundwater in Bangladesh relative to World Health Organization (WHO) standards.

Table 1: Extent of Arsenic contamination in groundwater

Percentage of tube wells	As concentration (ppb)
19	10-50
15.9	50 – 200
7.3	200 – 500
1.7	500 – 1000
0.1	> 1000

Table 2: Constituents in groundwater and their health risks

Constituent	Status (median concentration)
Antimony	Meets WHO standard
Boron	5% of wells above WHO standard
Cadmium	Meets WHO standard
Chromium	Meets WHO standard
Copper	Meets WHO standard
Fluoride	Normal (0.2 mg/L)
Iodide	Low, dietary supplements required
Iron	High, no health risk (1.1 mg/L)
Lead	Meets WHO standard
Manganese	Meets WHO standard (0.3 mg/L)
Molybdenum	Meets WHO standard
Nickel	Meets WHO standard
Phosphorus	High, no health risk (0.3 mg/L)
Sulfate	Meets WHO standard (1 mg/L)
Uranium	Varies significantly

The median concentration of uranium in Bangladesh tube wells is 0.42 ppb, which is within the WHO guideline of <2 ppb. However, in certain regions of the country, the concentration of uranium in the water is as high as 47 ppb. The British Geological Survey has identified regional uranium and boron contamination as problems that present a long-term health risk. Additional filtration or treatment techniques need to be employed in these areas, in addition to arsenic removal. However, these technologies would be deployed on a smaller scale, and are outside the scope of this project. Arsenic remains the much larger, and more immediate, problem.

Pathogens

The other primary danger pertaining to drinking water in Bangladesh is water-borne viruses existing in surface water. A water-borne disease is any disease that is transmitted or spread through contaminated water. Any pathogenic organism that is carried via water and thus enters the human intestine by drinking or eating food prepared with contaminated water is a water-borne pathogen. The most common of these water-borne pathogens include diarrhea and dysentery. Diseases such as these account for nearly a quarter of all illness in Bangladesh. This is exacerbated by the fact that around 80% of the population of Bangladesh lives in villages outside of the main cities. Sanitation and clean surface water are prominent problems throughout Bangladesh. For example, open-air defecation is common in Bangladesh. The majority of surface water in Bangladesh is unsanitary and has high pathogen levels. Tube well water has significantly lower pathogen contamination, and with the exception of the arsenic contamination, is safe alternative to surface water.

Preliminary Village Scale Implementation

It is recommended to conduct a pilot project before distributing the arsenic removal devices on a national level. The observed device performance and user feedback could be used to refine the final design. Gazipur Union, in the Haim Char Sub-District, of the Chandpur District has been selected as the target village for this pilot project. Gazipur is a typical village in Chandpur, a district with one of the highest average arsenic concentrations in the country. Some key statistics on the village are presented in Table 3, as well as a map showing its location in Figure 3,[8]

Table 3: Conditions in Gazipur, Bangladesh

Population (1991)	5442
Number of Households	977
Literacy Rate	28.1%
Median Arsenic Contamination	300-500 ppb

Figure 3: Map of Bangladesh, highlighting Gazipur (red X)

Countrywide Implementation

It is estimated that "the number of people exposed to arsenic concentrations above 50 ppb is 28-35 million and the number of those exposed to more than 10 ppb is 46-57 million."[9] The highest arsenic contamination occurs in the southeastern part of the country. Dhaka, the capitol city and proposed location for the manufacturing and distribution center, is only 100 miles north of the hardest hit regions.

The national standard for drinking water in Bangladesh is 50 ppb. This standard is an interim standard, due to the severity and wide scope of the contamination. The World Health Organization's recommended standard is 10 ppb. It is recommended that the first phase of the arsenic mitigation strategy be focused on the 28-35 million who are exposed to the levels of arsenic above 50 ppb before the additional 18-22 million people who are exposed to concentrations above 10 ppb are provided with arsenic removal units.

Health Effects

Arsenic's toxicity to humans has long been known. The specific results of human consumption of arsenic depend on the amount and rate of intake in the particular situation. The consumption of arsenic in even minute amounts can lead to injury, pain, and suffering, and eventual death. The details of the major symptoms, general minor symptoms, diagnosis criteria, and method of diagnosis are presented below.

Arsenic poisoning is called arsenicosis. This term characterizes the various clinical manifestations caused by chronic arsenic toxicity due to prolonged drinking of arsenic-contaminated water, or chronic exposure to arsenic via other sources.[10]

This differs from acute arsenic poisoning, which refers to the more immediate effect of intake of high concentrations of arsenic over short periods of time.

Figure 4: Spotted Melanosis

Many independent researchers have performed studies pertaining to arsenic poisoning. Currently, a rough algorithm for diagnosis of arsenicosis exists based on defined symptoms. The following is a description of these symptoms and their effects. The most common indicators of prolonged arsenic-contaminated water consumption are epidermal effects.

Of these, the most prevalent are hyper-pigmentation and hyper-keratosis. Chronic use of arsenic contaminated water results in pigmentation alterations on the trunk and extremities of the victim's body. These alterations often begin as hypo-pigmentation, or white spots on the body, and progress into hyper-pigmentation, appearing as dark freckles. Hyper-pigmentation can also develop into melanosis (Figure 4).[11]

Hyper-keratosis is a thickening of the skin. This develops mostly on victims' palms and feet, but can spread to the trunk and extremities. Initially, the formations make the skin tough or hard, almost grit-like, detectable simply by touching the skin. With further arsenic exposure the formations develop into lesions, or abnormal growths on the epidermis, which rise up from the skin similar to warts, easily visible. Eventually, severe cracks and fissures of the thickened skin can form on the soles and areas of formation. These formations can become malignant, forming cancers in the skin.[12] Another typical symptom of arsenicosis is Bowen’s disease. This is a squamous cell carcinoma, which can lead to internal malignancies.[13]

Symptoms beyond skin formations predominantly include chronic lung disease, hepatomegaly, peripheral neuropathy and peripheral vascular disease. Hepatomegaly is enlargement of the liver, which typically leads to other liver problems including jaundice. Peripheral neuropathy is the degeneration of a persons peripherals nerves resulting in reduced reaction time and body strength, endurance, atrophy, pain and numbness. Peripheral vascular disease is a circulatory disorder caused by insufficient blood supply to the hands and feet, resulting in cyanosis, numbness, pain, and in extreme cases, gangrene.

Figures 5 and 6 below display two victims of extreme skin lesions.

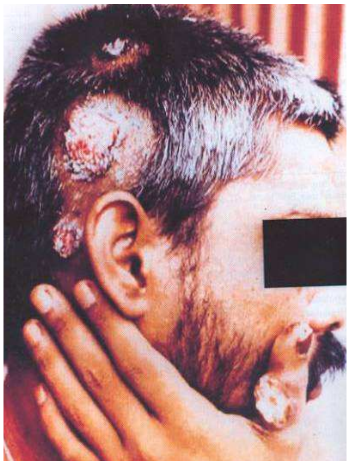

Figure 5: Malignancy

Figure 6: Malignancy (more than 2 lesions)

Minor symptoms are symptoms that often accompany arsenicosis, but are much less clearly indicative of acute arsenicosis. Table 4 shows these.

Table 4: Table of Minor Symptoms

1. Non-Cancer Systematic Minor Manifestations
    a. Weakness, diabetes mellitus, hypertension, ischemic heart disease, cardiac arrhythmia cerebrovascular accident, swelling of hands or feet, hearing defect, dim vision, headache, Mee's line in finger nails, conjunctivitis, chronic diarrhea, anemia, abdominal pain, anorexia, nausea
2. Cancers
    a. Cancer of the urinary bladder, cancer of lung, cancer of liver, kidney cancer

Based on 4,865 cases, the most common major dermatological symptom reported was diffuse melanosis, which occurred 100% of the time, the most common major non-dermatological symptoms reported were bronchitis and hepatomegaly, 43% and 28% of the time, respectively. The most common minor symptoms were weakness and anemia, occurring 14% of the time. Criteria for diagnosing arsenicosis without clinical tests can be found in the Appendix.

Treatment of Arsenicosis

The most convenient and viable solution to any case of arsenic poisoning is to change the water source to arsenic-free water. For minor cases of melanosis and skin pigmentations, this will reverse the effects. Other options include drug treatment, most typically by chelating agents such as British anti-Lewisite, which bond with minerals and can remove arsenic from the body. Any condition beyond that of well developed spotted keratosis on the palms and feet is irreversible. The only option is to remove the formations by surgery, which is not a viable option to those who most often suffer from arsenicosis.

Removal Technologies

There are a variety of chemical and physical methods that can be used to remove arsenic from groundwater. Many of these methods are listed below, with a short description of each. Activated alumina adsorption and reverse osmosis filtration are the methods that have been selected for in-depth study. These were selected for consideration because they are common techniques for arsenic removal with well-documented removal performances, but application to arsenic problems in the developing world has not been done.

Coagulation and Precipitation

Coagulation and precipitation involves adding a chemical to water that will coagulate with arsenic complexes and co-precipitate. Ferric chloride and potassium alum [$KAl(SO_4)_2$] have been used on a small scale for point-of-use treatment devices in Bangladesh. For these coagulants to be effective, the arsenite in the water must be oxidized to arsenate before it will coagulate. This method is not recommended, because there is a high overhead associated with continually distributing chemicals to rural locations. Also, the low literacy rate (44%) in Bangladesh raises concerns about the ability of end users to properly store and handle the chemicals involved. If this system were used, a cloth would be used to filter out the precipitate. However, this precipitate must be handled and disposed of properly.

Coagulation and Microfiltration

Coagulation and microfiltration works similarly to coagulation and precipitation, except that the precipitated particles are removed from the solution by a microfilter. This option has the same downfalls as listed above, although the precipitate is removed by the microfilter instead of a cloth. Membrane fowling and replacement would be a primary economic concern in this method.

Adsorption

Adsorption is a chemical process that effectively removes arsenic from water by a surface reaction. In the reaction, the arsenic in solution is attached to the surface of the adsorbent. Arsenate is a negatively charged arsenic complex, and is attracted to adsorbents that have positively charged surfaces. The arsenite present in the water must be oxidized to arsenate before this method is viable. This is a user-friendly reaction, especially if a solid-oxide material can be used to oxidize the arsenite, because it requires no chemical addition by the user. The lifetime of the adsorbent and ease of regeneration will determine the economic feasibility and sustainability of operation. Iron oxide coated sand, the arsenic bio-sand filter and activated alumina all use the adsorption process.

Iron Oxide Coated Sand

Filtration by iron oxide coated sand is an effective method for removing arsenic from water. The iron oxide coated sand is prepared by filtering out sand to a specific size range, soaking the sand in an iron oxide solution, and then baking the sand. This process is time-consuming, and would take centralized production facilities to economically produce on a large-scale. This method uses one step to remove arsenic, pathogens, and any colloidal material from the groundwater, and is very user-friendly.[14]

Arsenic Bio-Sand Filter

The arsenic bio-sand filter uses rusted nails as an adsorbent to remove arsenic from groundwater. It is combined with a slow sand filter to remove pathogens and colloidal material. Rusted nails are a cheap adsorbent source. This method has been researched by a group at MIT, and is being used, along with the iron oxide coated sand, as a comparison case discussed in the Comparison section of this report.[15]

Activated Alumina

Activated alumina removes arsenate from water by an adsorption process. This method has been selected for study, and more details can be found in the Activated Alumina section of this report.

Ion Exchange

Ion exchange is a chemical process by which an ion located on the surface of a material is replaced by an ion from solution. Arsenate is effectively removed by this method. Senior capstone groups at the University of Oklahoma spent two years analyzing this technology for its feasibility for use by the City of Norman.[16] This method generally requires expensive resins that necessitate periodic recharging to remain economically feasible. Also, regeneration produces arsenic-rich brine that would require proper disposal.

Ultrafiltration or nanofiltration

Ultrafiltration or nanofiltration uses fine membranes to filter out the arsenic complexes from the water. Pre-filtering would be required for this method to reduce the rate at which the membranes become fouled. Membrane filtration is studied in this report through the use of reverse osmosis.

Reverse Osmosis

Reverse osmosis is filtration through a semi-permeable membrane that occurs when a pressure differential is created across the membrane. Pre-filtering by a slow sand filter would be used to reduce membrane fouling, and both arsenate and arsenite are effectively removed by this process. This method has been selected for study, and more details can be found in the Reverse Osmosis section of this report.

PROBLEM STATEMENT AND RESULTS

This project aims to design an arsenic removal device that is sustainable, economically feasible, capable of large-scale implementation, and reasonably maintainable. An activated alumina based removal device has been selected as the recommended design. This design, as well as the reverse osmosis design, incorporates a slow sand filter to remove pathogens and particulate matter before the arsenic is removed. Reverse osmosis and activated alumina units were designed and optimized, and these designs were compared to two other designs: The Arsenic Bio-Sand Filter and Iron Oxide Coated Sand. The most cost effective and user-friendly solution was found to be the community-sized activated alumina design.

The World Health Organization's minimum water quantity for usages requiring sanitary water is 15-20 liters per person per day.[17] Adding a margin for heavier usage, these units are designed to provide 25 liters per person per day.

Household vs. community-scale devices

The size and placement of the arsenic removal devices are major parameters that must be selected before the devices can be designed. Community-sized units hooked directly into tube wells have been selected as the optimal solution for rural Bangladesh communities. The major influences in this decision were the logistics associated with the construction, distribution, and maintenance of the units. Also, seamless integration with existing wells ensures that everyone in the community has access to safe drinking water. A well-integrated device is more likely to be preferred over a device that adds an additional step at the residence before use.

Units on community property are more accessible for maintenance than household-based units, and the number of units to be serviced decreases as well. On average, there are ten to twenty families per tube well in Bangladesh. Thus, centralizing the maintenance greatly reduces the number of service visits required. Distribution logistics are also simplified in the same manner by using community units. Construction is simplified by reducing the total number of units that need to be produced, even though the units are larger.

Slow Sand Filtration

Theory

Slow sand filtration is a low-cost pre-filtration system that is used for both the activated alumina and reverse osmosis designs. In slow sand filtration, water is fed to the top of the filter, and is gravity-fed into a standing water layer and through a fine sand layer. The standing water is maintained by using a spigot located at the same height of the standing water as the filter's exit.

Slow sand filtration removes colloidal particles from water, including pathogens, through a biological process. Slow sand filters require no power and no added chemicals, creating a low operating cost. The primary filtration mechanism is not the sand, but by a biological layer, or *Schmutzdecke*. The *Schmutzdecke* consists of "algae, bacteria, protozoa, and small invertebrates," as well as decaying organic material, and is formed as these components in the inflowing water deposit on the top layer of sand.[18] For cases of water with low incoming bacteria concentrations, bacteria can be initially placed on the top of the sand to start the growth of the *Schmutzdecke*. The *Schmutzdecke* layer is also called a "bio-film" in some literature, and also in this report.

Slow and filters require a sufficient amount of bacteria to form the *Schmutzdecke*. Pertaining to this, a microbiological analysis in 2001 in Matlab, Bangladesh, analyzed five tube-wells for selected biophysicochemical parameters. Matlab is located ten miles north of Gazipur Union, which this report recommends as a pilot village-scale implementation. The results showed that all tube-well water samples contained zooplankton and bacteria, some being greater than the accepted limits recommended by the World Health Organization for drinking water. It was concluded that water from tube-wells should be treated for pathogens if used as drinking water. This data indicates that there will be no need to seed the biological formation of the bio-film, since the tube-well water already contains bacteria in significant amounts.[19]

The efficiency of a slow sand filter is greatly impaired by the addition of disinfectant agents to the influent water. Bellamy determined that the addition of chlorine to the influent reduced the filter's bacteria removal efficiency from 98% to 60%.[20] It has been speculated that the biological removal method at work in the *Schmutzdecke* has an adsorption mechanism.

The following table summarizes typical removal characteristics of slow sand filtration.[21]

Table 5: Typical removal characteristics of slow sand filters

Water Quality Parameter	**Removal Capacity**
Turbidity	< 1.0 NTU
Coliforms	90-99.9%
Enteric Viruses	99-99.99%
Giardia Cysts	99-99.99%
Cryptosporidium Oocysts	>99.99%
Dissolved Organic Carbon	<15-25%
Biodegradable Dissolved Organic Carbon	<50%
Trihalomethane Precursors	<20-30%
Heavy Metals (Zn, Cu, Cd, Pb)	>95-99%
Iron, Manganese	>67%
Arsenic	<47%

Design

The primary operating variables in slow sand filtration are sand size, sand bed depth, hydraulic loading rate, level of influent biological activity, and temperature. The operating temperature and the level of influent biological activity are parameters that vary based on the tube well location, time of day, and time of year. The sand size, sand bed depth, and hydraulic loading rate have been optimized to give the smallest, lowest maintenance system that still meets water quality standards. The maintenance method has also been selected to minimize sand bed depth and increase the lifetime of the sand. The table below summarizes the design of the slow sand filter. A process flow diagram is also shown below.

Table 6: Optimized Sand Filter Variables

Variable	Optimized Value
Sand size (diameter)	0.35 mm
Tank diameter	170 cm
Sand bed depth	50 cm
Supernatant Water Height	35 cm
Maximum hydraulic loading	400 L/hour
Maintenance type	Wet harrowing

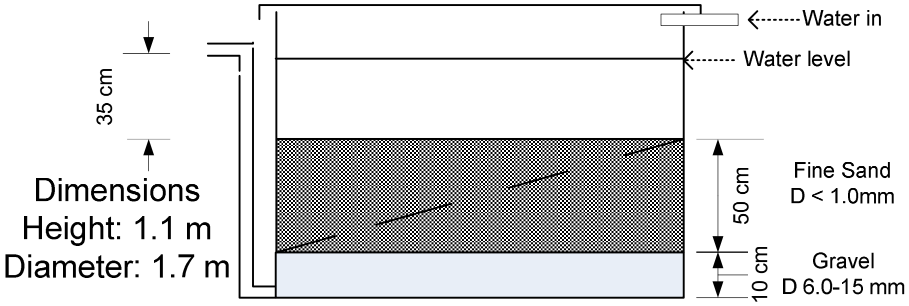

Figure 7: Slow Sand Filter Process Flow Diagram

Sand Size

The sand size had a direct effect on how deeply the bio-film layer penetrates into the sand bed. The finer the sand, the more pathogens and other biological material will be trapped on top of the sand, and in the first few centimeters. As the sand size increases, more of the pathogens travel deeper into the sand, creating a deeper bio-film layer. The sand size does not have a large effect on the pathogen removal capability of the filter, as shown in Figure 8 below.

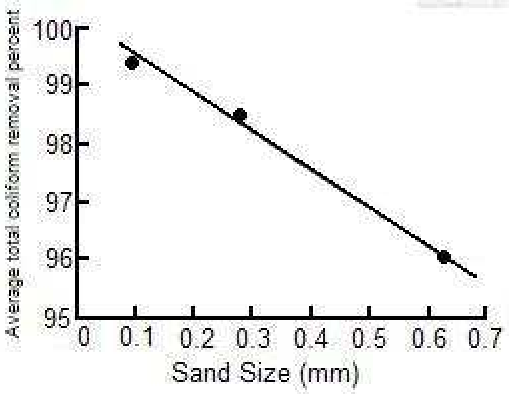

Figure 8: Effect of sand size on total coliform bacteria for slow sand filtration.[22]

(Each point is an avg. of results from 18 runs for each filter;
hydraulic loading rate was 0.12 m/h, and sand bed depths were 0.97m.)

The size of the sand can safely be determined from local availability, and varied within the 0.1 to 0.6 mm diameter range. However, the maintenance method used will work better for finer grains of sand. Bellamy cited a paper in which 0.35 mm was determined to be the economical optimum for sand size, based on penetration depth of the bio-film layer, and the replacement cost of the sand.[23] Thus, 0.35 mm sand is the grade of sand recommended for this project; however, this is a flexible manufacturing parameter.

Sand Bed Depth

The depth of the sand bed must be sufficiently large for the bio-film layer to be fully supported and contained. While most of the bio-film layer resides in the first few centimeters of the sand layer, it grows deeper into the sand over time. Bellamy did extensive experimental work on the effect of sand bed depth on coliform bacteria removal, and his results are shown below.

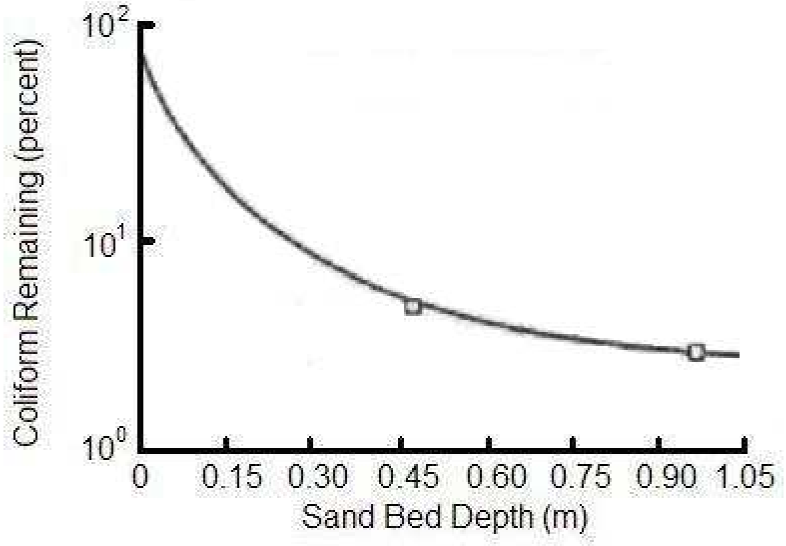

Figure 9: Effect of sand bed depth on % remaining of total coliform bacteria in effluent during slow sand filtration[24]

(The 2 plotted points are avg. of 164 coliform analyses for each point; hydraulic loading rates were 0.12 m/h, and sand bed depths were 0.97m.)

There is not a significant increase in removal efficiency for sand bed depths above 48 centimeters. The small difference in removal abilities is most likely due to the small amount of the bio-film layer that developed in the second 49 centimeters of the deeper sand filter.

The optimum sand bed depth was determined to be 50 centimeters. This is based off of Bellamy's research, as well as adding a small margin of error for construction deviances and for the effects of the wet harrowing maintenance.

In traditional slow sand filters, several smaller layers of coarser sand are placed below the fine sand layer in order to prevent the slow sand from falling through the drains at the bottom of the filter. However, these layers can be removed from the design if an alternative method of containing the fine sand is in place. For this design, a polyester cloth will be used in place of the coarse sand layers. In the activated alumina design, cloths will be used to separate the fine sand from the manganese dioxide, the manganese dioxide from the activated alumina, and the activated alumina from gravel that will be placed on the lowest level of the filter. This gravel provides a drainage system from the activated alumina layer so that the water flows through the activated alumina vertically.

Hydraulic Loading Rate

The hydraulic loading rate in slow sand filtration must be slow enough to allow the biological and adsorptive processes at work in the bio-film layer to have the contact time necessary to remove pathogens, organic material, and small particles from the water. Bellamy studied the effects of varying the hydraulic loading rate on the removal abilities of the slow sand filter. Coliform bacteria removal was 99% or higher for all loading rates tested. The figure below shows the effect of varying the hydraulic loading rate on the total bacteria removal.

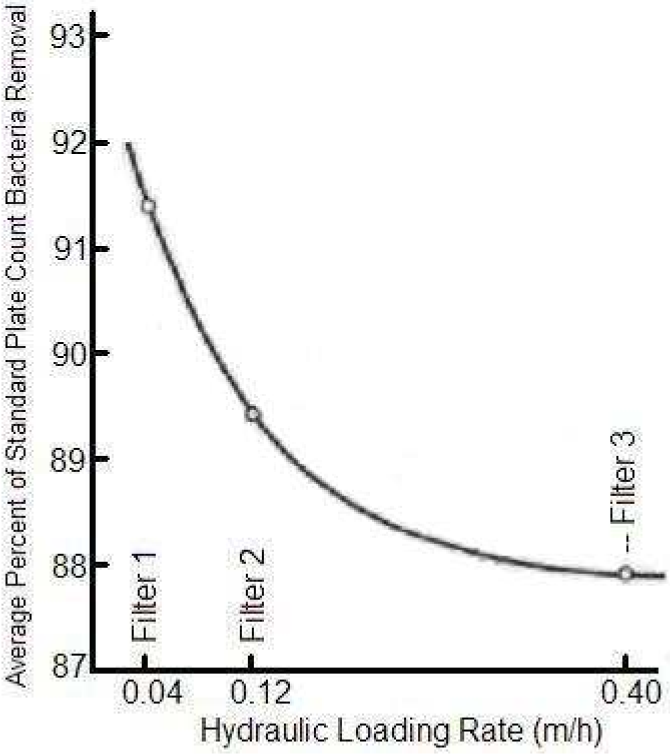

Figure 10: Standard plate count bacteria removal as affected by hydraulic loading in slow-rate sand filters[25]

(Plotted points are the average % of removal of standard plate count bacteria for the 3 hydraulic loading rates, calculated for all operating and filter conditions.)

Increasing the hydraulic loading directly decreases the surface area of the sand filter for the same flow rate through the filter. The removal abilities of the slow sand filter are satisfactory at 0.4 m/h, and this point was selected as the maximum hydraulic loading. The effects of varying the hydraulic loading rate on turbidity removal are shown in the figure below.

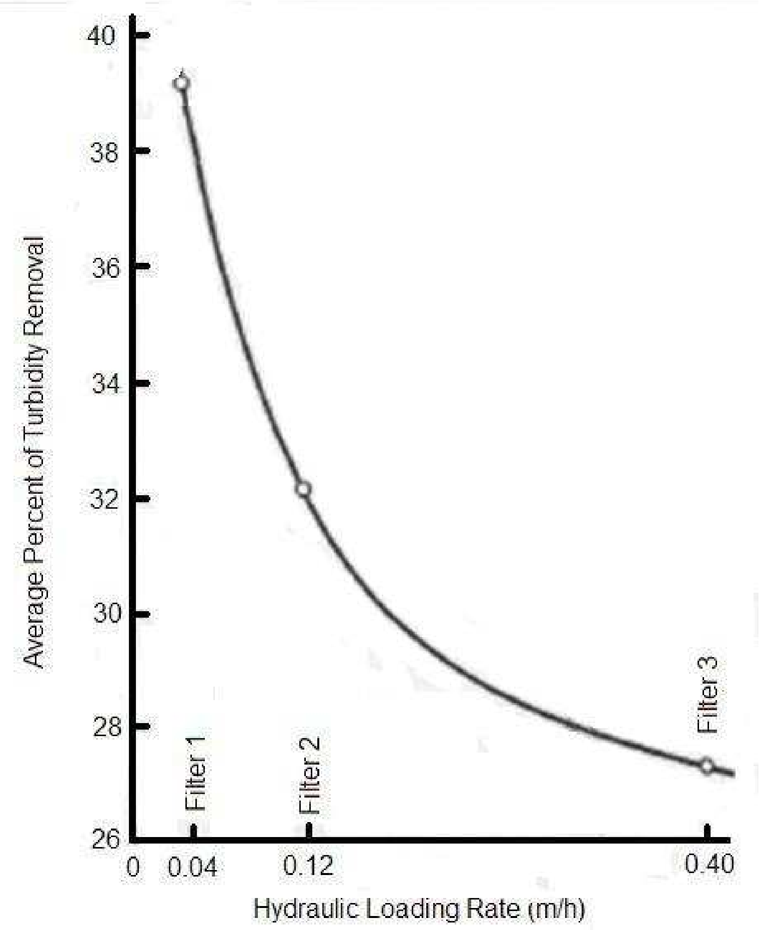

Figure 11: Turbidity removal as affected by hydraulic loading in slow-rate sand filters[26]

(Plotted points are the average % of turbidity removal for the 3 hydraulic loading rates, calculated for all operating and filter conditions.)

Maintenance

Slow sand filter maintenance is required when the flow rate through the filter decreases beyond a usable rate, due to the build up of trapped particles within the bio-film layer. The frequency of maintenance is directly correlated to the amount of particles in the influent water. This varies from well to well. However, since centralized maintenance is proposed in the business model, a maintenance cycle time of six months is used. This estimate is based off of the low turbidity rates present in the groundwater, and published guidelines.

Wet harrowing has been selected as the optimal maintenance method for the slow sand filtration unit. Table 7 below highlights the differences between wet harrowing and the traditional scraping method.

Table 7: Slow sand filter maintenance methods

	Scraping	**Wet Harrowing**
Maintenance time	Every 6 months	Every 6 months
Labor intensity	High	Medium
Time for bio-film re-growth	Weeks	Hours
Waste produced	Bio-film + 5cm sand	Dirty water
Sand loss	5 cm / cycle	none

Traditional slow sand filter maintenance has involved draining water in the filter to below the sand level, and physically removing the bio-film layer, along with the first few centimeters of sand. This sand is then discarded, and the filter is returned to service. After repeated maintenance cycles, the sand level is below the lowest allowable sand level for proper filtration. The volume of sand that has been removed must then be replenished. This method is labor-intensive, requires high volumes of sand, and completely destroys the bio-film layer with every maintenance cycle, which takes weeks to develop. Slow sand filters reach and maintain their peak filtering characteristics after one week to one month, dependent on the influent concentration of bacteria and other organic matter which forms the bio-film layer.[27]

Wet harrowing is a relatively new approach in the history of slow sand filtration, developed in the latter half of the 20th century. It involves agitating the supernatant water and raking the bio-film layer. This action dislodges the trapped particles from the bio-film layer, as well as part of the bio-film layer. The murky water containing the particles and part of the bio-film layer is then removed from the filter using buckets or a portable pump. Then, the outlet is unplugged, and water is pumped back through the filter until the water returns to its normal operating level and the effluent water is clear.[28]

This method has the advantages of greatly reducing the time that it takes for the filter to return to its optimal filtering performance, and reducing the amount of labor that is required for routine maintenance. However, even with the wet harrowing method, the bio-film layer will eventually grow to a point at which it must be removed. This occurs between eight and ten years in municipal slow sand filters in the northeastern United States, and eight years has been selected as the replacement time for this design.[29]

Supernatant Water Height

Standing water must be maintained above the *Schmutzdecke* layer in order for the bacteria and microorganisms to stay alive. Literature is inconclusive about the minimum level of water required to maintain the biological activity. The National Drinking Water Clearinghouse[30] recommends a range from 0.7-1.5 m, while the MIT Arsenic BioSand Filter project in Nepal[31] has achieved inconsistent successful results while using a water level of only 0.05m above the sand. Many of the bio-sand filter failures were ascribed to water pouring into the filter and disrupting the top layer of sand, and not allowing the bio-film layer to properly develop. A standing water level of 0.35

m has been selected for the designs in this report, to maintain the unit height at a level accessible to most people, while ensuring that the bio-film layer can develop undisturbed.

Reverse Osmosis

Theory

Reverse osmosis (RO) is a separation technique used for solutions. With reverse osmosis, a semi-permeable membrane separates two liquids. This membrane is permeable to the solvent of the solutions, but not the solute. When the concentration of solutes on one side of the membrane is higher than the other, the solvent on the lower concentration side will pass through the membrane, diluting the higher concentration solution, driven by the difference in chemical potential, until equilibrium is reached. The osmotic pressure is the pressure difference required to make the chemical potential equal on both sides. In reverse osmosis, this natural pressure is overcome, and the opposite flow of solvent occurs. For example, consider a solution of pure water separated from a solution with a toxic concentration of 50 ppb arsenic (Figure 12). The membrane separating the two sides is permeable to the water, but not to the arsenic complexes. Due to the difference in chemical potential, the pure water will have a tendency to pass into the high arsenic side to decrease its concentration, until the chemical potentials on both sides of the membrane are equal. But, if sufficient pressure is applied to the arsenic side of the system, the pressure will overcome the osmotic pressure and force water from the high arsenic concentrated side into the side with no arsenic. This effectively removes the arsenic from the water by concentrating the arsenic rich side.

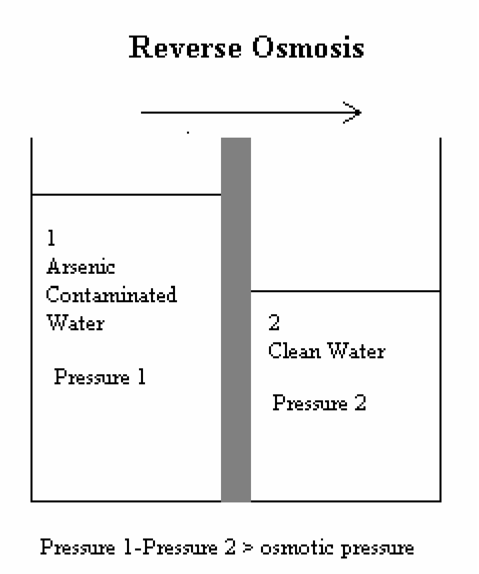

Figure 12: Reverse Osmosis

When a semi-permeable membrane separates a liquid, the liquid on both sides of the membrane (side α and β) naturally moves toward equilibrium. At equilibrium, the fugacities on both sides are equal

$$f_1^{\alpha} = f_1^{\beta} \Rightarrow a_1^{\alpha} f_1^{o}\{T, P_{\alpha}\} = a_1^{\beta} f_1^{o}\{T, P_{\beta}\}$$

Assuming one side of the membrane to be at or near pure (i.e. clean water), the fugacity of α would be 1 and thus,

$$a_1^{\alpha} f_1^{o}\{T, P_{\alpha}\} = f_1^{o}\{T, P_{\alpha}\}$$

For the side with the solute, the activity will be equal to the mass fraction times the activity coefficient γ,

$$a_1^{\beta} f_1^{o}\{T, P_{\beta}\} = x_1^{\beta} \gamma_1^{\beta} f_1^{o}\{T, P_{\beta}\} = f_1^{o}\{T, P_{\alpha}\}$$

The key is that at standard-state, pure-component fugacities increase with increasing pressure, so if $x_1^{\beta}\gamma_1^{\beta}$ is less than one, then $P_{\beta} > P_{\alpha}$ at equilibrium. This difference is known as the osmotic pressure, π. Using the Poynting correction, we can relate the solvent and solute concentrations to the pressure difference,

$$f_1^{o}\{T, P_{\alpha}\} = f_1^{o}\{T, P_{\beta}\}\exp\left[\frac{v_1(P_{\beta} - P_{\alpha})}{RT}\right]$$

where R is the gas constant and v_1 is the specific volume of the liquid, which can be solved for the pressure difference, π,

$$\pi = (P_{\beta} - P_{\alpha}) = -\frac{RT}{v_1}\ln(x_1^{\beta}\gamma_1^{\beta})$$

Assuming the solute concentration is dilute, $\gamma_1^{\beta}=1$, and $x_1^{\beta} = 1 - x_2^{\beta}$, and when x_2^{β} is small $\ln(1 - x_2^{\beta}) \approx -x_2^{\beta}$, thus

$\pi = -\frac{RT}{v_1}(-x_2^{\beta}) = RTc_2$ where c_2 represents the concentration of the solute.[32] The osmotic pressure is directly related to the concentration of the solute in the liquid, and is related linearly to the concentration difference.[33]

General Data

Since the 1960's when reverse osmosis research began to accelerate, there has been ample study on numerous types of membranes, their operating conditions, and their performance. Important reverse osmosis criteria are the design of the membrane, the flux of the membrane, and the quality of the membrane.

The transport properties of reverse osmosis can be described by the flux of the membrane. Flux is the volumetric or mass permeation rate per membrane area

$$J_w = \frac{mass\ permeation\, rate}{membrane\, area} = K_w(\Delta P - \pi)$$

where K_w is the permeability coefficient of the membrane to pure solvent, ΔP is pressure drop across the membrane and π is the osmotic pressure difference across the membrane. Typical flux rates range from 0.001 – 0.1 kg/m^2/s (2-200 gal/ft^2/day or “gfd”).[34,35]

There are four types or modules of membranes commonly used. They are spiral-wound, plate-and-frame, tubular, and hollow-fiber modules. The spiral-wound is like a plate-and-frame that has been rolled up into a cylinder. In this design, the feed stream flows down the length of the spiral and through the membrane, and the permeate flows down the center of the tube. The ratio of permeate flow to the non-permeate (or rejected flow) is called the recovery. Typical recovery rates are about one gallon of treated water for every 3 gallons of rejected water.

The hollow-fiber modules consist of a membrane around a center tube. In this design, however, the feed is introduced in the center tube and flows radially over the membranes and the reject (concentrate) exits one end of the vessel. The product emerges at the other end of the tube. One difference between hollow-fiber and spiral-wound is that hollow-fiber designs cannot be placed in series in a single pressure vessel. A variation of this is the tubular design, where multiple tubes are connected. These types of designs are most commonly used in food-related applications.[36] Below is an illustration of a typical spiral wound design.

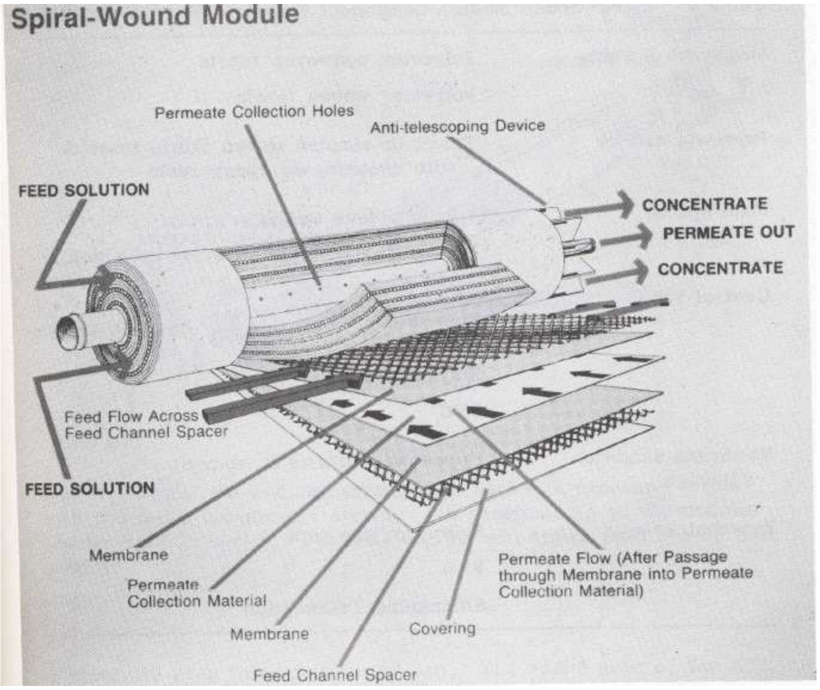

Figure 13: Spiral Wound Reverse Osmosis Module Schematic[37]

Reverse osmosis membranes are able to remove particles of diameter 10 Angstroms. Metal ions, such as arsenate and arsenite are on this scale of particle size.

General Equipment/Essential Parts

General equipment needed for typical reverse osmosis use, in addition to a membrane with a high surface-to-volume ratio (to minimize space and capital costs) include an adequate structural support to withstand the pressure that is applied to the system, as well as the pressure drop through the membrane, a pump and some form of pretreatment. Also important to successful performance is low pressure drop on the concentrate side to maintain driving pressure difference, turbulent flow to limit possibility of concentration polarization and fouling, easy cleaning and long membrane life.[38]

Design

This project has concluded that the use of a reverse osmosis system to treat tube wells in rural Bangladesh is not a preferable method. Reverse osmosis is a reliable method of arsenic removal, but it is not as easily implemented, conveniently sustainable and operable, or as economical as the activated alumina design.

Introduction

One of the most important factors is the durability of the constructed design. This includes the durability and lifetime of the membrane. Thus, the type and quality of the membrane are major factors. The economics are vital criteria for feasible implementation, even at the cost of lowering membrane quality, providing that the device performs the necessary functions.

Small-Scale Explanation

Typical commercial reverse osmosis systems used for desalination require an operating feed pressure of about 1,000 psi. Revere osmosis systems for water with lower concentration of minerals still requires pressures of over 200 psi. The notable criterion for this case study as it pertains to reverse osmosis is the lack of electricity. Due to this pressure requirement, it was initially concluded that a single large system to operate for an entire village (of approximately 1,000 people) was not possible to achieve without energy via electricity. Thus, it was concluded that the optimal option was to create a system designed to operate for a household. Typical home units are capable of operating at feed pressures of 50 psi, a reasonable amount of energy that can be supplied by human powered pump.

The optimal time the reverse osmosis system will be run is 6 hours per day. At this rate, and the typical flux of 20 gfd, a membrane area of 1 m^2 is required when operating at 50 psi.

Pre-filter

An important pre-requisite for successful reverse osmosis system operation is pre-filtration. One main reason for membrane degradation and shortened life cycle is fouling of the membrane due to poor water quality. General requirements for successful membrane operation include removing turbidity, keeping consistent pH levels, reducing scale, and removing slime growth and oils.[39] The slow sand filter that is used in our design provides this needed filtration to allow the membranes to endure to their specified lifespan.

Hydraulics

As has been noted, an essential criterion to successful reverse osmosis operation is supplying pressure. The consideration of supplying the needed pressure via human energy is one that has not been researched thoroughly. In fact, some reverse osmosis suppliers found this option to be quite foreign to their knowledge. This is due to the foreseen difficulty that would arise in keeping a constant pressure applied to the system by use of human power. One local option was a pump referred to as "the treadle pump," developed in Bangladesh in the 1980's to aid in irrigation water supply. It is able to move water from a depth of about 3.5 meters, or about 5 psi. This pump would be cumbersome and would likely not yield the desired result even after modification.

A hydraulic hand pump was then considered. Small low-pressure hand pumps suitable to supply water pressure to a system are not common. One pump able to supply the needed pressure is Model MK1930 Hydraulic Pump.[40] The cost of this type of pump is $150. This was used to carry out cost estimates for the reverse osmosis design. This is a US cost and not a local cost, but is the best estimate available.

The most promising method of pressure supply that has been performed successfully with a reverse osmosis system was studied by J.I. Oh in 2000.[41] Oh used a bicycle pump that supplied pressure to a reverse osmosis system. An individual was required to literally pedal a bicycle, supplying a pressure to the system of about 4 MPa. This setup was tested for arsenic removal in Bangladesh. It accomplished arsenic removals of 90% (from 210 ppb to 20 ppb). The bicycle pump is the preferred source of pressure. However, pricing information was not available for the bicycle pump, so the calculations were performed using the hydraulic pump cost.

Brine

Disposal of the concentrate is a major disadvantage to the reverse osmosis design. It is essential to communicate to the users that this water is non-potable. Usage options would include the washing of bodies. However, there exists a high possibility that users will not follow the given instructions, in light of low literacy. This is addressed by coloring the arsenic free exit and the concentrate exit green and red, respectively. These are colors commonly used in rural areas of Bangladesh to differentiate between potable wells and non-potable wells.

Membrane and Makeup

The most economical membrane able to supply the needed pressure and flow rate is the Rioflow 4-Stage RO Systems Model # USRO4-50, supplied by H2OFilter.[42] This system operates at 50 psi and provides a flow of 50 gallons per day. This system comes with a pre-filter and a post filter, both of which are unnecessary with the optimized design. The pre-filter already exists by way of the slow sand filter, nor is the carbon post-filter essential. However, quotes for only the membrane section were not available.

Cost Considerations[43]

Because individual units are the optimal design for reverse osmosis the cost considerations did not need to address land acquisition and development for the system, or additional utility cost. The costs are only dependent on initial installation and maintenance. Maintenance includes membrane replacement (with eventual unit replacement) and technician payment. These costs are shown below.

Table 8: Capital Costs for Designed Reverse Osmosis System

	Cost	Specs
RO System	$ 133.00	
Storage Tank	$ 3.00	
Bucket	$ 3.00	Simple plastic
Pipe	$ 2.50	
Sand	$ 0.10	
Pump	$ 150.00	High Pressure Hand
Total	$ 291.60	

Table 9: Maintenance Costs for Designed Reverse Osmosis System

	Cost	Life Span	Yearly
Membrane	$ 39.00	3	$13.00
Storage Tank	$ 3.00	2	$1.50
Bucket	$ 3.00	3	$1.00
Pipe	$ 2.50	6	$0.42
Sand	$ 0.10	6	$0.02
Pump	$ 150.00	10	$15.00
Total Yearly			**$30.93**

The reverse osmosis process flow diagram is shown below. Water is carried to the slow sand filter and poured into the top. This slow sand filter is a 50 cm by 50 cm square unit, with a height of 150 cm. The water flows into a storage tank prior to the reverse osmosis section. It will take 25 minutes for the water to flow through the individual slow sand filter. After this period, the hand pump can be used to operate the reverse osmosis system.

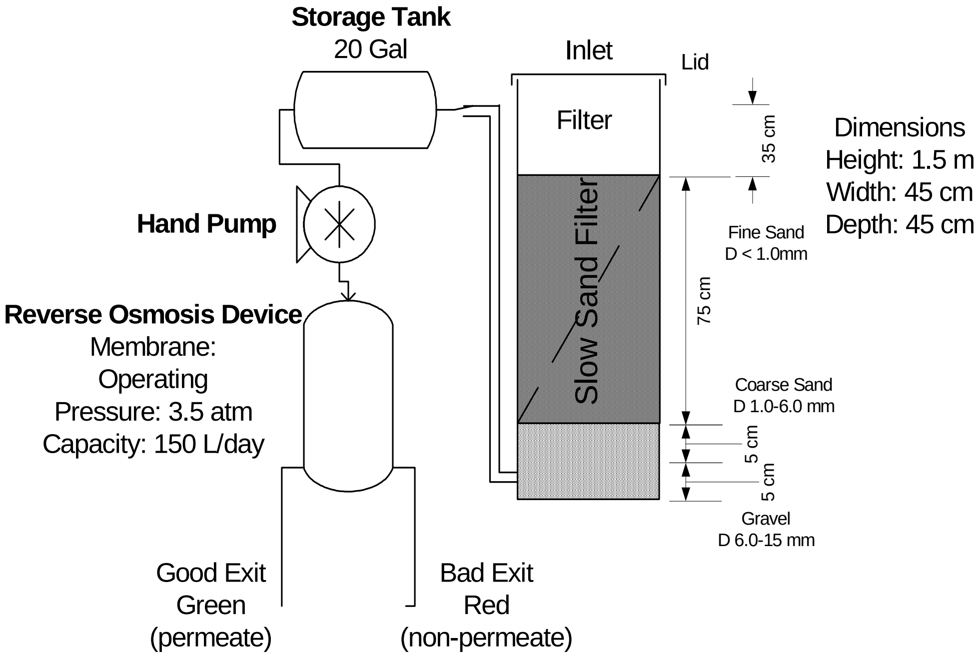

Figure 14: Reverse Osmosis System Process Flow Diagram

Global Water Trust

Global Water Trust (GWT)[44] is a philanthropic organization whose chief aim is providing clean water to the developing world. In 2004, GWT proposed a water mitigation plan for Bangladesh based on reverse osmosis technology that would be operated via pressure supplied directly from the tube well hand pump. Contact was attempted, but no valuable information about the success of the project was reported. Furthermore, GWT seems to offer no evidence of the implementation of this plan.

The reverse osmosis design is not the chosen design for optimization. It would be difficult to supply the pressure adequately, leading to difficult implementation. There is little proof that this design would function efficiently in these case study specifications. The variable pressure from a hand pump, if used, may cause inconsistent removals. Most importantly, as will be discussed later in the comparison section, this is not the most economical choice.

Activated Alumina

Theory

Activated alumina is a granular form of aluminum oxide (Al_2O_3), a ceramic compound with a high internal surface area, typically on the order of 200-300 m^2/g. This allows for many sorption sites within a small amount of activated alumina. At pHs below 9, the surface of activated alumina is positively charged. The positively charged sorption sites allow for chemical adsorption to occur between the surface and negatively charged arsenate complexes. Activated alumina also removes other negatively charged complexes from the water, and has been used in the past in the United States to remove both arsenic and fluoride from water.[45]

Below a pH of 9.2, arsenic occurs in groundwater in both negatively charged arsenate complexes and neutral arsenite complexes. Arsenite complexes become negatively charged at pH above 9.2. The groundwater in Bangladesh is typically in the pH range of 6.5 to 7.6[46]. Arsenite generally constitutes approximately half of the arsenic in groundwater in Bangladesh. Oxidation of the arsenite to arsenate is required for effective arsenic removal.

Oxidation methods

“Arsenite can be directly oxidized by a number of… chemicals, including gaseous chlorine, hypochlorite, ozone, permanganate, hydrogen peroxide, and Fenton’s reagent [hydrogen peroxide with catalytic iron particles]. Some solids such as manganese oxides can also oxidize arsenic”.[47] Ultraviolet radiation can also be used, but it is a very slow process, and requires large open-air tanks.

Using a gas, such as chlorine or ozone, requires a more complicated device construction and a larger infrastructure to facilitate gas storage and distribution. Using a liquid chemical that is added on a per-use basis raises the same storage and distribution issues. For safety, logistical, and ease-of-use reasons, a bed of solid manganese dioxide pellets has been selected. Manganese dioxide also removes iron and manganese from water.[48] This removal should be minimal due to the slow sand filter’s removal of over two-thirds of these metals, and the low initial concentrations in the groundwater.

Pre-filtering

Pre-filtering the groundwater with a slow sand filter increases the activated alumina and manganese dioxide lifetime. Filtration removes colloidal particles that would otherwise foul the adsorbent and oxidant particles by plugging pathways to internal surface areas.

Removal of arsenic from groundwater

Once the slow sand filter has removed colloidal particles and pathogens, and the arsenite has been oxidized to arsenate, the only health concern remaining in the groundwater is the arsenate. This can be effectively removed by activated alumina, because it is preferred over many other common ions that may occur in the groundwater. The arsenate complex that occurs in the pH range of 5.5 to 8.5 is $H_2AsO_4^-$.

Clifford [49] determined the selectivity sequence of activated alumina in the pH range of 5.5 to 8.5 as:

$OH^- > \underline{\mathbf{H_2AsO_4^-}} > Si(OH)_3O^- > HSeO_3^- > \underline{\mathbf{F^-}} > \underline{\mathbf{SO_4^{2-}}} > CrO_4^{2-}$

$\gg HCO_3^- > Cl^- > NO_3^- > Br^- > I^-$

The only major competing ions present in the groundwater in Bangladesh are fluoride and sulfate, which have concentrations of 0.2 mg/L and 1.0 mg/L respectively.[50] These ions compete for sorption sites on the activated alumina. This reduces the equilibrium arsenic capacity of the activated alumina, because sorption sites are taken up by the fluoride and sulfate. The fluoride and sulfate also slow the adsorption kinetics, requiring a larger contact time between the water and the activated alumina to achieve arsenic removal.

Regeneration

The ability to regenerate the activated alumina after it becomes saturated with arsenic is essential to the economic viability of this removal method. As shown above, hydroxide adsorbs more strongly than arsenate on activated alumina. By passing a highly basic solution through the activated alumina bed, the majority of the arsenic can be removed, restoring the activated alumina to near its original capacity. A highly concentrated caustic soda (potassium hydroxide) solution is a cost effective solution. After this solution has been run through the filter, removing the arsenic, groundwater will be run through the filter until the pH returns to normal conditions.[51] Regeneration can also be accomplished using sodium hydroxide, or any other water-soluble hydroxide compound. Potassium hydroxide is preferred in this report due to a lower price quote.

After each regeneration cycle, approximately five percent of the activated alumina surface area is either deactivated or still bound to arsenate ions. Deactivation is caused by hydroxide, arsenate, or other molecules irreversibly chemisorbing to the surface of the activated alumina.[52] Complete equilibrium is not reached between the caustic soda flushed through the system and the activated alumina. The one hour flush corresponding to 95% regeneration is a compromise between maximizing well downtime and the lifetime of the activated alumina. This decay and its effects on arsenic removal capacity has been taken into account in determining the lifetime of the activated alumina.

The caustic soda solution kills the bio-film layer that forms on top of the slow sand filter when the activated alumina is regenerated. This layer will take several weeks to return to its peak filtering performance after regeneration, but will provide adequate filtration in the time that it takes to re-form.

Adsorption Isotherm and Concentration Wavefront

The shape of the arsenic concentration wavefront as it moves through the activated alumina adsorption bed is dependent on the shape of the adsorption isotherm. The adsorption of arsenic onto activated alumina is favorable, as shown by increasing equilibrium amounts of arsenic depositing onto the activated alumina as the concentration of arsenic increases.[53] Examples of different types of adsorption isotherms are shown in the figure below.

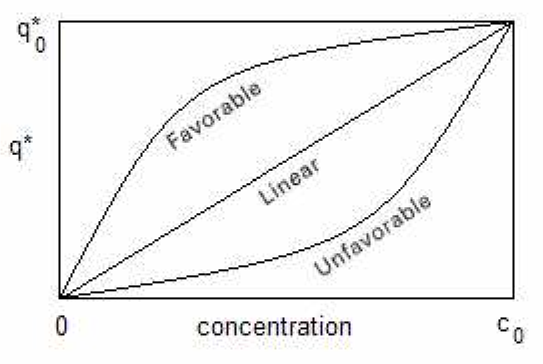

Figure 15: Types of adsorption isotherms (adapted from Seader)[54]

This favorable adsorption creates a self-sharpening adsorption wavefront.[55] The sharper the wavefront, the higher percent of adsorbent in the bed is saturated with the adsorbate before breakthrough occurs. The figure below shows an example of a self-sharpening wavefront. The left side of the diagram represents the inlet, and the right side represents the outlet. The lines represent the position of the wavefront as time passes, with the leftmost line being the earliest time.

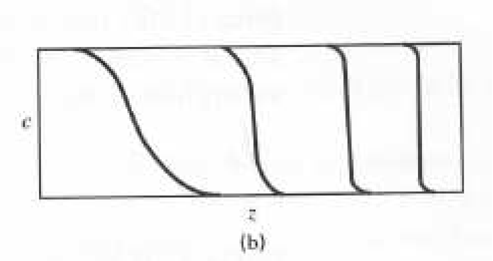

Figure 16: Self-Sharpening adsorption wavefront (from Seader)[56]

The intermittent use of the filter also increases the amount of activated alumina that is used by increasing the contact time between the arsenic-laden water and the activated alumina.

Projected Flow Path

The projected flow path through the manganese dioxide and the activated alumina is vertical flow, due to the gravity feeding of the column. However, with an outlet only available on one side of the tank, there will be considerable horizontal flow in the bottom region of the tank. This is taken into account by placing a 10-centimeter layer of gravel beneath the activated alumina. Any curvature of the flow through the activated alumina region will increase the contact time between the water and the activated alumina, but will create uneven adsorption in the activated alumina layer.

Design

Design Summary

The activated alumina design was selected as the recommended design because it minimized the total cost while maximized ease of use. The table below shows a summary of the important physical properties of the device.

Table 10:Design summary of activated alumina-based arsenic removal device

Physical Property	**Size**
Shape	Round
Diameter (cm)	170
Standing Water Height (cm)	35
Fine Sand Depth (cm)	50
Gravel Depth (cm)	10
MnO_2 Depth (cm)	3.3
Activated Alumina Depth (cm)	14
Total Unit Height (cm)	112.3
Total Unit Height (ft)	3.7
Mass of MnO_2 (kg)	114
Mass of Activated Alumina (kg)	254

The process flow diagram below shows how the arsenic removal device seamlessly integrates with the existing tube well hand pump system. The water from the well flows from the pump outlet into the top of the slow sand filter. The water travels down through the filter, oxidizing media, and activated alumina before exiting at the spigot shown on the left. A bypass valve between the pump and the device allows for water to be drawn in the event that the device is not working.

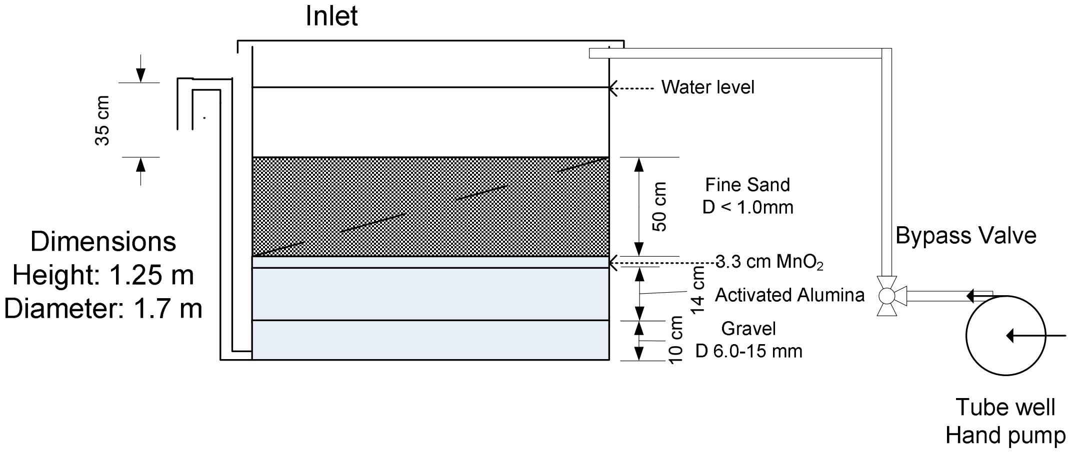

Figure 17: Process Flow Diagram of Activated Alumina Arsenic Removal Device

Manganese Dioxide Layer

The thickness of the manganese dioxide layer was determined to be 3.3 cm, which gives an empty-bed contact time between the water and the manganese dioxide of five minutes, which is sufficient time for 99% of the arsenite to be oxidized to arsenate. This contact time was experimentally determined by Ghurye and Clifford when manganese, iron, and sulfate are present in the influent water.[57] These compounds are also oxidized by the manganese dioxide, creating competition for the aresenite complexes. If none of these competing ions were present, an empty-bed contact time of 90 seconds would oxidize 99% of the arsenite. This amount of manganese will last the lifetime of the activated alumina in the unit, which is 20 years.

A price quote was obtained from Akola Chemicals in India, which was approximately $525 per 1000 kg, with cost, insurance, and freight to the United States. It was intended for this price quote to be for Dhaka, Bangladesh, but there was a miscommunication, and a corrected quote was not able to be obtained. This price was used, even though it will most likely be lower for shipping to Bangladesh.[58] The manganese dioxide is 80% MnO_2, with a specific gravity of 5.026, and size of 80 mesh. A price quote from Galaxy Corporation India was also obtained, for 65% MnO_2 at $325 per ton, shipping not included.[59]

Activated Alumina Layer

The optimal thickness of the activated alumina layer was determined to be 14 cm. This thickness has been optimized to give the lowest cost per year of operation, taking into account replacement costs. Annual regeneration costs are similar for all of the depths of activated alumina, since the same amount of arsenic would need to be removed from each. The figure below shows the optimization of the filter thickness. The lowest point, $800 initial cost, corresponds to the 14 cm thickness. The annualized alumina cost is the sum of the total cost of the alumina divided by the number of the years the alumina will last, and the annual maintenance cost for that amount of alumina.

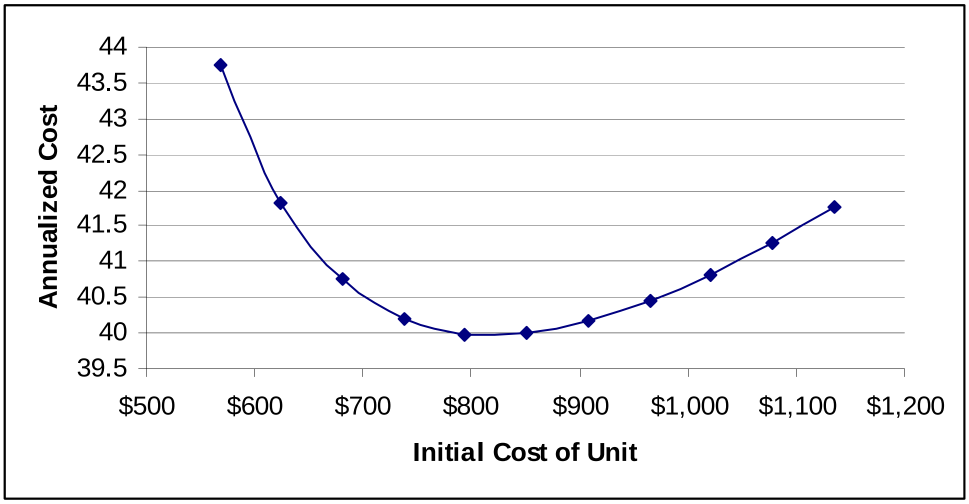

Figure 18: Optimization of amount of activated alumina in device

This depth gives an empty-bed contact time of 21 minutes, which is sufficient for achieving arsenic removal close to equilibrium values. There are only marginal gains for increasing the empty-bed contact time past 12 minutes.[60] A price quote was obtained from Sorbead India, an Indian chemicals company.[61] The quote was $3125 per 1000 kg. This is for activated alumina beads, with sizes ranging from 0.5 to 2 mm in diameter, which they specifically produce for removal of arsenic and fluoride from groundwater.

Regeneration

The potassium hydroxide solution for regenerating the activated alumina will be 4% KOH. Contact times of 30 minutes to three days have shown comparable arsenic removal abilities, so a regeneration contact time of one hour has been selected.[62] The potassium hydroxide will be transported to the well sites in solid form, and then mixed with the well water to form the 4% solution. This water will then be added to the system until one bed volume of water has been added. The solution will then be left in the bed for one hour, and then several bed volumes of well water will be added to flush the arsenic-laden brine out. Field-testing will be done to see how many bed volumes of water need to be flushed through the system before the pH returns to normal, and then guidelines will be developed from these field tests for future regenerations.

No direct price quote for potassium hydroxide has been obtained from suppliers in India. The cost estimate of 49 Rupees per kg ($1.11/kg) is based off of mean prices in India from the Indian Chemical Industries website[63], which tracks current price trends in the Indian chemical industries. This price quote is for solid potassium hydroxide flakes.

Manufacture

Manufacture of the activated alumina arsenic removal units will occur in two parts. The first part is preparation of the tank to hold the materials, and the second step is the actual placement of the materials into the tank. The first step will take place at the Dhaka location as the units arrive. The second step will be performed on site at the head of each tube well.

An outline of the manufacture process is shown below.

- Step 1
  - Arrival of tank at Dhaka shop location
  - Construction of spigot onto the tank
  - Attach polyester cloth to spigot entrance
- Step 2
  - Transport of tank & materials to tube-well site
  - Tank construction
    - Placement of gravel layer, placement of polyester separator
    - Placement of activated alumina, placement of polyester separator
    - Placement of manganese dioxide, placement of polyester separator
    - Placement of fine sand
    - Lid

Manufacturing and Maintenance Cost Summary

The manufacturing cost of an activated alumina-based arsenic removal device for a community of 250 people is $1140, or $4.56 per person. The annual maintenance costs, including chemicals and labor, come to $29.33 per unit, or $0.12 per person.

Comparisons

Activated alumina devices have been selected as the best solution to the arsenic problem in Bangladesh. Activated alumina devices were compared with reverse osmosis, iron oxide coated sand, and the Arsenic BioSand Filter. The table below summarizes important advantages, disadvantages, costs, and other parameters that the different removal methods were compared by.

Table 11: Comparison of Arsenic Removal Technologies

	AA	RO	IOCS	ABF
Advantages	Cheap, Simple	Simple Operation	One Step Process	User Friendly
Disadvantages	Large OD-5.6 ft	Rejected water; Requires pressure	IOCS; Manufacturing is complicated	Unconventional; Unproven
Cost Install Maintenance	 $1140 $29.33	 $290 $31	 N/A N/A	 $40 N/A
Cost/Person/Yr Install Maintenance	 $4.56 $0.12	 $29 $3.10	 N/A N/A	 $4.00 N/A
Arsenic Removal	Sufficient	Sufficient	Sufficient	Testing Inconclusive
Design	2 Additional Steps: Oxidation & AA	Additional RO system	Substitute IOCS for fine sand	Additional Layer of Nails
Lifetime	20 years for AA & MnO_2 replacement	3 years membrane replacement	Replace/regenerate	N/A
Maintenance	Regenerate AA yearly	Membrane lasts 3 years	Must Replace Sand	Must Replace Nails
Manufacture	Very similar to slow sand	Addition of RO unit	Complicated IOCS manufacture	Addition of nail container
Credibility	Untested; technically sound	Trusted – Manufacturer	OU Master Thesis Env. Engr.[64]	MIT MBA Report[65]
	WINNER			

MITIGATION PLAN AND RECOMMENDATIONS

Mitigation Plan

The large-scale implementation business plan will be carried out over a 10-year period. Within this ten-year period, the plan mitigates for 80 million people. 30 million of these Bengali people are within the high risk category of exposure to higher than 50 ppb arsenic contaminated water, specified as Phase One, and 50 million are exposed to higher than 10 ppb, specified as Phase Two. The total cost of phase one is $150 million, and the total cost of phase two is $233 million. Within these two phases there are four different production rates that are used.

The overall period of the mitigation plan is 120 months. This plan begins on a small and manageable scale in 1300 square feet of space in downtown Dhaka, the capital city of Bangladesh. Initially, the units to be installed per month are a relatively small amount, only 20. This is done in order to insure quality of development of the business before any large-scale implementation begins. During this time, four local citizens of Dhaka will be employed to construct the systems at the Dhaka location. From this point on, four people will be employed for every 20 units that are constructed a month.

Pertaining to the stages of progress, there will be three stages of development. The stages pertain to the number of units produces monthly. Stage one is 20 units per month, stage two is 1000 units per month, stage three, is 3000 units per month, and stage four is 6600 units per month. A timeline of this plan is shown below. These stages accomplish the required production per month to meet mitigation for 80 million people. For each stage transition, the location will change in order to accommodate the increase in space needed to construct the additional units. As rental space increases, rent costs increase proportional to square feet. Rental costs are tabulated in the following costs section.

The duration of phase one is 7.5 years, and is the mitigation for the population at high risk, and phase two is the final 2.5 years of the plan, which mitigates for the remaining lower risk population.

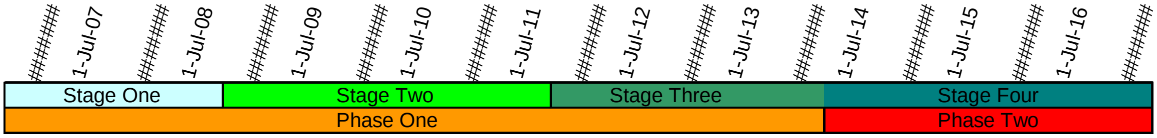

Figure 19: Implementation Timeline

Costs

The major costs of the plan can be broken down into capital costs, overhead cost, and maintenance costs. The capital costs, or initial installation costs of each unit, includes the price of purchasing and shipping the activated alumina, as well as the cost of manganese dioxide, sand, and tank for each unit. These costs are tabulated in Table 13 below.

Table 12: Manufacturing cost of activated alumina-based arsenic removal device

Manufacturing Costs	
AA ($3.125 / kg)	$793.75
MnO2 ($0.525/kg)	$59.85
Sand	$1.77
Tank	$250.00
Polyester Cloth	$5.00
Labor	$10.00
Piping	$20.00
Total	$1,140.37

The overhead costs incorporate rent and employees to construct the units. These costs are tabulated below in Table 14.

Table 13: Overhead Costs

Rent Stage 1) Stage 2) Stage 3) Stage 4)	 $270/month $12000/month $40000/month $80000/month
Employee Pay	$50/employee/month

The maintenance costs include the cost of regenerating the sand, replacing the sand, regenerating the activated alumina, tank and manganese dioxide, and the cost of maintenance employees per 100 units. These costs are tabulated in Table 15.

Table 14: Maintenance Costs for activated alumina-based arsenic removal device

Maintenance Costs	
KOH for regeneration	$24.32
Regeneration Labor	$1.67
Harrowing Labor	$3.34
Annual Cost	$29.33

Taxes

This mitigation plan is for the benefit of the people of Bangladesh, and operates on the basis of a non-profit aid organization. It will be a tax-exempt project.

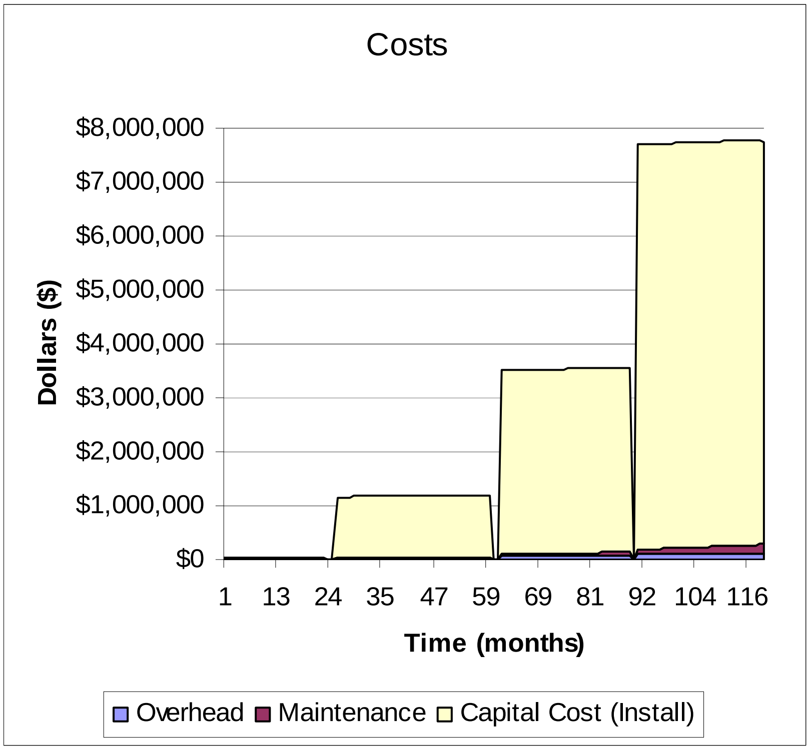

Figure 20: Contribution of Cost Elements

As figure 18 shows, most of the costs are due to the capital costs of the units. Efforts in decreasing the overall cost should be focused on minimizing the capital cost, and this was the motivating factor for this project.

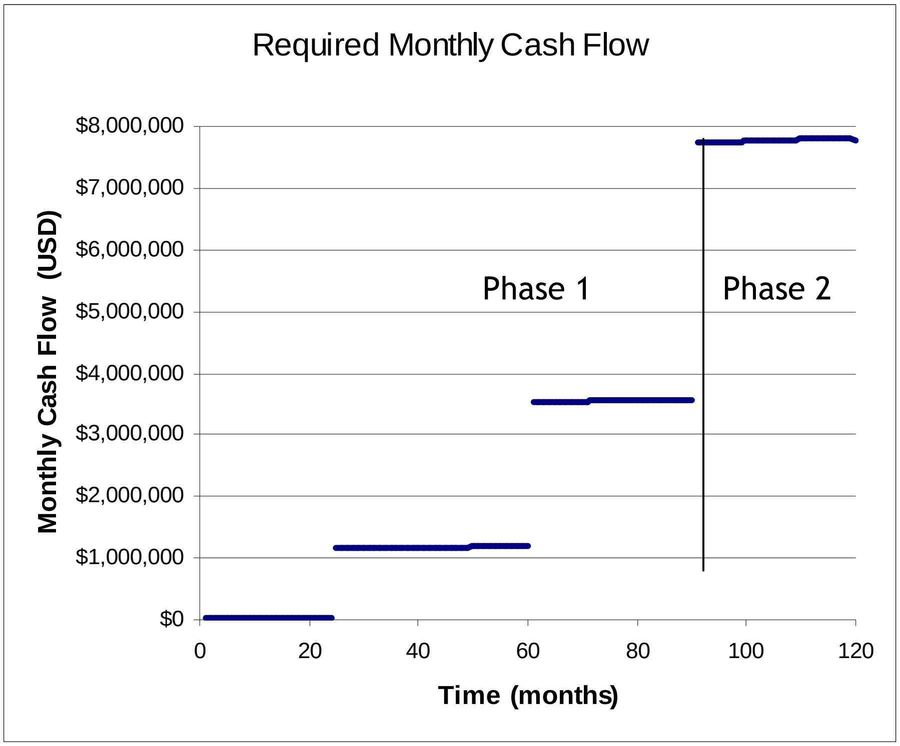

Figure 21: Required Monthly Cash Flow

Figure 19 shows how the required monthly cash flow changes as the project continues and expands in scope. The initial monthly cash flow required is less than $25,000, and the final monthly cash flow is nearly $8 million. It is anticipated that as agencies become aware of the project and start seeing positive results that more funding will become available.

Transportation

Flat bed trucks will be purchased in order to transport the units to the sites. For Stage One, only one flatbed truck will be needed, Stage Two four more trucks will need to be supplied for a total of five, and for Stage Three, ten more trucks will be needed, for a total of 15 trucks. If possible, trucks from other aid organizations or the government should be used, in order to minimize capital investment. The price of gasoline in Dhaka is about 2.60/gallon (45 Taka/liter), and has been included in cost calculations. [66]

Shipping options and availability in Bangladesh include land, water and railway. Within recent years the amount of paved-road access in Bangladesh has increased by more than 400%, and nearly half of Bangladesh is now road accessible to within 3 miles. Railways effectively cover about 32% of the country. About two thirds of the country is wetland laced. There are eleven airports active in Bangladesh. The costs of incoming shipping to Dhaka are included in the materials costs, and the outgoing shipping is accomplished by the trucks, the costs of which are included in capital cost calculations.[67]

Funding

The widespread nature of the arsenic problem, combined with the costs of mitigation, requires that many sources of funding be sought for successful and timely implementation of this plan. Potential sources of funding include the government of Bangladesh, World Bank, Asian Development Bank, the United Nations International Children's Fund (UNICEF), and the United States Agency for International Development (USAID). The appendix contains contact information and procedures for applying for funding.

Recommendations

Pilot scale testing of the activated alumina-based arsenic removal device is recommended before full scale implementation occurs. This testing would allow for the performance of the device to be verified, as well as determining the specific type of adaptor required to connect to common types of well pumps. Also, valuable feedback can be obtained from the villagers using the device about ease of use and water aesthetics. Once the design has been tested in a village, and adjustments made as necessary, it will be ready for full-scale implementation.

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APPENDIX

Supporting Documents

Support1-ActivatedAluminaDesign.xls
This spreadsheet details the design of the slow sand filter, manganese dioxide, and activated alumina layers in the activated alumina-based arsenic removal device

Support2-ActivatedAluminaCosts.xls
This spreadsheet contains itemized costs for the activated alumina device, as well as a summary of the physical properties.

Support3-ReverseOsmosisCosts.xls
This spreadsheet details the individual item costs for the reverse osmosis design.

Support4-TotalCostForImplementation.xls
This spreadsheet contains the overall economic analysis for the project.

Calculations

Slow Sand Filter

The surface area required by the slow sand filter is given by the equation:

$$A = \frac{Q}{HL}$$

Where:

A is the surface area in m^2

Q is the volumetric flow rate in L/hour

HL is the hydraulic loading rate in $L/(m^2h)$

For this system, with a typical hand pump capable of a 15 L/min flow rate (Ajay Industrial Corp - website), and area of 2.25 m^2 is required.

$$A = \frac{\frac{15L}{\min} * \frac{60\min}{hr}}{400\frac{L}{m^2 hr}} = 2.25m^2$$

If this is in a cylindrical container, the diameter of the container will be:

$A = \pi r^2$

$D = 2\sqrt{\frac{A}{\pi}}$ = 1.7 m

Activated Alumina

Equilibrium Capacity

Rosenblum and Clifford reported the equilibrium arsenic capacity of activated alumina, in the presence of 15 meq/L Na2SO4, in the concentration range of 200 ppb arsenic, as 7 mg As / g Activated Alumina. These are the median arsenic and sulfate conditions in the groundwater in Bangladesh.

The equilibrium amount of activated alumina required to remove 500 ppb of arsenic from groundwater for 250 people for 1 year is:

$$\frac{25\text{ L}}{\text{day}} * 250\text{ people} * \frac{365\text{ days}}{\text{year}} * \frac{500\times10^{-6} g\text{ As}}{L} * \frac{1\text{ g AA}}{7\times10^{-3}\text{ g As}} * \frac{1kg}{1000g} = 163\text{ kg activated alumina}$$

Time before regeneration of activated alumina

$$\text{Time} = \frac{\text{Amount of Activated Alumina}}{\text{Annual required amount of activated alumina per year}}$$

Five percent of the activated alumina loses its capacity with each regeneration. The number of regenerations before the unit can not adsorb for a full year is:

[Amount of AA] = $(1.05)^n$ * [Annual amount of AA]

Where n is the number of regenerations

log [Amount of AA] = n*log(1.05*[Annual amount of AA])

$$n = \frac{\log[\text{Amount of AA}]}{\log[1.05 * [\text{Annual amount of AA}]]}$$

Empty Bed Contact Time (minutes)

$$\text{EBCT} = \frac{\text{Height} * (\text{Cross-sectional Area})}{\text{Volumetric flow rate}} = \frac{h * A}{Q}$$

Where:
h has the units of cm
A has the units of cm^2
Q has the units of cm^3/min

Concentration Wavefront

The velocity of the concentration wavefront can be determined for a constant-concentration solution flowing through the adsorption bed as:

$$u_c = \frac{u}{1 + \left(\frac{1-\varepsilon_b}{\varepsilon_b}\right) * \frac{dq}{dc}}$$

Where u_c is the velocity of the concentration wavefront through the bed
u is the interstitial velocity through the bed
ε_b is the coefficient relating the superficial velocity to the interstitial velocity, where $u_{superficial} = \varepsilon_b u$
(dq/dc) is the slope of the adsorption isotherm for the given concentration.

This equation can be used to determine the amount of time that it will take for arsenic breakthrough to occur in the column. However, u_c changes at every differential point in the bed, as arsenic is adsorbed and the concentration goes down.

Reverse Osmosis

Membrane Area

20 gal/ ft^2/day * A(ft^2) = 40 gal/day (only operated at 6 hours a day)

A = 40/(20/(24/6))= about 1 m^2

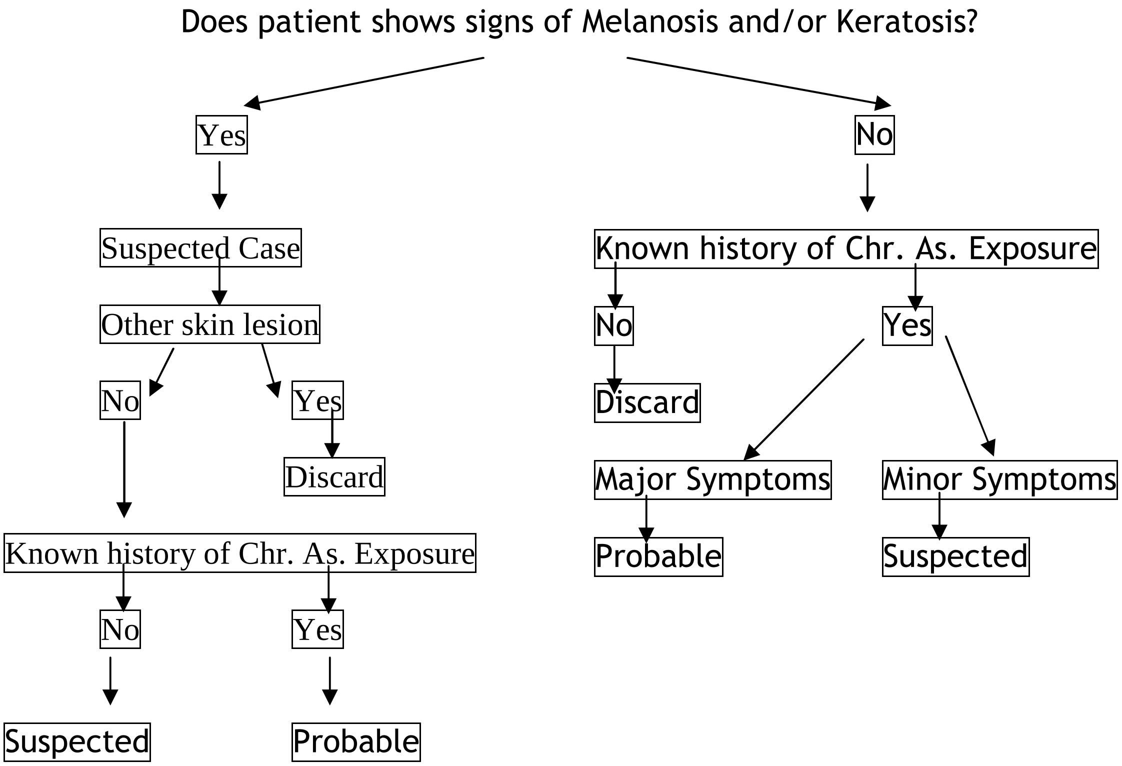
Criteria for diagnosing arsenicosis

Table A.1: Criteria for Diagnosing Arsenic Poisoning

1. Prolonged intake of water with arsenic levels greater than 50 ppb (more than 6 months)
2. Characteristic dermatological features
    a) Hyper/hypo-pigmentation, spotty pigmentation of the body
    b) Keratosis of palms/ soles
3. Non-cancer systematic manifestations
    a) Symptoms of chronic lung disease – breathlessness, chronic bronchitis, pulmonary fibrosis; hepatomegaly – liver enlargement and cirrhosis of the liver, neuropath and vascular diseases.
4. Cancers
    a) Bowen's disease, squamous cell skin cancer; internal and external cancers

Figure A.1: Suggested Algorithm for Diagnosis

(Assuming no clinical tests are accessible)



Funding: Contact Information and Procedures

This section contains suggested courses of action for contacting the government of Bangladesh, World Bank, Asian Development Bank, UNICEF and USAID, as well as contact information. Procedures on applying for grants have been included where available.

The Government of Bangladesh

For any arsenic mitigation project to be successful, it must have the support of the government of Bangladesh. It is recommended that the Bangladesh ambassador to the United States be contacted with a copy of this plan. Bangladesh's response to the plan will determine its feasibility.

Contact Information:

His Excellency
Mr. Shamsher M. Chowdhury
Bangladesh Embassy in Washington DC
3510, International Drive NW
Washington, DC 20008, USA
Telephone : (202) - 244 - 0183
Fax :(202) - 244 - 5366
Web: http://www.bangladoot.org

World Bank

World Bank is an aid organization that provides low-interest loans, interest-free credit and grants to developing countries for education, health, infrastructure, communications and many other purposes. In 1998 World Bank assisted in giving $32 million to funding BAMWSP to help test tube wells for arsenic. They are heavily involved in poverty issues in Bangladesh and will be a likely contributor. World Bank typically works directly with governments and not aid organizations, so it is recommended that the government of Bangladesh initiate contact with World Bank. World Bank can either be contacted in their Dhaka office or their Washington, D.C. office.

Contact Information:
In Dhaka: Rehnuma Amin
Phone: (880-2) 8159001
Fax: (880-2) 8159029
E-mail: ramin1@worldbank.org

In Washington: Benjamin S. Crow
Phone: 1-202-473-5105
E-mail: bcrow@worldbank.org

Asian Development Bank

Asian Development Bank (ADB) is a multilateral financial institution owned by 64 members, with Bangladesh owning a little over 1% of the shares. ADB is a likely contributor to the mitigation plan, because ADB is already involved in giving to Bangladesh[68] It is recommended that the government of Bangladesh initiate discussion with ADB in regard to implementing this mitigation plan.

Contact Information:
Asian Development Bank – Bangladesh Resident Mission
Plot No. E-31
Sher-e-Banglanagar
Dhaka 1207
GPO Box 2100
Telephone: +880 2 815 6000 - 8, 815 6009 - 16
Fax: +880 2 815 6018 - 19

United Nations International Children's Fund (UNICEF)

UNICEF is an international aid organization sponsored by the United Nations, focusing on issues that affect childen. UNICEF is currently involved in arsenic mitigation in Bangladesh, with their "Arsenic Mitigation and Measurement Project" <http://www.unicef.org/bangladesh/wes_420.htm>. Part of this project is to research effective arsenic removal technologies and implement them. It is recommended that UNICEF Bangladesh be directly contacted and informed of this research and mitigation plan.

Contact Information:
Zafrin Chowdhury
Communication Officer
UNICEF Bangladesh
9336701-10/Ext. 397
zchowdhury@unicef.org

United States Agency for International Development (USAID)

USAID is an independent agency of the United States federal government that exists for the "purpose of furthering America's foreign policy interests in expanding democracy and free markets while improving the lives of the citizens of the developing world." (USAID) USAID operates a mission in Dhaka, Bangladesh, and accepts proposals for grants from both U.S. and non-U.S. based non-profit aid organizations. Prior to submitting a proposal, aid groups must register with USAID and qualify under their criteria for a "Private Voluntary Organization." The application process is outlined at:

<www.usaid.gov/our_work/cross-cutting_programs/private_voluntary_cooperation/reg.html>

Guidelines for preparing unsolicited proposals can be found in Publication CIB 99-18: "Unsolicited Proposals for Acquisition and Assistance", which is located online at:

<http://www.usaid.gov/business/business_opportunities/cib/pdf/cib9918.pdf>

Contact Information:
Bangladesh
USAID/Dhaka
Department of State
Washington, DC 20521-6120
Tel: 880-2-885-5500
Fax: 880-2-882-3648
Web: http://www.usaid.gov

Endnotes

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