Nepal Water Project

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ABSTRACT

A group of five MIT MEng students, together with their project advisor, traveled to Nepal in January 2001 to evaluate six drinking-water treatment systems. Three treatment systems for microbial contamination were studied: the CerCor filtration system, BioSand water filter (BSF), and household solar disinfection (SODIS). Three arsenic remediation technologies were also studied: the three-gagri system, jerry can system, and Apyron Technologies' arsenic treatment unit (ATU). These technologies were evaluated based upon the twin concepts of effectiveness (ability to remove microbial or arsenic contamination) and appropriateness (simple design, easily produced, low cost, utilization of local materials, and rural focus). Various microbial, turbidity and arsenic tests were carried out to assess the effectiveness of the technologies. Additionally, an evaluation of the BSF pilot project was made along with an examination of the water practices, needs and considerations of the rural Nepalese. The study found that while most of these treatment systems were both effective and appropriate, there were several drawbacks to each system that precludes its immediate adoption by the general Nepalese population. The team concludes that SODIS and BSF are the most effective and appropriate technologies for treatment of microbial contamination and the three-gagri system is the most effective and appropriate technology for removal of arsenic contamination.

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1.0 INTRODUCTION

For three weeks in January, 2001, a group of five Massachusetts Institute of Technology (MIT) Master of Engineering (MEng) students, along with their advisor traveled, in Nepal, examining the water quality situation, investigating appropriate household water treatment systems and continuing the studies conducted by the previous year's group. The 2000 MEng Nepal Water Project team worked to assess the water quality of several urban and rural locations by gathering data on the occurrence of microbial and arsenic contamination in the drinking water. They also evaluated several other water treatment methods for their effectiveness at removing microbial contamination. One of their findings was that while several types of two-container candle filtration systems exist in Nepal, they were not adequately addressing the needs of the rural Nepalese population in terms of flow-rate, disinfection, and appropriateness[1]. Additionally, they found that naturally occurring arsenic was contaminating 18% of the wells tested in the lowland Terai region[2]. Motivated by these results, the 2001 group focused their work on improved treatment of microbial contaminants and arsenic, incorporating disinfection in filtration systems, evaluating the appropriateness of filtration systems, and gaining a better understanding of how water and sanitation practices affect health. These studies were conducted in order to identify systems that could treat the microbial and arsenic contamination, disinfect the remaining microbes, as well as evaluate the social and practical considerations of implementing a point-of-use water treatment project in rural Nepal. This paper is a discussion of the results discovered by this year’s group and recommendations for further research.

1.1 WORLD WATER BACKGROUND

On November 10th, 1980 the United Nations officially declared the 1980s as the UN International Drinking Water Supply and Sanitation Decade (IDWSSD), with a goal of providing clean water and adequate sanitation for all by 1990[3]. At the time, approximately 1.6 billion people worldwide were without clean water and about 2 billion were without adequate sanitation. Ten years after the IDWSSD ended, the situation remains dire. 28% of the world’s population, or 1.7 billion people, are without access to clean water and 2.4 billion are without adequate sanitation[4]. A child dies of water-related diseases every eight seconds. Five million people die annually from illnesses linked to unsafe drinking water and improper sewerage. At any given time perhaps one-half of all peoples in the developing world are suffering from water-borne diseases including diarrhea, cholera, ascaris, dracunculiasis, hookworm, schistosomiasis or trachoma. On top of this is another burden that includes the annual expenditure of over ten million person-years of time and effort by women and girls carrying water from distant, often polluted sources[5].

1.2 WATER QUALITY ISSUES IN NEPAL

Nepal shares in the developing world's water quality problems, despite its freshwater wealth. Unfortunately this freshwater wealth is unequally distributed around the country, a situation exacerbated by droughts during the dry season and flooding during the monsoons. Landlocked between China and India, Nepal is the seventh poorest nation in the world with an average annual income of US$220[6]. This poverty may be the cause of some of the worst national health statistics in the world. Life expectancy in Nepal is 58 years, as compared to 77 years in the United States[7]. Estimates of infant mortality are 79 per 1000 births, over ten times the American rate of 5 per 1000[8], and eleven percent of children die before the age of five[9]. Also, stunting is widespread due to an inability during infancy and childhood to retain essential nutrients during diarrheic episodes.

The extreme poverty mentioned above, combined with a de-centralized, rural population, precludes the government from installing centralized water treatment and sewerage systems. Therefore, if public health is to be protected in the near-term, water treatment systems must be implemented on a household-by-household basis.

The rural population relies on a variety of water sources, depending on their region. In the hill district, most of the water is collected from spring-fed streams that are piped to a local standpipe, or "stonetaps" (in villages), or to the yard (in remote areas). In the flatlands of the Terai, water is collected either from a private hand-dug well, local stream, tubewells or piped from distant sources. In examining water collected from these sources, we found that 93% of our random water samples had microbial contamination and 87% of the water sampled in a district with known arsenic contamination had elevated arsenic levels.

Table 1-1: Distribution of drinking water sources among rural population in Nepal[10]

Drinking Water Sources	*Percent*
Piped water	29.1%
Well water	7.0%
Hand pump	33.3%
Spring water	20.8%
River/stream	7.6%
Stone tap	1.6%
Other	1.7%

1.3 PURPOSE OF STUDY

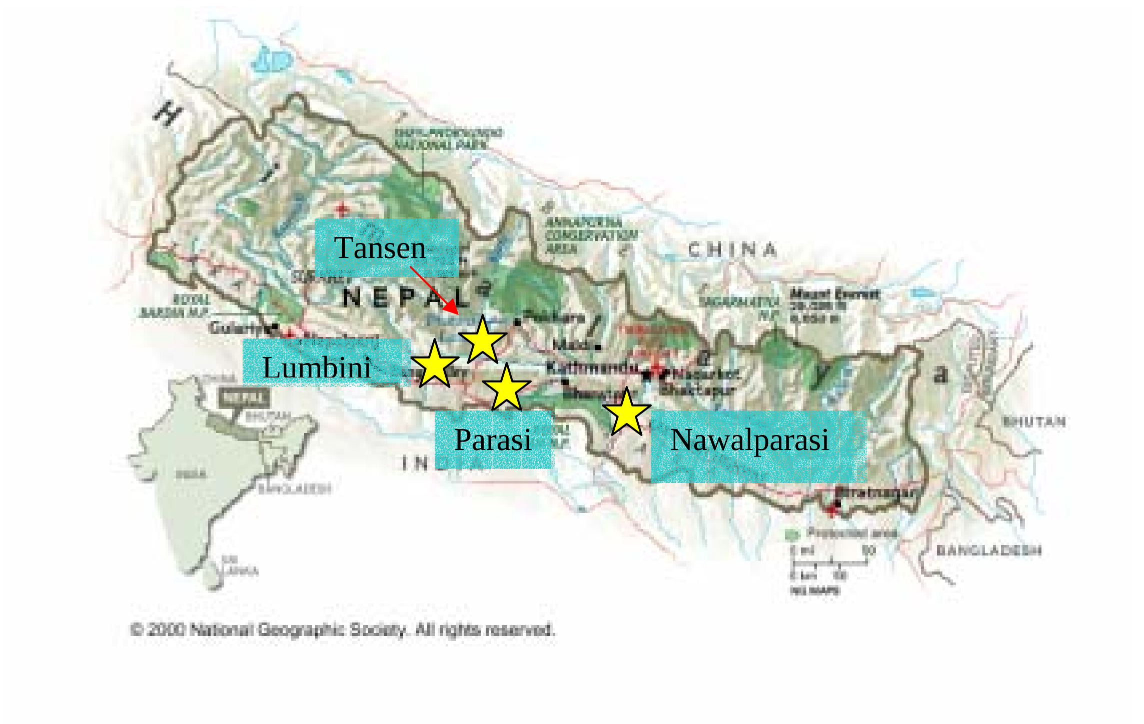
The purpose of this study is to continue the work of last year's group. To do this we evaluated six types of drinking water treatment systems in terms of effectiveness and appropriateness. Because many of the filters examined in 2000 were deemed inappropriate, we examined the following new technologies. Two of the treatments were designed to filter microbial contamination – the Corning CerCor filter and the BioSand Water Filter (BSF) – one to disinfect pathogens – SODIS - and three to treat arsenic contamination – three-gagri, jerry can systems, and ATU systems. Additionally, an evaluation of the BSF pilot project was made along with an examination of the water practices, needs and considerations of the rural Nepalese. The criteria for evaluating the systems, effectiveness and appropriateness, are defined as follows.

For the purpose of this report, *effectiveness* is defined as the measure of the ability of a water treatment system to remove microbial or arsenic contamination. The definition of *appropriate technology,* or *appropriateness,* 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 focus[11].

1.4 PROJECT LOCATIONS

The MIT students split into three teams; two teams stayed in the Terai district of Nepal while one team traveled between the Terai and hill regions. The Terai is the lowland region of Nepal that borders India on the south. The Terai Plain is comprised of alluvium and composes part of the Gangetic flood plain, which receives a heavy sediment and nutrient load from the rivers flowing from the north. The combination of this nutrient influx with the ample ground and surface waters makes the Terai an agriculturally favorable region. Close to half of the population of Nepal lives in this region while most of the other half of the population lives in the hill region. The hill region, or midlands, is composed of the Himalayan foothills, a rugged region with terraced ridges and deep valleys. Much of Nepalese industry and its largest population center are located there in the capital, Kathmandu.

Figure 1-1: Map of Nepal and project locations[12]



Jessie Hurd evaluated three arsenic removal technologies in Parasi, which is a town in the district of Nawalparasi in the Terai. See Figure 1.1. She went here because the Nepal Red Cross Society, who had been testing tubewells for arsenic contamination in the

Terai, had found relatively high levels in one well in this town, so she knew she could use water from this well as influent to the removal technologies.

The second group of students, Meghan Smith and Timothy Harrison, spent two weeks in Lumbini, also located in the Terai, near the Indian Border, studying microbial contamination of tubewells and removal technologies. A local NGO, Crossflow, runs a village health program in the Lumbini District and provided services and information to facilitate the studies. A survey of microbial contamination of village tubewells and water use issues was conducted in seven of the district villages: Lumbini, Lankapur, Mahadeva, Bhagawanpur, Dhodahawa, Sonbarsha, and Bhagatpurwa. Practical household solar disinfection (SODIS) experiments were performed on the roof of the health clinic in Lumbini.

The third group of students, Nathaniel Paynter and Tse Luen Lee spent four days in the vicinity of Tansen in the central Palpa region and nine days in the Nawalparasi district in the Terai investigating the BSF pilot project in Nepal. The Palpa region is in the foothills of the Himalayas and is a highly mountainous terrain. The pilot project was started in these locations in Nepal about two years ago by a local NGO; Hope for the Nations (HFTN), Nepal. Currently, there are a total of 15 such filters in Tansen[13] and more than 100 in Nawalparasi[14] and the numbers are increasing.

2.0 WATER QUALITY PARAMETERS

2.1 MICROORGANISMS

Pathogens in water are usually few in number and difficult to isolate[15]. Instead of determining the actual concentrations of pathogens, indicator organism concentrations are often measured to determine the level of contamination in water. Indicator organisms are typically microbes that do not cause diseases themselves, but are found in conjunction and in higher concentrations than waterborne pathogens. Coliforms are one of the most common indicator organisms because they are so numerous in fecal matter. A problem arises when trying to determine the origin of coliform because they may come from benign sources, such as soil, as well as from harmful fecal sources[16]. One coliform entirely of fecal origin, *Escherichia coli*, is considered direct evidence of fecal contamination from warm-blooded animals[17]. The World Health Organization (WHO) drinking water guidelines state that the total coliform and *E. coli* concentrations in the water must be zero colony forming units (cfu) per 100 mL of sample. Absence of coliform bacteria indicates that water is potentially free from other disease-producing organisms.

Two simple tests manufactured by the HACH chemical company were used to analyze for microbial contamination in Nepal. The first of these tests is the Presence/Absence (P/A) test; it gives a positive or negative result to total coliform as well as *E. coli* [18]. This test only requires that the reactive medium be combined with 100 mL of sample and incubated for 24 to 48 hours at 35ºC.

The culture medium acts as the food source for the bacteria that may be present in the water sample. During an incubation period, if bacteria are present, they will reproduce in large numbers resulting in a color change (from purple to yellow if total coliform is present) in the media. The P/A test may also indicate the presence of *E. coli* by using a 4-methylumbelliferyl-β-D-glucuronide (MUG) reagent that fluoresces under long-wave ultraviolet light when *E. coli* are present.

The second test is the PathoScreen™ Medium test for the hydrogen sulfide (H_2S) producing bacteria commonly associated with fecal coliforms. This test statistically predicts the number of H_2S-producing microorganisms in a water sample by using a specified number of test tubes. We performed Presence/Absence H_2S tests. We also made our own H_2S reagents following procedures available from International Development Research Center[19].

During the microbial testing a novel incubator designed by Amy Smith of MIT was field-tested. The device utilizes a polymer that changes from liquid to solid at 36°C, body temperature. The device was practical for field conditions because it did not need an electric power supply to provide heat. The incubator was boiled in water until the internal temperature reached 36°C, at which point the polymer melted from a white waxy solid to a clear liquid. The incubator was able to keep samples at this temperature for over 20 hours with proper insulation. Once the polymer was visibly hard and white again (indicating a temperature less than 36°C) the incubator can be reheated to the proper temperature.

2.2 TURBIDITY

Turbidity is a water quality parameter that quantifies the degree to which light traveling through a water column is scattered by suspended particles. The scattering of light increases with increased particulate suspension. Turbidity is commonly measured in Nephelometric Turbidity Units (NTU), but may also be measured in Jackson Turbidity Units (JTU)[20]. Turbidity was measured in the field using a HACH 2100P Portable Turbidimeter and a HACH Pocket Turbidimeter™. The instrument operates on the nephelometric principle of measurement, monitoring light scattered by the sample at 90º to the incident beam. The turbidimeter is capable of measuring in the range of 0.1 to 400NTU[21].

Excessive turbidity, or cloudiness, in drinking water is aesthetically unappealing and may also represent a health concern. Suspended particles can provide food and shelter for pathogens; if not removed, turbidity can promote regrowth of pathogens in distribution systems, leading to waterborne disease outbreaks, and significant cases of gastroenteritis throughout the United States and the world[22]. Although turbidity is not a direct indicator of health risk, numerous studies show a strong relationship between removal of turbidity and removal of protozoa[23]. The WHO guideline for the turbidity level in drinking water is set at 5 NTU. In Nepal, the inflow water to the Sundarigat water treatment plant was found to have turbidity levels varying between 8 and 15 NTU[24].

2.3 ARSENIC

Arsenic is ubiquitous, found at trace levels in the earth's crust, atmosphere, waters, and organisms; it can arise naturally or be distributed in the environment by human influences. In either situation, arsenic is a highly toxic element.

Stable in the –III, 0, +III, and +V oxidation states, the most important species with regard to toxicity in humans are arsenite (As (III)) and its oxidized form, arsenate (As (V)). Humans may be exposed to the metal by a number of pathways including inhalation and consumption of arsenic-contaminated food, but it has been suggested that the most critical pathway is through ingestion of arsenic-contaminated water[25]. Long-term, low-level arsenic ingestion is commonly the cause of harm, as chronic exposure can have very serious adverse health consequences. After several years of drinking water with low levels of arsenic, skin lesions may appear, including hyperpigmentation, hypopigmentation, and keratoses of the hands and feet. After a dozen or more years, skin cancers can develop, with the possibility of internal cancers (bladder, liver, kidney and lung) appearing following twenty to thirty years of exposure[26]. Due to these damaging health effects, the WHO has set the guideline for maximum allowable arsenic in drinking water at 10 ppb (parts per billion, or micrograms per liter).

MEng studies of the extent of arsenic contamination in Nepal and of remediation technologies for arsenic contaminated drinking water were influenced by the discovery of elevated concentrations of arsenic in the tubewells of neighboring West Bengal, India and Bangladesh. Like the Indians and Bangladeshis, much of the Nepalese Terai population obtains their drinking water from tubewells. The arsenic in West Bengal, India and

Bangladesh is thought to be of natural origin, derived from parent materials in the subsurface. The arsenic becomes exceedingly concentrated due to the highly fluctuating water table caused by monsoons, thought to provide the dynamic subsurface environment necessary for arsenic accumulation. Since the climate and subsurface characteristics of the southern region of Nepal are similar to those of West Bengal and Bangladesh, there was reason to posit that high levels of arsenic contamination might also be a threat in the Terai.

Last year, MEng student Tricia Halsey surveyed 139 drinking water sources in the Terai region and found that 18% of those samples had arsenic concentrations above the WHO guideline of 10 ppb[27]. Since then, several water agencies and NGOs in Nepal have conducted arsenic contamination surveys of drinking water sources in the Terai. The Water Engineering & Training Center has conducted two such studies; in one they found that 5.1% of 590 samples were above the WHO guideline[28] and in the other they found that 10.8% of sixty-five samples were above it[29].

This year, MEng student Jessie Hurd tested influent arsenic-contaminated tubewell water from Parasi and the effluent from various treatment technologies using three methods. Two different field tests were used in Nepal, EM Quant® test strips and Arsenic Check™, followed by the use of a Graphite Furnace Atomic Adsorption Spectrometer (GFAAS) upon returning to MIT.

EM Quant® test strips were used in the field for a presence/absence evaluation of arsenic content in water samples. Because the detection limit for this test is 100 ppb and arsenic contamination in Nepal was found by Halsey to be between 0 and 100 ppb, this test did not give valuable information regarding the extent of the level of contamination other than whether or not it existed. To use this test, a sample of water is capped in a test vessel and mixed with two reagents, 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 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 kit[30].

Arsenic Check™, with a detection level of 20 ppb, was used in the field to provide a more specific value of contamination of the water samples. Utilizing a similar theory as the EM Quant® test strips in that acid and zinc powder react to produce a gas, this test differs only in that it uses tartaric acid ($C_4H_6O_6$) instead of hydrochloric acid. Again, this acid reacts with zinc powder and the arsenic in the water sample to produce arsine gas that contacts mercuric bromide on a suspended paper to causing a color change to indicate the concentration of arsenic in the sample[31].

Samples from most tests conducted in Parasi were split, collected in plastic tubes and brought back to the Ralph M. Parsons laboratory at MIT. There the samples were preserved with ten percent hydrochloric acid and heated so that any arsenic sorbed to iron hydroxides in the water would return to aqueous state. Small amounts of each sample were analyzed using a GFAAS, a US Environmental Protection Agency (USEPA) approved method for measuring arsenic in drinking water[32]. This is the most accurate method of analysis of the three tests described, with a detection limit of 5 ppb. The GFAAS unit heats up a small amount of the sample at different time steps to reach the volatilization temperature of arsenic. The concentration of the atoms is determined based on their absorption at a 193.7nm wavelength. Ten samples were analyzed in each GFAAS run and standards ranging from 0 to 100 ppb were run before and after each sample group in order to get an average calibration curve against which the concentrations of the samples were calculated. Those samples showing concentrations above 100 ppb were diluted before they were tested.

3.0 TREATMENT

For several decades, a number of international organizations, government organizations, and NGOs, such as UNICEF-Nepal, Peace Corps, and Water Aid have been working to address the water supply issues in Nepal. Much of the focus of these groups has been providing people with gravity feed collection systems and tubewells so they did not have to rely on surface water, which is often microbially contaminated. Unfortunately, some issues have arisen with the tubewells the water may be microbially and/or arsenic contaminated. The economic state of rural Nepal precludes the possibility that any large-scale water treatment facilities will be available in the foreseeable future. This has drawn our focus to treatment at the household level. Last year's MIT MEng team investigated the applicability of small-scale, point-of-use water treatment systems to address the water quality issues at the household level Nepal. For example, Junko Sagara (MEng 2000) identified and collected current methods of filtration and made observations about their shortcomings, namely the candle filter's slow filtration rate and failure to remove microbial contamination[33]. In addition, Peter Moulton, the founder and sponsor of the NGO Global Resources Institute, has been working to study and introduce disinfection to the Terai using the energy of solar radiation[34]. Last year, Amer Khayyat (MEng 2000) studied the possibility of using SODIS in Kathmandu concluding that the effectiveness of the treatment system is seasonally dependent and the feasibility would need to be studied at different locations throughout the country due to the prevalence of microclimates in Nepal[35].

3.0.1 Filtration Theory

Filtration is the most commonly used water treatment process in water treatment plants. Suspended particles, typically measured as turbidity, are significantly decreased in filtered water or "filtrate." Particles are removed during filtration as a result of any one or combination of the following mechanisms: mechanical straining, sedimentation, flocculation, adsorption, and/or biological metabolism[36].

Filters can be used without the addition of coagulant chemicals, making them appropriate options for countries in which coagulant chemicals are either unavailable or expensive.

In order to ensure microbial removal, filtration should be combined with a disinfection process. For example, in the United States in the revised Surface Water Treatment Rule (SWTR) the USEPA mandates that some form of disinfection be combined with filtration for surface waters[37]. Boiling the water in combination with filtration is a disinfection process used by the educated middle class in Kathmandu and other urban areas of Nepal. This method results in pathogen-free water it has a high energy cost that is beyond the means of many people. A kilogram of wood is required to bring one liter of water to boil[38]. The fuel required for boiling is expensive and can contribute deforestation and to the further depletion of dwindling resources.

Ceramic candle filters are a water-treatment option that has been adopted and promoted by several groups, such as Potters for Peace[39] and Ceramiques d'Afrique[40], as a viable household treatment option in developing countries. Local artisans are employed to manufacture the ceramic candle filters. Currently, the candle filter of Indian or Nepalese origin is the main method of filtration employed in Nepal. The shortcomings of the candle filter identified by Sagara prompted the current investigation into other methods of filtration such as the BSF and CerCor.

3.0.2 Disinfection Theory

Water with microbial contamination often needs to be disinfected before consumption. The primary goal of water disinfection is the removal or inactivation of pathogenic microorganisms from drinking water. Disinfection can be achieved using physical, chemical, or biological methods to reduce the incidence of water-borne diseases and prevent disease outbreaks. Some common disinfectants are chlorine, ozone, chlorine dioxide, UV radiation, and heat.

Around the world, the main disinfectant process used for water treatment is chlorination, a well-studied and accepted practice. In the cities of Nepal with public water supplies such as Kathmandu, Biratnaga, and Pokhara chlorination is used, however, sometimes infrequently and ineffectively. In Nepal, since liquid chlorine is not readily available for purchase, the only form of chlorine available to local people is bleaching powder.

Bleaching powder is much more difficult to use for water disinfection than liquid chlorine. The powder does not readily dissolve into liquids and must be put through several processes to get a useable bleaching solution, with an appropriate concentration, such as 0.5% chlorine. A local NGO in Nepal, Environmental Public Health Organization (ENPHO), has developed such a manufacturing process to produce a liquid chlorine solution with low chlorine content from this bleaching powder. Despite this venture to introduce chlorination to Nepal, the practice has not yet become widespread because of lack of supply and public awareness.

An alternative to chlorine disinfection is solar disinfection (SODIS). This is a unique point-of-use water treatment that can be easily implemented in developing countries both in urban and rural areas. One of the concerns of chlorine disinfection that is not a problem with SODIS is the formation of harmful disinfection by-products. Chlorination forms trihalomethanes (THM) in water during disinfection, which have been shown to cause cancer[41]. The alteration of the taste and smell of chlorinated water is also something that people do not like. SODIS does chemically not alter the taste or smell of water.

3.1 BIOSAND WATER FILTRATION

3.1.1 BioSand Water Filter

The BioSand Water Filter (BSF) is a household-scale sand filter developed by Dr. David Manz of the University of Calgary, Canada. This filter has been tested by several government, research and health institutions, as well as NGO agencies in Canada, Vietnam, Brazil, Nicaragua, and Bangladesh. A Nepali NGO, Hope For The Nation (HFTN), has been promoting the filter in the central foothill region of Palpa and the southern flatland region of Nawalparasi.

3.1.2 Theory

The BSF works similarly to a slow sand filter. Slow sand filters operate at low filtration rates 0.1-0.4m/hr, use very fine sand, and usually operate without pre-chlorination[42]. The low filtration rate results in long detention times in both the water above the filter sand and within the bed of the sand. This results in substantial biological life in the slow sand filtration process.

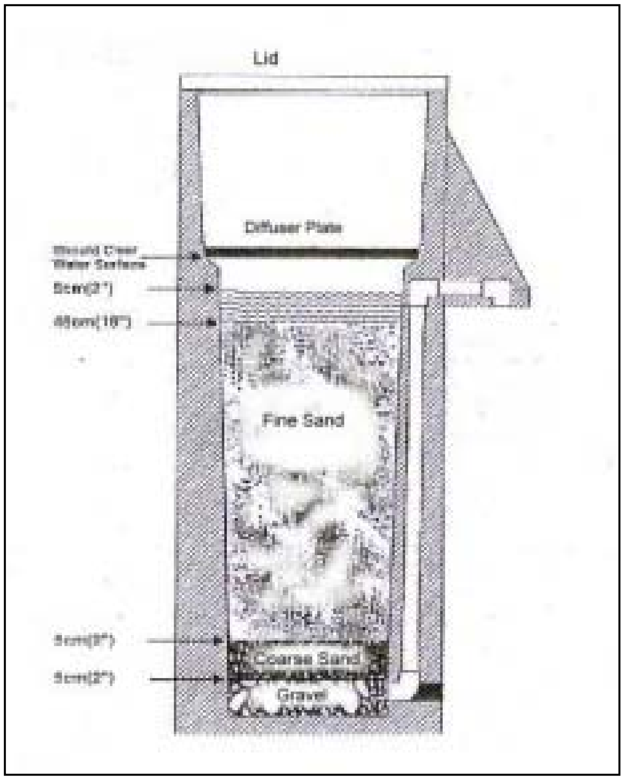
Water that requires filtration usually contains various kinds of organic matter, including living organisms. When water passes through sand, the particles it contains collide with individual grains and once a particle comes in contact with a grain, it adsorbs onto the sand. These particles and organisms accumulate in the uppermost layers of a slow sand filter, where the greatest number of collisions take place, and eventually develop into a dense population. This dense population is commonly referred to by its German description, the *Schmutzdecke* (=dirt blanket), or biofilm. The biofilm is not a layer of biology on the interface between the top of the sand layer and the water, but rather a film coating the surface of sand grains. The biofilm consists of threadlike algae and many other organisms including plankton, protozoa, and bacteria. Together these organisms comprise an intensely active food chain, breaking down the organic matter in the water as it deposits on the sand grains. The layer also strains out particles that cause cloudiness and much of the organic matter responsible for color, taste and odor of water. What few particles remain in the water after passing through the biological layer is removed by the lower portion of sand, a region of little biological growth.

The BSF is different from a slow sand filter with respect to its higher flow rate and its ability to sustain the biofilm during intermittent flow. Two elements of the design contribute to the preservation of the biofilm. First, the filter is designed to hold 5cm of water above the top surface of the sand column while at rest. A constant aquatic environment is necessary for the organisms present in the sand layer to survive, but the water layer cannot be too deep or oxygen will not diffuse and the microorganisms will suffocate. Second, a diffuser plate or basin prevents input water from disturbing the top layer of sand[43].

3.1.3 Set-up

A cross section of a BSF is shown in Figure 3.1. There are several main components of a BSF: the concrete shell, sand and gravel, diffuser plate, and lid. The BSF shell can be made of plastic or concrete. The concrete version used in Nepal is cast in a steel mold. Casting is carried out on site because transportation over long distances under the rough, bumpy conditions of roads in Nepal might cause damages to the BWF shell. Gravel and sand are then put into the shell according to the layer heights specified in Figure 3.1.

Figure 3-1: Cross-section of a BSF



A lid is essential to prevent debris and insects from entering and contaminating the filter. The lid should cover the filter at all times, except when adding water or performing maintenance. The lid may be made out of any material, but it must be clean, must not contain gaps that insects might pass through and should be secure and heavy enough so young children cannot disturb it.

3.1.4 Results

A total of thirty-nine sets of BSF samples were tested. Each set of samples consisted of two individual tests; one sample of water before filtration and one after filtration by the BSF for a total of seventy-eight individual tests. All seventy-eight samples were tested for H_2S-producing bacteria and turbidity. Due to a constraint of resources, not all samples were tested for total coliform and *E. coli*. Table 3.1 summarizes the number of samples that were tested for each of the tests performed at each location.

Table 3-1: Number of BSF test samples analyzed

	Turbidity	*H_2S*	*Total Coliform*	*E. coli*
Palpa	12	12	2	2
Nawalparasi	66	66	36	36
Total	78	78	38	38

Of the thirty-nine BSFs that were evaluated in Nepal, fourteen of them did not show favorable results in terms of the removal of microbial contamination (i.e. H_2S bacteria, total coliform, *E. coli*). Of the subset that did not work, 63% were found to have problems either with the diffuser plate, the resting water level or the maturity of the biofilm. Since these filters may not be representative of the microbial removal efficiency of the BSF, they were excluded in the results. The results of the analyses are shown in Figure 3.2 and Figure 3.3.

Figure 3-2: BSF microbial tests results

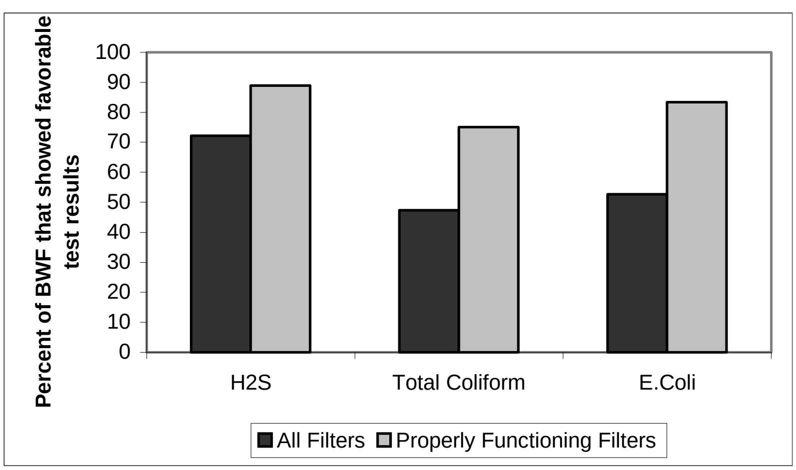
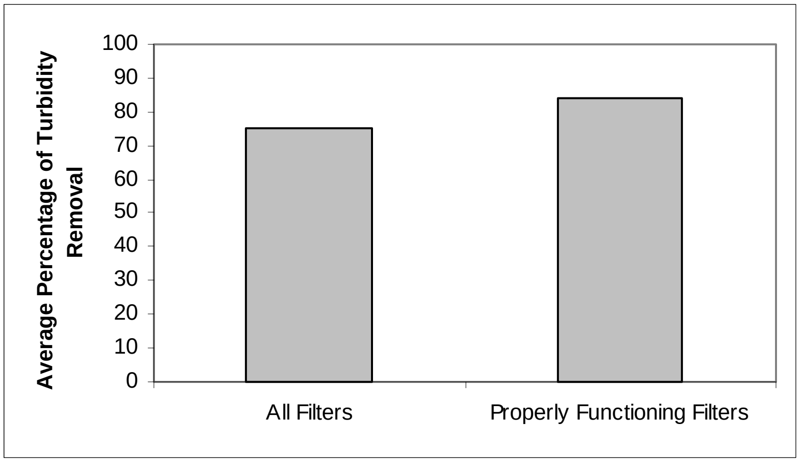


Figure 3-3: BSF turbidity results



The results of filters that were working properly shows 75% removed total coliform, 83% removed *E. coli* and 89% removed H_2S-producing bacteria. This is a significant improvement in the drinking water quality as compared to the Indian and Nepali ceramic candle filters and the Haitian Gift of the Water purifier that were tested in Nepal by the previous MIT MEng group which showed (1) no removal of total coliform, and (2) removal of *E. coli* only by the Indian filter[44]. Additionally, the average flow rate of the BSF was about 30L/hr, which is also significantly higher than that of the other filters tested last year, which averaged 0.25L/hr[45].

We noted several problems with implementing the BSF. There were cases such as a round diffuser plate in a square filter, a rusty metal diffuser plate with a large hole in the middle, and several plastic diffuser plates that were floating on the top of the water surface. In these cases, the effectiveness of the BSF was reduced, since the protective function of the diffuser plate was compromised. Also, the level of the topmost sand layer was found to be another important factor affecting the non-performance of some BSF units. In some BSFs, the sand level is either too high or too low, leading to substantial variations in the resting water level. The water layer cannot be too deep or oxygen will not diffuse and the microorganisms will suffocate. Because the construction of the BSF shells is not a manufactured process, many quality control problems can arise. During our field study, two BSFs were found to be leaking due to problems with the casting of the concrete shell. Depending on the extent of the problem, the BSF had to be mended or discarded.

3.1.5 Drawbacks

Although the BSF has the potential to provide sufficient amounts of purified drinking water, it does not seem to improve water quality in all cases. The percentages of all the BSFs that were investigated that met the WHO guidelines for total coliform and *E. coli* were only 47% and 53% respectively. For the ones that were working properly, 75% met the guidelines for total coliform and 83% for *E. coli*.

Turbidity of source water to the BSF cannot be too high since the filter can clog easily. There will be a need to clean the filter more frequently since more clogging is expected to occur with higher levels of source water turbidity. If the cleaning has to be carried out too often, allowing insufficient time for the biology to mature (typically it takes one to two weeks for the biofilm to mature), then the effectiveness of the BSF could be reduced. Hence, the performance of the BSF in the monsoon season (when the source water may be more cloudy) may be compromised. Pretreatment of the source water by settling could be necessary in the monsoon season.

3.2 **CERCOR FILTRATION**

3.2.1 CerCor Filtration

One option investigated for use in Nepal was the Corning CerCor ceramic membrane filter. The goal of the CerCor study was to evaluate the filter's ability to remove all microbial contamination from drinking water. Additionally an assessment was made as to what kind of maintenance would be required of the filter to determine if the filter would be an appropriate option for use in Nepal.

The CerCor filter provides a significantly higher flow rate (18.0 L/hr) than the candle filters because it is operated at higher pressures (20 psi) than the candle filters. The pore size of the filters is 0.2 μm, much smaller than the pore size of the hand-made candle filters resulting in the removal of microbes. Once the filter becomes clogged it can be cleaned for re-use.[46]

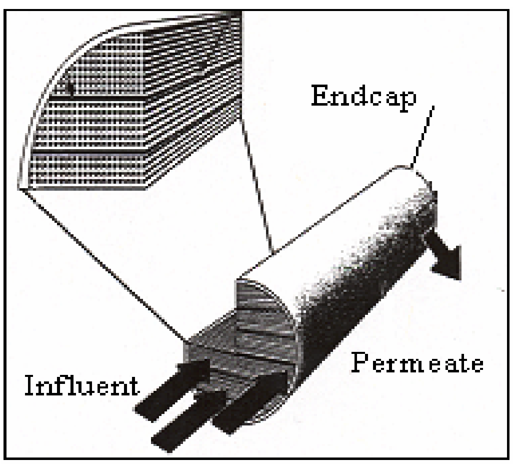
Table 3-2: Comparison of ceramic candle filter, CerCor filter, and BioSand filter

Filter	*Pore Size*	*Flow-rate*
Candle Filter	>1.0 µm	0.3 L/hr
CerCor Filter	0.2 µm	18 L/hr
BioSand Filter	N/A	30 L/hr

3.2.2 *Set-up and Testing Plan*

The CerCor filter was tested at MIT with influent water from the Charles River in Cambridge, MA. The river water tested positive for three types of organisms during the following tests: H_2S HACH PathoScreen™, P/A Total coliform and P/A *E. coli* Hach tests. Corning Corporation has performed initial flux feasibility tests for the filter, which showed satisfactory removal of turbidity and a flux performance of the lab scale filter at low pressures (13 psi). Two CerCor units were made available to the M. Eng. Program from Corning.

Figure 3-4: CerCor diagram



The lab-scale filter used in the study has the dimensions given in the table below.

Table 3-3: Lab-scale filter dimensions

Diameter	*Length*	*Membrane Area/ Module*
27 mm / 1.05”	305 mm/ 12”	0.13 m^2 / 1.4 ft^2

The filter is made from a ceramic monolith. A very thin ceramic coating, <100 µm, is applied to the monolith to create the 0.2 µm pore size. This technology results in a filter that can produce high flow-rates at low pressures. The filter was developed for use in food processing, solvent recovery, and in wastewater treatment plants.

The filter was connected to a small pump (Sears Quality Water pump Utility Centrifugal Model S48HZEC11, 0.5 Hp, 9.4 Amp) at one end and the other end was capped off. Flow enters the filter through one end and since the other end has been capped is forced through the walls of the filter. The resulting permeate is collected and tested. The operating pressure was 20 psi, providing an average permeate flow of 18L/hr. Twenty-one trials using Charles River water determined the Total coliform, *E. coli* and H_2S removal efficiency of the filter to be 100%. To determine failure time, tap water spiked with kaolin to artificially produce feed water with >40NTU was run through the filter. After running for fourteen hours (210L total) at >40 NTU the filter was successfully clogged.

To lengthen filter life, intermittent back flushing was used to unclog the pores. First, the end cap was removed and the filter flow was reversed for thirty minutes, during such cross-flow operation there is no permeate flow. The flow was then reversed again for another thirty minutes. This back flushing operation increases the life of the filter and extends the time between more comprehensive cleanings. Bleach or detergents can be used to sanitize the filter and to remove debris. Ideally hot permeate water should be used in the cleaning process.

3.2.3 Results, Benefits, and Drawbacks

The filter removed 100% of microbial contamination in the indicator tests. The trials were run at 20 psi, and resulted in an average flow rate of 18L/hr. The turbidity of the filtrate was near zero for all runs. Back flushing the filter with cross-flow water has been shown to restore the flow rates between runs.

Currently, the high cost of the filter is the major drawback. It is a specialty product manufactured by the Corning Corporation for clarifying organic process streams, treating wastewaters containing solvents, reclaiming solvents, and recovering energy by recycling hot streams[47]. The purpose of our testing was to ensure the filter could remove the indicator organisms tested and could be adequately maintained. However, currently a suitable cleaning method for Nepal has not been identified. During industrial use, the filter is often cleaned with hot acid or caustic solutions[48], but this will not be a feasible maintenance operation for Nepal. Further work with the filter needs to focus on more comprehensive microbial testing and on reducing the cost of manufacturing and designing a unit that can be easily installed and maintained. In Nepal the filter would best be utilized in a school, medical clinic, or at a pump once the issues identified above are solved.

3.3 ARSENIC REMOVAL TECHNOLOGIES

Due to the serious adverse health effects that people in Bangladesh and India are experiencing because they have been drinking arsenic contaminated water[49] and due to the fact that arsenic concentrations in some tubewells in Nepal are above the WHO guideline of 10 ppb, this part of the project was dedicated to evaluate, in a field site in Parasi, Nepal, several remediation technologies that claim to effectively remove arsenic from drinking water. Because of Nepal's relative poverty, the removal technologies were also evaluated for their appropriateness, as defined previously. Three such technologies were investigated: the three-gagri system, the jerry can system, and an arsenic treatment unit (ATU) made by Apyron Technologies, Inc.

3.3.1 Three-Gagri Water Filtration 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 water[50].

The theory behind the success of the three-gagri system is identical to that behind the success of the three-kalshi and the set-up of the three-gagri system varies only slightly.

Theory

In the three-gagri system, arsenic is removed from influent water by iron species either by compound formation, adsorption or both[51]. The system uses these theores 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. 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.

As mentioned, the arsenic in the water poured into the system will be removed by iron species provided by the iron filings in the top gagri. Since the system is aerobic, meaning oxygen is present, hydroxide species can form on the metallic iron. These hydroxide species can function as adsorption sites for anions of arsenate and arsenite at neutral pH, and 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[52]. Fe (II) in contact with air will then oxidize to Fe (III) and precipitate as iron oxyhydroxide ($Fe(OH)_3$), hydrous ferric oxide (HFO), etc.[53]. The solid $Fe(OH)_3$ can sorb arsenic and the suspended particle can be removed from the water column by settling[54]. The settled particles will not be allowed to flow to the bottom gagri due to trapping by the sand and cloth. 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 processes[55]. 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. Recent data also show that besides arsenate, arsenite can be strongly sorbed by Fe (III) oxides. Finally, arsenate anions bound to HFO can form common naturally occurring arsenate minerals such as Scorodite ($FeAsO_4$, $2H_2O$) and Symplesite ($FeHAsO_4$, $8H_2O$) 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[56].

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 (L) of water and are often made out of aluminum. These 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. Tibetan prayer flags, widely available in Nepal, were chosen as the cloth to put over the holes, because water passes easily through their rough weave.

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 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. To wash the sand, it was rinsed repeatedly with arsenic-free 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.

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 previously. The coarse and 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.

Results and Discussion

While in Nepal, nine batches of arsenic-contaminated water from one well were run through the three-gagri system. See Table 3.3. Approximately ten liters of water with an average arsenic concentration of 215 ppb were added each time yielding an effluent with an average concentration of 4 ppb. The influent water to each of the systems all came from the same tubewell. This well was located behind the house where Jessie was staying in Parasi. Fifteen samples from this tubewell were analyzed with the GFAAS to obtain an average arsenic concentration of 215 ppb. Sometimes influent water samples were not taken; in those cases, the average concentration is given in place of the actual influent concentration.

Table 3-4: GFAAS results for three-gagri system

RUN #	C_{IN} *(ppb)*	C_{OUT} *(ppb)*
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

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

Since the sand was free and the iron donated, the system cost US$10.50, the cost of three gagris. Although this is a bit expensive, most families observed had at least one gagri, requiring only US$7 to complete the system. Of course, Connelly-GPM cannot donate iron to all the families in Nepal so the price (US$7 per ton)[57] and availability of iron filings is a major drawback to the system. It has been suggested that iron nails could be cut up and used in the system instead of iron filings[58]. Iron nails and the tools to cut them are available in Nepal. Three kg of nails cost about US$3 and the nail cutting tool cost about US$1.50. The problem with using nails as opposed to filings is that the relatively smaller surface area of the nails is less efficient and there is much labor involved in cutting the nails into small pieces. To make an evaluation of its efficiency, a three-gagri system was set up using iron nails instead of filings and again ten liters of influent water with about 215 ppb water was added. Though the system took much longer to filter (over eight hours), it did lower the effluent arsenic concentration to 9 ppb.

Besides the questionable availability of iron filings, another drawback of this system is the difficulty in disposing of the spent sand and iron as they become hazardous wastes. Also, it is unknown if the system promotes bacterial growth in the water due to the long residence time in the filter. Finally, it has been observed that the three-kalshi system clogs easily, especially if iron is naturally occurring in the source water. The nine runs in Nepal took an average of two and a half hours to complete; the first run took an hour and a half and each successive run took longer. Therefore, there might also be problems with clogging for this system.

3.3.2 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.

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, jerry can, 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 at rest.

It was also suggested by the researchers that adding sulfate to the water would enhance the arsenic removal[59]. This process can be demonstrated by the following reactions:

$2Fe^{0} + O_2 + 4H^{+} = 2Fe^{+2} + 2H_2$

This reaction will utilize 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:

Iron Oxidation: $Fe^{0} = Fe^{+2} + 2e^{-}$

Iron Oxidation: $Fe^{+2} = Fe^{+3} + e^{-}$

Sulfate Reduction: $8\ e^{-} + 9H^{+} + SO_4^{-2} = HS^{-} + 4H_2O$

Hydrolysis of water: $2\ e^{-} + 2\ H^{+} = H_2(g)$

Arsenate Reduction: $2\ e^{-} + 4\ H^{+} + HAs\ O_4^{-2} = H_2O + H_3AsO_3$

The products of these reactions can later form precipitates that can include the formation of $Fe(OH)_3$, $FeAsO_4$, FeAsS[60] and arsenic sulfide precipitates[61]. 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 process[62]. Also, since we want to be able to reuse the residue in the jerry can, precipitation in the form of arsenopyrite is desired becasue it is a stable mineral.

It was suggested that equimolar amounts of sulfate and arsenic be in the system to allow the above reactions to take place[63].

Set-Up

Jerry cans come in various sizes but for our purposes a jerry can is a 10L plastic jug that, in India, is commonly used for tubewell water collection and is widely available at a minimal cost (US$0.50)[64]. 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, with an average arsenic concentration of 215 ppb, was pumped from the well into the jug leaving no headspace and creating an iron concentration of 625 mg/L. The jug was either agitated for forty-five minutes or allowed to rest for about three hours, as recommended by researchers at the University of Colorado.

Results and Discussion

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, as is tabulated below.

Table 3-5: GFAAS results for jerry can system

TIME IN JERRY CAN	*INFLUENT (ppb)*	*EFFLUENT (ppb)*
3 hours	186	186
3 hours	215*	244
45 minutes	215*	260

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

Only after analyzing the samples, returning from Nepal, and contacting the developers at the University of Colorado, was it discovered that the system only works if there is sulfate in the influent water. Apparently, the water used in Parasi did not have a sufficient amount of sulfate. It was suggested that gypsum could be added to the water to increase the sulfate content[65]. Although gypsum is a common mineral that is safe for consumption, Nepalese citizens tend to dislike adding chemicals to their water before drinking it[66]. Another drawback, apart from the fact that it doesn’t remove arsenic, is that people using the system would need to replace the packet of iron after 100 uses to avoid allowing arsenic to leach from spent iron.

3.3.3 ATU

While the three-gagri and jerry can systems are household-size point of use (POU) treatment systems, the arsenic treatment unit (ATU), from Apyron Technology, Inc. (ATI), system is a point-of-entry (POE) system, intended for use 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. This system also uses the theory of adsorption, but the media is an inorganic granular activated alumina metal oxide, instead of iron.

Theory

The ATU uses the theory of adsorption 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 ions[67].

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.

Set-Up

Apyron Technologies, Inc. donated an ATU to MIT for use in Nepal. 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 because both pressure and water elevation head are requirements for the ATU to function as desired[68].

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[69].

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 attached[70].

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 diffusive plate, which ensures that the large influx of water does not disturb the underlying media, and is spread over a layer of sand. This 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 this 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.

Results and Discussion

The ATI system was tested over eleven consecutive days. The results, shown in Table 3.5, are impressive, as the system, except in the first run, removed all of the arsenic.

Table 3-6: GFAAS results for ATU

RUN #	*INFLUENT (ppb)*	*EFFLUENT (ppb)*
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 most serious drawback of this system is its high cost of US$2000 per unit. It can provide water for many people for a long time so the estimated cost is US$0.22 per liter[71]. One of the benefits of this system that is different than the previously discussed technologies is that the media is non-hazardous and non-leaching and can therefore be disposed via normal sanitary means, such as in a typical landfill.

3.3.4 Conclusion and Recommendations

The jerry can system is not effective for removing arsenic from Parasi drinking water because the water does not have a sufficient amount of sulfate in it. In order for this system to work, sulfate, perhaps in the form of gypsum, would have to be added to the jerry can with the iron. This process would require that those using the jerry can system know exactly how much arsenic was in the water to be treated, calculate the molar concentration of that 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.

The ATU system is also inappropriate due to its high cost. While it is effective at removing arsenic and bacterial contamination from tubewell water, it is not feasible that the local population in the Terai could afford it.

The three-gagri system is the system that is most appropriate for use in Nepal. It is effective at removing arsenic from drinking water, it is composed of mostly locally obtainable material, and it is available at a low cost. Before it could be recommended that the three-gagri system be put to use in Nepal, several aspects of the system would need to be evaluated further. First of all, can iron filings be found in Nepal, and if not, what design modifications would need to be made so that iron nails would be effective at removing the arsenic while providing a reasonable flowrate? Secondly, the question of whether or not this system promotes bacterial contamination of water would have to be answered. Lastly, an environmentally safe method for disposing of the spent media would have to be developed.

3.4 PRACTICAL HOUSEHOLD SOLAR DISINFECTION

3.4.1 SODIS Theory

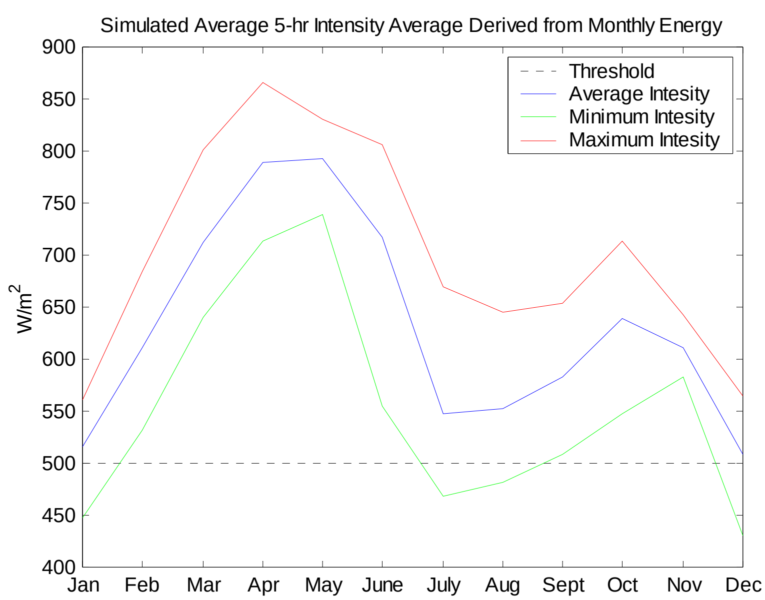
SODIS is the application of solar disinfection at the household level to treat small quantities of drinking water. The technique utilizes solar radiation to inactivate and kill pathogenic microorganisms, thereby disinfecting the water.

Microorganisms are sensitive to changes in both temperature and light. During SODIS, the infrared light of solar radiation increases water temperature. Water is commonly boiled to remove pathogens, but pathogens can also be effectively killed when held at lower temperatures for longer times, a technique known as heat pasteurization. For instance *Vibrio Cholera*, the microbe responsible for causing cholera, is effectively inactivated after one hour at 45°C [72]. The UV-A light (wavelength: 320-400 nm) of solar radiation causes lethal changes in the nucleic acids of microorganisms. Radiation with longer wavelengths does not effectively inactivate bacteria, and UV-B or shorter wavelength light is neither transmitted though the PET bottles well nor present in high amounts at ground level[73].

The synergistic effect of heat pasteurization and UV-A irradiation makes SODIS effective. For example, Peter Wegelin has found that without this synergistic effect it would take 5 hours of midday sun (555 W h/m^2) to inactivate *E. coli*[74]. With the synergistic effect of raising temperature to 50°C *E. coli* is effectively inactivated in only one hour of midday sun (140 W h/m^2)[75]. The combination of both effects induces stress on the microorganisms, increases the effectives of disinfection, and makes SODIS a viable water treatment option because disinfection occurs in ambient conditions and in short times.

The threshold level for SODIS solar radiation is (500 KW/m^2)[76]. Locations with incidence of solar radiation above this threshold will be good locations for SODIS. The available solar radiation is dependent on geographic location, latitude, season, and time of day. Regions between 15° and 35° N latitude are the most favorable for SODIS application[77]. Nepal is located between 26°22' and 30°27' N latitude and 80°4' and 80°12' E longitude on the southern slopes of the Himalayas. Data on the amount of electromagnetic energy (solar radiation) incident at the surface of the earth, insolation (kW/m^2/day), for an average day each month was obtained from NASA Langley Atmospheric Data Center[78]. The insolation data for an average day was converted to the average insolation for the five midday hours, when insolation is much higher than the daily average. The data were simulated for the five midday hours using a method developed by Peter Oates[79]. Looking at the 5-midday hours, when the incidence of solar radiation hitting the Earth is highest, Nepal is above the SODIS threshold a majority of the time.

Figure 3-5: Simulated solar energy available in Nepal from a ten-year average

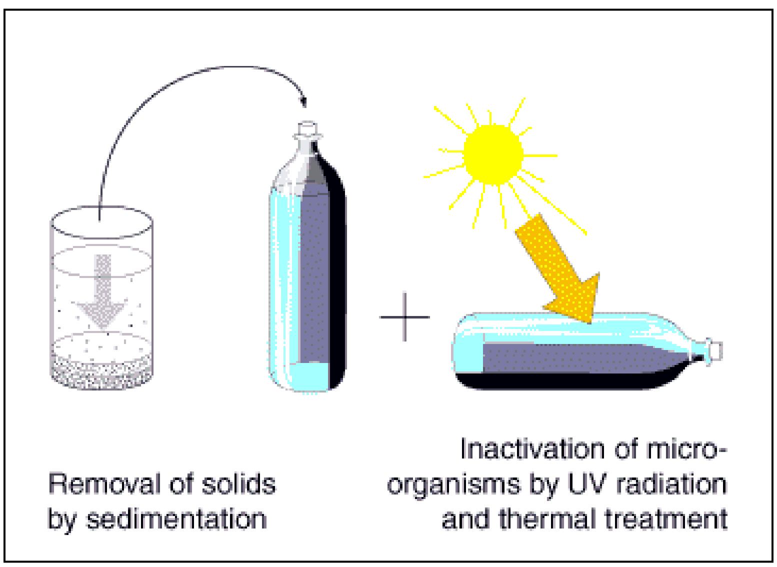


Aside from the UV-A light directly absorbed by the organisms, oxygen compounds also absorb the radiation[80]. This process creates highly reactive oxygen free radicals and hydrogen peroxides. The reactive oxygen compounds oxidize the microorganism causing an effect known as photo-oxidative disinfection. The oxygen compounds are short-lived intermediates that do not provide a residual disinfectant but do inactivate the pathogens initially present in the water. Photo-oxidation can be increased by ensuring water is fully saturated with oxygen before it is set out in the sun for treatment.

3.4.2 Set-Up

SODIS is carried out in glass or plastic bottles. The typical clear plastic soft drink or bottled-water bottle from any store is appropriate, but clear materials with high light transmittance are the best choice for SODIS treatment containers. PET (polyethylene terephtalate) drinking water bottles are a good choice, and are readily available in Nepal.

Figure 3-6: SODIS set-up



It is important that the bottle is in good condition since excessive scratching reduces that amount of light that can reach the water, which would reduce disinfection. It is also important that the water have a turbidity level below 30 NTU because the suspended particles scatter light, reducing the amount of light penetrating into the bottle. Additionally, half of the bottles can be painted black to increase light absorbance and hence increase the water temperature.

Water is collected in the morning and put into the SODIS bottles. To increase the dissolved oxygen content the bottle can be capped and vigorously shaken when half full and then it can be completely filled. The bottles should be set out in an area that receives full sun, such as on a roof. It is important that the bottles remain in full sunlight throughout the treatment and do not become covered by shade. Depending on weather conditions and geographic location, the bottles should remain in the sunlight for anywhere from four hours on a sunny day to two full days when the sky is overcast[81].

3.4.3 Results

SODIS data collected by MIT MEng student Meghan Smith in Lumbini, during January 2001 and unpublished data collected by Harvard School of Public Health Doctoral student Cathy Pham in Kathmandu, during the monsoon season June and July 2000 indicate that SODIS should be a viable treatment option. In Lumbini January 2001, fourteen tests were performed. The effectiveness of SODIS was evaluated on the following basis: tests of source water must be positive for both hydrogen sulfide producing bacteria and total coliform, and the resulting treated water must test negative for both types of bacteria. One day of SODIS was 92% effective, while two days of SODIS was 100% effective and the data from Kathmandu showed a similar trend; one day of SODIS was not sufficient to provide clean water. The effectiveness of one day of SODIS was only 54%. Two days, however, again provided 100% effectiveness.

The data collected during these two times of the year in Nepal, the dry and the monsoon seasons are very important because they represent the technical limits of SODIS in Nepal.

These two times of the year are when SODIS is least likely to work, due to rainy weather conditions blocking solar radiation, during the monsoon season, and because of lowest year-round temperatures during January. Since SODIS was found to work in both times of the year, it appears that it can be implemented and effective year round.

3.4.4 Benefits

SODIS offers a practical, effective water treatment method that can be easily implemented. By providing people with clean water SODIS implementation can reduce the incidence of waterborne disease with little capital investment beyond initial training and monitoring expenses. Since SODIS does not rely on the addition of chemical its does not alter the taste of water and is a sustainable option for people in developing countries. Also SODIS enables people to use surface water sources that had been previously been abandoned in favor of tubewells due to microbial contamination.

3.4.5 Drawbacks

Despite the many benefits of SODIS, there are still some factors limiting its widespread use. SODIS is useful only for treating small volumes of water on a household scale. It is dependent on solar radiation and inclement weather can decrease effectiveness. There are plenty of opportunities for error in the process and people must be thoroughly trained in the use of SODIS at its introduction. Moreover, because there has been some evidence of bacteria re-growth, further testing is still required to determine the nature of this re-growth and to recommend limits on storage time.

4.0 SOCIAL AND PRACTICAL CONSIDERATIONS, AND BIOSAND EVALUATION

Section 3 of this report examines the technical aspects of providing effective water treatment to the rural population of Nepal. However, any development project, including household water treatment, must be combined with a thorough understanding of social and practical considerations in order to be successful. The necessity of this becomes clear when one considers that a well-engineered project is useless if the target population does not, will not, or cannot use it. There are numerous examples of well-meaning projects that failed because of poor understanding of needs and attitudes of the local population. For example, there was a project to install latrines in a very poor region. The latrines were well built, of bricks and mortar, with strong locks on the doors. However, the houses in the area did not have locks on their doors, so the local people used the new latrines for storing their valuables, not for sanitary needs. In their mind, the project was a great success for storing chickens and bicycles[82].

Figure 4-1: BSF with three types of gagris

In an effort to evaluate the issues regarding filtration systems, MIT MEng student Nat Paynter traveled with Tse Luen Lee as he examined the technical aspects of the BSF, such as the one illustrated in Figure 4.1. As Lee took water samples, Paynter interviewed the BSF owners about their water concerns, wishes, and needs. These data have been compiled to illustrate the necessary criteria of social and practical considerations, as defined in Section 4.1. Additionally, the respondents discussed their reactions and attitudes towards the BSF, allowing an evaluation of this pilot project.

4.1 DEFINITION

Every development project will probably have its own criteria of social and practical considerations that need to be addressed before a project can be considered successful. For the BSF project, the criteria are as follows:

1. The project must be socially acceptable. *Social acceptability* is defined in this report as a project and/or technology that does not conflict with the target population's social, religious, and cultural mores.
2. The implementers must have a thorough understanding of whose habits and workload are going to be directly affected by the project.
3. The current water needs of a family should be evaluated and incorporated into the implementation.
4. The local understanding of the connection between contaminated water and poor health should be evaluated. This includes an assessment of the understanding that clear water may be contaminated.
5. The project must incorporate appropriate technology, as defined in Section 1.3.

4.2 METHOD

A survey instrument was developed from a base survey created by MIT Assistant Professor Jennifer Davis for a broad evaluation of people's willingness and ability to pay for water infrastructure. Her survey was restructured to focus more specifically on drinking water practices and to reflect the unique situation that we expected to find in Nepal. The restructured survey was broken into five sections: Background, Current Practices (including shared and private resources), Improvements, Filtration, and Current Sanitation Services.

This instrument proved to be inadequate for this fieldwork, and it, too, was reorganized and expanded from thirty-eight to fifty-three questions. The expanded survey had to be re-divided into eight sections in the following order: Background, Water Source Information, Health, Filtering, Maintenance/Cleaning, Water Use, Water Distribution System, and Latrine Availability and Use.

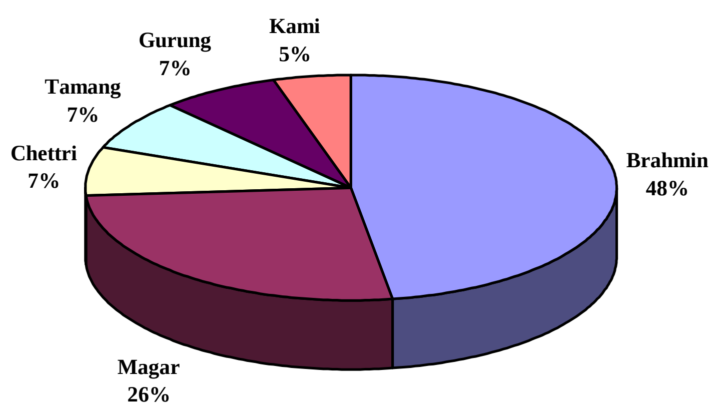
Once we arrived on site, Arjun Chettri of HFTN guided Lee and Paynter to the BSFs. The BSFs were typically installed in either remote households in the Tansen area of the Palpa region, or along the main East-West highway in the Naranghat area of the Nawalparasi region. While Lee collected his samples, the BSF owners were interviewed by Paynter via Arjun, who translated. Although a long survey, the interview typically lasted about twenty to thirty minutes. After the interview, the longitudinal, latitudinal, and altitudinal coordinates were collected with the Garmin E-Trex Summit Global Positioning System sensor. This methodology was repeated one to two times a day in Palpa, and up to seven times in Nawalparasi. The higher rate of interviewing in the second region was due to the relatively accessible terrain of the flat Terai.

4.3 RESULTS AND DISCUSSION

4.3.1 Background

Thirty-eight interviews were conducted in twelve villages within the two regions. The respondents were almost evenly split by gender, with 51% of them being women and the remaining 49% being men. There were two religions represented in the sample population, Hindu and Christian, with a 94% Hindu majority. The BSFs were owned by seven castes, of which the majority, 48%, were high-caste Brahmins, as illustrated in Figure 4.2.

Figure 4-2: Caste/Ethnicity



4.3.2 BioSand Evaluation

The BSF technical evaluation results, as described in Section 3.1.4, are promising as a technology, but several of the social and practical considerations must also be addressed. Thirty-six BSFs out of forty-two visited had been used in the last week, while three others had been used in the past four months. The remaining BSFs were not in use either because of problems with the construction (two BSFs) or because the BSF was inconveniently located. 93% of the respondents overwhelmingly liked the BSF, particularly citing the treated water's taste, and the BSF's high flow rate, cooling properties, as well as turbidity removal. The only common complaints were that the BSF is too heavy and that users did not like the continuous flow of water believed necessary to keep the biofilm viable, because it demanded extra time and work to supply the BSF with water. The BSF's extreme weight is actually beneficial and necessary for it to function properly: if the BSF is moved, the carefully layered sand will compact and the flow rate will be compromised. Also, since the BSF was designed for intermittent flow - filtering water only when necessary – these respondent were misinformed and do not need to provide constant flow.

The respondents were less enthusiastic about the health benefits of the BSF. Only 54% of them indicated that they felt healthier, with significant reductions in diarrheic episodes since using the BSF. In examining the correlation between improved health and the parameters that Lee used - H_2S, total coliform and *E. coli* removal – there appeared to be almost no connection, as illustrated in Table 4.1.

Table 4-1: Correlation between improved health and microbial removal

Parameters	*Correlation*
Health, H_2S	32%
Health, Total coliform	47%
Health, *E. coli*	5%

This non-correlation shows that there must be another, unidentified parameter affecting health. This parameter may be the water consumption habits in rural Nepal. While all the respondents who were using the BSF drank from it at home, very few actually took filtered water with them when they left the house. Only two reported taking filtered water with them, while one family bought mineral water when not at home. Because much of the rural Nepali population is engaged in labor-intensive outdoor activities (i.e. farming and construction), they probably consume most of their water away from their home. This water likely comes from the nearest well or stream, and our research indicates that total coliform bacteria contaminate 93% of the sources we tested during our fieldwork in Palpa and Nawalparasi[83]. However, if the BSF is used and maintained properly, and if the respondents exclusively drink filtered water, the health benefits may be enhanced.

While 70% of the respondents filter their water in order to improve their health, there is a high incidence of people who filter the water purely to remove the cloudiness that occurs seasonally. This attitude appears to occur more often in the Terai than in the hill region, possibly indicating a more severe water problem there. The apparent benefit of filtering to clear the cloudiness is that the respondents tended to use the filtered water for everything - drinking, washing, and cooking. While filtered water use would normally be beneficial in the reduction of microbial contamination, that is probably not the case in this situation. Because more water with higher turbidity is filtered, the BSF clogs faster, as discussed in Section 3.1. As the BSF clogs, the flow rate drops, which the owners properly use as an indication that it is time to clean the sand. As has been noted in Section 3.1.4, every time the sand is cleaned the biofilm is killed and it takes about two weeks of biofilm re-growth before the BSF is working properly again. However, if the turbidity is such that the sand appears to need cleaning every two weeks, the biofilm will never have time to grow and the efficacity of the BSF will be greatly compromised. This level of turbidity occurs during most of the monsoon season and late in the dry season when the water level in the shallow, hand-dug wells gets low. The respondents noted that higher incidences of diarrhea frequently coincide with periods of cloudy water.

Both of these comments, the consumption of unfiltered water and the improper maintenance of the BSF, indicate that the Nepalese neither have a clear grasp of the source of contamination, how contamination travels, nor of the working of the BSF.

While 70% of the sampled population knows that their household source water is dirty - even when it is clear - they do not appear to be aware of the prevalence of contamination (i.e. that the water they are drinking in the field is contaminated as well). Alternatively, they may simply not be in the habit of taking water with them. While changing habits is notoriously difficult, even with notable life improvements, this pilot group offers promise since they have already changed their drinking water habits in the purchase and use of the BSF.

The BSF program does have a major drawback in the cost of the filter. While the BSFs in Palpa were provided free of charge by HFTN, the ones in Nawalparasi were purchased. The average cost is Rps2,100 (US$27), but that includes a 20% promotional reduction. HFTN is planning on developing a micro-enterprise that will sell the BSFs for Rps2,500 (US$32) once the market awareness rises sufficiently. This price puts the BSF effectively beyond the reach of most of the population, who have an annual income of US$210, and this disparity is reflected in the distribution of castes in the sample population. With the majority of respondents being Brahmin and other high castes, the BSF distribution network has clearly not yet reached the marginalized sectors of society, possibly the sectors most in need of filtration.

4.3.3 Social and Practical Considerations

The BSF fulfills many of the criteria defined above; it is simple, effective, durable, and constructed from readily available resources. Although the program was not designed with the family members who perform most of the water-labor, the women, it does not add significantly to their labor. The same amount of water would need to be collected, with or without the BSF, and the only additional labor is the occasional maintenance. The maintenance was rarely noted as a complaint, but for those regions with extremely high turbidity during the rainy season, the maintenance may become a significant labor diversion. The BSF is well designed to handle the filtration needs of a family. No respondent noted that the BSF did not provide enough water for their family's needs, be it drinking, washing, or cooking. In one instance, an owner filtered nineteen gagris (266 L) a day, and the upper limits of the BSF's POU capacity to filter water have yet to be measured.

Figure 4-3: Constructing a BioSand Filter, with the mold in the background and a finished model in the foreground.

The program suffers from its failure to make sure that the users are aware of microbial contamination in their water, and in Nepal all water should be viewed as suspect[84]. If the BSF distribution were complemented with a brief explanation of contamination and how it travels, the program would likely be significantly more successful in reducing incidences of diarrhea. Another drawback is that the BSF is priced prohibitively - it is unlikely that a family will invest 15% of their annual income in a filter. The price may drop a bit if the demand rises sufficiently to justify mass production, with associated lower production costs. An alternative is that the BSF program may be subsidized, either through the government or an NGO. An example of this in Haiti, where the NGO, Gift of Water, has subsidized the construction and maintenance costs of their filters[85]. If a similar situation can be arranged in Nepal, the cost issue might be resolved. However, a concern then arises about sustainability of the program - if the funding were to be cut off, then the BSF and maintenance program would collapse[86]. Another consideration is that the BSF's use must be restricted to populations without access to chlorinated water. Any water source that has been chlorinated will destroy the biofilm, greatly reducing the filter efficiency in microbial removal. Such systems supply water in part to large population centers such as Kathmandu, Tansen, and Naranghat.

Although there have been reports of water in Nepal being held as intrinsically pure[87] as well being an important element in Hindu rituals, there was little evidence of religion being a constraining factor in the adoption of this filter. Nonetheless, there was resistance to using the filtered water for washing hands and dishes. This resistance may also be attributable to a resistance to the extra work involved in collecting water for the BSF for washing in addition to the water collected for drinking. Often the washing of clothes, bodies, and dishes is done at the source, so filtering this water would, in fact, be an increase in labor for the women. However, the effect of using filtered water for clothing/dish washing is thought to be negligible as the contamination concentrations are minor compared to those found on hands[88]. Similarly, there is little evidence that recontamination within families is a serious concern because the family members would have developed resistance to the pathogens originating from other family members[89].

4.3.4 Survey Considerations

The survey was clearly limited by the fact that only three weeks were spent in the field and only two regions were visited, and therefore, the widespread application of these data is debatable. That aside, a cross-section of Nepali society is not represented here, either. With over 90% of the respondents being Hindu, the other major religions of Nepal, Muslims and Buddhists, are not represented at all. These religions may have cultural and social water concerns that have not surfaced in this predominantly Hindu sample population. Finally, as mentioned above, the vast majority of respondents were of the upper castes, and so many marginalized members of society are not included.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The various technologies investigated in this study are presented in Table 5.1 below. The table summarizes the effectiveness, appropriateness, intended removal, and the cost of each removal technology.

Table 5-1: Comparison of technologies

Technology	*Effective*	*Intended Removal*	*Appropriate*	*Cost*
CerCor Filter	Yes	Microbial	No	US$ >400.00
BioSand Filter	Yes	Microbial	Yes	US$ 32.00
3-Gagri Filter	Yes	Arsenic	Yes	US$ 10.50
Jerry Can System	No	Arsenic	Yes	US$ 0.50
ATU System	Yes	Arsenic	Yes	US$ 2000.00
SODIS	Yes	Microbial	Yes	US$ 0.00

For determination of which technology to use in areas with microbial and/or arsenic contamination of their water supplies, the specific type of contamination needs to be identified. Once the water quality issues are identified, the sources of the contamination can be addressed and technology can be selected. The selection of the technology depends on several factors: cost, acceptability, climate, access to the technology, community participation and awareness, and a network to provide support for technology implementation and training. The technology that is the best choice for one area and one socio-economic group may not be appropriate for use in another area or with another group. For example, the BioSand filter is an appropriate technology for use in the middle classes of Nepal at the current time, but could not immediately be made available to the lower classes in rural Nepal. SODIS, on the other hand is a technology that can be implemented in the lower and middle classes of rural Nepal immediately. The technology requires no capital investment from users and is simple and easy to implement. Seminars could be held in villages on market days to introduce people to the technology and they could begin using it the next day. However, it is climactically dependent, and improper application can reduce or eliminate the solar disinfection.

A limiting factor in implementation of some of the technologies is cost. Both the CerCor filter and the ATU System resulted in high removal efficiencies of the intended contaminant, but their cost will hinder their implementation in Nepal. The high price precludes them from being a simple household treatment option and they move into the realm of community treatment options. They would both be well suited for use at a school, a hospital, or other area where there is a high water usage and someone responsible for cleaning and maintaining the unit.

To achieve the greatest impact from technology implementation it is important that users are educated on basic public health, hygiene, and sanitation practices. People need to understand what is making them sick, and that these waterborne illnesses do not have to be a part of life they can be prevented.

6.0 REFERENCES

[1] Bittner, Andrew, et al, Drinking Water Quality and Point-of-Use Treatment Studies in Nepal (Cambridge: MIT, 2000)

[2] Halsey, Patricia M., Arsenic Contamination Study of Drinking Water in Nepal (Cambridge: MIT, 2000)

[3] Schiller, Eric J., Water Supply and Sanitation in Developing Countries (Ann Arbor: Ann Arbor Publishers, 1982)

[4] World Health Organization (WHO), Global Water Supply and Sanitation Assessment 2000 Report, 23 Apr. 2001, http://www.who.int/water_sanitation_health/Globassessment/Global1.htm#Top

[5] WHO, 1996

[6] World Bank, Nepal at a Glance, 23 Apr. 2001, http://www.worldbank.org/data/countrydata/aag/npl_aag.pdf

[7] Ibid

[8] Ibid

[9] United Nation's Children's Fund (UNICEF), Nepal, 23 Apr. 2001, http://www.unicef.org/statis/Country_1Page123.html

[10] Adapted from United Nations Development Project (UNDP), Nepal Human Development Report 1998 (New York: UNDP, 1998)

[11] Schumacher, E. B. F., Small is Beautiful (New York: Harper & Row, 1973)

[12] Adapted from National Geographic Society, National Geographic Magazine On-line, 22 Apr. 2001, http://www.nationalgeographic.com/ngm/0011/feature6/index.html

[13] Chettri, Arjun, personal interview, Jan. 2001

[14] Magar, Durga Bahadur Ale, personal interview, Jan. 2001

[15] Metcalf and Eddy. Wastewater Engineering: Treatment Disposal and Reuse, McGraw Hill, New York, 1991

[16] Ibid

[17] Meyers, D.N. and Sylvester, M.A. “7.1 Fecal Indicator Bacteria.” U.S. Geological Survey TWRI Book 9. USGS, 1997.

[18] Products For Analysis, Hach, Loveland, CO. 2001

[19] IDRC, Module 7, 1998.

[20] Metcalf and Eddy. Wastewater Engineering: Treatment Disposal and Reuse, McGraw Hill, New York, 1991

[21] Products For Analysis, Hach, Loveland, CO. 2001

[22] USEPA, “The importance of turbidity”, Guidance Manual Turbidity Provision. 1999

[23] Ibid

[24] Sagara, J. Study of Filtration for Point-of-Use Drinking Water Treatment in Nepal. Master thesis, Massachusetts Institute of Technology. 2000.

[25] Baut-Menard, P. Group report: Arsenic. In: J. Nriagu, editor. Arsenic in the Environment. New York: Wiley, 43-49. 1994.

26 Harvard University. The Arsenic Project website. November 3, 2000. http://phys4.harvard.edu/~wilson/arsenic_project_introduction.html

[27] Halsey, P. Arsenic Contamination Study of Drinking Water in Nepal. Master thesis, Massachusetts Institute of Technology. 2000.

28 Water Engineering & Training Center. Research on Arsenic Contamination in the Groundwater of Terai, Nepal (Jhapa, Saptari & Sarlahi Districts). Final report submitted to NRCS in April, 2000.

29 Water Engineering & Training Center. Research on Arsenic Contamination in the Groundwater of Terai, Nepal (Jhapa, Morang, Sunsari, Udayapur, Mahottari, Dhanusa, Rautahat, Bara, Parsa, Chitwan & Kapilvastu Districts). Final report submitted to NRCS in September, 2000.

30 EM Science. "10026 EM Quant® Arsenic Test." Internet. April 12, 2001. www.emscience.com/literature/index.asp.

31 Industrial Test Systems, Inc. "Instruction Sheet." Arsenic Check field test kit. 2000.

32 Water: Analytical Methods." U.S. Environmental Protection Agency. "Arsenic in Drinking Internet. April 3, 2001. www.epa.gov/OGWDW/ars/ars7.html.

33 Sagara, J. Study of Filtration for Point-of-Use Drinking Water Treatment in Nepal. Master thesis, Massachusetts Institute of Technology. 2000.

34 Moulton, P. "Water Survey and Testing" Global Resource Institute, 1999.

35 Khayyat, A. Study of Point-of-Use Treatment Methods for the Disinfection of Drinking Water in Nepal. Master thesis, Massachusetts Institute of Technology. 2000

36 American Water Works Association (AWWA), Water Quality and Treatment – A Handbook of Community Water Supplies, 5th Edition, McGraw-Hill, New York, 1999, Edited by Raymond D. Letterman.

37 US EPA's Surface Water Treatment Rule (SWTR) http://www.epa.gov April 2, 2001.

38 http://almashriq.hiof.no/lebanon/600/610/614/solar-water/unesco/35-46.html page1

39 Potter's for Peace website (http://www.cc.cc.ca.us/pfp/Pfpfilter.htm) April 15, 2001

40 Ceramiques d'Afrique website (http://www.geocities.com/ceramafrique) February 14, 2001

41 USEPA Reseach Plan for Microbial Pathogens and Disinfection By-Products in Drinking Water, November, 1997.

42 Schulz, C.R. and D.A. Okum 1984. Surface Water Treatment for Communities in Developing Countries. John Wiley and Sons, New York.

43 Ritenour, R. BioSand Household Water Filter: A Transfer of Slow Sand Filtration Technology to Developing Countries. Samaritan's Purse. 3rd Edition, May 1998.

44 Sagara, J. Study of Filtration for Point-of-Use Drinking Water Treatment in Nepal. Master thesis, Massachusetts Institute of Technology. 2000.

45 Ibid

46 Personnal Communication with Ken Drury, Corning Corporation.

47 Corning CerCor Filter Product Literature, 1999

48 Ibid

49 Harvard University. The Arsenic Project website. November 3, 2000. http://phys4.harvard.edu/~wilson/arsenic_project_introduction.html

50 Khan, A. H., Rasul, S.B., Munir, A. K. M., Habibuddowla, M., Alauddin, M., Newaz, S. S., Hussam, A. "Appraisal of a Simple Arsenic Removal Method for Groundwater of Bangladesh." Journal of Environmental Science and Health. A35(7), 1021-1041 (2000).

51 Ibid

52 Nikolaidis, N. P., Lackovic, J., and Dobbs, G. "Arsenic Remediation Technology – AsRT" Environmental Research Institute. Internet: www.eng2.uconn.edu/~nikos/arst-brochure.html. Available November 14, 2000.

53 Khan, A. H., Rasul, S.B., Munir, A. K. M., Habibuddowla, M., Alauddin, M., Newaz, S. S., Hussam, A. "Appraisal of a Simple Arsenic Removal Method for Groundwater of Bangladesh." Journal of Environmental Science and Health. A35(7), 1021-1041 (2000).

54 Hemond, H. and Fechner-Levy, E. J. Chemical Fate and Transport in the Environment 2nd Edition. 2000. Academic Press, San Diego, California.

55 Khan, A. H., Rasul, S.B., Munir, A. K. M., Habibuddowla, M., Alauddin, M., Newaz, S. S., Hussam, A. "Appraisal of a Simple Arsenic Removal Method for Groundwater of Bangladesh." Journal of Environmental Science and Health. A35(7), 1021-1041 (2000).

56 Ibid

57 Stevn Klein (President of Connelly-GPM, Inc.). Email correspondence. April 2001.

58 Khan, A. H., Rasul, S.B., Munir, A. K. M., Habibuddowla, M., Alauddin, M., Newaz, S. S., Hussam, A. "Appraisal of a Simple Arsenic Removal Method for Groundwater of Bangladesh." Journal of Environmental Science and Health. A35(7), 1021-1041 (2000).

59 Ramaswami, A., Isleyen, M., Tawachsupa, S. "Low-Cost Sorbents for Treatment of High Arsenic Waters." Submitted for publication in April, 2001.

60 Nikolaidis, N. P., Lackovic, J., and Dobbs, G. "Arsenic Remediation Technology – AsRT" Environmental Research Institute. Internet: www.eng2.uconn.edu/~nikos/arst-brochure.html. Available: November 14, 2000.

61 Lackovic, J. A., Nikolaidis, N. P., Dobbs, G. M. "Inorganic Arsenic Removal by Zero-Valent Iron." Environmental Engineering Science. 17(1), 29-39 2000.

62 Ramaswami, A. Email contact. April 2001.

63 Ibid

64 Ramaswami, A. Iron Filings in Jerry Can. "Fact Sheet" submitted to Susan Murcott. 2000.

65 Ramaswami, A. Email correspondence. February 2001.

66 DWSS sanitation workers. Personal interview in Kavre district of Nepal. January 2001.

67 Apyron Technologies, Inc. Technical Description of the Aqua-Bind™ Media for Arsenic Removal. 2000.

68 Apyron Technologies, Inc. ATU Installation Instructions. Undated.

69 Ibid

70 Ibid

71 Apyron Technologies, Inc. Technical Description of the Aqua-Bind™ Media for Arsenic Removal. 2000.

72 Wegelin, M. et al "Solar Water disinfection: Scope of the Process and Analysis of Radiation Experiments" J Water SRT-Aqua, 1994, 43, No.3 154-169.

73 Wegelin, P. SODIS Technical Notes, 1998, http://sodis.ch , February 10, 2001.

74 Ibid

75 Ibid

---

[76] Ibid
[77] Ibid
[78] NASA Langley Atmospheric Science Data Center NASA Surface Meteorology and Solar Data Set http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi March 20, 2001
[79] Oates, P Solar Disinfection in Haiti Master thesis, Massachusetts Institute of Technology. 2000
[80] Wegelin
[81] (SODIS Technical notes, 1998)
[82] Feuerstein, Marie-Therese, Partners in Evaluation: Evaluating Development and Community Programmes with Participants (London: Macmillan, 1986)
[83] Lee, Tse Luen, personal interview, Jan. 2001
[84] Moran, Kerry, Nepal Handbook, 3rd ed., (Emeryville, CA: Avalon, 1999)
[85] Mohamed, Farzana, personal interview, Mar. 2001
[86] Ibid
[87] Allen, Carin, personal interview, Dec. 2000
[88] VanDerslice, James and Briscoe, John, “All Coliforms Are Not Created Equal: A Comparison of the Effects of Water Source and in-House Water Contamination on Infantile Diarreal Disease,” Water Resources Research, Vol. 29, No. 7, Pp 1983-1995, July, 1993
[89] Ibid