

EVALUATION OF THREE ARSENIC REMOVAL
TECHNOLOGIES IN NEPAL

by

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ABSTRACT

This study was conducted in Nepal and at MIT as part of the 2000-2001 MIT Nepal Water Project (NWP) and is a continuation of work done by the 1999-2000 MIT Nepal Water Project team. The arsenic project, a subsection of the NWP, was started in 1999 with the goal of documenting the occurrence and extent of arsenic in water sources in Nepal. The goal of this year's project was to begin the process of recommending treatment technologies to remove arsenic from drinking water.

An evaluation of three arsenic removal technologies, the Three-Gagri System, the Jerry Can System, and the Arsenic Treatment Unit (ATU), was conducted. In addition, a comparison of two arsenic field tests, EM Quant® test strips and Arsenic Check™, was made. Finally, water source samples from Parasi, Nepal were analyzed to determine their arsenic content.

The three arsenic removal technologies were evaluated for their effectiveness and appropriateness. Effectiveness is the measure of a technology's ability to remove arsenic to or below 10 ug/L (micrograms per liter or parts per billion), the guideline set by the World Health Organization (WHO) for arsenic in drinking water. The WHO set this guideline because drinking arsenic contaminated water above this limit can cause adverse health effects. Appropriate technologies are easy to assemble, simple to use in rural settings, and made with locally available, inexpensive materials.

The Three-Gagri System was found to be both effective and appropriate, but the clogging problem and the question of whether or not this system promotes microbial growth in the water need to be addressed. The Jerry Can System was found to be ineffective and inappropriate with its current design. The ATU, while very effective, is inappropriate for implementation in Nepal due to its high cost. This study has also concluded that the Arsenic Check™ test is a safer and more accurate than the EM Quant® test strips. Finally, this study found that groundwater from some water sources in Parasi Nepal is contaminated with arsenic above the WHO guideline.

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Dr. Eric Adams and the administrative staff at MIT made it possible for us to travel to Nepal and provided the Nepal Water Project team with the necessary resources to continue our research in Cambridge.

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1 Introduction

1.1 Nepal Water Project

The Nepal Water Project was a collective effort of five Master of Engineering (MEng) students at the Massachusetts Institute of Technology (MIT) to evaluate six types of drinking water treatment systems in Nepal. These five students and their advisor traveled to Nepal for three weeks in January 2001 to do field studies and to try to understand the culture of the peoples for whom they were attempting to recommend treatment systems. The Nepal Water Project was completed as part of the degree requirement for the Master of Engineering program at MIT; each student had an independent project and they collaborated on these projects to produce a group report. This thesis is one of those independent projects and is submitted as a part of the overall project goal.

Susan Murcott, the project advisor, initiated the Nepal Water Project in 1999. Murcott, an environmental engineer, was a keynote speaker at the Second International Women in Water conference in Kathmandu, Nepal in 1998. During this conference, water quality problems in Nepal were explained to her and her help was requested. In order to try and address the issues of concern, she began the Nepal Water Project with a group of seven students the following fall. Her main goals were to understand the quality of the drinking water sources in Nepal and then to try and develop point of use, household water treatment systems, following the advice and recommendations that Murcott had received from the Nepali women.

In the first year of the project, seven students traveled to Nepal to document and analyze several parameters that qualify drinking water quality. This was to satisfy the goal of gathering data on the general state of the drinking water in Nepal. They also evaluated the performance of several household water filters regarding their ability to remove microbial contamination from drinking water. This year's group continued the work of the previous MEng students and their study's

goals were built upon the recommendations of the 1999-2000 group, Murcott's observations of opportunities to help and the requests of several water agencies in Nepal.

1.2 Arsenic Project

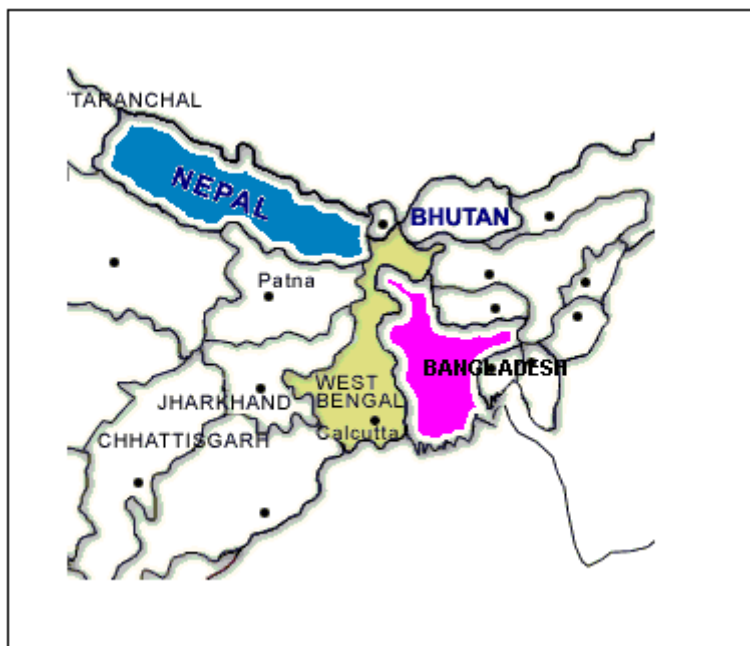
Part of the 1999-2000 Nepal Water Project involved an arsenic contamination study in Kathmandu, the capital, and in the Terai, or lowland region of Nepal. This study was motivated by the recent health crisis in Bangladesh and West Bengal, India caused by arsenic contamination of their drinking water. Drinking arsenic contaminated drinking water can cause serious adverse health effects (see Section 2.3) and it is because of these harmful effects that the World Health Organization (WHO) has set the guideline for arsenic in drinking water at 10 ug/L (micrograms per liter or parts per billion).

People in West Bengal and Bangladesh used to get their drinking water primarily from surface water sources. In the 1970s, the fact that many of these sources had severe microbial contamination and were causing illnesses was addressed. To fix the problem, tubewells were installed so that groundwater could be extracted for drinking purposes since groundwater is much less likely to be contaminated with water-borne pathogens. Unfortunately, the groundwater was contaminated with arsenic. It was not until widespread installation of tubewells was implemented in both West Bengal and Bangladesh that the arsenic contamination was realized, in the 1980s, and broad public awareness of the problem did not happen until the mid 1990s. Now, as many as thirty million people in Bangladesh are thought to be drinking water with unsafe levels of arsenic¹, as fifty-nine of the sixty-four districts in Bangladesh are arsenic-affected². Also, nine of eighteen districts in West Bengal were found to have elevated levels of arsenic in their groundwater, affecting as much as eight percent of West Bengal's population³.

The arsenic in West Bengal and Bangladesh is thought to be natural origin (see Section 2.1.2). It is believed that natural processes deposited naturally occurring arsenic, which was bound to solid

substrates, in the subsurface. Because Nepal is close to both of these affected areas (see Figure 1.1), has similar hydrology and geology, and most of the population uses groundwater as their primary source of drinking water⁴, it was suspected that arsenic contamination might also be a problem in Nepal. Because of this, Tricia Halsey of the 1999-2000 Nepal Water Project team went to Nepal to collect data on where and to extent levels arsenic existed in its water sources.

Figure 1.1: Map of Nepal, Bangladesh, and West Bengal, India⁵



While Halsey found that none of the thirty-one samples tested from sources in Kathmandu had arsenic levels above the WHO guideline, she found that 18% of the 139 samples gathered in the Terai region did surpass the WHO guideline⁶. Since then, more studies on the occurrence of arsenic have been conducted in the Terai region. The Water Engineering & Training Center in Nepal has conducted two such studies; in one they found that 5.1% of 590 samples were above the WHO guideline⁷ and in the other they found that 10.8% of sixty-five samples were above it⁸. The Department of Water Supply and Sewerage (DWSS) in Nepal also conducted an arsenic contamination study in 1,999 in the Terai, using a combination of field and lab tests, and found that 9% of the 268 samples tested had arsenic levels above 10 ug/L. When the Nepal Red Cross Society (NRCS) and the Japanese Red Cross Society conducted an arsenic survey of seventeen

districts in the Terai, they found that 17% of the 1990 samples contained arsenic levels exceeding the WHO limit and found that one district, Rautahat, had a high incidence of arsenic contamination. A graduate student working for DWSS then did a more comprehensive study in Rautahat and found that, in one study, 39% of eighty-nine samples and in another, 53% of thirty-two samples collected had arsenic levels above 10 ug/L⁹.

The combination of the adverse health effects caused by arsenic in drinking water and the occurrence of arsenic in the Terai region of Nepal was the motivation for this year's arsenic project. This year we set out to work on the solution to the confirmed problem. There needs to be arsenic removal technologies for those threatened by health problems caused by arsenic. Though many technologies have been proposed by researchers around the world, none of them have been field tested in Nepal and been deemed appropriate technologies for a country with such few resources and little money (Nepal is the seventh poorest country in the world, with a per capita average annual income of US\$210¹⁰). It is important that we evaluate technologies to determine if they will be appropriate for local conditions and needs.

1.3 Evaluation of Arsenic Removal Technologies

This year's arsenic project goal was to evaluate three different arsenic removal technologies for their effectiveness and appropriateness under field conditions in rural Nepal.

For the purpose of this report, *effectiveness* is defined as the measure of the ability of a water treatment system to remove arsenic contamination to 10 ug/L or below. The definition of *appropriate technology*, has four components: 1) the technology must be of simple design and easily produced; 2) it must be low cost; 3) it must use local, easily accessible materials; 4) it must have a rural focus¹¹.

The three removal technologies chosen were the Three-Gagri System, the Jerry Can System and the Arsenic Treatment Unit (ATU) made by Apyron Technologies, Inc. (ATI). The Three-Gagri System was chosen because variations of it have historically been used as a general water filtration unit and because many people in Bangladesh and West Bengal adapted it for arsenic

removal. It was thought that this technology would be socially accepted if it proved effective since people in similar socio-economic situations, such as those in India and Bangladesh, have adopted a very similar treatment unit, the Three-Kalshi System. In early 2000, BRAC, a Bangladeshi development organization distributed 9,000 three-kalshi filters in Bangladesh and the Dhaka Community Hospital distributed another 3,000 similar filters¹². The Jerry Can System was chosen for its simple design and its low cost. Though the system had not been field-tested and only limited literature had been published on it before the submission of this report^{13,14}, it seemed like, if effective, it could be a very promising treatment option. Finally, the ATU was chosen because it had been tested in West Bengal, India and Bangladesh and was proven successful, also it is the only technology to be designated as “Best Available Treatment Technology” by the Public Health and Engineering Directorate (PHED) in West Bengal thus far¹⁵.

The effectiveness of these technologies was evaluated by testing the arsenic concentration of influent and effluent water, i.e. before and after being treated. The water was tested using three testing methods; two field tests were used in Nepal, EM Science’s EM Quant® test strips and Industrial Test System’s Arsenic Check™ kit, and a Graphite Furnace Atomic Adsorption Spectrometer (GFAAS), made by Perkin and Elmer, model 4100ZL was used upon returning to MIT. If the technology removed arsenic below 10 ug/L, it was deemed effective.

The author assembled each technology in a rural field site, in the town of Parasi, in the Terai region of Nepal, where she lived for two weeks. Therefore, she was in a good position to evaluate the appropriateness of each technology. She could determine how easy it was to assemble, how readily available and how costly the needed materials were. Since she also used the technologies in Parasi, she could evaluate how convenient they were to use in a rural setting.

2 Background on Arsenic

This chapter provides the reader with the necessary background on arsenic. The general chemistry of the element will be presented and then the explanations for its occurrence in the groundwater of West Bengal, Bangladesh and Nepal will be given. Finally, the harmful consequences associated with drinking arsenic contaminated water will be described.

2.1 General Chemistry

Arsenic is a naturally occurring, group V element that is a semimetallic and crystalline solid¹⁶. Stable in the -III, 0, +III, and +V oxidation states, the common forms of arsenic are arsenate (As(V)), in the +V oxidation state, and its reduced form arsenite (As(III)), in the +III oxidation state. In the aqueous environment arsenate is commonly found as H_2AsO_4^- (in acidic soil) or HAsO_4^{2-} (in alkaline soil) and arsenite is commonly found as H_3AsO_3 ¹⁷. Arsenate is therefore relatively immobile because it tends to sorb onto positively charged particles, such as iron hydroxides. Arsenic species containing the metalloid in the +V oxidation state are most commonly found in oxidized environments (0.2-0.5 V) and those containing arsenic in the +III state in reduced environments (0-0.1 V)¹⁸. Therefore, factors such as pH and the oxidizing or reducing states of the particular environment can drastically affect the state of arsenic in the subsurface.

2.2 Reasons for Arsenic Contamination

The problem of arsenic-contaminated groundwater arises because of an unfortunate combination of three factors: a source of arsenic (arsenic must be present in the aquifer sediments), mobilization (arsenic must be released from the sediments to the groundwater) and transport (arsenic is flushed away in the natural groundwater circulation).

There are anthropogenic sources of arsenic, as it is commonly produced as a by-product of copper and lead smelting, glass making, and pesticide and herbicide production¹⁹. It is generally

agreed on, though, that the arsenic in the sediments of Bangladesh and West Bengal is naturally occurring in the alluvial sediments in the area. Studies have shown that there is a high level of arsenic in a type of rock called pyrite in the alluvial regions of Bangladesh²⁰. Other studies have suggested that a high proportion of the arsenic in these sediments is present as adsorbed arsenic. This conclusion came out of the recognition that there is a good correlation between extractable iron and arsenic in the sediments and by noticing that a large proportion (often half or more) of the arsenic can be dissolved by acid ammonium oxalate, which selectively dissolves hydrous ferric oxide and other poorly ordered oxides²¹. Arsenic present in primary minerals such as arsenic-rich pyrite would not be dissolved by the acid. Since the Terai region in Nepal is also composed of alluvial soil, it is suspected that the arsenic source in Nepal is also natural and is a combination of adsorbed arsenic and arsenic present in pyrite.

The mobilization of arsenic from the sediments to the groundwater could be due to forces of nature or of man, but this is also generally agreed to be due to natural processes. Some scientists believe that the use of phosphates in chemical fertilizers is influencing the displacement of arsenic from the sediments in Bangladesh and West Bengal. Since there is no correlation between areas of most intense groundwater contamination and the distribution of fertilizers, the anthropogenic explanation cannot account for the regional extent of groundwater contamination in Bangladesh and West Bengal²².

There are two theories as to how arsenic is naturally mobilized, the pyrite oxidation theory and the oxyhydroxide reduction theory. The pyrite oxidation theory says that air or water with dissolved oxygen penetrates into the groundwater in response to pumping of wells. This introduction of oxygen results in the decomposition of sulfide minerals and the release of arsenic²³. The oxyhydroxide reduction theory states that arsenic-rich oxyhydroxides are naturally reduced by the oxygen deficient groundwater. Due to the high carbon content of the sedimentary organic matter, the groundwater in Bangladesh, West Bengal and Nepal is commonly in a reducing state. When iron or manganese oxyhydroxides are in a reducing environment, they tend to breakdown, releasing arsenic. Also, the reduction of arsenate would result in a transformation to arsenite, which might cause general desorption of arsenic since

arsenite less strongly sorbs to oxyhydroxides than does arsenate²⁴. It is generally agreed that the second theory is the more likely of the two^{25,26}.

2.3 Health Effects

Arsenic has long been known as a poison and is best known for its harmful acute effects. The recent health crisis in West Bengal and Bangladesh has brought the devastating chronic effects of arsenic to our attention. Acute effects are symptoms that occur directly after brief exposure to high concentrations while chronic effects occur gradually and are due to long-term exposure to low levels of arsenic.

2.3.1 Acute

If one ingests a large dose of arsenic at one time, acute arsenic poisoning effects could manifest immediately; if the dose is as large as 60 milligrams per liter (mg/L), it could be fatal²⁷. Common symptoms of acute arsenic poisoning are muscle pain and weakness, which can lead to numbness. Also, severe nausea often occurs and it followed by abdominal pain and diarrhea. Finally, drowsiness and confusion can preempt paranoid delusions and hallucinations. In the most severe of cases, seizures, coma or death could occur²⁸.

2.3.2 Chronic

The levels of arsenic in the groundwater of West Bengal, Bangladesh and Nepal are less than 60 mg/L and are not likely to cause acute arsenic poisoning, but are greater than the WHO guideline and have been shown (in West Bengal and Bangladesh) to cause adverse chronic health effects.

Chronic arsenic poisoning symptoms often start after a few years of exposure and show up first as skin ailments²⁹. First hyperpigmentation and/or hypopigmentation can occur, which shows up as dark or light spots, respectively. Then keratosis can begin, hardening the skin often on the

Figure 2.1: Feet of an Arsenicosis Sufferer³⁰



hands and feet, causing arsenical skin lesions (see Figure 2.1). In a survey of twenty-seven arsenic-affected districts in Bangladesh, patients with arsenical skin lesions were identified in twenty-five of those districts. In West Bengal, persons suffering from keratosis were identified in seven of the nine districts surveyed. When people from those affected villages were examined at random, 24.5% and 15% of those in Bangladesh and West Bengal, respectively, had lesions³¹. Arsenical skin lesions such as these are expected with ingestion of water with at least 300 ug/L arsenic³², but in a study of 7,683 people drinking contaminated water with up to 3000 ug/L arsenic in West Bengal, twenty-nine people drinking water with less than 100 ug/L showed hyperpigmentation and twelve people drinking water with less than 100 ug/L showed keratosis³³. The disease, arsenic poisoning or arsenicosis, is very painful as parts of the body develop gangrene and eventually fall off³⁴, and unfortunately, there are no known cures for arsenicosis³⁵.

If and when arsenical skin lesions appear depend on many factors. The concentration of arsenic contamination in one's drinking water source is important; the more concentrated the water, the more likely one is to be adversely affected. Also important is how long one has been exposed, and to how much arsenic contaminated water they have been exposed. The longer one has been drinking the arsenic contaminated water and the more of it he/she drinks in a day, the more likely he/she will experience harmful consequences. The nutritional status of the people drinking the contaminated water also plays an important role. Those suffering from malnutrition were found

to have more skin lesions than those with better nutrition drinking water with the same concentration³⁶.

After about ten years of exposure, skin cancer can develop, and after twenty to thirty years, internal cancers, such as lung, bladder and kidney, can occur³⁷. It is because of its carcinogenic effects that the WHO set the guideline for arsenic in drinking water to 10 ug/L. This guideline results in an excess lifetime cancer risk of 6×10^{-4} . If the guideline were made strictly on a health basis, it would be set at 0.17 ug/L in order to reduce the cancer risk to 10^{-5} (38). The reason that the guideline cannot be this low and must be 10 ug/L is that the testing methods to measure arsenic in water are often not sophisticated enough to detect arsenic below 10 ug/L³⁹.

3 Analytical Methods

3.1 Sample Gathering

While in Parasi, the arsenic concentration in water from seven different sources was analyzed. Samples were collected and analyzed with the field kits in Parasi brought back to MIT for further analysis. All of the sources were in Parasi, near the house in which the author stayed. Six of the sources were tubewells while the other two were municipally supplied pipes. See Table 3.1 for further description.

Table 3.1: Type and location of the water sources analyzed

	<i>Type of water source</i>	<i>Location of water source in Parasi, Nepal</i>
1	Tubewell	Behind the author's residence
2	Tubewell	In front of the old Nepal Red Cross office
3	Tubewell	Behind the new Nepal Red Cross office
4	Tubewell	West of the author's residence
5	Tubewell	East of the author's residence
6	Pipe	In front of the author's residence
7	Pipe	In front of the Department of Water Supply and Sewerage

Samples were collected in capped 500mL (milliliter) plastic bottles so that they could be easily transported from the source to the workplace. The workplace was a lab that the author set up on the front porch of the house in which she stayed. To obtain a sample, the tubewell or pipe was pumped or turned on and water was allowed to flow through for at least ten seconds, or about two pumps worth of water from a tubewell, in order to get groundwater and not water that had been sitting stagnant in the tube or pipe. The plastic bottle was then filled about halfway with the source water, capped, shaken and emptied; this was repeated three times in order to rinse the

sample bottle. Finally, the bottles were filled, allowing headspace, labeled and taken back to the house for testing. Typically, samples were collected in the late morning or early afternoon and were analyzed in the late afternoon or early evening.

Besides water from tubewells and municipally supplied pipes, water that had been treated by the three arsenic removal technologies was also analyzed (see Chapter 4). Samples from the three removal technology systems were collected in clean 50mL plastic beakers or directly into the testing vessels, which are described below, and tested soon after (within an hour) being decanted from the system. There was no need to collect these samples in 500mL plastic bottles since no transport was needed, as the removal technologies were located at the workplace where the analysis took place.

3.2 How Samples were Analyzed

Source water from Parasi and effluent from various treatment technologies were tested using three methods. Two different field tests were used in Nepal; EM Quant® test strips and Arsenic Check™. Split samples of those tested with field kits were brought back to MIT and tested with a Graphite Furnace Atomic Adsorption Spectrometer (GFAAS).

3.2.1 Field Test Kits

Two field test kits, EM Quant® test strips, also known as “Merck Tests”, and Arsenic Check™, were brought from MIT to Parasi, Nepal so that water samples could be analyzed on site. These kits were chosen because they were both portable and rugged and did not require electricity or refrigeration.

3.2.1.1 EM Quant® Test Strips

EM Quant® test strips were used for a presence/absence evaluation of arsenic content in water samples. Because the detection limit for this test is 100 ug/L and arsenic contamination in Nepal

was found by Halsey to be between 0 and 100 ug/L, this test did not give valuable information regarding the extent of the level of contamination other than whether or not it existed.

Theory

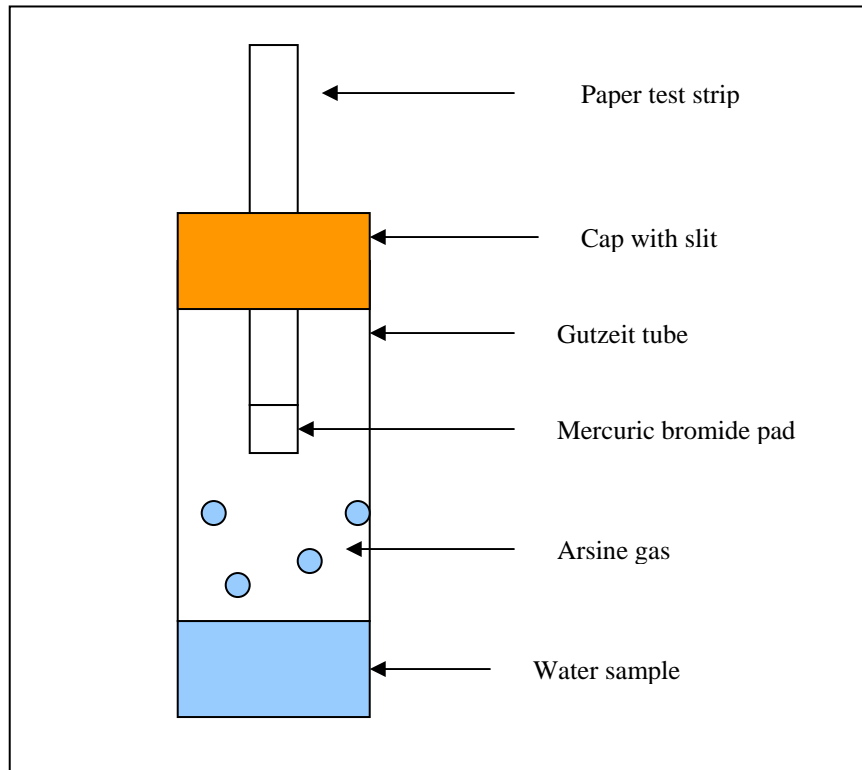
The test uses chemical reactions to produce arsine gas to determine ranges of arsenic concentrations; 0-100 ug/L, 100-500 ug/L, 500-1000 ug/L, 1000-1700 ug/L, >1700 ug/L. Water is capped in a glass test vessel and mixed with two reagents, 32% hydrochloric acid (HCl) and zinc (Zn) powder, which react with both arsenite and arsenate to produce arsine gas (AsH_3). The gas rises above the sample and contacts a paper test strip containing mercuric bromide (HgBr_2), which reacts with the gas, producing a stain. The concentration of the arsenic in the sample is determined by the hue of the stain and can be read based on a color chart provided in the kit⁴⁰.

Procedure

EM Quant® test strips were used on both the water source samples and on effluent from removal technologies. The first step in the analysis was to insert the test strip containing the mercuric bromide into the slit of the cap of the reaction vessel, or Gutzeit tube (see Figure 3.1). The slit is very thin so that there is little room for the arsine gas to escape from the tube once it is generated. About half of the test strip should be on the underside of the cap and half should be sticking out the top. If it was a source water sample being analyzed, the 500mL sample bottle was shaken to stir up any particles that might have settled in the time between when the sample was collected and when it was tested. Next, 5mL of the sample was collected with a clean 10mL plastic syringe and delivered to a clean Gutzeit tube⁴¹. If the sample to be analyzed was from the removal technologies, effluent was poured into a 50mL beaker, from which the 5mL of sample was collected. One scoop, provided in the kit, of zinc powder was added to the water sample and then the tube was swirled and lightly shaken to collect and dissolve any zinc remaining on the walls of the tube. Ten drops of hydrochloric acid was then added and the tube was swirled again. Finally, the cap was placed on the Gutzeit tube, making sure that the mercuric bromide pad was inside the tube. Once the tube was capped, it was placed in a well-ventilated area (outside or near a window) where it would not be disturbed for thirty minutes. Following the thirty minutes,

the cap was removed and the color change on the pad was compared to the color chart on the test strip bottle in order to find the range of arsenic concentration in the sample⁴².

Figure 3.1: Schematic of EM Quant® test



3.2.1.2 Arsenic Check™

Arsenic Check™, with a detection level of 20 ug/L, was used to provide a greater sensitivity as regards the contamination of the water samples than was provided by EM Quant® test strips.

Theory

Utilizing a similar theory to the EM Quant® test strips, this test differs only in that it uses tartaric acid ($C_4H_6O_6$) instead of hydrochloric acid. The concentration ranges that this test can determine are 0-20 ug/L, 20-50 ug/L, 50-100 ug/L, 100-250 ug/L, 250-500 ug/L, 500-750 ug/L, and over 750 ug/L. Not only is the detection limit lower with the Arsenic Check™ kit compared to the EM Quant® test strips but this range of concentrations is more appropriate for the levels of arsenic concentrations found by past studies in the Terai region of Nepal. Again, the acid reacts with zinc powder and arsenic in the water sample to produce arsine gas that contacts mercuric bromide on a suspended paper to cause a color change that indicates the concentration of arsenic in the sample⁴³.

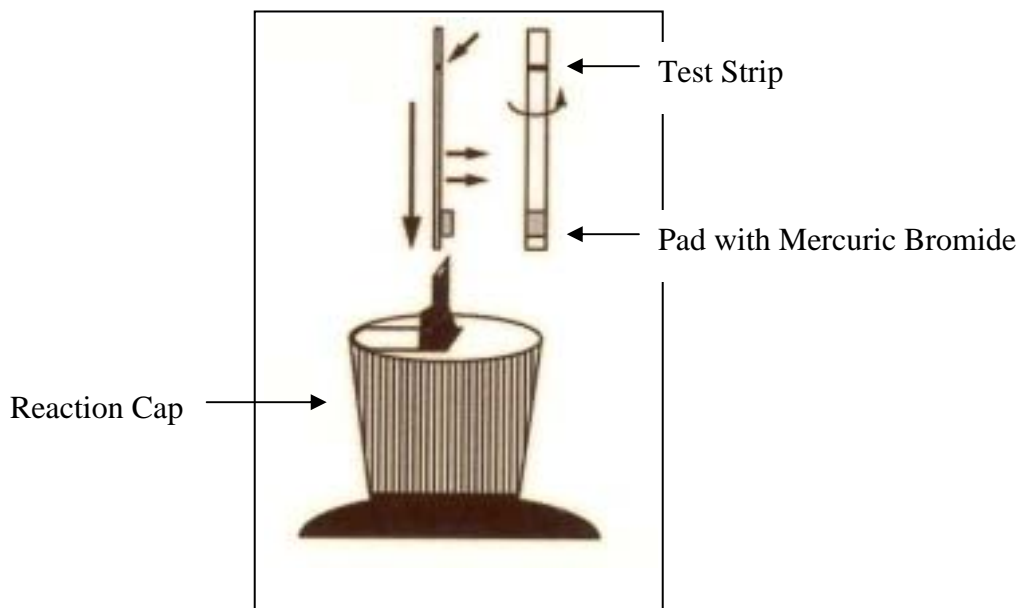
Procedure

Arsenic Check™ was also used on source water and removal technology effluent samples. To use this field test, 100mL of sample was added to the plastic bottle that came in the kit. There was a yellow line on the bottle indicating the 100mL level so that one does not have to measure 100mL, but rather fill the bottle to the line⁴⁴. Again, water from the 500mL bottles was shaken before it was added to the test bottle and effluent from the removal technologies was poured directly from the system into the test bottles. The author had two different versions of the Arsenic Check™ tests; one was pre-made with the chemicals included in the bottle or pre-measured in the kit and another which required that the user measure and add the chemicals.

The author had four pre-made tests and used these first. To use these, water was added to the yellow line of the bottle that already had tartaric acid crystals in it. The bottle was then capped and shaken for twenty seconds in order to dissolve all the acid. Then the bottle was uncapped and the pre-measured vial of zinc dust was added. Using the reaction cap, different from the first cap in that it had a spout, the bottle was immediately capped again. Without shaking or stirring the water and chemical mixture, a test strip, which again contained a pad of mercuric bromide, was inserted into the spout with the pad facing toward the back (see Figure 3.2). The strip was

inserted to the red line and the spout was closed. After putting the bottle in a well-ventilated area where it would not be tampered with, it sat for sixty minutes to allow for the reaction of the arsenic, acid, zinc, arsine gas, and mercuric bromide to occur. Finally, the strip was removed and the color change on the reaction pad was compared to a color chart on the test strip bottle in order to obtain an arsenic concentration range for the sample⁴⁵.

Figure 3.2: Schematic of Arsenic Check™ reaction cap⁴⁶



The tests where the user measured and added all the chemicals worked similarly except that there were three reagents to add. This kit came with two more plastic test bottles with two caps for each; a normal cap to use while shaking the bottle and a reaction cap to insert the test strip into, three reagents; first, tartaric acid, second, potassium peroxydisulfate, and third, zinc powder, and three measuring spoons, one for each reagent. Another difference between this test and the pre-made one was that it required the test water to be at twenty-five degrees Celsius before analysis; sometimes this meant that the sample had to sit in the sun and warm up before the test could begin. Instead of the tartaric acid, or first reagent, already in the test bottle, three spoonfuls of it were added to the 100mL of water and the bottle was capped and shaken for fifteen seconds. Then three spoonfuls of the second reagent were added, the bottle was capped

and shaken for fifteen seconds, and then allowed to sit undisturbed for two minutes. The second reagent is a chemical mixture whose active ingredient is potassium peroxymonosulfate (43% of mixture)⁴⁷. Finally three spoonfuls of zinc powder, the third reagent, were added and the bottle was given a last fifteen second shake before the reaction cap was put on and the test strip was inserted, in the same manner as with the procedure for the pre-made test. Again, the bottle was left to sit, this time for thirty minutes, so the reaction could take place and the color change could occur on the test strip to indicate the arsenic concentration range⁴⁸.

3.2.2 GFAAS

In addition to using field kits to obtain the water samples' arsenic concentration, the samples were also tested using a more sensitive and sophisticated instrument, the GFAAS, upon returning to the US, in order to get a more accurate measurement. The GFAAS (Perkin and Elmer, model 4100ZL) at the Ralph M. Parsons Laboratory (Parsons lab) at MIT was used. This instrument is large, expensive and requires electricity and therefore it was not practical to transport to Nepal or to have in the field.

The GFAAS test method was the only one of the three used that is a US Environmental Protection Agency (USEPA) approved method for measuring arsenic in drinking water (Standard Method #3113B⁴⁹)⁵⁰. This is also the most accurate method of analysis of the three tests performed, with a detection limit of 5 ug/L.

Theory

Atomic adsorption spectrometry uses the principal that atoms excited above a water sample will absorb light at a characteristic wavelength when an optical beam is passed through them. The GFAAS uses a graphite furnace tube to heat a sample to volatilization so that arsenic atoms (regardless of form, organic or inorganic, and regardless of oxidation state) will rise into the headspace of the sample⁵¹. Then an optical beam is passed through the headspace and the absorption of the atoms is analyzed. Recording the absorption focused around the 193.7-

nanometer (nm) wavelength, specific to arsenic, the instrument will report the peak area. This peak area, or amount of light absorbed, can be linearly correlated to the amount of arsenic present in the sample by comparing it to peak areas of standards.

Procedure

Sixty-five water samples, including those from most tests conducted in Parasi, were brought back to the Parsons lab at MIT. In Parasi, Nepal, source water samples were split; once water was decanted from them for either or both of the field tests it was also decanted into a 10mL plastic capped tube. Effluent from the removal technologies was poured directly into the tubes. To protect the collected samples during travel in Nepal and back to MIT, they were placed in a Styrofoam box. The samples were not preserved in Nepal due to the danger involved with traveling with highly concentrated acid.

Once at the Parson's lab, the samples were preserved with 34.7% HCl (11-12 molar) and heated so that any arsenic sorbed to iron hydroxides in the water would return to aqueous state. Iron hydroxides are not stable at the low pH that the HCl causes. The samples required preservation to 10% acidification⁵². Therefore, 1mL of HCl was added to each of the 10mL samples.

Before the samples could be analyzed, a standard calibration curve had to be determined. Since there are variances associated with the instrument, standards were run and a calibration curve was developed before and after the analysis of each set of samples. To make a standard calibration curve, the peak areas associated with seven standards ranging in concentration from 0 to 100 ug/L arsenic were analyzed. These standards, 0 ug/L (the blank), 5 ug/L, 10 ug/L, 25 ug/L, 50 ug/L, 75 ug/L, and 100 ug/L, were made in 5% nitric acid (HNO₃) by researchers at the Parsons lab. Once the peak area was found, a graph of concentration versus peak area for the standards was created. The slopes and y-intercepts of the calibration curves calculated before and after each sample group were averaged in order to get the equation and R² value associated with the average calibration curve. Those curves with R² values less than 0.95 were rejected and standards were rerun.

To do the analysis, the seven standards, ten samples, and two matrix modifiers were placed in the automatic sampler. The two matrix modifiers, magnesium nitrate (MgNO_3) and lead (Pb), were included in order to avoid interferences and correct for background concentrations. First, the standards were run, then the samples, and then the standards again. The matrix modifiers were included in the analysis of each sample. The GFAAS would record and report the peak areas of each sample. With this information, one can calculate an averaged equation for the calibration curve and fit the peak areas of the samples to this averaged curve to solve for the concentrations (see Appendix A for data on all samples tested with the GFAAS and see Appendix B for calibration information).

If the sample concentrations were found to be over 100 ug/L, they were diluted four, five, or eight times and reanalyzed. They were diluted with 5% HNO_3 since that was the solvent with which the standards were made.

4 Removal Technologies

Tests in the past several years have identified the presence of arsenic above WHO guidelines in groundwater from some tubewells used for drinking water in the Terai region of Nepal^{53,54,55,56}. Researchers have also discovered that long-term exposure to low levels of arsenic can cause adverse health effects (see Section 2.3). Due to these problems in Nepal and to the arsenic crisis in Bangladesh and in West Bengal, India, it is important that appropriate arsenic remediation technologies be developed so that those in danger of arsenic poisoning can have access to clean drinking water.

Researchers have heard the call and have responded to the arsenic problem by creating new technologies or modifying existing technologies to remove arsenic from drinking water. More importantly, some of these researchers are adapting these technologies to be effective in developing country village settings by using low cost, locally available materials to build point-of-use (POU) technologies, or by creating point-of-entry (POE) systems that can be used by entire communities.

This chapter will introduce some of the proposed treatment processes for POU and POE systems which can be used to remove arsenic from tubewell water, since the most common sources of water in Nepal, Bangladesh and West Bengal, India are tubewells^{57,58}. Also, this chapter will discuss the theory and set-up of the technologies as well as the reuse potential, cost and availability of materials for the three removal technologies evaluated in Nepal; the Three-Gagri System, the Jerry Can System and the Arsenic Treatment Unit (ATU), evaluated in Nepal.

4.1 Possible Removal Processes

There are eight general categories of treatment processes used for arsenic removal from tubewell water. These categories are oxidation, precipitation, coagulation, sedimentation, filtration, adsorption, ion exchange, and membrane separation.

Oxidation is a reaction involving the loss of an electron by an atom, which can come about with the addition of oxygen to a compound⁵⁹. Supplying oxygen to, or aerating, water with arsenic oxidizes the arsenic and iron that co-occurs, resulting in the formation of precipitate. Therefore, passive precipitation occurs when naturally occurring iron is in solution with arsenic in the presence of oxygen. Precipitation, in this case, is the process by which dissolved ions in solution form an insoluble solid due to a chemical reaction. Coagulation is similar to precipitation in that it converts soluble arsenic into insoluble reaction products, but it is different in that it encompasses all reactions, mechanisms and results in the overall process of particle growth and particle aggregation. This is a chemical process that involves the addition of a chemical coagulant such as alum or ferric sulfate to the arsenic-water⁶⁰.

The resulting aggregated precipitate or particle (also called *floc*) can be removed from the water column by sedimentation and/or filtration. Sedimentation is a physical process. It is the gravity separation of solids from liquid by settling. Filtration is a physical process by which solids are separated from liquid by passing the mixture through a medium which retains the solid on its surface and allows the water to pass through.

Adsorption is the general term for a mass transfer, chemical partitioning process in which a chemical sticks to the two-dimensional surface of a solid and becomes bound by chemical or physical forces⁶¹. Arsenic is adsorbed onto the surface of granular materials, clays and processed cellulosic materials such as activated carbon, oxides, clay minerals, and sawdust⁶². Ion exchange is a specific type of adsorption process by which ionic substances can sorb onto solids. Ion exchangers have a structure containing an excess of fixed negative or positive charge. These solids take up ions as needed to neutralize the charge. Clays can commonly have an excess of negative charge and may take up, or adsorb, arsenic cations from the water⁶³.

Membrane separation is a physical process and uses semi-permeable membranes that are selectively permeable to water and certain solutes but can retain certain dissolved solids, including arsenic⁶⁴.

The three arsenic removal technologies that were evaluated in Nepal used one or a combination of several of the above processes. The Three-Gagri System works by combining the processes of oxidation, precipitation, adsorption, and filtration; the Jerry Can System uses the processes of precipitation, adsorption and sedimentation; and the ATU combines adsorption and filtration.

4.2 Three-Gagri System

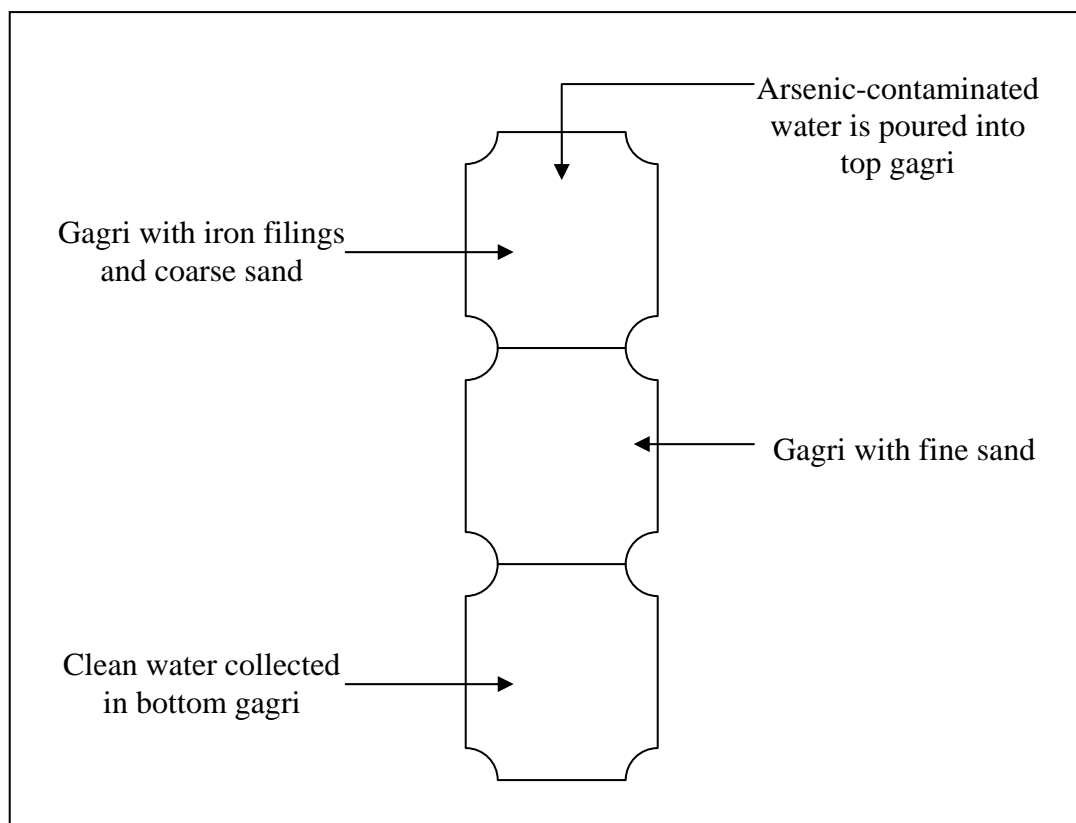
The Three-Gagri System is a variation of the Three-Kalshi System, a traditional water purification method used in Bangladesh and adapted there for arsenic removal. Khan, et al. has shown that the Three-Kalshi System is effective at removing arsenic from water⁶⁵. The theory behind the success of the Three-Gagri System is the same as that behind the success of the three-kalshi; the systems remove arsenic by adsorption, precipitation and filtration, and the set-up of the Three-Gagri System varies only slightly.

4.2.1 Theory

In the Three-Gagri System, arsenic is removed from influent water by iron species via precipitation and adsorption⁶⁶. The precipitate or sorbed solid is then filtered out of the effluent water. The system takes advantage of these processes by incorporating iron filings and sand into its design.

The Three-Gagri System consists of three pitchers stacked on top of each other. Known locally as *kalshis* in Bangladesh, the pitchers are called *gagris* in Nepal. The top gagri contains coarse sand and iron filings, the middle gagri contains fine sand and the bottom gagri is used as a collection pitcher (see Figure 4.1). There is a hole in the bottom of the top and middle gagri, which is covered by a cloth, so that water poured into the top gagri will percolate and be filtered down to the bottom gagri.

Figure 4.1: Schematic of Three-Gagri System



As mentioned, the arsenic in the water poured into the system will be removed by iron species. The iron filings in the top gagri provides these iron species. Since the system is aerobic, meaning oxygen is present, hydroxide species form on the metallic iron. These hydroxide species can function as adsorption sites for anions of arsenate and arsenite at neutral pH. Since the influent to the Three-Gagri System had a pH of about seven this could be one removal technique that the Three-Gagri System used.

The iron filings can also provide a constant input of soluble iron in the water which can aid in the removal of arsenic from the influent water. Elemental iron will oxidize to ferrous iron (Fe (II)) in the presence of oxygen. Fe (II) in contact with air will then oxidize to Fe (III) and precipitate as iron oxyhydroxide ($\text{Fe}(\text{OH})_3$), hydrous ferric oxide (HFO), etc. (Khan, et al., 2000). The solid $\text{Fe}(\text{OH})_3$ can sorb arsenic and the suspended particle can be removed from the water column by settling⁶⁷. The settled particles are prevented from flowing through the system into the bottom

gagri by the sand layers and cloth layers. Also, in the presence of zero-valent iron in the filings, manganese (II) (Mn^{2+}) in the groundwater, and manganese oxyhydroxides (MnO_2) in the sand, arsenite can be catalytically oxidized to arsenate in the media. Both the oxidation of arsenite and the formation of HFO provide for the precipitation of colloidal HFO particles since arsenate is known to bind to HFO during slow percolation processes⁶⁸. This process allows arsenic free water to flow into the bottom gagri since the colloidal HFO particles cannot filter through the fine sand in the middle gagri. Finally, arsenate anions bound to HFO can form common naturally occurring arsenate minerals such as Scorodite ($FeAsO_4 \cdot 2H_2O$) and Symplectite ($FeHASO_4 \cdot 8H_2O$) as the dominant solid phase, which will also settle and be trapped by the sand or cloth, allowing clean water to filter into the bottom gagri.

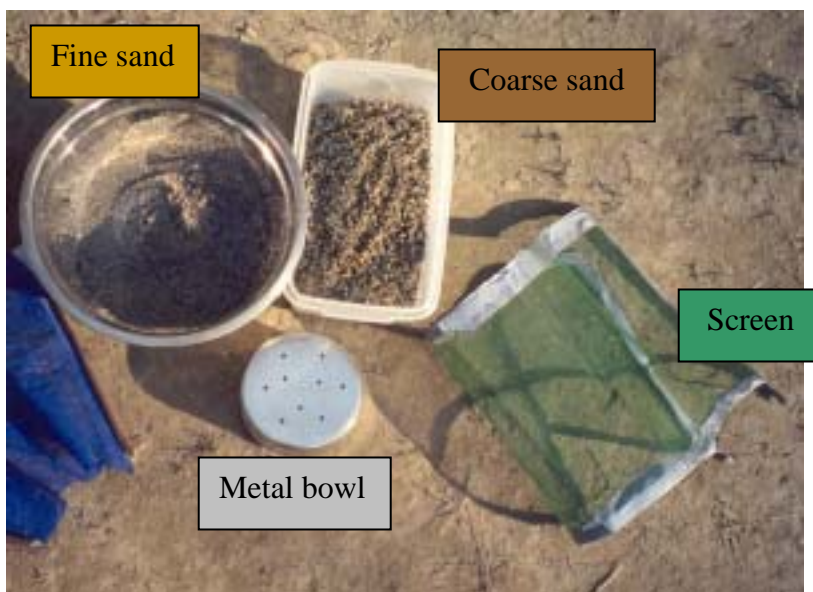
4.2.2 Set-Up

While in Parasi, the author assembled a Three-Gagri System. As previously mentioned, this system consists of three gagris stacked on top of each other. Gagris typically hold 14-18 liters of water and are made of various materials – ceramic, plastic, copper, and often, aluminum. Three aluminum gagris were obtained locally, cleaned with soap and rinsed with boiled water before use. The top and middle gagris needed a 0.5cm hole drilled in the bottom and had to be covered by a cloth. The hole was made with a hand powered drill and Tibetan prayer flags, widely available in Nepal, were chosen as the cloth to put over the holes because their coarse weave allows water to pass easily through them.

In the design tested in Nepal, the top gagri contained 3kg iron filings on top of 2kg coarse sand and the middle gagri contained 2kg fine sand. The -8+50 mesh, zero-valent iron filings were donated by Connelly-GPM, Chicago, Illinois, and brought from the United States to Nepal. The sand was obtained in Nepal from a river and sieved, with a locally obtained screen, into fine and coarse grades. The sand was sieved through the screen once to obtain fine and medium sand, i.e. that which passed through the screen, and coarse sand and rocks, i.e. that which was retained on the screen. To separate the coarse sand from the rocks, that media which was retained on the screen was sieved again through a metal bowl which had 0.5 cm holes drilled in it with the hand powered drill, retaining the rocks and passing the coarse sand. The fine sand was separated from

the medium sand by again sieving it through the screen; this time the screen was folded into three sections in order to trap more sand particles. Sand passing through the folded screen was designated as fine. Though this is not the most accurate way to separate coarse and fine sand, defined as 2.0-0.6mm and 0.2-0.06mm in diameter respectively⁶⁹, it was the best way the author could accomplish the separation with the materials she could find locally (see Figure 4.2). To wash the sand, it was rinsed repeatedly with non-arsenic contaminated water until the rinse water appeared clean. It was then boiled for fifteen minutes to remove any bacterial contamination. The filings, like the sand, were also rinsed and boiled before being placed in the top gagri.

Figure 4.2: Sand and the materials used to sieve it



Once assembled, arsenic-contaminated water was slowly poured into the top gagri being careful not to disturb the media. As it passed through the system, arsenic was removed from the water by the mechanisms described in Section 4.2.1. The coarse sand, and later the fine sand, acted as a filter to prevent the precipitate from flowing through the middle gagri, which allowed clean water to flow into the bottom gagri. See Chapter 5 for results from the nine runs and see Chapter 6 for a discussion of the appropriateness and effectiveness of the Three-Gagri System.

4.2.3 Reuse Potential

In the paper published by Khan, et al., which describes the Three-Kalshi System tested in Bangladesh, the daily capacity of the Three-Kalshi or Three-Gagri System should vary between 42 and 148 L/day⁷⁰ or 1.75 – 6.2 L/hour. In a subsequent paper by Khan et al. (a one year critical evaluation of the filter system), the system is said to be suitable for five people for five months at a capacity of fifty liters per day⁷¹. When the author used the Three-Gagri System in Parasi, each run of approximately ten liters took an average of two and a half hours, meaning the system had a daily capacity of about 96 L or a flowrate of about 4 L/day. Unfortunately, the system slowed down with the addition of each new batch of water; the first run took about an hour and a half and it took longer for each successive run.

Using laboratory data with real groundwater, Khan et al. found that the breakthrough capacity of the Three-Kalshi or Three-Gagri System was 7000 liters. They found that once 7000 liters of water with an average arsenic content of 500 ug/L was treated, breakthrough was to 60 ug/L. Once the system is close to breakthrough, one should regenerate the system by replacing the top sand layers of both gagris⁷². It was found that there was very low leaching of sand at a pH of 4 and 7 in deionized and rainwater⁷³.

4.2.4 Cost and Availablitiy

The system cost the author US\$10.50 (Rs 756 - Rupees, Nepali currency), the cost of three gagris and the screen, to build. If one could find cheaper water pitchers, the price of the system would be greatly reduced. The gagris were readily available in the larger towns, where other goods were sold, in the Terai region. Connelly-GPM iron costs about US\$7 (Rs 504) per ton⁷⁴ but would have to be shipped to Nepal, which would add to the price, since Connelly GPM, Inc. is located in the US. Iron filings might be able to be obtained from local foundries in some areas⁷⁵. It has also been suggested that iron nails could be cut up and used in the system instead of iron filings⁷⁶. Iron nails and the tools to chop them are available in Nepal. Three kg of nails cost about US\$3 (Rs 216) and the nail cutting tool cost about US\$1.50 (Rs 108). There are

problems with using nails as opposed to filings. The smaller surface area of the nails is less efficient and there is much labor involved in cutting the nails into small pieces, also one must be sure not to use galvanized (containing zinc) iron nails or alloy materials⁷⁷. Finally, clogging can significantly slow the flow rate. To make an evaluation of its efficiency, a Three-Gagri System was set up using iron nails instead of filings (see Section 5.3). This system took much longer (over eight hours) to process the influent ten liters, giving a flowrate of 1.25 L/hour.

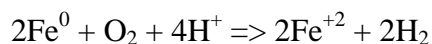
4.3 Jerry Can System

The Jerry Can system is a point-of-use arsenic removal technology that was developed at the University of Colorado at Denver. It, like the Three-Gagri System, uses zero-valent iron. Instead of filtering the water, the Jerry Can System uses a sorption-decantation method which combines the processes of adsorption, precipitation and sedimentation.

4.3.1 Theory

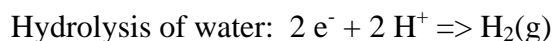
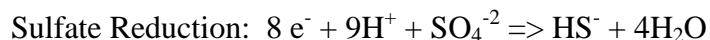
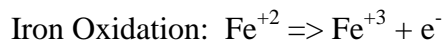
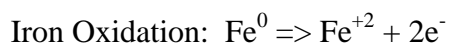
The sorption-decantation method involves putting water in contact with iron filings, forming a precipitate and then decanting the clean effluent, leaving the arsenic-sorbed iron species behind. This sequence takes place in a 10L jug with no headspace. Researchers at the University of Colorado suggested that the water be in contact with the iron for forty-five minutes to three hours depending on the amount of mixing. If the jug were shaken frequently, as would be the case for water being carried long distances from a well, less contact time would be required than for a jug that just sits still.

It was also suggested by the researchers that adding sulfate to the water would enhance the arsenic removal⁷⁸. This process can be demonstrated by the following reactions:

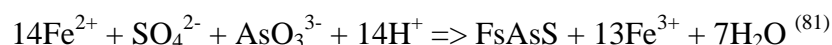


This reaction will utilize the oxygen in the system.

When the solution becomes anaerobic (no oxygen is present), iron oxidation will be coupled with the hydrolysis of the water and the arsenate and sulfate reduction will be as follows:



The products of these reactions can later form precipitates that can include the formation of $\text{Fe}(\text{OH})_3$, FeAsO_4 , FeAsS and arsenic sulfide precipitates⁷⁹. A hypothesis is that arsenopyrite (FeAsS) forms much faster than co-precipitation with iron hydroxides so the sulfate is needed to speed up the arsenic removal process⁸⁰. The equation for the formation of arsenopyrite is as follows:



Also, since we want to be able to reuse the residue in the jerry can, precipitation in the form of arsenopyrite is desired since it is a stable mineral.

4.3.2 Set-Up

Jerry cans come in a variety of sizes, but for our purposes, a jerry can is a 10L plastic jug that, in India, is commonly used for tubewell water collection⁸². Although nothing called a jerry can could be found in Nepal, a 10L plastic jug that looked as if it may have been intended for gasoline or kerosene collection (since it was sold at the same location the fuel was being sold) was substituted.

A packet with 6.25g of zero-valent iron (the same Connelly iron used in the Three-Gagri System) was added to the jug and then 10L of arsenic-contaminated water was pumped from the well into the jug leaving no headspace and creating an iron concentration of 625 mg/L, as was instructed by the “Fact Sheet” filled out by Ramaswami⁸³. To test the system, the jug was shaken for forty-

five minutes in one experiment as well as being left undisturbed for three hours in two additional experiments. See Chapter 5 for results from the three tests and see Chapter 6 for a discussion of the appropriateness and effectiveness of the Jerry Can System.

4.3.3 Reuse Potential

The literature describing the Jerry Can System suggests that the iron residue can be reused up to one hundred times before it has to be replaced. Since each batch treats ten liters, this would mean that at least 1,000 liters of water could be treated before replacement was required. Once 1,000 liters have been treated, the 6.25 grams of iron filings must be replaced.

4.3.4 Cost and Availability

Literature states that jerry cans are widely available at a minimal cost (US\$0.50) in India⁸⁴ and the author's observation was similar in Nepal. As mentioned, nothing called a jerry can could be found in Nepal, but the 10L plastic jugs intended for gasoline or kerosene collection were available almost everywhere fuel was being sold. The cost and availability of iron for the Jerry Can System is the same as that for the Three-Gagri System except that there is no data to suggest that iron nails could be substituted for filings in the jerry can. Finally, gypsum is available in the Indian state of Uttar Pradesh, directly south of the Terai region in Nepal⁸⁵. Information was not available as to the cost of this mineral.

4.4 The Arsenic Treatment Unit

While the Three-Gagri and Jerry Can Systems are household-size, POU treatment systems, the Apyron Technology, Inc. (ATI) system is a POE system, meant to be used by an entire community. ATI's system is directly attached to a tubewell and can deliver arsenic free water at flow rates comparable to that of the unaltered well, about 810 L/hour⁸⁶.

4.4.1 Theory

The Arsenic Treatment Unit (ATU) operates according to the theories of adsorption and filtration and is composed of aqua-bind™, an inorganic granular metal-oxide based media. This media can selectively bind As (III) and As (V). It consists of highly activated hybrid aluminas and alumina composites. These materials have enhanced pore and surface properties for effective removal of arsenic, even in the presence of competing ions⁸⁷.

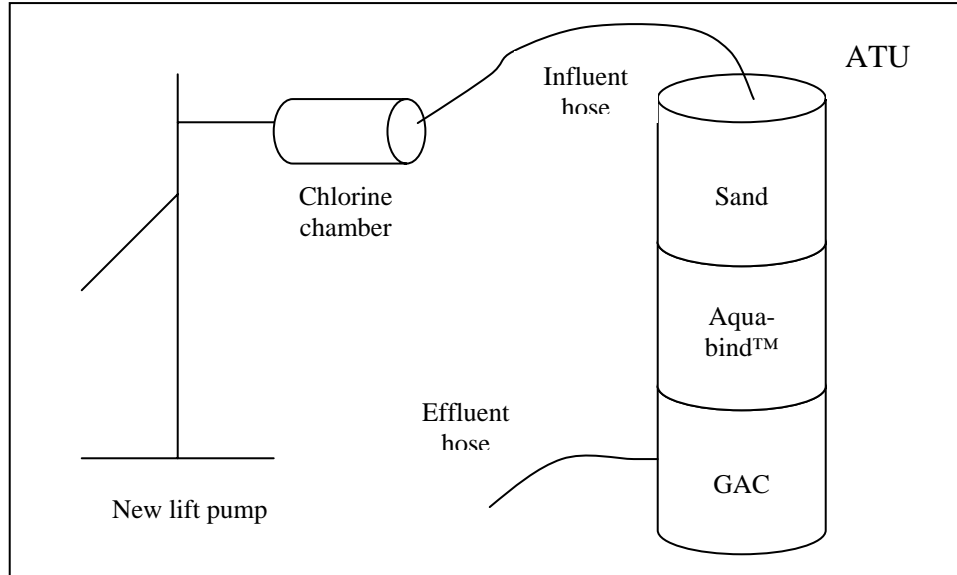
In addition to the aqua-bind™ media, the ATU also includes a chlorine tablet chamber to remove organic impurities, a layer of sand to remove large particles from the influent water, and a layer of granular activated carbon (GAC) to improve the taste of the effluent water.

4.4.2 Set-Up

Apyron Technologies, Inc. donated an ATU to MIT for use in Nepal, which was in turn donated to a local Nepali NGO, Environment and Public Health Organization (ENPHO). From the US, we took a lift pump and the ATU for installation in Parasi. Gravity pumps are often used in Nepal for tubewells, but a lift pump must be used with the ATU because both pressure and water elevation head are requirements for the ATU to function as desired⁸⁸.

The first step in the set-up was to remove the existing gravity pump and replace it with the new lift pump. Then the chamber that contained the chlorine tablets was attached to the well. An influent hose was attached to the chamber and led to the lid of the ATU. The ATU is a one-foot diameter, three-feet tall column containing sand, aqua-bind™ media and GAC (see Figure 4.3).

Figure 4.3: Schematic of lift pump and ATU



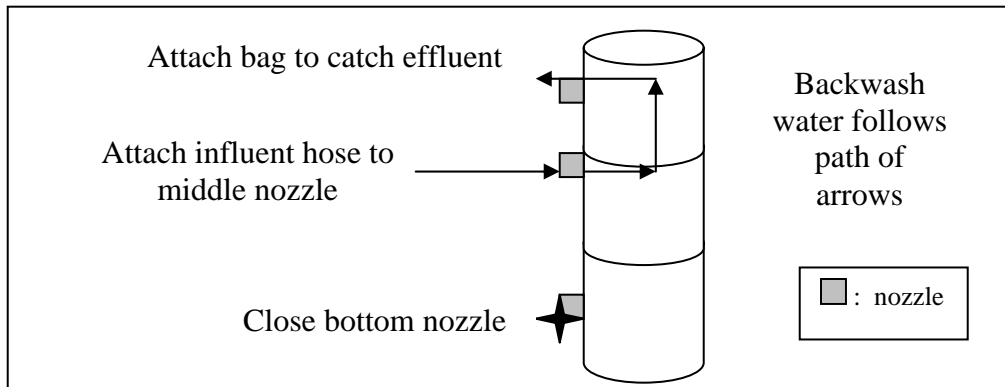
To assemble the ATU, one-gallon volume of GAC was put into the column. Then four gallons of aqua-bind™ media were poured on top of the GAC. A plastic grate and a foam disc were then placed on top of the media. Finally, three gallons of sand were placed on top of the foam disc and a diffuser plate and the lid were secured onto the column. At the bottom of the column, the effluent hose was attached⁸⁹.

Water pumped from the well is first disinfected by the chlorine tablets. The influent hose then takes the water to the ATU column and the filtering/adsorption process begins. First the water encounters the diffuser plate, which ensures that the large influx of water does not disturb the underlying media, and is spread evenly over a layer of sand. This sand layer removes any big particles that the influent water may contain. From there, the water passes through the foam pad to trap any sand and particles before reaching the aqua-bind™ media. While passing through the aqua-bind™ layer, the arsenic in the water is selectively bound to the media and removed from the aqueous phase. Lastly, the water reaches the GAC layer and any remaining organics and the chlorine taste in the water are removed. After being filtered by one last foam pad, the water is dispensed from the hose. See Chapter 5 for results of the analysis and see Chapter 6 for a discussion of the appropriateness and effectiveness of the ATU.

4.4.3 Reuse Potential

The “Fact Sheet” on the ATU provided by Rich Cavagnaro, a Vice President of Apyron Technologies, Inc., states that the ATU can treat as much as 3,500 liters of water per day, or 810 L/hour, with influent water containing an arsenic concentration of about 250 ug/L⁹⁰. In order to keep the system running at its full potential, the ATU should be backwashed every two weeks to prevent clogging. To backwash, the hose providing the influent should be moved from the top nozzle to the middle nozzle, a collection bag should go on the top/side nozzle and the bottom nozzle should be closed. When the well is pumped, water will go up through the sand layer and out the top nozzle to the bag (see Figure 4.4). The aqua-bind media should be replaced about every six months. Due to its aggressive binding characteristics, the spent media is designated as non-hazardous per USEPA Toxic Characteristics Leaching Procedures (TCLP) and can be disposed of via landfills⁹¹.

Figure 4.4: Backwash schematic



4.4.4 Cost and Availability

The cost of the system is US\$2,000 with a five-year guarantee. The media change is expected to cost between US\$200 and US\$400 per year depending on arsenic concentration. This system is only available through Apyron Technologies, Inc., a company based in Atlanta, Georgia.

5 Results

This chapter will provide the results of the comparison of the three testing methods and of the efficiency of the three arsenic removal technologies. It will also present the data on seven water sources in Parasi, Nepal that were tested for arsenic contamination.

5.1 Comparison of Testing Methods

Three different test methods were used to analyze water samples from Parasi; EM Quant® test strips, Arsenic Check™ and GFAAS. As mentioned, each has a different detection limit, that with the lowest detection limit (GFAAS) being the most precise, that with the highest (EM Quant®) being the least. Because of this and the fact that the GFAAS is a USEPA approved method (Standard Method #3113B⁹²), the author has assumed that the GFAAS is the most precise method of testing used. Therefore the accuracy of the field test kits shall be judged based on how their results compare with the results from the GFAAS.

Due to time constraints in Nepal, not all samples tested on the GFAAS in the Parsons Lab at MIT in spring of 2001 were tested with the field kits in Nepal in January 2001. Therefore, the thirteen samples tested with both the EM Quant® test strips and the GFAAS are used to determine the performance of the EM Quant® test strips and the twenty-six samples tested with both the Arsenic Check™ and GFAAS are used to determine the performance of Arsenic Check™. Tables 5.1 and 5.2 show comparisons of the EM Quant® test strip results and Arsenic Check™ results, respectively, with those of the GFAAS.

Table 5.1: Comparison of EM Quant® results and GFAAS results (Conc in ug/L)

<i>Sample Number</i>	<i>EM Quant® results</i>	<i>GFAAS results</i>	<i>Correlation</i>
1	0-100	81	Yes
2	0-100	84	Yes
4	100-500	183	Yes
5	100-500	223	Yes
7	0	24	No
16	100-500	192	Yes
17	0-100	26	Yes

18	0-100	59	Yes
19	0-100	62	Yes
20	100-500	186	Yes
21	100-500	186	Yes
22	0	11	No
24	0-100	29	Yes

As seen in Table 5.1, the EM Quant® test strips were fairly accurate with an 85% correlation with the GFAAS results (11 matches out of 13). It did give two false negatives for sample numbers 7 and 22, which is a slight problem since those samples have arsenic concentrations above the WHO guideline and according to EM Quant® results water from those sources was free from arsenic contamination.

Table 5.2: Comparison of Arsenic Check™ results and GFAAS results (Conc in ug/L)

<i>Sample Number</i>	<i>As Check™ results</i>	<i>GFAAS results</i>	<i>Correlation</i>
3	20-50	70	No
4	100-250	183	Yes
5	100-250	223	Yes
6	50-100	72	Yes
12	0-20	6	Yes
13	0-20	3	Yes
14	0-20	10	Yes
15	100-250	209	Yes
16	100-250	192	Yes
17	0-20	26	No
18	50-100	59	Yes
19	50-100	62	Yes
22	0-20	11	Yes
24	0-20	29	No
25	0-20	3	Yes
26	100-250	242	Yes
29	50-100	64	Yes
34	0-20	0	No
36	50-100	64	Yes
37	0-20	0	No
40	0-20	0	No
41	100-250	252	No
43	100-250	266	No
44	0-20	4	Yes
45	100-250	260	No
46	0-20	9	Yes

Table 5.3: Non-correlation results for Arsenic Check™

<i>Sample Number</i>	<i>As Check™ results</i>	<i>GFAAS results</i>
3	20-50	70
17	0-20	26
24	0-20	29
34	0-20	29
37	0-20	0
40	0-20	0
41	100-250	252
43	100-250	266
45	100-250	260

Arsenic Check™ also gave fairly accurate results, as seen in Table 5.2, because even though it only had a 65% correlation (17 matches out of 26 samples), the Arsenic Check™ results were only slightly off when they did not match the GFAAS results (see Table 5.3). Arsenic Check™ arguably gave three false positives and the other six times that the results of the two tests did not match, Arsenic Check™ gave results slightly

lower than the actual, GFAAS, results. The three false positives are arguable because the detection limit for this test is 20 ug/L, so any result less than 20 ug/L can be classified as “below detection limit.” Since there was a color change on the mercuric bromide pad from its original white to a pale yellow, defined as 0-20 ug/L in the kit, the author understood this to mean that arsine gas must have been generated from arsenic in the water sample in order to cause the reaction that caused the color change.

Both the EM Quant® and Arsenic Check™ tests were easier to use than the GFAAS. Using the GFAAS required training and it took many steps to complete the analysis. The Arsenic Check™ test that was not pre-made was slightly more complex to prepare than the EM Quant® test strips since three chemicals must be added and a certain amount of time had to pass between each chemical addition.

In terms of the tester’s health, the Arsenic Check™ test was safer to perform than the EM Quant® test. First of all, Arsenic Check™ used tartaric acid, which is less corrosive and less dangerous to handle than hydrochloric acid, which the EM Quant® test used. Second, the Arsenic Check™ reaction cap was better designed. With the design of the EM Quant® Gutzeit tube’s cap, arsine gas, which is highly toxic, was allowed to escape through the cap as the test strip did not fully block the slit. The Arsenic Check™ reaction cap, on the other hand, corrected that danger. In this design, the spout into which the test strip was inserted could be closed, preventing the gas from escaping.

The testing methods also differ in their cost. The list price of the EM Quant® kit is US\$73.15 for 100 tests⁹³. The Arsenic Check™ kit, which had barely hit the market at the time we took it to Nepal, has a list price of approximately US\$125 per 100 tests⁹⁴. Although Arsenic Check™ costs more, Industrial Test Systems, Inc. (the company that produces Arsenic Check™) will sell the reagents to the kit separately. EM Science, producers of EM Quant® test kit, does not sell the reagents separately and it is suggested that the plastic case for the kit is at least 20% of its total cost⁹⁵. The GFAAS has a very high capital cost and it costs between US\$15 and US\$50 to run each batch of samples and standards⁹⁶.

Since the GFAAS was the most accurate of the three tests, water sample concentrations will be presented using the GFAAS results for the remainder of this document.

5.2 Data on the Water Sources Tested

As mentioned in Section 3.1, samples from seven water sources in Parasi, Nepal were taken back to MIT to be analyzed on the GFAAS. This section will provide information on the arsenic concentration and the pH of the water in the source and the depth and age of the source, when available.

Figure 5.1: Approximate relative locations of water sources

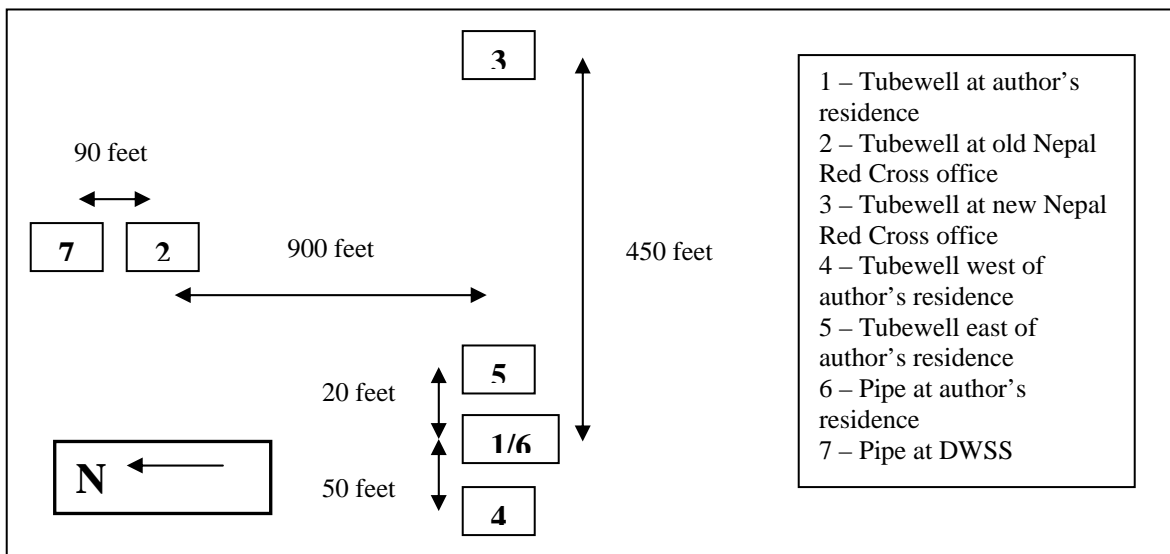


Figure 5.1 shows the approximate locations of the water sources that were tested with the GFAAS. This figure also shows the relative distances between the sources. Please note that the figure is not to scale and only represents approximate distances.

Table 5.4: Arsenic concentration from source 1

<i>Sample #</i>	<i>Conc (ug/L)</i>		
4	183	The most important of the sources analyzed was the tubewell located behind the house that the author stayed at in Parasi (see Figure 5.1, source1). It is located at North, 27 degrees and 31.930 minutes and East, 83 degrees and 39.725 minutes. This was the most important source because it was the one from which all of the influent water to the three technologies came. This source was used because it had water with a relatively high arsenic concentration (see Table 5.4) and was located close to the technologies.	
5	223		
8	175		
9	195		
10	189		
11	241		
15	209		
16	192		
20	186		
26	242		
31	263		This tubewell was 65 feet deep and was about twenty-eight years old. The pH of the water was between 7.0 and 8.0.
33	212		
35	244		
41	252		Fifteen samples were taken from this tubewell and analyzed with the GFAAS to obtain an average arsenic concentration of 215 ug/L.
42	217		

Table 5.5: Arsenic concentration from source 2

<i>Sample #</i>	<i>Conc (ug/L)</i>	
1	81	The reason why the people at the Kathmandu-based NGOs, ENPHO, Nepal Red Cross, and Japan Red Cross, who had previously engaged in arsenic testing in various Terai districts, thought that the author should go to Parasi to evaluate the three technologies was because a past study had determined that the tubewell located at the old Nepal Red Cross office in Parasi
2	84	
3	70	
6	72	
19	62	

(see Figure 5.1, source 2) had an elevated arsenic concentration and it was thought that water from it would be suitable as influent to the arsenic treatment technologies. With an average arsenic concentration of 74 ug/L (see Table 5.5), the water from this tubewell did not provide enough arsenic contamination to get meaningful results for the removal efficiency of the technologies.

This tubewell was eleven years old and was between 70 and 80 feet deep. The pH of the water from this tubewell was also between 7.0 and 8.0.

Table 5.6: Arsenic concentration from source 3

<i>Sample #</i>	<i>Conc (ug/L)</i>	
18	59	The tubewell at the new Red Cross office (see Figure 5.1, source 3) was also tested for arsenic contamination. The two samples taken from this source show that water from this tubewell had an average arsenic concentration of 62 ug/L (see Table 5.6). This tubewell was two years old and was about 65 feet deep.
36	64	

Table 5.7: Arsenic concentration from source 4

<i>Sample #</i>	<i>Conc (ug/L)</i>	
29	45	Water from the tubewell west of the author’s residence (see Figure 5.1, source 4) was analyzed for arsenic contamination to see if there was an arsenic “hot spot” near the author’s residence. The average concentration of this water was 46 ug/L (see Table 5.7). It was difficult to communicate with the owners of the house behind which the tubewell was located because they did not speak English, so it was hard to find out how old and how deep the tubewell was. The author assumes (from local children who served as translators) that it was about 35 feet deep and it was more than twenty years old. The water from this source had a pH between 7.0 and 8.0.
38	47	

Table 5.8: Arsenic concentration from source 5

<i>Sample #</i>	<i>Conc (ug/L)</i>	
37	0	Looking again for the arsenic “hot spot,” the water from the tubewell behind the house to the east of the author’s residence (see Figure 5.1, source 5) was analyzed and it was found that this water was free from arsenic (see Table 5.8).

This well was two years old and was 105 feet deep. The pH of this water was also between 7.0 and 8.0.

Table 5.9: Arsenic concentration from source 6

<i>Sample #</i>	<i>Conc (ug/L)</i>
7	24
24	29

There was a pipe that offered municipally supplied water in front of the house in which the author was staying. Even though it was supplied by an aquifer over 700 feet deep, it still contained water with an average arsenic concentration of 27 ug/L (see Table 5.9). This water had a pH of 7.0. Data on the source's age is unknown.

Table 5.10: Arsenic concentration from source 7

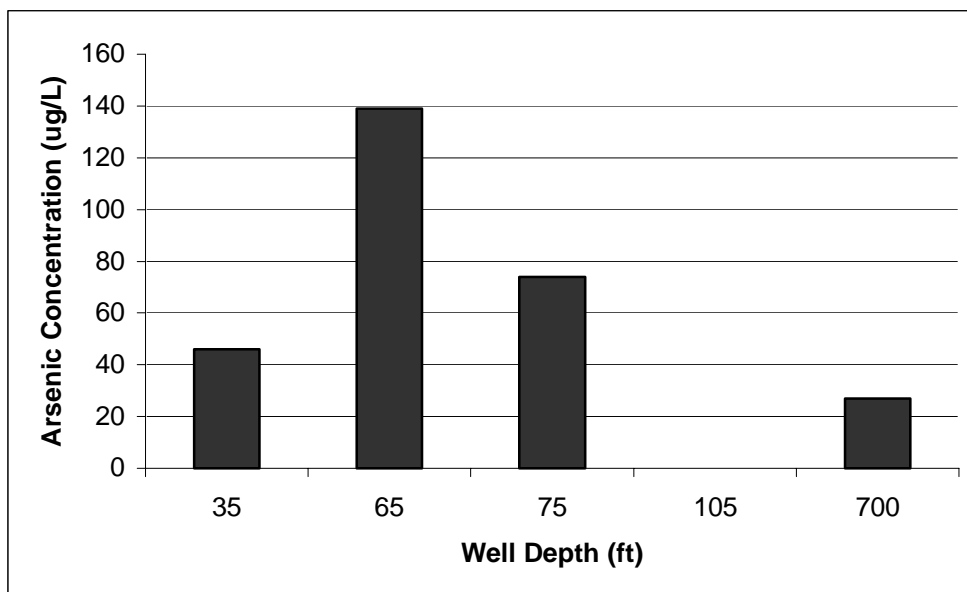
<i>Sample #</i>	<i>Conc (ug/L)</i>
17	26

The Department of Water Supply and Sewerage (see Figure 5.1, source 7) had a tap at its office that took water from 700 feet deep, the same water that was piped to the front of the house in which the author stayed. It can be seen from Table 5.10 that this water had the same arsenic concentration as the piped water collected in front of the author's residence, which is a good cross-check of these results.

A correlation between the age of the tubewell and presence or absence of arsenic contamination was not found. Both the oldest and the newest tubewells were found to contain arsenic.

A correlation between depth and arsenic contamination, on the other hand, was noticed (see Figure 5.2). Note that Figure 5.2 shows average concentration for average depths. The four tubewells at a depth less than eighty feet contained water with arsenic above the WHO guideline and the one deeper tubewell, at 105 feet, showed no trace of arsenic. Since only five sources were tested, no conclusion can be made about the location of arsenic in the subsurface, but it can be speculated that the arsenic exists somewhere between thirty and eighty feet and does not exist around 105 feet.

Figure 5.2: Relationship between tubewell depth and arsenic concentration



Surprisingly, arsenic contamination was also found at depths of 700 feet. Deep aquifers are generally considered to be arsenic-free⁹⁷ and digging deeper wells has often been suggested as a remediation alternative⁹⁸⁹⁹. On the contrary, other deep tubewells have been found to contain levels of arsenic above the WHO guideline. 2,146 tubewells, ranging from 330 feet to 1,476 feet deep, from six out of the nine arsenic affected districts in West Bengal were tested for arsenic contamination in a recent study. 22.3% of those samples were found to have arsenic concentrations greater than 10 ug/L and 9.9% of samples had concentrations above 50 ug/L¹⁰⁰.

5.3 Effectiveness of Removal Technologies

The influent water to the three arsenic removal technologies evaluated in Nepal came from the tubewell located behind the house that the author stayed at while in Parasi. Fifteen samples collected and analyzed by the author from this tubewell to get an average concentration of 215 ug/L arsenic in the water, see Section 5.2, Table 5.4. In some instances, samples of influent water were not taken before the water was run through a technology. In those cases, the average concentration of 215 ug/L is given in lieu of an actual influent concentration. Tests on the Three-Gagri and Jerry Can Systems were run and the average tubewell water concentration was calculated from samples taken before the gravity pump on the tubewell was replaced with a new lift pump for use with the ATU (see Section 4.4.2).

5.3.1 Three-Gagri System

Table 5.11: GFAAS results of Three-Gagri System's effluent

<i>Run #</i>	<i>Conc in (ug/L)</i>	<i>Conc out (ug/L)</i>
1	215*	11
2	215*	3
3	242	6
4	215*	3
5	263	3
6	212	0
7	244	0
8	215*	0
9	252	8

While in Nepal, nine batches of arsenic-contaminated water from the tubewell behind the author's Parasi residence were run through the Three-Gagri System. Approximately ten liters of water with an average arsenic concentration of 215 ug/L were added each time yielding an effluent with an average concentration of 4 ug/L. Each run took an average of two and a half hours, giving an average flowrate of 4L/hour. See Table 5.11 for the results of the nine runs.

* Indicates that influent sample was not taken so average concentration is given

The Three-Gagri System was a success. Except for the first run, this system removed arsenic contamination to below the WHO guideline of 10 ug/L.

As mentioned in Section 4.2.4, another Three-Gagri System was assembled using 3kg of locally purchased iron nails in place of the iron filings. The nails were left whole instead of being cut. Ten liters of water from the tubewell behind the house was run through the system to yield the results shown in Table 5.12.

Table 5.12: GFAAS results of effluent from Three-Gagri System with nails

<i>Run #</i>	<i>Conc in (ug/L)</i>	<i>Conc out (ug/L)</i>
1	215*	9

* Indicates that influent sample was not taken so average concentration is given

The system removed arsenic below the WHO guideline but the flowrate was very slow, it took over eight hours for the ten liters of water to filter, giving a flowrate of 1.25L/hour, which is considerably slower than the flowrate with the

filings. The slow flow may be due to hasty preparation of the sand. Due to time constraints, the sand used in this Three-Gagri System was not sieved well enough to obtain the proper grades.

5.3.2 Jerry Can System

Three batches of water were run through the Jerry Can System, using water from the previously mentioned tubewell. One test was run on the jerry can by shaking the jug for forty-five minutes and two were run by leaving the jug undisturbed for three hours, see Table 5.13, as was mentioned in Section 4.3.2.

Table 5.13: Results of effluent from Jerry Can System

<i>Time in jug</i>	<i>Conc in (ug/L)</i>	<i>Conc out (ug/L)</i>
3 hours	186	186
3 hours	215*	244
45 minutes	215*	260

* Indicates that influent sample was not taken so average concentration is given

Unfortunately, whether the water was in contact with the iron for 45 minutes with shaking or three hours left still, the system was not a success. Decanted water showed no decrease in concentration from the influent. The problem with the Jerry Can System may have been that sulfate was not

added. Not until after the author returned from Nepal and discussed the performance of the system with the aforementioned researchers at the University of Colorado was it understood that equimolar amounts of sulfate and arsenic reputedly needed to be in the jerry can in order to achieve arsenic removal.

5.3.3 Arsenic Treatment Unit

Table 5.14: GFAAS results of effluent from ATU

<i>Run #</i>	<i>Conc in (ug/L)</i>	<i>Conc out (ug/L)</i>
1	266	4
2	177	0
3	245	0
4	383	0
5	364	0
6	465	0
7	263	0
8	271	0
9	301	0
10	282	0

The ATU system was tested over ten consecutive days, and one influent and one effluent sample from each day were analyzed. Since we installed this system the day before we left Parasi, the author collected only the samples for the first day. For the nine days following, representatives from the Nepal Red Cross Society, who had been instructed on the proper method of sample collection, took samples and express mailed them to MIT so

that the author could analyze them with the GFAAS. The results from the ten runs are shown in Table 5.14. The ATU was a success because it removed arsenic to below the WHO guideline every time it was run.

The influent water to this system was the same as the influent to the other systems except that a new lift pump was installed for this system to replace the gravity pump. It can be seen that the influent concentrations are quite variable and this is due to the stronger suction applied to the aquifer by the new pump. The stronger suction may have allowed more particles or colloids, to which arsenic may have sorbed, to be introduced to the well; this effect was probably exaggerated by the fact that the filter in the pump was missing.

6 Conclusions and Recommendations

6.1 Testing Methods

Three different methods were used to test the arsenic concentration of the water samples from Parasi, Nepal. Two field test kits were used in Nepal in January 2001; EM Sciences EM Quant® and Industrial Technology, Inc.'s Arsenic Check™. A Graphite Furnace Atomic Adsorption Spectrometer (GFAAS), made by Perkin and Elmer, model 4100ZL, was used in the Parsons lab at MIT in spring of 2001. Because the detection limit for the GFAAS is lowest and because it is a USEPA approved method for testing the arsenic concentration in drinking water, this method was deemed the most accurate of the three tests. Therefore the arsenic concentrations of seven water sources in Parasi and of the influent and effluent concentrations to and from the three evaluated treatment technologies were determined from the results of the GFAAS. Unfortunately, the GFAAS is large (non-transportable), expensive, and requires electricity.

Since the use of the GFAAS is inappropriate in rural field sites in Nepal, it was important to compare and evaluate the two field test kits, EM Quant® and Arsenic Check™. The Arsenic Check™ kit had a lower detection limit than the EM Quant® test strips (20 ug/L compared to 100 ug/L) and is therefore more accurate. This test is also safer to use because it contains a less corrosive acid than the EM Quant® kit and its reaction cap prevents the user from being exposed to harmful arsine gas.

Results from both kits correlated well with the GFAAS results. The EM Quant results had a stronger correlation but gave two false negative results. The Arsenic Check™ results did not correlate as strongly but gave no false negatives and was never off by more than 20 ug/L.

Although it is more expensive to buy the first kit of Arsenic Check™ as compared to the EM Quant® kit, it might save the user money over the long term since Industrial Systems, Inc. offers replacement chemicals at a lower price than the price of a new kit.

Due to the lower detection limit and the safety provided by the Arsenic Check™ kit, it is recommended that Nepalis and future MIT Nepal Water Project members use this kit over the EM Quant® test strips.

6.2 Source Water in Parasi, Nepal

Some tubewell water in Parasi is contaminated with dangerous levels of arsenic as four of the five tubewells tested were shown to be contaminated above the WHO guideline. Tubewells at a depth of less than eighty feet showed arsenic contamination while the one at a depth of 105 feet did not. Since only five sources were tested, no conclusion can be made about the location of arsenic in the subsurface, but it can be speculated that the arsenic exists somewhere between thirty and eighty feet and does not exist around 105 feet.

Also, since water from 700 feet below the surface was found to be contaminated with arsenic, it is recommended that Parasi, Nepal not use deep tubewells as a remediation alternative until a more complete understanding of the subsurface is determined.

6.3 Removal Technologies

6.3.1 Three-Gagri System

As shown in Section 5.3.1, the Three-Gagri System was effective in removing arsenic from drinking water to below the 10 ug/L in eight out of nine runs, and to 11ug/L in the remaining run. The results gave an average removal rate of over 98%. The average flowrate for the system was 4L/hour.

Besides being effective, it is also an appropriate technology. The system has a simple design and was easily constructed. It has a relatively low cost of about US\$10.50. The materials necessary to assemble the system were obtained locally, with the exception of the iron filings. As mentioned, it is expected that zero valent iron filings, or turnings, could be obtained at a local foundry but this was not confirmed during the field site visit to Nepal. It was shown that iron nails could be obtained locally, replace the filings, and successfully remove arsenic below the WHO guideline; although this approach was also shown to result in a very low flowrate.

There are two drawbacks to this system. One of the drawbacks is that it has been known to become easily clogged. In Parasi, it was observed to take longer and longer for each batch of water to filter through. If the system becomes too clogged, it will not be able to provide an adequate supply of water to its users. Also, it is not known if this system encourages bacterial growth due to the water's long residence time. It has been suggested that wood charcoal be added to the middle gagri for the purpose of removing organic impurities¹⁰¹, but wood charcoal was not found in Parasi so it was left out of the design.

The results of the Three-Gagri System compared well with results found in recent literature about a study on the Three-Kalshi System but there were some differences. The Three-Gagri System proved to be more effective at removing arsenic than the results from the Three-Kalshi. While the Three-Gagri System removed arsenic to an average concentration of 4 ug/L (with an average influent concentration of 215 ug/L) in field tests in Parasi, Nepal in January 2001, the Three-Kalshi System had an average removal of 17 ug/L (with an average influent concentration of 90 ug/L)¹⁰². Since the testing for the Three-Kalshi System was done in Bangladesh, where the drinking water standard for arsenic in drinking water is set at 50 ug/L, the results for that system were satisfactory. Nepal, on the other hand, does not have drinking water quality standards, so we were aiming to remove arsenic to the WHO guideline. Also, there were differing results for flowrate as the Three-Gagri System flowed at 4L/hour and the Three-Kalshi System is reported to have flowed at an average of 5L/hour¹⁰³.

There are differences associated with building the system out of the aluminum ggris as opposed to the Bangladeshi kalshis, also known as *kolshis*. The kalshis used in the above study were fired, unglazed clay pitchers. These cost less than the aluminum ggris, US\$5-6 for three kalshis as opposed to US\$10.50 for three ggris. The clay also allows for continuous diffusion of air and water vapor through the porous ceramic kalshi¹⁰⁴. This provides a more oxidizing environment to allow for the complete conversion of zero valent iron to hydrous ferric oxide, the active component for arsenic removal in the Three-Gagri/Kalshi System.

6.3.2 Jerry Can System

The Jerry Can System set up in Parasi, Nepal was not effective at removing arsenic, as was shown in Section 5.3.2, Table 5.12. As was mentioned, this inefficiency might be due to the lack of sulfate in the water.

Unfortunately, even if this system was effective, it is not appropriate. Although it is inexpensive, it is not simple. According to the researchers the University of Colorado claim that in order for this system to work, sulfate, perhaps in the form of gypsum, in addition to iron filings would have to be added to the jerry can in an equimolar amount with the arsenic. This process would require that those using the Jerry Can System know exactly how much arsenic is in the water to be treated, calculate the molar concentration of arsenic, convert this number to a sulfate concentration and determine how much gypsum to add to the jerry can to obtain the correct sulfate content. This is a complex process, making the jerry can an inappropriate technology.

6.3.3 ATU

While the ATU was very effective, removing arsenic to below 5 ug/L in each of the ten runs, this technology does not meet the criteria for being an appropriate technology. First, it is not simple; it is composed of many parts and detailed instructions are need for its construction. Second, it cannot be assembled with locally available materials and Apyron Technologies, Inc. must

provide everything necessary for its construction. Last and most important is that it costs too much. It is not reasonable to think that Nepalis could afford to purchase this system.

6.3.4 Recommendations

Before any treatment technology is recommended for use in Nepal, several issues must be addressed. The Three-Gagri System is effective and appropriate but it is suspected that the system could clog easily. Since only nine batches of water were run through the system in Nepal, the author did not observe excessive clogging, but did notice that the flowrate slowed with each run. It is recommended that a similar system be constructed and that many more batches of water be run through the system to get an idea of the flowrate decrease with time. The user could then try and create more flow by poking holes in the cloth at the bottom of the gagri with a needle or develop new strategies to increase the flowrate. Also, the question of whether or not the system promotes bacterial growth needs to be addressed. It is recommended that field tests (with real local groundwater) be conducted and that several microbial tests be done on influent and effluent water to and from the system.

The Jerry Can System needs to be simplified in order for it to be appropriate. It is recommended that a simple method to determine gypsum addition be created, if sulfate indeed enhances arsenic removal. If the system's user could use a field test for arsenic that has a simple conversion from arsenic concentration to amount of gypsum addition, the Jerry Can System might be an appropriate treatment technology. Also, the availability of gypsum and the health consequences associated with ingestion of sulfate would have to be determined.

Finally, the ATU by Apyron Technologies, Inc. is a very effective technology that is inappropriate mainly due to its high cost and the inability to avoid these high costs, since no cheaper local material can replace the components of the ATU. It is recommended that grants be sought in order to implement this system.

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1 Appendix A