

Point-of-Use Arsenic Removal from Drinking Water in Nepal
Using Coagulation and Filtration

by

Soon Kyu Hwang

B. S. Civil and Environmental Engineering
The University of Kansas, 2001

Submitted to the Department of Civil and Environmental Engineering in Partial
Fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING IN CIVIL AND ENVIRONMENTAL ENGINEERING

at the


MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2002

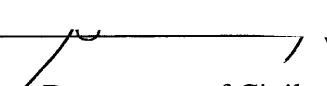
© 2002 Soon Kyu Hwang. All Rights Reserved.

*The author hereby grants to MIT permission to reproduce and to distribute publicly paper
and electronic copies of this thesis document in whole or in part.*

Signature of Author: _____

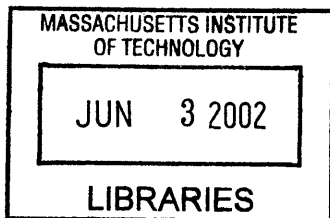

Soon Kyu Hwang
Department of Civil and Environmental Engineering
May 17, 2002

Certified by: _____


Susan E. Murcott
Lecturer, Department of Civil and Environmental Engineering
Thesis Supervisor

Accepted by: _____


Oral Buyukozturk
Chairman, Departmental Committee on Graduate



BARKER

Point-of-Use Arsenic Removal from Drinking Water in Nepal Using Coagulation and Filtration

by

Soon Kyu Hwang

Submitted to the Department of Civil and Environmental Engineering in
Partial Fulfillment of the Requirements for the Degree of
Master of Engineering in Civil and Environmental Engineering

ABSTRACT

Arsenic contamination of groundwater was discovered in the Terai, the southern region of Nepal, in the late 1990's. This poses a serious public health risk as the majority of the population in the region relies on tubewell water as the main source their water. In order to address the problem, a non-governmental organization, the Environment and Public Health Organization (ENPHO) in Nepal, has been working to find a solution by providing a cost effective arsenic treatment system that can be implemented at the household level. In 2001, ENPHO has started distributing one such treatment system that utilizes coagulation and filtration as a treatment technique as a part of a large-scale pilot program.

The purpose of this study, conducted in Nepal and in the United States from January to April, 2002 as part of the 2001-2002 Nepal Water Project, was to evaluate the ENPHO Arsenic Removal System on the basis of technical performance while considering the cost as well as social acceptability.

Initial field evaluation in Nepal showed that the ENPHO Arsenic Removal System, prior to recent modifications in coagulant dose and procedure made by ENPHO, could not achieve adequate arsenic removal from the arsenic contaminated drinking well water, mainly due to insufficient coagulant dose. However, additional evaluation showed that with the modified coagulant dose and procedure, the ENPHO Arsenic Removal System is able to reliably reduce arsenic concentrations below the interim Nepali Standard of 50 $\mu\text{g/L}$. Further investigations in the U.S. indicated that the modified coagulant dose seems to be appropriate. In addition, experimental results showed that it may be possible to modify the procedure in order to improve the usability of the system without significantly sacrificing arsenic removal efficiency.

Thesis Supervisor: Susan Murcott

Title: Lecture, Department of Civil and Environmental Engineering

ACKNOWLEDGEMENTS

I would like to thank my advisor, Susan Murcott, for her guidance throughout this project.

I would also like to thank all the wonderful people who took part in the 2001-2002 MIT Nepal Water Project, including Jason Low, Xuan Gao, Luca Morganti Heather Lukacs, and Hanna Sullivan, and especially, the members of the arsenic group, Barika Poole and Tommy Ngai for making this experience an unforgettable one.

I would like to extend my sincere gratitude to all the ENPHO staff for their hospitality while we were in Nepal.

Finally, I would like to thank my family and friends who provided me support and encouragement throughout the year.

TABLE OF CONTENTS

ABSTRACT	2
1.0 INTRODUCTION.....	8
1.1 MIT NEPAL WATER PROJECT	8
1.2 ARSENIC IN NEPAL	8
1.3 EXTENT OF ARSENIC CONTAMINATION IN NEPAL	9
2.0 ARSENIC BACKGROUND	12
2.1 SOURCES OF ARSENIC	12
2.2 HEALTH EFFECTS OF ARSENIC	13
2.3 ARSENIC CHEMISTRY	15
2.4 ARSENIC MOBILITY IN GROUNDWATER	17
3.0 POINT-OF-USE ARSENIC REMOVAL	19
3.1 GOAL OF THE STUDY	19
3.2 ENPHO ARSENIC REMOVAL SYSTEM.....	20
3.3 REVIEW OF CURRENT TECHNOLOGIES IN USE	25
3.3.1 <i>Bucket Treatment Unit</i>	25
3.3.2 <i>Household Coagulation and Filtration System</i>	27
3.3.3 <i>Co-precipitation With Naturally Occurring Iron</i>	28
4.0 ARSENIC REMOVAL USING COAGULATION.....	30
4.1 ARSENIC REMOVAL MECHANISM.....	30
4.2 IMPORTANT FACTORS AFFECTING ARSENIC REMOVAL EFFICIENCY	31
4.2.1 <i>Arsenic Speciation</i>	31
4.2.2 <i>Coagulant Type and Dose</i>	32
4.2.3 <i>Competing Ions Effect</i>	34
4.2.4 <i>Mixing</i>	35
5.0 EXPERIMENTAL PROCEDURES AND ANALYTICAL METHODS.....	37
5.1 DESCRIPTION AND SCOPE OF EXPERIMENTS	37
5.2 FIRST PHASE EVALUATION.....	38
5.2.1 <i>Field Evaluation in Parasi</i>	38
5.2.2 <i>Laboratory Experiments</i>	39
5.3 SECOND PHASE EVALUATION.....	41
5.4 ANALYTICAL METHODS	42
5.4.1 <i>Arsenic Analysis</i>	42
5.4.1.1 <i>Field Test Kit</i>	43
5.4.1.2 <i>Atomic Absorption Spectrometry</i>	44
5.4.1.2 <i>Sample Preservation</i>	46
5.4.2 <i>Membrane Filtration Test</i>	46
5.4.3 <i>Turbidity, Iron and pH Measurements</i>	47
6.0 RESULTS AND DISCUSSION.....	48

6.1 RESULTS FROM FIRST PHASE EVALUATION.....	48
6.1.1 Parasi Field Test Results	48
6.1.2 ENPHO Laboratory Test Results	48
6.1.2.1 Arsenic Test Results.....	48
6.1.2.2 Microbial Test Results	51
6.1.2.3 Filter Flow Rate Measurements	51
6.2 RESULTS OF SECOND PHASE EVALUATION.....	51
7.0 SLUDGE DISPOSAL	57
8.0 CONCLUSION.....	60
REFERENCES	63
APPENDIX A	66
APPENDIX B.....	68
APPENDIX C	75

LIST OF TABLES

TABLE 1-1: SUMMARY OF ARSENIC SURVEY CONDUCTED TO DATE	10
TABLE 2-1: DISSOCIATION CONSTANTS FOR ARSENATE AND ARSENITE.....	15
TABLE 3-1: SUMMARY OF CHEMICALS USED BY ENPHO ARSENIC REMOVAL SYSTEM.....	22
TABLE 3-2: ENPHO ARSENIC REMOVAL SYSTEM COST SUMMARY.....	24
TABLE 3-3: ARSENIC CONCENTRATIONS OF SOURCE WATER IN BTU STUDY.....	26
TABLE 3-4: ARSENIC CONCENTRATIONS OF TREATED WATER IN BTU STUDY.....	26
TABLE 5-1: CHEMICAL MAKEUP OF THE ORIGINAL PACKETS FOR THE TREATMENT OF 20 LITERS OF WATER	38
TABLE 5-2: ADJUSTED CHEMICAL COMPOSITION FOR THE TREATMENT OF 10 LITERS OF WATER.....	40
TABLE 6-1: PARASI FIELD TEST RESULTS.....	48
TABLE 6-2: ARSENIC TEST RESULTS FROM ENPHO LABORATORY TESTS	49
TABLE 6-3: WATER CHARACTERISTICS OF UNTREATED WATER DURING ENPHO LABORATORY TESTS	50
TABLE 6-4: TREATED WATER CHARACTERISTICS FROM ENPHO LABORATORY TESTS.....	50
TABLE 6-5: RESULTS OF MEMBRANE FILTRATION TEST FOR FECAL COLIFORM.....	51
TABLE 6-6: SOURCE WATER CHARACTERISTICS IN PEPPERELL, MA AND SALEM, NH.....	52
TABLE 6-7: COAGULANT CONCENTRATIONS USED DURING SECOND PHASE STUDY	52
TABLE 6-8: PEPPERELL FIELD TEST RESULTS	52
TABLE 6-9: SALEM FIELD TEST RESULTS	53

LIST OF FIGURES

FIGURE 1-1: MAP OF NEPAL.....	9
FIGURE 2-1: HANDS OF ARSENICOSIS PATIENT	14
FIGURE 2-2: SOLUBILITY DIAGRAMS FOR AS(III) AND AS(V)	16
FIGURE 2-3: ARSENIC SPECIATION AND E_H /PH CONDITIONS.....	16
FIGURE 3-1: ENPHO ARSENIC REMOVAL SYSTEM	21
FIGURE 3-2: CHEMICALS IN A 20-LITER PLASTIC BUCKET	22
FIGURE 3-3: INSTRUCTIONAL PAMPHLET USED BY ENPHO	23
FIGURE 4-1: IRON HYDROLYSIS PRODUCTS.....	30
FIGURE 4-2: SOLUBILITIES OF ALUM AND FERRIC CHLORIDE	33
FIGURE 6-1: ARSENIC REMOVAL EFFICIENCY OBTAINED USING MODIFIED PROCEDURE AND REFORMULATED CHEMICAL COMPOSITION	49
FIGURE 6-2: ARSENIC REMOVAL EFFICIENCY WITH VARYING FERRIC CHLORIDE DOSES – PEPPERELL, MA.....	54
FIGURE 6-3: ARSENIC REMOVAL EFFICIENCY WITH VARYING FERRIC CHLORIDE DOSES – SALEM, NH.....	54
FIGURE 6-4: ARSENIC REMOVAL EFFICIENCY AFTER VARIOUS MIXING/SETTLING TIMES USING 80 MG/L $FeCl_3$ - PEPPERELL	55
FIGURE 6-5: ARSENIC REMOVAL EFFICIENCY AFTER VARIOUS MIXING/SETTLING TIMES USING 80 MG/L $FeCl_3$ – SALEM.....	56

1.0 Introduction

1.1 MIT Nepal Water Project

The Nepal Water Project is an on-going effort by a group of Master of Engineering students from Massachusetts Institute of Technology supervised by project advisor, Susan Murcott, to investigate ways to improve the quality of drinking water in Nepal. Since its inception in 1999, the teams from respective years have investigated the viability of implementing various household water treatment filters and disinfection options, including solar disinfection and household chlorination, as well as analyzing and documenting various water quality parameters.

During years 2001-2002, eight Master of Engineering students participated in the project with each member focusing on an individual project that culminated in a comprehensive group project report. This thesis is a product of one of the individual projects and is concerned with providing simple, household scale treatment solutions to the recently discovered problem of arsenic in the drinking water in the Terai region of Nepal.

1.2 Arsenic in Nepal

In the late 1990's, arsenic contamination of tubewell water was reported in Terai, the southern region of Nepal (Nepal National Arsenic Steering Committee, 2001). Due to its proximity to West Bengal, India and Bangladesh, where high levels of naturally occurring arsenic in drinking water from wells have caused a public health crisis, the groundwater in the region had been suspected of being contaminated with arsenic.

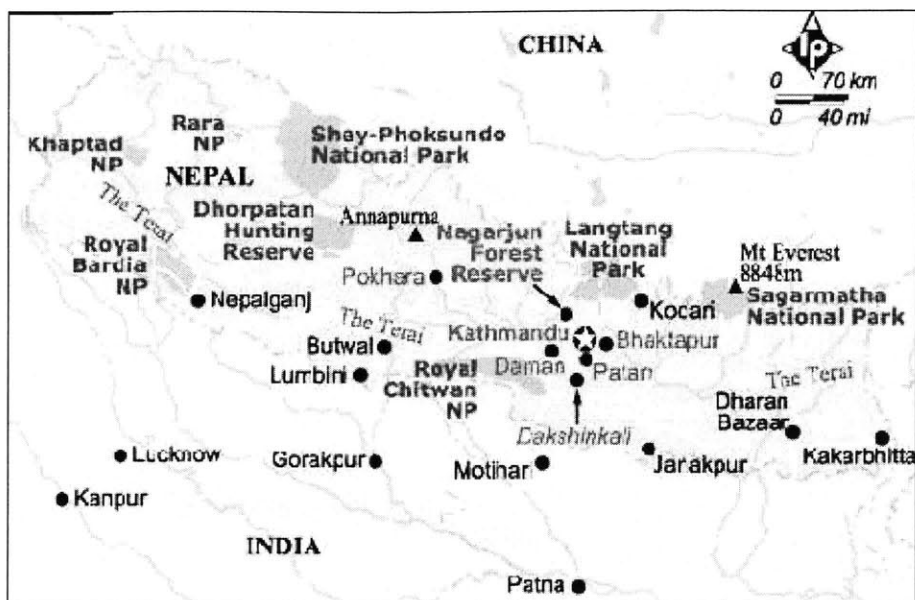


Figure 1-1: Map of Nepal

Arsenic is a toxic substance that occurs naturally in the environment. In addition to being a carcinogen, chronic exposure to high levels of arsenic through drinking contaminated water can cause damaging health effects such as hyperpigmentation, muscle spasms, hypotension, and cardiovascular collapse (World Health Organization, 2001). Because of these adverse health effects, the World Health Organization (WHO) had previously established a recommended guideline of 10 micrograms per liter (μL) or parts per billion (ppb). Bangladesh has adopted a standard of 50 micrograms per liter, which is the interim standard in the case of Nepal (Nepal National Arsenic Steering Committee, 2001).

1.3 Extent of Arsenic Contamination in Nepal

The exact extent of arsenic contamination of drinking well water in Nepal is not well known. However, various non-governmental organizations, including the Environment

and Public Health Organization (ENPHO)[♦], have analyzed water samples from tubewells in the Terai, and have found that out of approximately 4,200 wells tested so far, about 4% contain arsenic content greater than 50 µg/L, the interim Nepali standard (Nepal National Arsenic Steering Committee, 2001).

Table 1-1: Summary of arsenic survey conducted to date

District	Source of data	Number of wells tested	% of samples with arsenic concentrations		Maximum concentration detected (µg/L)
			> 10 µg/L < 50 µg/L	> 50 µg/L	
Jhapa	DWSS/NRCS	34	34	0	36
Morang	DWSS	101	9	0	50
Sunsari	DWSS/NRCS	92	10	2	75
Saptari	NRCS	250	27	0	29
Udayapur	NRCS	3	0	0	5
Dhanusha	NRCS	11	0	1	14
Mahottari	NRCS	2	0	0	5
Sarlahi	NRCS	251	30	1	44
Rautahat	NRCS	526	260	87	146
Bara	NRCS	615	62	12	102
Parsa	NRCS	665	71	9	158
Chitwan	NRCS	15	0	0	7
Nawalparasi	NRCS	432	191	41	205
Rupandehi	NRCS	236	32	8	303
Kapilbastu	NRCS	209	28	2	56
Banke	NRCS/FINNIDA	190	15	5	165
Bardiya	NRCS	182	58	5	160
Total		4167	~ 20	~ 4	

(Nepal National Arsenic Steering Committee, 2001)

Further studies conducted by Nepal Red Cross Society (NRCS) and the Japanese Red Cross Society have found that 17% of 1,990 samples taken from seventeen districts in the Terai contained arsenic level exceeding the WHO guideline (Hurd, 2001). Particularly, the district of Rautahat had high occurrences of arsenic contamination. A follow-up study by the Nepal Department of Water Supply and Sewerage (DWSS) found

[♦] ENPHO is an NGO operating in Nepal that provides environmental services

that 39% of 89 samples in one study and 53% of 32 samples in another study had arsenic concentration exceeding 10 µg/L (Hurd, 2001). A brief summary of field arsenic studies that have been conducted to date is shown in Table 1-1.

2.0 Arsenic Background

2.1 Sources of Arsenic

Arsenic is a well known toxic semi-metal, ranking 52nd in natural abundance among the elements present in earth's crustal rocks. It may be present in the common ore, arsenopyrite (FeAsS), and other minerals such as realgar (As_2S_2), orpiment (As_2S_3), and arsenic trioxide (As_2O_3). Occasionally, arsenic may be present in nature in its pure elemental form.

Arsenic has many agricultural and industrial uses. In the past, inorganic forms of arsenic have commonly been used in the production of insecticides, herbicides, and silvicides (Gulledge and O'Connor, 1973). Lead arsenate and calcium arsenate are highly toxic insecticides that were commonly produced in the United States from the early 1900's until the advent of organic pesticides in the post World War II era. It is estimated that the use of lead and calcium arsenate during its peak usage period in the 1930's and 1940's averaged approximately 50,000,000 pounds of each annually (Metcalf, 1962). Production and use of these chemicals have ceased due to their apparent deleterious effects on the environment. In more recent years, the production of organic arsenicals such as Disodiummethylarsenate (DSMA) and cacodylic acid has replaced many of the inorganic forms. The highly desirable biological properties of arsenic have enabled arsenic compounds to be used as medicines and wood preservatives. Some of the industries that use arsenic and its derivatives include glass manufacturing, paint, and electronics industry.

Arsenic contamination of surface water and groundwater can come from either anthropogenic or natural sources. Anthropogenic sources include effluents from industrial outfall and agricultural areas where arsenic based insecticides or herbicides were applied. Natural occurrence of arsenic comes from the dissolution of minerals and ores. Arsenic occurrence in Nepal is believed to be geogenic.

2.2 Health Effects of Arsenic

Chronic arsenic poisoning that occurs as result of a long-term exposure is very different from acute poisoning. Acute symptoms occur immediately, following ingestion of a large dose of arsenic. Acute poisoning typically includes vomiting, oesophageal and abdominal pain, and bloody “rice water” diarrhea. In severe cases, seizures, coma, or fatality is possible (World Health Organization, 2001).

Arsenic concentrations found in groundwater are relatively low (i.e. in the parts per billion range), and therefore not likely to cause acute poisoning. Rather, chronic symptoms will start to appear after a few years of continued low-level of arsenic exposure. The symptoms appear to differ between individuals, population groups and geographical areas. Thus, there is no universal definition of the disease caused by arsenic. In most cases, however, the first sign of chronic arsenic poisoning, known as arsenicosis, shows up as various skin ailments. These ailments include hypopigmentation and hyperpigmentation, and are collectively called melanosis by some physicians, and keratosis, or break up of the skin on hands and feet (see Figure 2-1).



Figure 2-1: Hands of arsenicosis patient

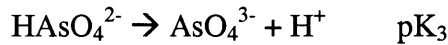
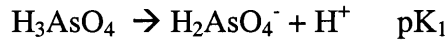
Most of health data concerning arsenicosis are the results of case studies from Taiwan, Chile and more recently in Bangladesh, where elevated levels (i.e., above 50 $\mu\text{g/L}$) of arsenic have been found in drinking water. Studies conducted in both Taiwan and Chile have found that after a latency of about 10 years, skin cancers can show up, and after a latency of 20 to 30 years, internal cancers - particularly bladder and lung cancers, can appear. In addition, various other symptoms including hypertension and cardiovascular disease, diabetes and reproductive effects have been reported in some studies (EPA, 2001).

The risk of arsenic poisoning through means other than ingestion is minimal. Absorption of arsenic through skin is minimal, and thus hand-washing, bathing, laundry, etc. with water containing arsenic do not pose a significant human health risk (World Health Organization, 2001).

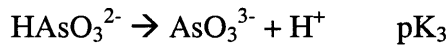
2.3 Arsenic Chemistry

Arsenic occurs in four oxidation states, semi-metallic (As 0), arsine (As -III), arsenate (As +V), and arsenite (As +III). The oxidation state at which it exists is dependent on the condition of environment in which it occurs. Soluble arsenic occurring in groundwater is almost exclusively in the form of arsenate and arsenite, which have chemical formulas, H_3AsO_4 and H_3AsO_3 , respectively. Hydrogen atoms in both species dissociate leading to the formation of various anions.

Arsenate, H_3AsO_4 , dissociates to form $H_2AsO_4^-$, $HAsO_4^{2-}$, and AsO_4^{3-} :



Arsenite, H_3AsO_3 , dissociates to form $H_2AsO_3^-$, $HAsO_3^{2-}$, and AsO_3^{3-} :



The propensity for this ionization process to take place is described by dissociation constant, pKa, values (see Table 2-1).

Table 2-1: Dissociation constants for arsenate and arsenite

	pK ₁	pK ₂	pK ₃
Arsenate H_3AsO_4	2.19	6.94	11.5
Arsenite H_3AsO_3	9.2	14.22 ⁽¹⁾	19.22 ⁽¹⁾

Values extrapolated from the strength of oxygen acid rules (Pauling, 1970)

The pKa values are expressed as a negative log. Therefore, smaller pKa values indicate higher degrees of dissociation. Various ionic forms of arsenate and arsenite are illustrated in Figure 2-2.

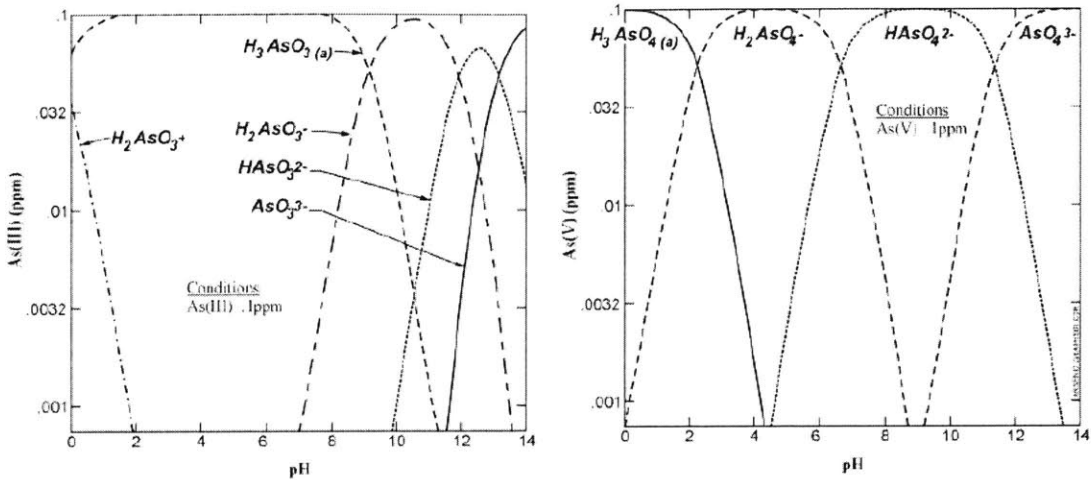


Figure 2-2: Solubility diagrams for As(III) and As(V) (Fields et al., 2000)

The dominant arsenic species present in water is a function of both its pH and oxidation-reduction (redox) potential, Eh. This relationship is graphically illustrated in Figure 2-3.

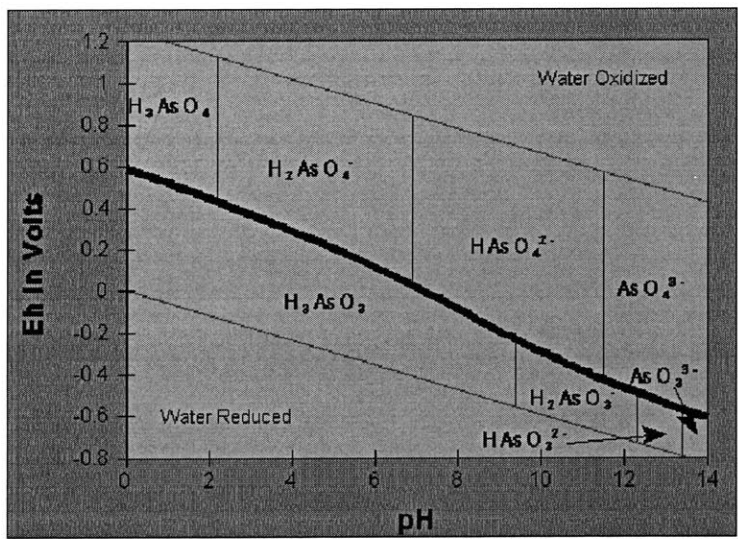


Figure 2-3: Arsenic speciation and E_h/pH conditions (Vance, 2001)

2.4 Arsenic Mobility in Groundwater

Arsenic mobility in groundwater systems is mainly governed by adsorption and desorption processes. Attachment of arsenic to an iron oxide surface is an example of an adsorption reaction. The reverse of this reaction, arsenic becoming detached from such a surface, is an example of desorption reaction.

Arsenic adsorption and desorption reactions are influenced by changes in pH, occurrence of reduction/oxidation or redox reactions, presence of competing ions, and solid-phase structural changes at the atomic level. Because arsenic is a redox sensitive element, it may be present in a variety of redox states, as previously discussed. Arsenate predominates under oxidizing conditions, whereas arsenite predominates when the condition becomes sufficiently reducing. Under the pH conditions that prevail in most groundwater, arsenate is present as negatively charged oxyanions, whereas arsenite is present as the uncharged species. The strength of adsorption and desorption reactions between these different arsenic species and solid-phase surfaces in aquifer differs, in part, because of these differences in charge. Arsenite and arsenate adsorb to surfaces of a variety of aquifer materials including iron oxides, aluminum oxides, and clay minerals. Adsorption and desorption reactions between arsenate and iron oxide surfaces are particularly important controlling reactions because iron oxides are widespread in the hydrogeologic environment as coatings on other solids, and arsenate adsorbs strongly to iron-oxide surfaces in acidic and near-neutral pH water (Waychunas et al., 1993). Arsenite, to a lesser extent, is also adsorbed onto iron-oxide surfaces, and both arsenate and arsenite adsorb to aluminum oxides and clay mineral surfaces. In all cases, the tendency for arsenic species to adsorb/desorb is sensitive to the pH.

Arsenic Background

Because of pH dependence of arsenic adsorption and desorption, changes in ground-water pH can promote adsorption or desorption of arsenic. In the same way, redox conditions can control dissolved arsenic concentration by their effects on arsenic speciation, and thus, arsenic adsorption and desorption. For instance, reduction of arsenate to arsenite can lead to increased arsenic mobility in the groundwater because arsenite is less strongly adsorbed than arsenate

3.0 Point-of-Use Arsenic Removal

3.1 Goal of the Study

Various technologies can be used to remove arsenic from the contaminated water. The most common methods include: coagulation and co-precipitation using various coagulants, adsorption onto activated alumina, ion exchange, and membrane processes such as nanofiltration and reverse osmosis. These processes achieve arsenic removal through physical and/or chemical mechanisms. Implementing a suitable point-of-use treatment technology is a challenge in rural Nepal either because of prohibitive cost of implementing such treatment options or simply from the lack of the needed materials.

The purpose of this study has been to evaluate the effectiveness of the ENPHO Arsenic Removal System to determine if it is an appropriate for implementation at the household level in Nepal. In evaluating the viability of the ENPHO Arsenic Removal System, three assessment criteria were considered. These include technical performance, social acceptability, and cost.

Evaluation Criteria

Current international standards for arsenic in drinking water range from 10 to 50 $\mu\text{g/L}$. These standards are based on the toxicity of the chemical and its effects on human health. Nepal has adopted an “interim” standard of 50 $\mu\text{g/L}$. For the purpose of this study, the technical performance is measured by the system’s ability to meet the interim Nepali standard. In addition to arsenic removal efficiency, the system’s ability to provide sufficient treated water quantity for drinking and cooking needs, and safety and disposal issues related to sludge that results from the treatment were considered.

The second criterion used to evaluate an appropriate arsenic remediation technology is that the system has to be socially acceptable to the users in rural Nepal. The primary users of the treatment system will be rural village women who are poorly educated. On average, the illiteracy rate among women in Nepal is 76% (The World Bank Group, 2002). Furthermore, Nepali women engage in heavy agricultural labor in addition to housekeeping responsibilities. Therefore, an “appropriate” technology would use a relatively simple procedure for operation and maintenance and place minimal burden on the users.

The final evaluation criterion is the economic feasibility of implementing the selected technology for use. Nepal is one the poorest countries in the world, having a Gross National Income per capita of \$ 220 (The World Bank Group, 2000). Therefore, it is important that the unit be evaluated for its cost effectiveness. The cost would involve initial capital cost to obtain a unit and additional costs associated with operation and maintenance of the unit to keep the unit functioning properly. One other factor related to economic feasibility is the local availability of materials make up any given arsenic remediation system.

3.2 ENPHO Arsenic Removal System

Starting in 2001, with funding from the Japan Red Cross and in collaboration with the Nepal Red Cross, ENPHO began distributing coagulation and filtration-based household arsenic removal system as a pilot program. The plan calls for distribution of approximately 1,000 ENPHO Arsenic Removal Systems to people who are in the highest risk group from arsenic contaminated wells. This group of people has been identified by

ENPHO through well sampling and health surveys conducted throughout various towns and villages in the Terai region. Households using well water contaminated with high concentrations of arsenic for drinking purposes and households found to have member(s) showing signs of arsenic poisoning are identified as the high risk group.

Arsenic removal is achieved with the ENPHO system by using coagulation and co-precipitation followed by filtration. Arsenic removal through coagulation and co-precipitation using ferric chloride as the coagulant has several advantages over other arsenic treatment technologies in that the materials needed are readily available and relatively inexpensive.

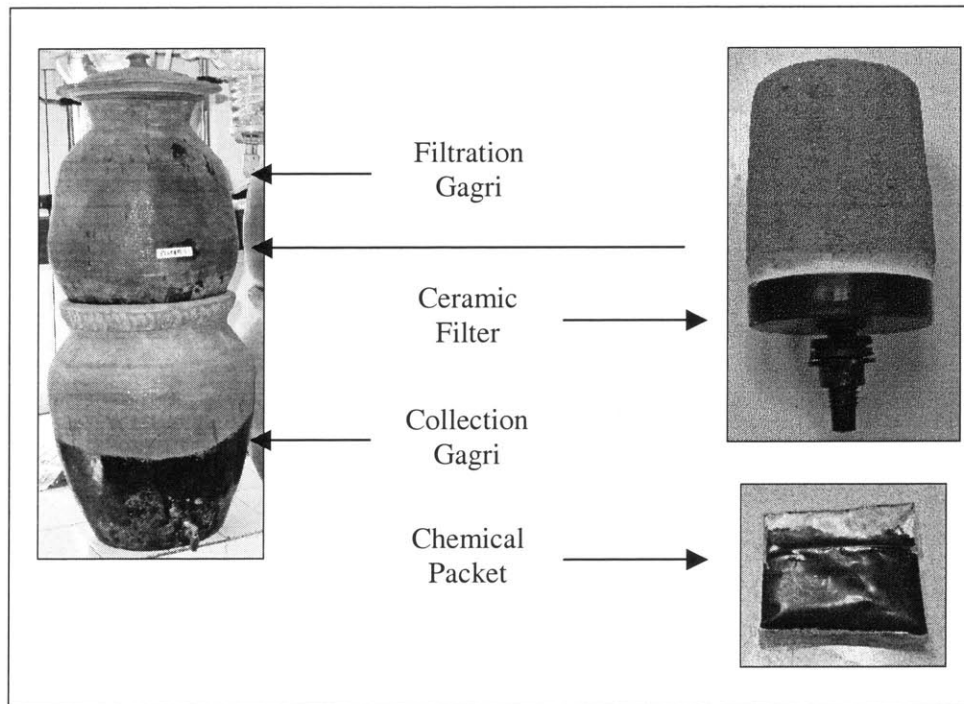


Figure 3-1: ENPHO Arsenic Removal System

The filter is locally manufactured in Thimi, Nepal, and chemicals needed are readily available from supply stores in Kathmandu. The system consists of a 20 liter plastic mixing bucket, a filtration unit consisting of a gagri, a local term for a round shaped

ceramic water collection or storage vessel, with a ceramic filter, and a collection unit consisting of another gagri (see Figure3-1).

ENPHO’s suggested procedure for using the system is as follows: first, a plastic sealed packet containing ferric chloride, charcoal powder, and sodium hypochlorite is added in to a bucket containing 20 liters of collected well water (see Figure 3-2). The water is stirred several times intermittently (approximately every thirty minutes) for 2-hour duration. After allowing the solids to settle, the water is poured into the top gagri, which contains the filter. The treated water then trickles down through the filter into the bottom collection gagri.



Figure 3-2: Chemicals in a 20-liter plastic bucket

Each chemical packet weighs 4 grams and is used to treat 20 liters of contaminated water. The packet contains a 1:1 ratio, by weight, of ferric chloride and charcoal powder and 800 milliliters of 8% sodium hypochlorite solution. Table 3.1 lists each constituents and the main functions it serves.

Table 3-1: Summary of chemicals used by ENPHO Arsenic Removal System

	Quantity (per 20L water)	Concentration (mg/L)	Main Function
8% Sodium Hypochlorite (NaOCl) Solution	0.8 milliliters	1.5 mg/L Cl ₂	Oxidant
Ferric Chloride (FeCl ₃)	1.6 grams	80 mg/L	Coagulant/Co-precipitant
Charcoal Powder	1.6 grams	80 mg/L	Adsorbent

Hypochlorite is used as an oxidant to facilitate the oxidation of arsenite to arsenate as arsenate is more effectively removed than arsenite. In addition, hypochlorite significantly reduces the microbial contamination of treated water (see Section 6.1). The charcoal powder is used as an adsorbent. It removes residual chlorine resulting from the use of hypochlorite and helps reduce other contaminants in the water. Finally, a locally manufactured ceramic filter is used to filter the treated water.

As mentioned previously, ENPHO is currently in the process of distributing approximately 1,000 units to various households. Each household is given a filtration unit, a collection gagri, and a year supply of chemical packets. ENPHO's trained field personnel then gives both verbal instruction as well as a demonstration on how to use the system. Instructional pamphlets are also used to educate the users (see Figure 3-3).

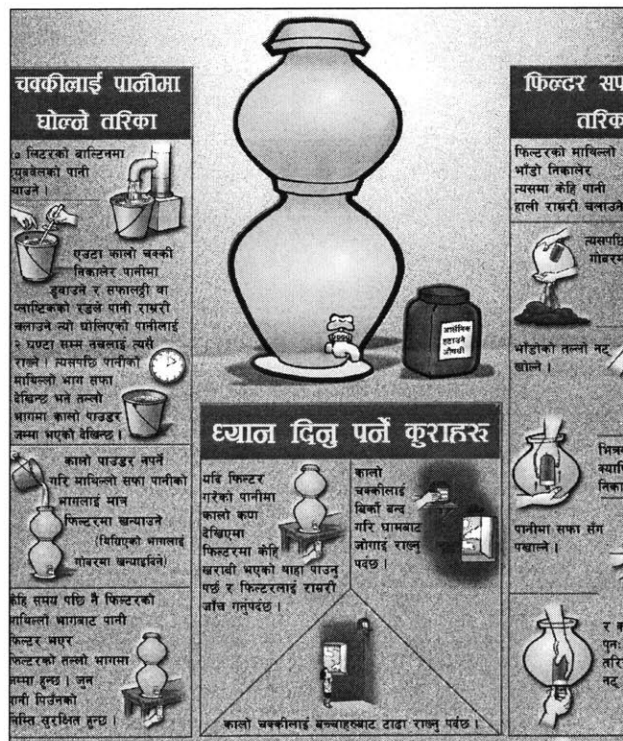


Figure 3-3: Instructional pamphlet used by ENPHO

ENPHO's procedure for training households in the use of this system is as follows:

1. Collect approximately 20 liters of water in a bucket.
2. Pour the contents of 1 packet of chemicals into the collected water.
3. Stir vigorously using a wooden stirring rod for approximately 1 minute to achieve thorough mixing.
4. Allow to settle for 30 minutes and then stir again in a similar manner for 1 minute, and repeat the same procedure every 30 minutes until 2 hours have passed since the initial mixing, but not stirring at the 2 hour mark.
5. Pour the supernatant water into the filtration unit and dispose of the sludge into cow dung.
6. Collect the treated water from the spigot of the collection unit and use this water for drinking and cooking.

Cost Consideration

The cost of ENPHO Arsenic Removal System is summarized in Table 3-2. The initial capital cost for the system includes two gagris (filtration and collection unit), and the 20-liter capacity plastic bucket, the total cost of which is NRs. 425 or US \$7. The cost of a year's supply of chemicals is NRs. 730 or US \$ 9.70.

Table 3-2: ENPHO Arsenic Removal System cost summary

	Cost in Nepali Rupees	Cost in US Dollars
Filtration & Collection Gagris, and Terracotta Filter	NRs. 325	\$ 4.30
20-Liter Capacity Plastic Bucket	NRs. 200	\$ 2.70
1 Year Supply of Chemical Pouches	NRs. 2 / each x 365 = NRs. 730	\$ 9.70
Total Cost (First Year/Subsequent Years)	NRs. 1,255 / NRs. 730	\$ 16.70 / \$ 9.70

(Currency conversion uses exchange rate as of January 2002)

3.3 Review of Current Technologies in Use

On account of a much more extensive problem of arsenic contamination of groundwater in Bangladesh, many household arsenic removal technologies have been tested and implemented in Bangladesh with varying degrees of success. Several of these household scale technologies share similarities to the ENPHO Arsenic Removal System, and therefore, are pertinent to this study. A few of these technologies will be discussed in this section

3.3.1 Bucket Treatment Unit

The Bucket Treatment Unit (BTU), developed by DANIDA, a Danish aid agency operating in Bangladesh, has been promoted by various organizations in Bangladesh (Tahura et al, 2001). Despite the wide-spread use of the technology until 2000, no extensive study had been carried out, prompting, NGO Forum for Drinking Water Supply and Sanitation to conduct a large scale evaluation study in the Manikgonj District (Tahura et al., 2001).

The BTU system combines different water treatment processes. The first stage of the chemical process is pre-oxidation of arsenite (As III) to arsenate (As V) by an oxidant, potassium permanganate, followed by coagulation and co-precipitation using the coagulant, alum, $\text{Al}_2(\text{SO}_4)_3$. This is followed by sedimentation and filtration. The doses of potassium permanganate and alum are 2 mg/L and 200 mg/L, respectively. The BTU consists of two 20-liter plastic buckets. In order to use the system, the water is collected into the first 20-liter bucket. Chemicals composed of 4 g of powdered alum and 40 mg of potassium permanganate are added, and the water is stirred with a wooden spoon. The

bucket is then covered with a lid and precipitates are then allowed to settle for three hours. Then, the water is poured into the other 20-liter bucket, which contains the sand media. The treated water is collected via a plastic pipe located in the lower end of the bucket (Tahura et al., 2001).

During the 2000 study, the Bucket Treatment Unit was distributed to 60 different households. Samples of source water and treated water were collected 3 times over the duration of 78 days. Out of these 60 selected households, 29 used well water having arsenic concentrations between 50 µg/L and 100 µg/L, 21 between 101 µg/L and 200 µg/L, and 7 greater than 200 µg/L (see Table 3-3). The samples of treated water taken from these households through out the duration of the study are shown in the Table 3-4.

Table 3-3: Arsenic concentrations of source water in BTU study

As Concentrations (µg/L)	Number of Households	Minimum As Concentration (µg/L)	Maximum As Concentration (µg/L)	Mean As Concentration (µg/L)	Standard Deviation
50-100	29	50	98	74	14
101-200	21	109	192	149	32
> 200	10	250	580	353	123

(Tanhura et al., 2001)

Table 3-4: Arsenic concentrations of treated water in BTU study

As Concentrations (µg/L)	Number and percentage of households having respective arsenic concentrations after shown number of days since BTU installation		
	30 days	55 days	78 days
<= 50	55 (91.7%)	60 (100%)	58 (96.7%)
> 50	5 (8.3%)	0 (0%)	2 (3.33%)

(Tanhura et al., 2001)

In general, BTU was found to be effective in reducing arsenic concentration below 50 µg/L, the Bangladesh standard. In some cases when the source water arsenic concentration was high (i.e. above 500 µg/L), BTU was unsuccessful in reducing arsenic

concentration below the 50 $\mu\text{g/L}$ standard. While the BTU developers claim the system may be used using ferric chloride as the coagulant, it is uncertain why it has not been implemented insofar as ferric chloride has been found to be more effective in removing arsenic than alum on a weight basis and effective over a wider range of pH (see discussions in Chapter 4). Perhaps this is due to the lack of availability of ferric chloride, or perhaps this is due to alum having an economically advantage in Bangladesh.

3.3.2 Household Coagulation and Filtration System

Developed by Xiaoguang Meng of Stevens Institute of Technology, this system is similar to the BTU except for the choice of coagulant used. Conveniently sealed packets containing the coagulant, ferric chloride, are used with this system. The filters are made of 20-liter plastic buckets with a few inches of sand packed at the bottom of the filter. In order to use the system, 20 liters of well water is collected into the first bucket followed by addition of a packet of chemical. After the water is mixed, it is poured into the bucket filter and passes through the sand bed by gravity for the removal of the precipitates. The treated water is collected via a tube at the bottom of the bucket sand filter. This system was field tested in Bangladesh in 2000 with the help of Earth-Identity Project, an NGO in Bangladesh, who helped to distribute the units to 7 different households in Kachua, Thana, and Chandpur districts (Meng and Korfiatis, 2001).

During 35 days of demonstration study, the average arsenic concentrations in the untreated well water ranged from 87 to 313 $\mu\text{g/L}$. The average arsenic concentrations in the treated water ranged from 2 to 22 $\mu\text{g/L}$. The dose of ferric chloride used during the field study is uncertain. However, Meng noted that in order to reduce arsenic

concentration below 50 µg/L, the minimum of iron to arsenic (Fe/As) ratio of 40 is required (Meng and Korfiatis, 2001). Assuming an arsenic concentration of 300 µg/L in the source water, this would correspond to a minimum ferric chloride dose of approximately 35 mg/L. Another important finding from the field study was that the filter tended to become clogged by the precipitated solids easily, and the sand had to be either replaced or washed frequently. It is the author's opinion that this problem may be addressed by allowing the precipitates to settle and decanting only the supernatant into the sand filter.

3.3.3 Co-precipitation With Naturally Occurring Iron

In Bangladesh, the presence of arsenic in the tubewell water has been positively correlated to the presence of relatively high concentration of iron. It is estimated that approximately 65% of the area of Bangladesh contains dissolved iron concentrations in excess of 2 mg/L. In many areas, the concentration of dissolved iron is as high as 15 mg/L (Mamtaz and Bache, 2001). The presence of high concentrations of iron has the potential of providing a very low cost means of removing arsenic by co-precipitation and adsorption.

When dissolved iron comes in contact with air, it precipitates to form amorphous iron hydroxide, $\text{Fe}(\text{OH})_3$, which can then be used as a substrate for arsenic adsorption (see chapter 4 for detailed discussion of arsenic removal during precipitation of iron). In a laboratory test, provided that the iron concentration is sufficiently high (i.e. greater than 1.2 mg/L), Mamtaz and Bache (2001) were able to show that simply shaking a container and allowing the iron-arsenic complex to settle out for 3 days could reduce the

concentration of arsenic from 100 $\mu\text{g/L}$ to 50 $\mu\text{g/L}$. The proposed treatment scheme requires that 7 liter of water be collected into a 10-liter capacity container, leaving an air space. The container is shaken for 1 minute and then set aside for 3 days, allowing the particles to settle. The treated water is collected through a tap located slightly above the bottom of the container in order to prevent settled particles from being withdrawn with the treated water (Mamtaz and Bache, 2001).

This technology is certainly a simple technology that can be readily implemented since it is extremely inexpensive, amounting to nothing more than the cost of the 10-liter bucket. However, the conditions under which it can be used are limited, as presence of high concentrations of iron are required. Its applicability in Nepal needs to be assessed, as there is no data, as yet, to verify that the presence of arsenic is positively correlated with the presence of high levels of dissolved iron.

4.0 Arsenic Removal Using Coagulation

4.1 Arsenic Removal Mechanism

The main arsenic removal mechanism during coagulation treatment is primarily through co-precipitation and adsorption. When the metal salt, FeCl_3 is added to water, it dissociates to form trivalent ion, Fe^{3+} . The oxygen atoms of water molecules, H_2O , are strongly attracted to the highly positive metal ions and this leads to the formation of aquometal complexes, $\text{Fe}(\text{H}_2\text{O})_6^{3+}$. Due to high attraction forces between the metal salt and the oxygen molecules, the bond between the oxygen and hydrogen atoms in the six surrounding water molecules becomes weak and hydrogen atom gets release to the solution. This reaction is known as hydrolysis and the resulting ferric hydroxide species are called hydrolysis products (see Figure 4.1.1).

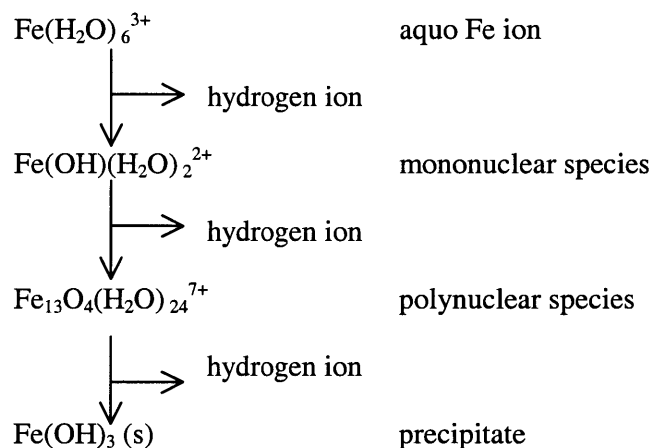


Figure 4-1: Iron hydrolysis products
(Letterman, 1991)

Precipitation of amorphous metal hydroxide, $\text{Fe}(\text{OH})_3$, is necessary for arsenic removal since its surfaces act as a substrate for arsenic adsorption during coagulation. The solubility of $\text{Fe}(\text{OH})_3$ is minimal at the pH of approximately 8. Dissolved inorganic

contaminants such as arsenic are removed during coagulation primarily through adsorption and subsequent co-precipitation. This process can be represented by the following representative chemical equation.



The exact products and stoichiometry of the above reaction are uncertain. Other mechanisms may also be involved (e.g., occlusion) as well. However, adsorption and co-precipitation are believed to be the dominant mechanisms (Ali and Hossain, 2000).

4.2 Important Factors Affecting Arsenic Removal Efficiency

There are several factors that effect arsenic removal efficiency during coagulation. Some of the important factors include, speciation of arsenic, coagulant type and dose, effect of competing ions, and type of mixing regime.

4.2.1 Arsenic Speciation

Many studies indicate that arsenate (As V) species are more effectively removed than arsenite (As III) species (Hering et al., 1997, Cheng et al., 1994). This effect is attributed to arsenate existing either as a monovalent anion, H_2AsO_4^- , or as a divalent anion, HAsO_4^{2-} , while arsenite is found in its uncharged form, H_3AsO_3 under most pH conditions. Since many removal processes including coagulation and co-precipitation, in which arsenic becomes bound or adsorbed on coagulant flocs, depend on the anionic nature of arsenic species, arsenite is much less readily removed. For this reason, oxidation of arsenite to arsenate may be necessary in order to effectively remove arsenic from water sources that contain high concentrations of arsenite. Ngai (2002) investigated

speciation of arsenic in groundwater in Nepal by analyzing approximately 37 samples taken from various tubewells located in the Terai region and have found that, in general, arsenate makes up about 20 percent and arsenite makes up 80 percent of total arsenic found in the samples. This indicates that it is important that arsenite be oxidized to arsenate prior to coagulation/co-precipitation treatment. The oxidation may be accomplished through aeration or through the addition of an oxidant such as bleaching powder, permanganate, or hypochlorite. Natural aeration may be used to oxidize arsenate to arsenite, but it is shown that this process may be too slow to have a practical use in a treatment scheme as Ngai has shown that the time required for the complete oxidation of arsenate to arsenite with simple aeration is in the order of magnitude of days (Ngai, 2002). Sodium hypochlorite, the oxidant used with the ENPHO Arsenic Removal System is an effective and widely used oxidant that is becoming readily available in Nepal.

4.2.2 Coagulant Type and Dose

It has been demonstrated by Hering (1997), Sheng (1973), and others that common coagulants, Ferric chloride (FeCl_3) and aluminum sulphate ($\text{Al}_2(\text{SO}_4)_3$), can be used to remove arsenic from drinking water. In all studies, however, when removal efficiency using ferric chloride was compared to using aluminum sulphate, ferric chloride showed much better removal efficiency on both weight and molar basis compared to its counterpart.

Alum, when added to water, undergoes similar chemical reactions as ferric chloride, forming aquometal complexes, which in turn, forms various hydrolysis products

including insoluble aluminum hydroxides, $\text{Al}(\text{OH})_3$. As discussed earlier, arsenic removal requires precipitation of this amorphous metal hydroxide as a substrate for arsenic adsorption. However, the range of pH where aluminum hydroxide solid is stable is much narrower than ferric hydroxide (see Figures 4-2 & 4-3). Therefore, metal hydroxide of iron (III) has lower solubility or greater stability of solid than that of aluminum over a wider range of pH. This makes ferric chloride more suitable as a coagulant when arsenic removal is required.

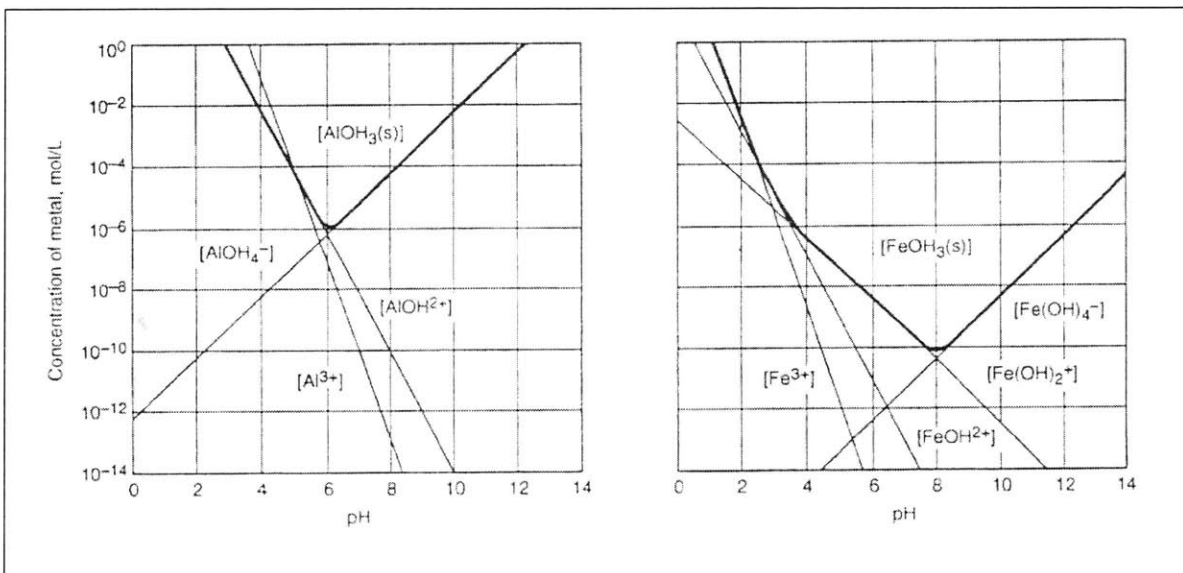


Figure 4-2: Solubilities of alum and ferric chloride
(Metcalf & Eddy, 1991)

In one of Hering's coagulation experiments, the relationship between coagulant doses and arsenic removal efficiencies was investigated (Hering et al., 1997). In order to achieve approximately 90% removal from water having spiked arsenic concentration of $20 \mu\text{g/L}$, $25 \mu\text{M}$ (4.9 mg/L) of ferric chloride (FeCl_3) was required whereas $60 \mu\text{M}$ (20.5 mg/L) of alum ($\text{Al}_2(\text{SO}_4)_3$) was required in order to achieve comparable removal rates. In this study, relatively low initial arsenic concentrations were used. In cases where source

water has much higher arsenic concentrations, the required doses of coagulants are expected to be much higher. The author's own experiments show that this is indeed the case (see Chapter 6.0).

4.2.3 Competing Ions Effect

It has been shown that high concentrations of competing anions in the source water can significantly lower the arsenic removal efficiency using coagulation (Meng and Korfiatis, 2001). It is believed that these ions compete with arsenate for the adsorption sites on the surface of the iron hydroxide formed through the addition of ferric salts, thus decreasing the adsorption capacity of the iron hydroxide for arsenate.

In Meng's study, arsenic removal efficiency using ferric chloride coagulation was compared by treating one arsenic contaminated source water having relatively high concentrations of phosphate and silicate and one source water having relatively low concentrations of phosphate and silicate. In these experiments, Bangladesh well water represented the water having high concentrations of phosphate and silicate (1.6-2.7 mg/L P and 14-20 mg/L Si) and water from a New Hampshire well represented the water having low concentrations of phosphate and silicate, (0.02 mg/L P and 6.6 mg/L Si). Both water sources had arsenic concentration of approximately 400 µg/L (Meng and Korfiatis, 2001).

Meng's results showed that in order to reduce arsenic concentration in the treated water to 50 µg/L, a 87.5% removal efficiency, approximately 60 mg/L of FeCl₃ was needed for the Bangladesh well water while only approximately 10 mg/L of FeCl₃ was needed for the New Hampshire well water. In addition, when phosphate and silicate

stock solutions were added to New Hampshire well water in order to spike the phosphate concentrations to match that of Bangladesh well water, the FeCl_3 dose required to reduce arsenic concentration to $50 \mu\text{g/L}$ was roughly the same as the previous dose that was required for the Bangladesh well water. In another experiment, when the source water was only subjected to spiked silicate concentration, the removal rate decreased moderately. On the other hand, when the source water was spiked only with phosphate, the removal efficiency was reduced to a much greater extent. At the applied coagulant dose of 15 mg/L FeCl_3 , a removal rate of about 80% was observed in the phosphate spiked water, while a removal rate of approximately 50% was observed for the silicate spiked water. Meng's findings indicate that the presence of phosphate and silicate in the Bangladesh well water were the major anions affecting the removal of arsenate by coagulation and co-precipitation with ferric chloride. In addition, he concluded that the presence of phosphate had a greater impact on the overall removal efficiency than the presence of silicate (Meng and Korfiatis, 2001). This suggests that the coagulant dose may need to be adjusted to account for additional coagulant that may be needed in order to account for the effects of competing ions when the source water contains high concentrations of these ions.

4.2.4 Mixing

Mixing of coagulants is important since in order to have efficient arsenic removal through co-precipitation, sufficient contact time between the ferric hydroxide precipitate and dissolved arsenic is required. Mixing in a conventional water treatment scheme, where mechanical mixing devices are used, is well characterized and can be reasonably

well replicated in the laboratory setting using jar tests. However, since mechanical mixing is not a feasible option in point-of-use water treatment in Nepal, manual mixing is used. The current procedure for using the ENPHO Arsenic Removal System recommends that the water be mixed several times intermittently over a 2-hour period to ensure sufficient mixing and contact time. The author has studied this effect using several mixing and settling patterns in this study.

5.0 Experimental Procedures and Analytical Methods

5.1 Description and Scope of Experiments

Experiments were carried out in two phases. The first phase of the experiments took place in Nepal and consisted of both field and laboratory experiments performed in the town of Parasi located in the Nawalparasi District in the Terai region and at the ENPHO laboratory in Kathmandu. The second phase of experiments were performed in field locations in Pepperell, Massachusetts and Salem, New Hampshire.

During the Parasi initial field evaluations, the ENPHO's original recommended procedure for using the system was followed. In addition, the chemical packets used contained a different chemical composition from what is now being recommended. This is because while the Parasi field evaluation was taking place, ENPHO was concurrently making revisions to the treatment procedure and the chemical composition of the chemical packets. After these modifications, the author performed additional tests at the ENPHO's laboratory following the new revised procedure and using the new revised chemical composition of the packets.

In the second phase of the investigation, experiments were performed in the U.S. to investigate ways to improve the efficiency of the current ENPHO Arsenic Removal System. The experiments consisted of varying the coagulant doses and using various mixing regimes.

5.2 First Phase Evaluation

5.2.1 Field Evaluation in Parasi

During the field evaluation, water from three tubewells in the town of Parasi, identified as arsenic contaminated sources, was treated using the ENPHO Arsenic Removal System. These wells were all located in a radius of about 200 meters from each other. The concentration in these wells ranged from 75 –300 µg/L.

As discussed, during the Parasi field test, the original procedure was followed. The main difference between the original procedure and the modified procedure was that the original procedure only uses the initial mixing to mix the chemicals, while the modified procedure uses intermittent mixing every 30 minutes for 2 hours. Also, the chemical packets used for the Parasi field test contained a smaller ratio of ferric chloride to charcoal powder by weight (see Table 5-1).

Table 5-1: Chemical makeup of the original packets for the treatment of 20 liters of water

	Quantity	Resulting Concentration
8% Sodium Hypochlorite (NaOCl) Solution	0.36 milliliters	1.4 mg/L Cl ₂
Ferric Chloride (FeCl ₃)	0.73 grams	36 mg/L
Charcoal Powder	2.91 grams	146 mg/L

Original Experimental Procedure:

1. 20 liters of source well water was measured using a combination of 1 liter and 100 ml graduated cylinders and poured into a plastic bucket.
2. Approximately 200 ml sample of the source well water was set aside for pH, arsenic and iron analysis.
3. A chemical packet containing ferric chloride, charcoal powder, and sodium hypochlorite, in the ratio given in Table 5-1, was added to the water and

stirred for 1 minute using a wooden stirring rod. Stirring motion was adjusted to accomplish mixing rate of approximately 2 revolutions per second.

4. After allowing to settle for 2 hours, the water was poured into the filtration unit.
5. Once the filtration was completed, approximately 200 ml of treated water sample was collected for pH, arsenic and iron analysis.

5.2.2 Laboratory Experiments

The next set of experiments was performed at the ENPHO laboratory in Kathmandu. Source water was obtained from a well located near the laboratory and stock solution of arsenic was used to spike the concentration of arsenic in the source water. The stock solution had a total arsenic concentration of 100 mg/L and consisted of 50% arsenate and 50% arsenite. The concentrations of arsenic in the arsenic spiked water ranged from approximately 100 µg/L to 280 µg/L.

In order to concurrently evaluate the disinfection property of the ENPHO Arsenic Removal System, microbial contamination was intentionally introduced into the feed water. This was accomplished by adding a small amount of sample of nearby surface stream, which was highly contaminated with bacteria. Membrane filtration tests for fecal coliform indicated that this stream water contained as high as 8,000,000 cfu/100ml, or colony forming units per 100 ml, in this surface stream. A small amount of this stream water ranging from 1 ml to 10 ml, exact amount depending on the desired bacterial concentration in the feed water, was added to the water to be treated, resulting in a feed water fecal coliform count of 100 to 3000 cfu/100 mL.

Since the author wished to evaluate the performance of the ENPHO Arsenic Removal System as it would be implemented, the experiments were carried out by following the exact procedure that ENPHO would recommend to its users, which had been modified since the initial Parasi field evaluation. The only change to the procedure was that instead of using 20 liters of feed water, only 10 liters were used. Pre-assembled packets would be used by the users. However, the chemical dose was reduced since the pre-assembled packet content is meant to treat 20 liters of water instead of 10 liters. The following table shows the composition of adjusted composition of the chemicals used for the experiment.

Table 5-2: Adjusted chemical composition for the treatment of 10 liters of water

	Quantity	Resulting Concentration
8% Sodium Hypochlorite (NaOCl) Soution	0.4 milliliters	1.5 mg/L Cl ₂
Ferric Chloride (FeCl ₃)	0.8 g	80 mg/L
Charcoal Powder	0.8 g	80 mg/L

Revised Experimental Procedure:

1. 10 liters of nearby well water was measured using a combination of 1 liter and 100 ml graduated cylinders and poured into a 20 liter bucket.
2. Stock solution of 100 mg/L arsenic solution was added to the well water in order to spike the arsenic concentration in the water in the desired concentration range of 100 to 300 µg/L.
3. 1 to 10 ml of stream water having high concentrations fecal coliform bacteria was added to the water.

4. 150 ml of sample was set aside as the feed water sample for analysis, of which approximately 50 ml was used for arsenic, turbidity, and iron analysis, and 100 ml was used for the membrane filtration test for fecal coliform.
5. Pre-weighted chemicals were added into the bucket containing the water to be treated and stirred for 1 minute using a wooden stirring rod. Stirring motion was adjusted to accomplish a mixing rate of approximately 2 revolutions per second.
6. The water was stirred in a similar manner at 30, 60, and 90 minute marks following the initial mixing, allowing the solution to settle after each mixing took place.
7. At the 120 minute, or 2 hour mark, the water was poured into the filtration unit.
8. Once filtration was completed, approximately 150 ml of treated water sample was collected for arsenic, turbidity, and iron analysis and the membrane filtration test for fecal coliform.

5.3 Second Phase Evaluation

The second phase of the experiments were performed in the U.S. to further investigate ways to improve the ENPHO Arsenic Removal System. The experiments took place in field locations in Pepperell, Massachusetts and Salem, New Hampshire. Both locations were conveniently located and offered easy access. The wells were private water supply wells owned and maintained by owners of the homes.

The purpose of this phase of investigation was to determine the effect of varying chemical doses on arsenic removal efficiency. Arsenic removal efficiencies were evaluated using four different doses of 40, 60, 80, and 100 mg/L of FeCl_3 . Filtration was

omitted since only the side-by-side comparison of efficiencies using different doses of chemicals was required, independent of efficiencies that would be achieved using filtration.

Again the procedure of mixing at every 30 minute interval was used. However, since the author wished to compare the effects of each additional mixing and settling after the initial mixing and settling, samples were taken at each 30 minute interval over 2 hours before additional mixing took place.

Experimental Procedure:

1. 10 liters of test well water was measured and poured into a 20 liter bucket.
2. Pre-weighted chemicals were added into the bucket and stirred 1 minute using a wooden stirring rod. Stirring motion was adjusted to accomplish a mixing rate of approximately 2 revolutions per second.
3. The water was allowed to settle for 30 minutes and 100 ml of sample was collected before additional mixing took place.
4. The water was stirred in the same manner as the previous mixing.
5. Steps 3 and 4 were repeated at 60 and 90 minutes after the initial mixing.
6. After 120 minutes, or 2 hours had passed since the initial mixing took place, the final 100 ml sample was taken.

5.4 Analytical Methods

5.4.1 Arsenic Analysis

Arsenic concentrations were measured using the field test kit and the atomic absorption spectrometry. The field test kit was used to analyze samples during the Parasi evaluation.

Arsenic in samples generated from the experiments conducted at the ENPHO laboratory were analyzed using hydride generation atomic spectrometry (HGAAS) technique while samples from the experiments performed in the U.S. were analyzed using graphite furnace atomic absorption spectrometry (GFAAS). Both HGAAS and GFAAS techniques are EPA approved analytical methods for arsenic and have a method detection limit (MDL) of 1 $\mu\text{g/L}$ (EPA, 1999). The accuracy of both analyses is dependent on the reliability of calibration obtained. Based on author's own experiences, the more realistic detection limit is 5 $\mu\text{g/L}$.

5.4.1.1 Field Test Kit

Arsenic CheckTM Field Test Kit by Industrial Test Systems Inc. was used for the analysis of arsenic in the field. The arsenic field test kit provides a safe, simple, and reliable method to test for aqueous inorganic arsenic concentration in the water samples. The detection range is from 0 to 800 $\mu\text{g/L}$. The upper detection limit can be extended to 4000 $\mu\text{g/L}$ with a simple 1 to 5 dilution. The test kit includes three chemical reagents with measuring spoons, a color chart, test strips, and reaction bottles. The test results are determined by colorimetry. The color chart is standardized at 25°C, starting at pure white for 0 $\mu\text{g/L}$ arsenic, a tint of yellow for 5 $\mu\text{g/L}$ arsenic, to slightly more yellow at 10 $\mu\text{g/L}$, and increasing yellow intensity at 20, 50, 100, 200, and 500 $\mu\text{g/L}$. At 500 $\mu\text{g/L}$ arsenic, the color is dark brown. It is recommended that the water sample temperature be between 20°C and 30°C for accurate reading of the color chart. This test tolerates up to 2 mg/L hydrogen sulfide and 0.5 mg/L antimony without test result interference. No interference from iron or sulfate was found.

The chemistry of reaction is based on the conversion of inorganic arsenic compounds in water to arsine gas (AsH_3) by the reaction of zinc dust and tartaric acid. First, a clean reaction bottle is filled with 100 ml of water to be tested. Three pink spoons of reagent 1, tartaric acid, are added to the bottle. The bottle is capped and shaken vigorously for 15 seconds. After allowing the content to sit for 15 seconds, three red spoons of reagent 2, which contains a mixture of ferrous salts as reaction catalyst, are introduced into the bottle and shaken vigorously for 15 seconds and allowed to sit for 2 minutes. Then, three white spoons of reagent 3, zinc dust, is added to the bottle and shaken vigorously for 15 seconds. The bottle cap is replaced with another cap with a special spout that allows a test strip containing mercuric bromide coating to be inserted into the bottle. The bottle is capped for the next 30 minutes. Both hydrogen gas and arsine gas is formed inside the reaction bottle. The arsine gas then reacts with mercuric bromide on the test strip to form mixed mercury halogens (such as AsH_2HgBr) that appear with a color change from white to yellow or brown. At the end of 30 minutes, the test strip is taken out of the bottle and compared to the color chart to determine the arsenic concentration.

5.4.1.2 Atomic Absorption Spectrometry

In their elemental forms, atoms will absorb light when they are excited above their ground energy state. Each element has a characteristic wavelength that will be absorbed. Arsenic, for example, has a characteristic wavelength of 193.7 nanometer (nm). The atomic absorption instrument looks for a particular element by focusing an optical beam of light at a specific wavelength corresponding to the element's characteristic wavelength

into a detector. When passed through this beam, the element of interest will absorb some of this light, thus reducing the intensity of light at the detector. The instrument measures the change in intensity. As concentration in the sample increases, absorbance also increases.

A calibration curve is obtained by running standards having known concentrations of arsenic through the instrument and recording corresponding absorbances. One can then determine the concentrations of the samples by comparing the observed absorbance against the calibration curve.

HGAAS and GFAAS are two of many atomic absorption spectrometry methods. The HGAAS technique is based on the atomic absorption measurement of arsenic generated by thermal decomposition of arsenic (III) hydride. Arsenic (III) is reduced to gaseous arsenic (III) hydride by reaction with sodium tetrahydroborate in a hydrochloric acid medium. Trivalent, As (III), and pentavalent, As(V), have different sensitivities using this technique so pentavalent arsenic must be reduced to trivalent arsenic prior to measurement. This reduction is carried out using hydrochloric acid, potassium iodide and ascorbic acid. For more detailed description of HGAAS technique the reader is referred to ISO 11969:1996 and SM 3114:1990.

GFAAS technique differs from HGAAS in that a graphite tube is used to heat the injected volume of sample step-wise to dry and remove the main part of the matrix and finally atomize arsenic. In this method, matrix modifier consisting of a mixture of Pd/MgNO₃ is added to the sample in order to permit a sufficiently high pyrolysis temperature to remove other components from the sample without the loss of arsenic.

5.4.1.2 Sample Preservation

Once a sample that is to be tested using HGAAS or GFAAS is collected, concentrated hypochloric acid is added in order to preserve the samples. This is done to prevent adsorption of dissolved arsenic onto the surface iron that may precipitate before the analysis. One drop, approximately 1 ml, of 6 M hydrochloric acid (HCl) solution was added for every 10 milliliter of sample that was to be preserved.

5.4.2 Membrane Filtration Test

The membrane filtration technique was used to analyze untreated and treated water samples for the number of fecal coliform bacteria present in the water. The membrane filtration technique is a widely used technique for the enumeration of bacterial density (Standard Methods, 1998). The samples were analyzed using the Millipore Portable Membrane Filtration Kit. One hundred milliliter water sample passes through a membrane filter having 0.7 μm pore size that retains the bacteria present in the sample. The filter containing the bacteria is placed on an absorbent pad and saturated with M-FC broth in a petri dish. The dish is then incubated at 44.5° Celsius for a twenty-four hour period. After incubation, typical blue fecal coliform colonies are counted, and the results are recorded as fecal coliform count per 100-milliliter sample, or colony forming unit per 100 milliliters (cfu/100 ml). For more detailed discussion of membrane filtration test technique as applied by the MIT Nepal Water Project team, see “Appropriate Microbial Indicator Tests for Drinking Water in Developing Countries and Assessment of Ceramic Water Filters” (Low, 2002).

5.4.3 Turbidity, Iron and pH Measurements

The turbidity of water samples was measured using the Hach portable turbidimeter (Model 2100P). The instrument was calibrated, and each measurement was taken twice in order to ensure accuracy. Iron concentrations and pH of the samples were analyzed using the Hach iron test kit (Model IR-18) and Digi-Sense Digital pH/ORP meter (Cole-Parmer Instrument Co., Model No. 5938-00) following the instructions provided by the manufacturers (For more detailed description of these test, see Ngai, 2002).

6.0 Results and Discussion

6.1 Results from First Phase Evaluation

6.1.1 Parasi Field Test Results

The field test results from Parasi showed poor arsenic removal efficiency when chemical packets containing the original chemical composition were used along with the original procedure. Average arsenic removal rate of roughly 60 percent was observed when three well water sources were treated, and the treated arsenic concentrations were not consistently below the interim Nepali standard (see Table 6-1). The system did, however, substantially reduce iron concentration in the treated water. Slight increase in pH of water was observed after treatment.

Table 6-1: Parasi field test results

Well ID	Sample No.	As Untreated (µg/L)	As Treated (µg/L)	Iron Untreated (mg/L)	Iron Treated (mg/L)	pH Untreated	pH Treated
A	1	300	100	2.5	< 0.01	7.00	7.60
A	2	300	50	2.5	< 0.01	7.00	7.70
B	1	50-100	20 - 50	7	< 0.01	6.60	6.80
B	2	50-100	20 - 50	7	< 0.01	6.60	6.80
C	1	250	150	3.5	< 0.01	6.9	6.90
C	2	250	150	3.5	< 0.01	6.9	6.90

(Arsenic concentration analyzed using the field test kit)

6.1.2 ENPHO Laboratory Test Results

6.1.2.1 Arsenic Test Results

The ENPHO Arsenic Removal System yielded reasonably good arsenic removal efficiency when the modified chemical composition and revised procedure were used.

Table 6-2 shows arsenic concentrations of samples taken before and after the treatment.

Table 6-2: Arsenic test results from ENPHO laboratory tests

Test Water ID	Arsenic Concentration Untreated ($\mu\text{g/L}$)	Arsenic Concentration Treated ($\mu\text{g/L}$)	Percent Arsenic Removed (%)
1	91	17	81 %
2	95	13	87 %
3	97	11	88 %
4	221	9	96 %
5	197	17	91 %
6	198	13	94 %
7	277	16	94 %
8	276	22	92 %
9	274	21	92 %

On average, the treatment yielded 91 % reduction in arsenic concentrations, and the range of arsenic concentrations in the treated samples was 9 to 22 $\mu\text{g/L}$. This is well below the interim Nepali standard of 50 $\mu\text{g/L}$. The concentration of arsenic in the feed water does not seem to have a significant effect on the removal efficiency of ENPHO Arsenic Removal system in the range of feed water arsenic concentrations tested (See Figure 6.1).

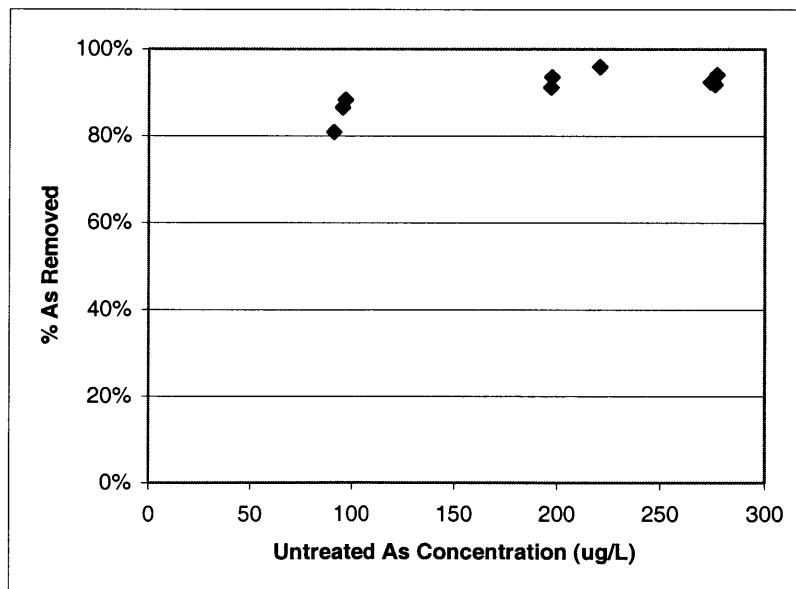


Figure 6-1: Arsenic removal efficiency obtained using modified procedure and reformulated chemical composition

Results and Discussion

The source water characteristics varied slightly from day to day. Table 6-3 shows various source water parameters for which it was tested.

Table 6-3: Water characteristics of untreated water during ENPHO laboratory tests

Test Water ID	PH	Iron Concentration (mg/L)	Turbidity (NTU)
1	6.7	1.13	28.1
2	6.7	1.18	29.7
3	6.9	1.13	28.6
4	6.8	0.99	16.6
5	6.7	1.00	16.7
6	6.7	0.93	16.6
7	6.8	1.54	14.3
8	6.8	1.52	15.4
9	6.9	1.48	14.7

Both iron and turbidity is substantially reduced in the treated water upon treatment through the ENPHO Arsenic Removal System (see Table 6-4). On average 93% of iron removal was observed. 95% average turbidity reduction was achieved. It was observed that the pH of water was slightly raised after the treatment.

Table 6-4: Treated water characteristics from ENPHO laboratory tests

Test Water ID	pH after treatment	Final iron concentration ($\mu\text{g/L}$)	Percent Iron Removed	Final Turbidity	Percent Turbidity Reduced
1	6.9	0.10	91 %	0.42	99 %
2	6.9	0.15	87 %	7.05	76 %
3	7.0	0.08	93 %	1.13	96 %
4	7.0	< 0.01	> 99%	0.27	98 %
5	6.9	< 0.01	> 99%	0.27	98 %
6	6.8	< 0.01	> 99%	0.28	98 %
7	6.9	< 0.01	> 99%	0.85	94 %
8	7.0	< 0.01	> 99%	0.35	98 %
9	7.0	0.48	67 %	1.05	93 %

6.1.2.2 Microbial Test Results

The membrane filtration tests performed for fecal coliform showed a good reduction of fecal coliform bacteria in the treated sample. Fecal coliform bacteria colonies could not be observed in many treated samples (i.e. 0 cfu/100 ml). On average, 99% reduction of fecal coliform was observed.

Table 6-5: Results of membrane filtration test for fecal coliform

Test Water ID	Fecal coliform count before treatment (CFU/100ml)	Fecal coliform count after treatment (CFU/100ml)	Percent fecal coliform removed
1	145	0	100 %
2	65	0	100 %
3	60	4	93 %
4	885	0	100 %
5	1220	0	100 %
6	3600	0	100 %
7	1090	0	100 %
8	1550	1	100 %
9	1160	10	99 %

6.1.2.3 Filter Flow Rate Measurements

Filter flow rate was observed as 2 to 4 liters per hour. The flow rate varies as the head of water to which the filter is subjected changes. When the upper filtration unit (i.e. the top gagri) is fully filled with 20 liters of water, a flow rate as high as 5 liters per hour is observed. When the water level in the top filtration unit decreases, the flow rate is significantly reduced.

6.2 Results of Second Phase Evaluation

Arsenic contaminated water from private household wells from Pepperell, Massachusetts and Salem, New Hampshire were used for conducting experiments in this phase of the

study. Table 6-6 shows source water arsenic contamination levels and other parameters of the source waters.

Table 6-6: Source water characteristics in Pepperell, MA and Salem, NH

Location	Arsenic Concentration ($\mu\text{g/L}$)	Percent As (III)	PH	Iron Content (mg/L)
Pepperell, MA	101 $\mu\text{g/L}$	80 %	6.6	0.3 mg/L
Salem, NH	1025 $\mu\text{g/L}$	4 %	6.4	0.6 mg/L

The effect of varying the coagulant, ferric chloride, concentration was investigated. The range of chemical dose used and corresponding ferric chloride concentrations for the experiments are shown in Table 6-7.

Table 6-7: Coagulant concentrations used during second phase study

Amount of total chemicals used (FeCl_3 + charcoal + HClO)	Corresponding ferric chloride concentration in water
1.0 g	40 mg/L
1.5 g	60 mg/L
2.0 g	80 mg/L
2.5 g	100 mg/L

In addition to varying the coagulant dose, various mixing and settling regimes were also studied. It is important to note that in these experiments, the filtration step was omitted because only relative efficiency was of interest. The samples were directly taken after coagulation/co-precipitation and sedimentation.

Pepperell and Salem field test results are summarized in Table 6-8 and Table 6-9, respectively.

Table 6-8: Pepperell field test results

FeCl_3 Conc.	As Conc. ($\mu\text{g/L}$) After:			
	30 min.	60 min.	90 min.	120 min.
40 mg/L	38	25	21	35
60 mg/L	22	20	29	19
80 mg/L	9	8	12	18
100 mg/L	11	13	14	5

(Arsenic concentration in the source water = 101 $\mu\text{g/L}$)

Table 6-9: Salem field test results

FeCl ₃ Conc.	As Conc. (µg/L) After:			
	30 min.	60 min.	90 min.	120 min.
40 mg/L	461	588	536	524
60 mg/L	427	528	440	363
80 mg/L	287	246	202	302
100 mg/L	374	324	273	273

(Arsenic concentration in the source water = 1025 µg/L)

Each show concentrations of arsenic in the treated water samples taken at various intervals between mixing after they have been treated using different concentrations of ferric chloride. In Figure 6-2 and Figure 6-3, the arsenic removal rates are plotted as a function of coagulant dose.

(Source water arsenic concentration = 101 µg/L)

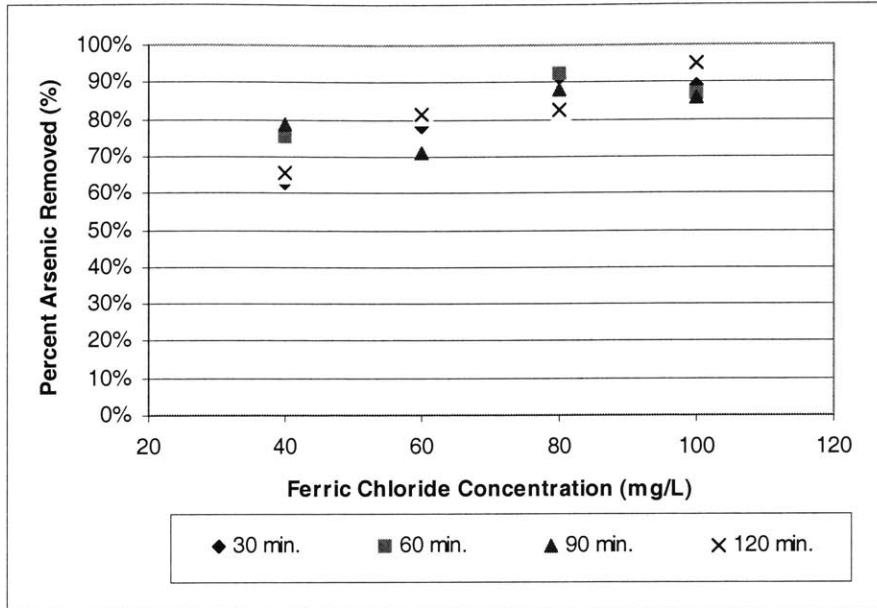


Figure 6-2: Arsenic removal efficiency with varying ferric chloride doses – Pepperell, MA

(Source water Arsenic concentration = 1025 µg/L)

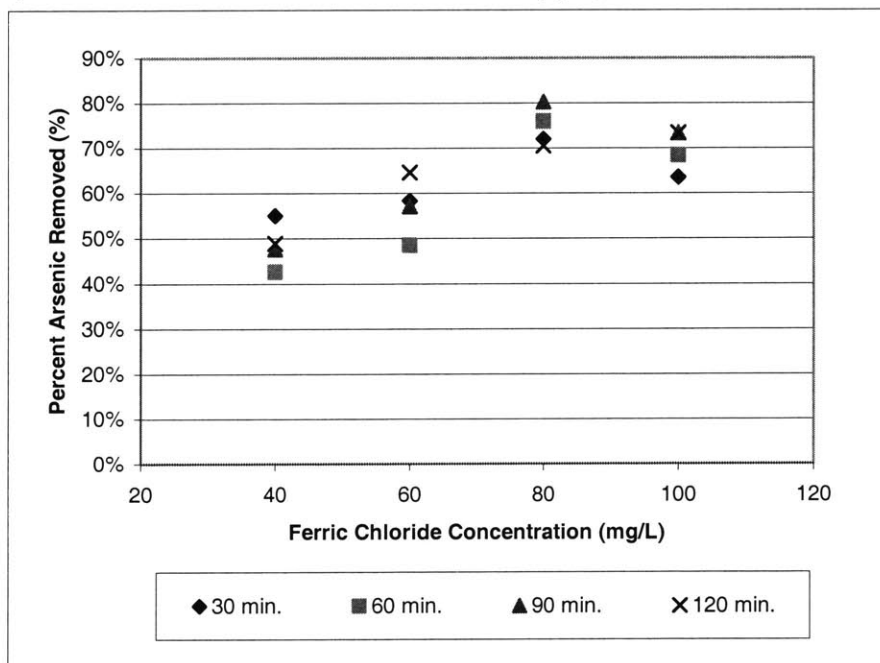


Figure 6-3: Arsenic removal efficiency with varying ferric chloride doses – Salem, NH

The results from both Massachusetts and New Hampshire field tests indicate that optimum ferric chloride dose under test conditions is in the near 80 mg/L range, as ferric

chloride dose below and above this dose arsenic removal rate decreases. The optimal chemical dose will depend on the property of the water being treated. Nonetheless, based on these results, it seems that the current coagulant dose being used by the ENPHO Arsenic Removal System is appropriate if, in fact, the property of groundwater in Nepal is similar to that of New Hampshire water.

Figures 6-4 and 6-5 look at the effect additional mixing and settling have on the arsenic removal rates.

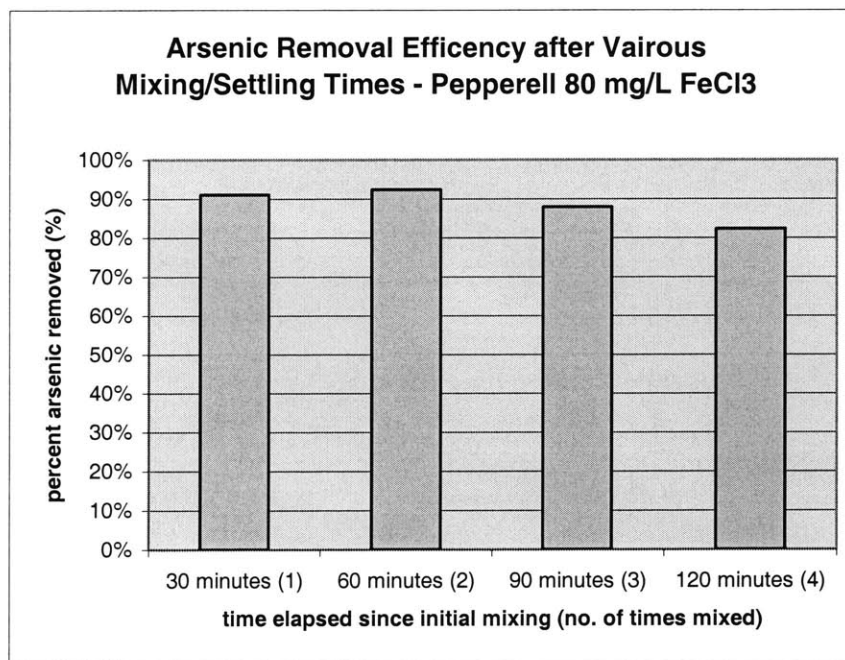


Figure 6-4: Arsenic removal efficiency after various mixing/settling times using 80 mg/L FeCl₃ - Pepperell

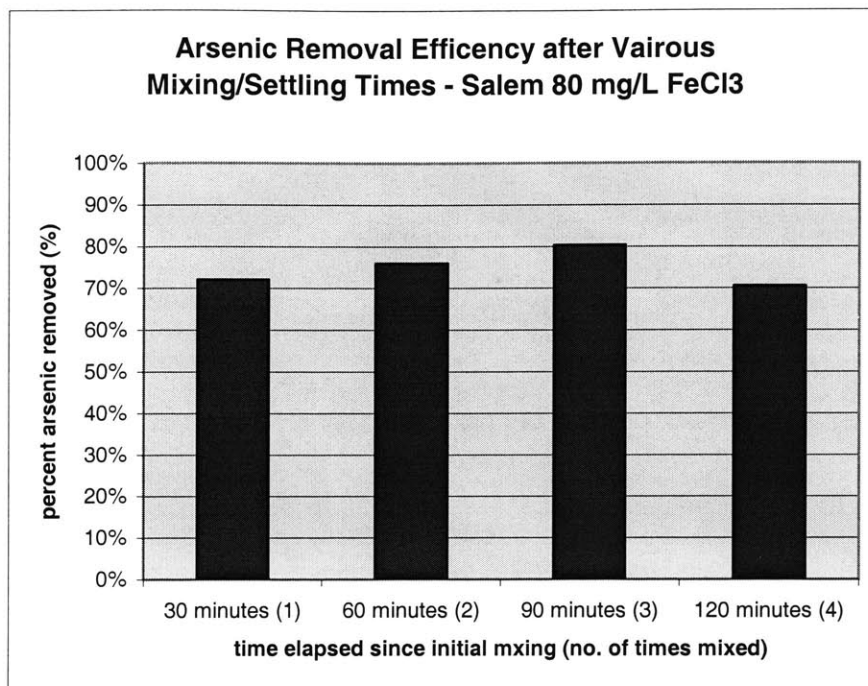


Figure 6-5: Arsenic removal efficiency after various mixing/settling times using 80 mg/L FeCl_3 – Salem

No significant relationship between the arsenic removal efficiency and the number of mixing and settling episodes was observed. In fact, additional mixing resulted in decreased arsenic removal efficiency in some cases, suggesting resuspension of the adsorbed arsenic. From these results, it seems that there is no appreciable benefit from having multiple mixing, as samples taken after being mixed several times do not show higher arsenic removal rates compared to samples collected after only the initial mixing and 30 minutes of settling. However, in order to conclusively confirm this finding, further experiments are required.

7.0 Sludge Disposal

In this section, the disposal method for the sludge generated during the ENPHO Arsenic Removal System treatment process and its environmental risk will be briefly discussed. The main concerns with sludge disposal are whether the current disposal methods are safe (i.e. it does not constitute a significant human health risk) and whether any appreciable quantity of arsenic is returned to contaminate the environment.

The current sludge disposal method suggested by ENPHO is to discard the sludge onto cow dung. A similar method for the disposal of arsenic treatment sludge has been practiced in Bangladesh. In Bangladesh, various NGO's have been involved in distribution and education of using various types of coagulation methods as a remediation method for arsenic contaminated groundwater. Study by Eriksen-Hamel and Zinia (2001) investigated appropriateness of the current method recommended by NGO's to dispose of sludge. In this study, cow dung and soil samples on which the liquid sludge had been disposed were collected and tested for leachate quality. Toxicity Characteristic Leaching Procedure (TCLP, EPA method 1311) was used to determine the quality of leachate produced.

TCLP is an extensive procedure developed by EPA in order to characterize leachate produced by various wastes. The procedure varies slightly, mainly in the type of extraction vessel and fluid used, depending on the type of analytes. In the case of arsenic sludge, the procedure used for the analysis of inorganic non-volatile chemicals can be used. A minimum of 100 grams of sample is placed in the extraction vessel along with extraction fluid 20 times the weight of the solid phase of the sample. Extraction fluid type II, prepared by diluting 5.7 ml of glacial acetic acid with American Society of

Testing and Materials (ASTM) Type II water to a volume of 1 liter, having pH between 2.83 and 2.93, is used as the extraction fluid. The extraction vessel is placed in an agitator that rotates the extraction vessel in an end-over-end fashion at the rate of 30 revolutions per minute. Following an 18-hour extraction, the material in the extraction vessel is separated into its component liquid and solid phases by filtering through a borosilicate glass fiber having an effective pore size of 0.6 to 0.8 mm. The TCLP extract can then be analyzed using EPA approved analytical methods for the analytes of concern (EPA, 2000).

For arsenic, under U.S. regulations, the sludge is classified as hazardous if the arsenic concentration in the leachate produced following the TCLP exceeds 5 mg/L (40 CFR - Chapter I - Part 261.24). In Eriksen-Hamel's study (2001), the concentration of arsenic in the leachate produced from all samples were well below 5 mg/L. The maximum concentration observed from the leachate was 0.012 mg/L, approximately 500 times less than the current hazardous classification limit. Further, solid concentrations in the samples were found to be in the range of 8.5 to 14.5 mg/kg dry weight. While the US EPA has not established a national regulation regarding arsenic in soil, under the Massachusetts law, the reportable concentration is 30 mg/kg for arsenic (Massachusetts Department of Environmental Protection, 2002). The author's own estimate of arsenic concentration in the soil after a single disposal of treatment sludge is consistent with this finding (see Appendix C for the calculation).

Studies in the U.S. evaluating degree of hazard posed by sludge generated by water treatment facilities that remove significant amount of arsenic through iron removal have found that the sludge generated by such plants does not qualify as hazardous waste

as leachate quality do not exceed previously discussed leachate concentration limit, and therefore may be disposed of as municipal solid waste (EPA, 2000).

The present arsenic treatment sludge disposal method appears to be safe, and there is no significant risk of contamination of the environment. It should also be noted that although there are serious health risks associated with the long-term exposure to low levels of arsenic, through ingestion for example, the risk of exposure through other means such as skin contact with low level concentration of arsenic found in the arsenic treatment sludge poses minimal health risk as arsenic absorption through skin is considered insignificant (World Health Organization, 2001).

8.0 Conclusion

Initial field evaluation in Nepal showed that the ENPHO Arsenic Removal System, prior to recent modifications, could not achieve adequate arsenic removal from the arsenic contaminated drinking well water, mainly due to insufficient ferric chloride dose. Additional evaluation at the ENPHO laboratory and in the U.S. indicated that coagulation/co-precipitation and filtration method can achieve reasonably good arsenic removal rate assuming an adequate coagulant dose.

ENPHO has reformulated the chemical composition of the packets in order to increase the ferric chloride dose along with implementing a new mixing procedure. The results from the author's experiments indicate that it is possible to achieve the arsenic concentration required to meet the interim Nepali standard of 50 $\mu\text{g/L}$ using the ENPHO Arsenic Removal System using the combination of increased coagulant dose (i.e. 80 mg/L FeCl_3) and the revised procedure (i.e. initial mixing followed settling and intermittent mixing every 30 minutes prior to filtration) assuming that the arsenic concentration in the source water is not very high. In general, arsenic surveys conducted to date indicate that arsenic concentrations found in Nepal are relatively low (i.e. do not exceed 300 $\mu\text{g/L}$), compared to those found in neighboring Bangladesh. The ENPHO Arsenic Removal System was able to reliably reduce arsenic concentration below 50 $\mu\text{g/L}$ in the source water arsenic concentration range tested, roughly 100 – 300 $\mu\text{g/L}$. However, the results from New Hampshire, when arsenic concentration of the source water was increased to above 1,000 $\mu\text{g/L}$, indicate that it would be unlikely that the ENPHO Arsenic Removal System would be successful in reducing arsenic concentration below 50 $\mu\text{g/L}$ at high source water arsenic concentrations.

Studies from Bangladesh and U.S. suggest that the current sludge disposal method is safe and poses no significant threat to either human health or contamination of the environment.

Questions that still remain unanswered are whether this technology would be socially acceptable and economically feasible. From the interviews with the ENPHO field personnel overseeing the distribution of the units and responsible for educating the users, the author has learned that most users seem to follow the ENPHO's guidelines for operation and maintenance of the units. In addition, preliminary test results indicate that there is no appreciable benefit from having multiple mixing events, as samples taken after being mixed several times do not show higher arsenic removal rates compared to samples collected after only the initial mixing and thirty minutes of settling. However, in order to conclusively confirm this finding further experiments may be required. This suggests that the settling regime currently being used can be improved upon. An improved mixing and settling scheme would enhance the usability of the system as well.

The cost is another obstacle this system faces. The current cost of unit consists of the cost of two ggris, the terracotta filter, a plastic mixing bucket, and the annual supply of chemicals, the most significant of which is the chemicals. Presuming that a family would treat 20 liters of water a day for drinking and cooking purposes, the cost of a one-year supply of chemicals would be US\$ 9.70. It is uncertain whether this cost can be reduced. The cost of other components is about US\$ 7.00 and could be reduced if a family already owns plastic buckets and ggris, which can be used as the mixing and collection units. Currently, the ENPHO Arsenic Removal System is being distributed

free of charge as funding comes from outside donors. It is uncertain whether local people will be willing to bear all or a portion of the cost associated with the system.

This study has found that the ENPHO Arsenic Removal System can be used to achieve effective arsenic removal, capable of reducing arsenic concentration below the interim Nepali standard. While ENPHO Arsenic Removal System is a viable option that can be immediately implemented in order to address a growing problem, several drawbacks are present. These include the question of social acceptability and cost. Improvements may be made in regards to making the system more user friendly by using a simpler procedure. The author's preliminary results showed that this may be possible without significantly sacrificing the arsenic removal efficiency. On the other hand, however, it is uncertain whether the cost can be reduced, and the author recommends that this be investigated by ENPHO.

References

- Ali, A. M. and Hossain, D. 2000, *Arsenic Removal from Groundwater by Co-precipitation*, BUET, Bangladesh.
- Benefield, L. D., Judkins, J.F., Weand, B.L. 1982, *Process Chemistry for Water and Wastewater Treatment*, Prentice Hall, Inc., N.J.
- Cheng, R.C., Liang, S. Wang, H.C. and Beuhler, M.D. 1994, 'Enhanced coagulation for arsenic removal' *Journal of American Water Works Association*, vol. 86(9), p. 79.
- Eriksen-Hamel, N. and Zinia, N. 2001 'A study of Arsenic Treatment Technologies and Leaching Characteristics of Arsenic Contaminated Sludge' *Technologies for Arsenic Removal from Drinking Water*, Preprints of BUET - UNU International Workshop, May, p. 207.
- Fields, K., Chen, A., Wang, L. 2000, 'Arsenic Removal from Drinking Water by Iron Removal Plants', *EPA Report EPA/600/R-00/086*.
- Gulledge, J. H. and O'Connor, J. T. 1973, 'Removal of As(V) From Water by adsorption on Aluminum and Ferric Hydroxide', *Journal of American Water Works Association*, August.
- Hering, J.G., Chen, C., Wilkie, J.A., Elimelech, M. 1997, 'Arsenic Removal from Drinking Water During Coagulation', *Journal of Environmental Engineering*, Vol. 123, No. 8, August, p. 800.
- Hurd, J. 2001, Evaluation of Three Arsenic Removal Technologies in Nepal, Master of Engineering Thesis. Massachusetts Institute of Technology.
- International Organization of Standardization 1996, *Determination of arsenic – atomic absorption spectrometric method*, ISO 11969.
- Letterman, R.D. 1991, *Filtration Strategy to Meet the Surface Water Treatment Rule*, American Water Works Association, Denver, CO.
- Low, C. S. 2002, *Appropriate Microbial Indicator Tests for Drinking Water in Developing Countries and Assessment of Ceramic Water Filters*, Master of Engineering Thesis, Massachusetts Institute of Technology.
- Mamtaz, R. and Bache, D.H. 2001, 'Low-cost Technique of Arsenic Removal from Water and Its Removal Mechanism' *Technologies for Arsenic Removal from Drinking Water*, Preprints of BUET - UNU International Workshop, May, p. 43.

Meng, X. and Korfiatis, G.P., 2001, 'Removal of Arsenic from Bangladesh Well Water Using A Household Filtration System', *Technologies for Arsenic Removal from Drinking Water*, Preprints of BUET - UNU International Workshop, May, p. 121.

Metcalf & Eddy 1991, *Wastewater Engineering: Treatment, Disposal and Reuse*, McGraw Hill Book Co., Singapore.

Metcalf, F. 1962, *Destructive and Useful Insects*, 4th Edition, McGraw Hill.

Nepal National Arsenic Steering Committee 2001, *Nepal's Interim Arsenic Policy Preparation Report*. May.

Ngai, T.K. 2002, *Arsenic Speciation and Evaluation of an Adsorption Media in Rupendehi and Nawalparasi Districts of Nepal*, Master of Engineering Thesis, Massachusetts Institute of Technology.

Pauling, L., 1970, *General Chemistry*, Dover Publications, Mineola, NY.

Shen, Y.S. 1973, 'Study of arsenic removal from drinking water', *Journal of American Water Works Association*, vol. 65(8), p. 543.

Standard Methods 1998, Clesceri, L.S. (ed.), Eaton, A.D. (ed.), Greenberg, A.E. (ed.) 1998, *Standard Methods for the Examination of Water and Wastewater*, 20th Edition, American Water Works Association, the American Public Health Association, and the Water Environment Federation.

Tahura, S., Shaidullah, S.M., Rahman, T., and Milton, A.H. 2001, 'Evaluation of an Arsenic Removal Household Device: Bucket Treatment Unit (BTU)', *Technologies for Arsenic Removal from Drinking Water*, Preprints of BUET - UNU International Workshop, May, p. 158.

Environmental Protection Agency 1999, EPA Report, EPA/815/R/00/010.

Environmental Protection Agency 2001, 'Arsenic in Drinking Water: Health Effects Research', Available: <http://www.epa.gov/safewater/ars/ars10.html>

Vance, D.B. Arsenic 2001, 'Chemical Behavior and Treatment', Available: <http://2the4.net/arsenicart.htm>

Waychunas, G.A., Rea, B.A., Fuller, C.C., and Davis, J.A. 1993, 'Surface chemistry of ferrihydrite--Part 1--EXAFS studies of the geometry of coprecipitated and adsorbed arsenate', *Geochimica et Cosmochimica Acta*, v. 57, p. 2251.

World Bank Group 2002, 'Nepal at a Glance', Available: http://www.worldbank.org/data/countrydata/aag/npl_aag.pdf

World Health Organization 2001, 'Arsenic in Drinking Water', Available:
<http://www.who.int/inf-fs/en/fact210.html>

Appendix A

Parasi Field & ENPHO Laboratory Test Data

Parasi Filed Test Data

Location	Filter Type	Sample No.	As Raw (ppb)	As Treated (ppb)	Iron Raw (ppm)	Iron Treated (ppm)	pH Raw	pH Treated	Redox Potential Raw (mV)	Redox Potential Treated (mV)
Backyard	Biosand	1	300	50	2.5	0	7.0	7.8	-45	-89
Backyard	Biosand	2	300	50 - 100	2.5	0	7.0	8.0	-45	-101
Backyard	ENPHO ARS	1	300	100	2.5	0	7.0	7.6	-45	-79
Backyard	ENPHO ARS	2	300	50	2.5	0	7.0	7.7	-45	-109
Backyard	3 Gagri	1	400	5 - 10	2.5	0	7.0	7.9	-45	-119
Backyard	3 Gagri	2	400	5 - 10	2.5	0	7.0	7.8	-45	-120
Restaurant	ENPHO ARS	1	50 - 100	20 - 50	7	0	6.6	6.8	-37	-52
Restaurant	ENPHO ARS	2	50 - 100	20 - 50	7	0	6.6	6.8	-37	-52
Restaurant	3 Gagri	1	50 - 100	0 - 5	7	0	6.6	7.8	-37	-102
Restaurant	3 Gagri	2	50 - 100	~ 0	7	0	6.6	7.4	-37	-91
Shop	ENPHO ARS	1	250	100 - 200	3.5	0	6.9	6.9	-61	-47
Shop	ENPHO ARS	2	250	100 - 200	3.5	0	6.9	6.9	-61	-47
Shop	3 Gagri	1	250	0 - 5	3.5	0	6.9	7.5	-61	-80
Shop	3 Gagri	2	250	0 - 5	3.5	0	6.9	7.5	-61	-80

ENPHO Laboratory Test Data

Sample No.	Arsenic Untreated (ppb)	Arsenic Treated (ppb)	Iron Untreated (ppm)	Iron Treated (ppm)	Avg. F. Coliform		Turbidity Untreated (NTU)	Turbidity Treated (NTU)	
					Untreated Count (cfu/100ml)	Untreated F. Coliform Count (cfu/100ml)			
1a	91.1	17.4	1.13	0.1	220	145	0	28.1	0.42
1b					70				
2a	95.4	12.8	1.18	0.15	60	65	0	29.7	7.05
2b					70				
3a	96.8	11.3	1.13	0.08	60	60	4	28.6	1.13
3b					60				
4a	220.8	9	0.99	0	960	885	0	16.6	0.27
4b					810				
5a	197	17.3	1	0	1360	1220	0	16.7	0.27
5b					1080				
6a	197.5	12.7	0.93	0	3600	3600	0	16.6	0.28
6b					3600				
7a	277	16.4	1.5406	0	900	1090	0	14.3	0.85
7b					1280				
8a	276	22.3	1.5158	0	1540	1550	1	15.4	0.35
8b					1560				
9a	274	20.9	1.4759	0.4872	1180	1160	10	14.7	1.05
9b					1140				

Appendix B

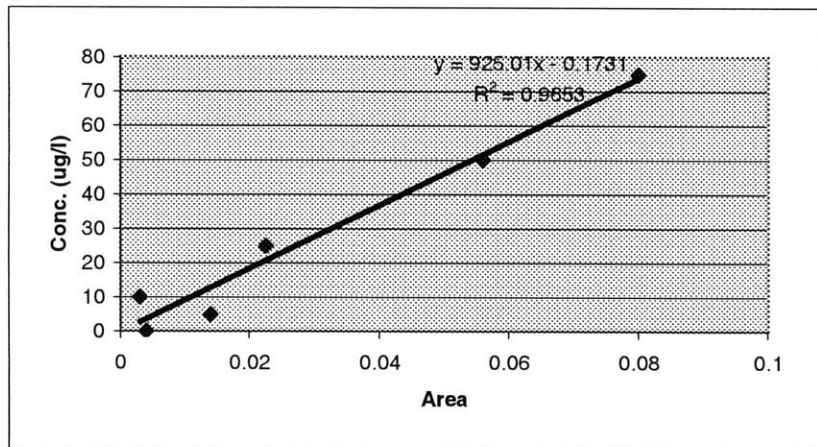
Pepperell & Salem Test Data

GFAAS Arsenic Analysis Data

Calibration curve was obtained by averaging two calibration runs using standards of known arsenic concentration.
 Note: number in *italic* represent erroneous data excluded in obtaining calibration.

Pepperell Samples

<u>Calibration 1</u>		<u>Calibration 2</u>		<u>Calibration using average calibration</u>		Sample ID	Peak Area	Conc. (ug/L)
Standard Concentration (ug/L)	Peak Area	Standard Concentration (ug/L)	Peak Area	Standard Concentration (ug/L)	Peak Area			
0	0.007	0	0.001	0	0.004	a30p	0.04	38
5	0.017	5	0.011	5	0.014	b30p	0.03	22
<i>10</i>	<i>-0.001</i>	<i>10</i>	<i>0.007</i>	<i>10</i>	<i>0.003</i>	c30p	0.01	9
25	0.029	25	0.016	25	0.0225	d30p	0.02	11
50	0.063	50	0.049	50	0.056	e30p	0.01	7
75	0.083	75	0.077	75	0.08	a60p	0.03	25
100	0.101	100	0.07	100	0.0855	b60p	0.02	20
150	0.154	150	0.126	150	0.14			



Calibration 1

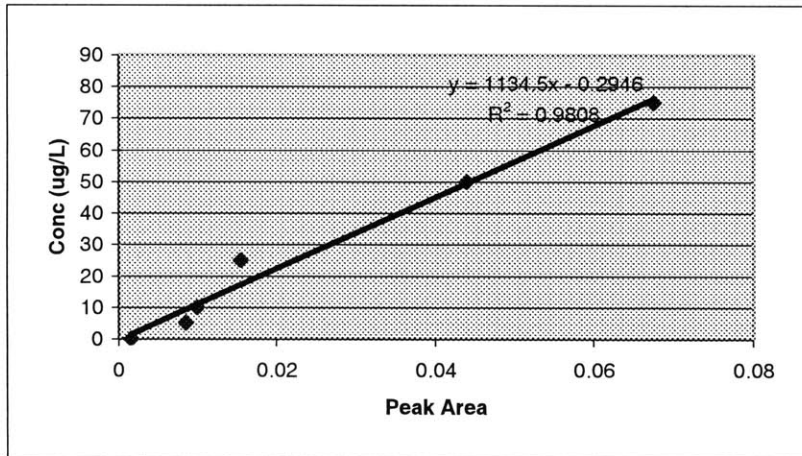
Standard Concentration (ug/L)	Peak Area
0	0.001
5	0.011
10	0.007
25	0.016
50	0.049
75	0.077
100	0.07
150	0.126

Calibration 2

Standard Concentration (ug/L)	Peak Area
0	0.002
5	0.006
10	0.01
25	0.015
50	0.039
75	0.058
100	0.081
150	0.104

Calibration using average calibration

Standard Concentration (ug/L)	Peak Area	Sample ID	Peak Area	Conc. (ug/L)
0	0.0015	c60p	0.01	8
5	0.0085	d60p	0.01	13
10	0.01	e60p	0.01	13
25	0.0155	a90p	0.02	21
50	0.044	b90p	0.03	29
75	0.0675	c90p	0.01	12
100	0.0755	d90p	0.01	14
150	0.115	e90p	0.01	10
		a120p	0.03	35
		b120p	0.02	19
		c120p	0.02	18



Calibration 1

Standard Concentration (ug/L)	Peak Area
0	0.002
5	0.006
10	0.01
25	0.015
50	0.039
75	0.058
100	0.081
150	0.104

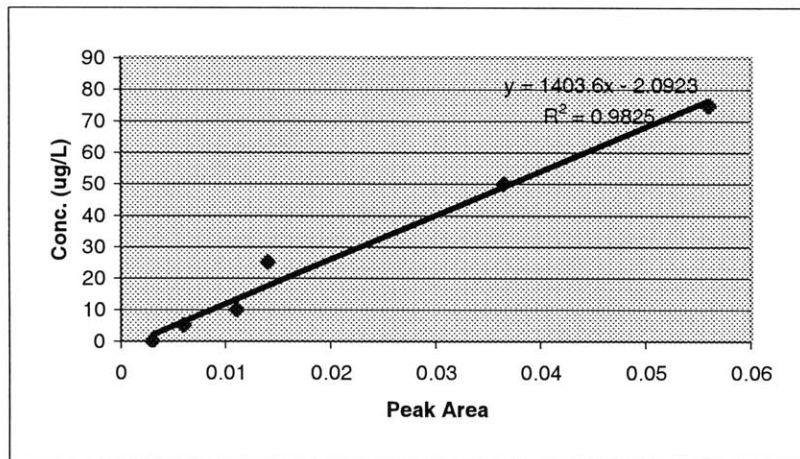
Calibration 2

Standard Concentration (ug/L)	Peak Area
0	0.004
5	0.006
10	0.011
25	0.013
50	0.034
75	0.054
100	0.076
150	0.105

Calibration using average calibration

Standard Concentration (ug/L)	Peak Area
0	0.003
5	0.006
10	0.011
25	0.014
50	0.0365
75	0.056
100	0.0785
150	0.1045

Sample ID	Peak Area	Conc. (ug/L)	Undiluted Conc. (ug/L)
d120p	0.01	5	-
e120p	0.02	26	-
nep 1-1	0.01	18	-
nep 1-2	0.03	37	-
nep 2-1	0.13	176	-
nep 2-2	0.11	145	-
salm. 1	0.04	50	997
salm. 2	0.04	53	1053



Salem Samples

Calibration 1

Standard Concentration (ug/L)	Peak Area
0	0.009
5	0.008
10	0.008
25	0.034
50	0.072
75	0.11
100	0.149
150	0.201

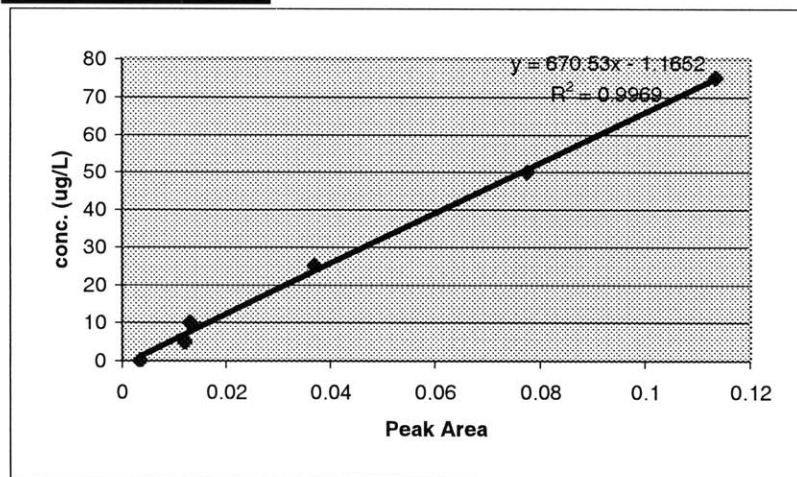
Calibration 2

Standard Concentration (ug/L)	Peak Area
0	-0.002
5	0.016
10	0.018
25	0.04
50	0.083
75	0.117
100	0.138

Calibration using average calibration

Standard Concentration (ug/L)	Peak Area
0	0.0035
5	0.012
10	0.013
25	0.037
50	0.0775
75	0.1135
100	0.1435

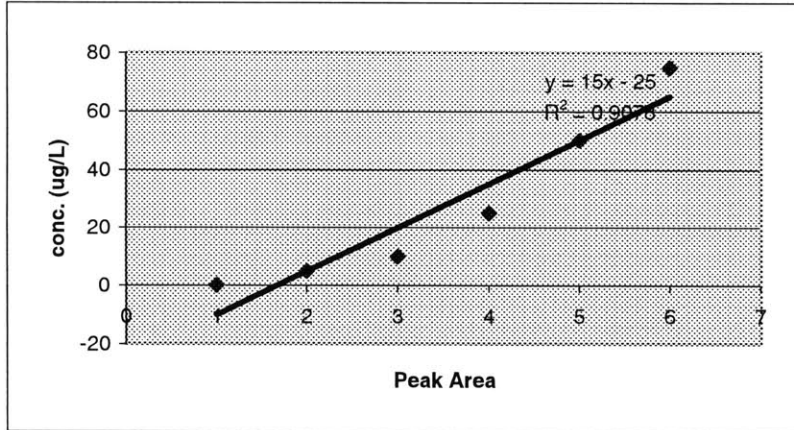
Sample ID	Peak Area	Conc. (ug/L)	Undiluted Conc. (ug/L)
a30s	0.07	46	461
b30s	0.06	43	427
c30s	0.04	29	287
d30s	0.05	37	374
e30s	0.05	31	313
a60s	0.09	59	588
b60s	0.08	53	528
c60s	0.04	25	246



Calibration using average calibration

Standard Concentration (ug/L)	Peak Area
5	0.016
10	0.018
25	0.04
50	0.083
75	0.117
100	0.138

Sample ID	Peak Area	Conc. (ug/L)	Undilute d Conc. (ug/L)
d60	0.05	32	324
e60	0.02	12	119
a90	0.09	54	536
b90	0.07	44	440
c90	0.03	20	202
d90	0.05	27	273
e90	0.03	18	183
a120	0.08	52	524
b120	0.06	36	363
c120			
d120	0.05	27	273
e120	0.02	9	93



Calibration 1

Standard Concentration (ug/L)	Peak Area
0	-0.005
5	0.011
10	0.02
25	0.021
50	0.055
75	0.071
100	0.13

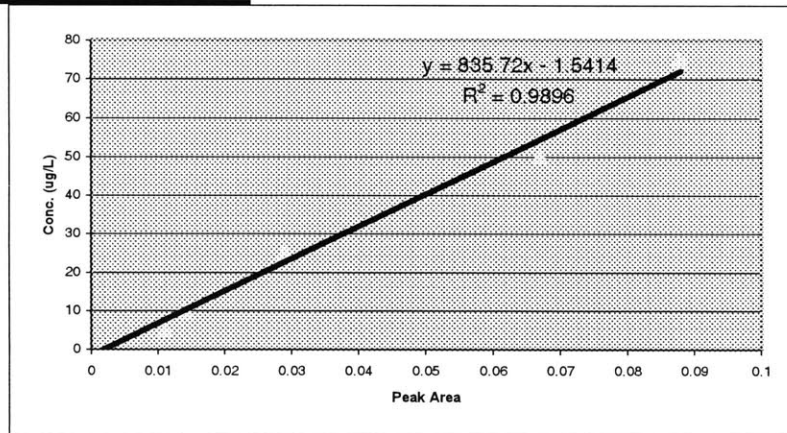
Calibration 2

Standard Concentration (ug/L)	Peak Area
0	0.004
5	0.017
10	0.014
25	0.037
50	0.079
75	0.105

Calibration using average calibration

Standard Concentration (ug/L)	Peak Area
0	-5E-04
5	0.011
10	0.014
25	0.029
50	0.067
75	0.088

Sample ID	Peak Area	Conc. (ug/L)	Undiluted Conc. (ug/L)
c120s	0.04	30	302



Appendix C

Calculation to Estimate of Arsenic Concentration in Soil Due to Sludge Disposal

Estimation of arsenic concentration in soil as result of treatment sludge disposal:

Assume that arsenic concentration in the water is 200 ug/L and that treatment removes 100 % of arsenic present, giving the maximum concentration of arsenic possible in the sludge. Also assume that 20 liters are treated.

Mass of arsenic in the sludge = $200 \text{ ug/L} \times 20 \text{ L} = 4000 \text{ ug}$ or 4 mg

Assume that the liquid sludge is then disposed onto cow dung and eventually deposited in the soil over an area of about 1 m^2 . Also assume the sludge then penetrates into the soil to a depth of 3 cm.

Assuming a typical unit weight of soil of 2000 kg/m^3 ,

Mass of 3 cm of soil spread over 1 m^2 of area = $2000 \text{ kg/m}^3 \times 1 \text{ m}^2 \times 0.03 \text{ m} = 60 \text{ kg}$

The arsenic concentration in the soil becomes,

Arsenic concentration in the soil = total mass of arsenic / (soil mass)
= $4 \text{ mg} / 60 \text{ kg} = 0.07 \text{ mg/kg}$