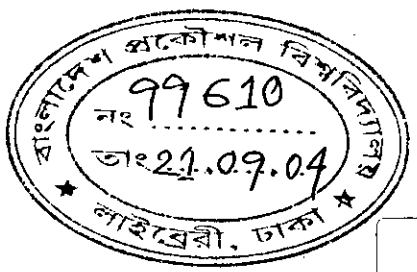
ARSENIC REMOVAL FROM GROUNDWATER BY ALUM

BY
MD. EHOSAN HABIB



A thesis submitted to the Department of Civil Engineering of Bangladesh University of Engineering and Technology, Dhaka, in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL AND ENVIRONMENTAL ENGINEERING

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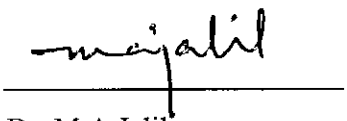

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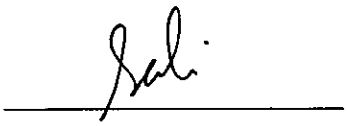

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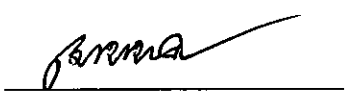

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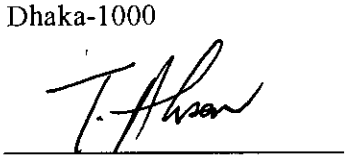

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DECLARATION

I hereby declare that the research work reported in this thesis has been performed by me and this work has not been submitted elsewhere for my other purpose (except for publication)

মো: এহসান হাবীব

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ABSTRACT

Widespread arsenic contamination of shallow aquifers in Bangladesh has posed a major public health concern as most of its population uses the aquifers as the sources of water supply. There is an urgent need to supply arsenic-safe drinking and cooking water to the millions of arsenic affected people in Bangladesh. The present study is focused on removal of arsenic from groundwater by alum coagulation. An arsenic removal unit based on co-precipitation-adsorption-sedimentation and filtration processes was used to study the arsenic removal efficiency under a variety of conditions both in the laboratory and field.

Optimum alum dose for As(V) removal was found to be 100 ppm and the percent removal efficiency was better for higher initial arsenic concentration. A moderate mixing of the coagulant was required for satisfactory removal of arsenic from water. The optimum sorbate/sorbent ratio was 75 μg As / mg Al. Under normal concentrations of pH, alkalinity, hardness, chloride, nitrate, ferric iron, silicate in Bangladesh groundwater, these parameters individually had no significant effect on arsenic removal efficiency. Fe(II) enhanced the efficiency slightly. Phosphate decreased the removal efficiency significantly. At low concentrations, anions had no synergistic effect on arsenic removal efficiency, but at medium to high concentrations, the anions reduced the removal efficiency very significantly. At low permanganate dose (1.0 ppm) and medium iron and phosphate concentrations (5.0 ppm and 3.0 ppm, respectively), the removal efficiency varied little with the form of arsenic. Higher concentration of Fe(II) in the feed water required higher dose of potassium permanganate for effective As(III) removal. Sand filtration was very effective in removing residual color and residual arsenic. One hour settling time in the top bucket was found enough for the alum based arsenic removal unit. It was found that the adsorption capacity of the iron present in the sand filter greatly enhanced the arsenic removal efficiency.

Performance of arsenic removal unit was evaluated in the field in order to determine their suitability at household levels. The variations of raw water arsenic and phosphate concentrations with time were found significant. The residual arsenic concentrations in the treated water of 3 field units were found to be mostly below 20 ppb, much below the Bangladesh standard at alum dose of 100 ppm and permanganate dose of 1 ppm. These doses were enough to remove arsenic effectively from natural groundwater if its iron content was high (≥ 9 ppm) and phosphate content was low (<1.0 ppm). Alum dose of 100 ppm and permanganate dose of 1 ppm could not produce arsenic-safe water of two field units where moderate amount of iron (4.0 ~ 5.0 ppm) and high concentration of phosphate (4.84 ~ 5.54 ppm) was present in the raw water. Higher permanganate dose was required for effective arsenic removal by the two field units. For arsenic and phosphate concentrations of 190 ppb and 4.84 ppm respectively, the required permanganate dose was 3 ppm. The permanganate dose requirement was 6 ppm for arsenic and phosphate concentrations of 278 ppb and 5.54 ppm respectively. Under favorable conditions (low phosphate concentration and high iron concentration), the unit removed arsenic satisfactorily without addition of any chemical. All the five tubewells were bacteriologically contaminated. So chlorine dose was introduced and it was found that 0.45 ppm was satisfactory for disinfections. Filtration removed a substantial amount of arsenic (39-49%) when natural iron content was 9 to 20 ppm. Proper operation of the system was essential to obtain satisfactory performance. Users' acceptability of the units was found to be satisfactory especially among the poor and conscious people.

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CHAPTER 1

INTRODUCTION

1.1 Background

Elevated levels of arsenic in groundwater are major concern for many countries in the world, because exposure to arsenic via drinking water leads to a wide range of health problem (WHO, 1996). In Bangladesh, high levels of arsenic have been detected in the shallow groundwaters in 59 out of 64 administrative districts; the southern, south-western and north-eastern regions of the country are worst-affected. On an average 27% of shallow tubewells in Bangladesh are producing water with arsenic in excess of Bangladesh standard of 50 ppb for drinking water and in acute arsgnkc"rrobngm areas more than 90% of shallow tubewells are contaminated (DPHE/DFID/BGS, 2000). This is a serious public health concern in Bangladesh as hand pump tubewell water is the major source of drinking water for almost all of her population. Now over ten thousands of people are reported to have already been suffered from arsenicosis by drinking arsenic contaminated water and millions are at risk of arsenic toxicity due to exposure to arsenic contaminated tube well water (EES/DCH, 2002; Rahman et al. 2002; DPHE/DFID/BGS, 2002).

Arsenic toxicity has no known effective medicine for treatment, but drinking of arsenic-safe water can help the affected people to get rid of the symptoms of arsenic toxicity. Hence the most important measure needed to combat the arsenic problem is to provide arsenic safe drinking water to the exposed people. There is an urgent demand to ensure supply of arsenic-safe water in the arsenic affected area in Bangladesh. There are various alternative options available to meet the demand. The alternative options are (1) Ground water from deep arsenic safe aquifers (deep tubewell), (2) Dug wells or Ring wells, (3) Rainwater harvesting (4) Surface water treatment and (5) Treatment of arsenic contaminated groundwater. The groundwater from deep tubewell is arsenic free but this option is too much expensive. And there is a possibility of contamination of the deep aquifers due to down flow of arsenic contaminated water during pumping. Dug wells are

also arsenic free but bacterial contamination may be difficult to avoid. It is not suitable for all over the Bangladesh and water may not be available in the dug wells in the dry season. Rainwater has the problems of very high seasonal variation of rainfall, proper storage, quality degradation and public acceptance. The surface water is contaminated with microbiological pollutions and the availability is not uniform throughout the year.

Unless suitable alternative drinking water sources are made available, arsenic removal from the shallow tubewell water through simple and low cost technologies appears to be an immediate and at least a short-term solution of this problem. A remarkable technological advancement in arsenic removal from groundwater has been taken place during the last 5-6 years in Bangladesh and a number of household and community type arsenic removal systems has been developed and evaluated (Ahmed, 2002).

1.2 Justification of the Study

The most common technologies utilized the conventional process of oxidation, co-precipitation and adsorption on coagulated flocs, adsorption onto sorptive media, ion exchange and membrane techniques for arsenic removal. All the technologies have their merits and demerits and are being refined to make suitable in rural condition. Alum and potassium permanganate, being easily available in the market in acceptable quality, stable, cheap and well known to users, have been most widely tried in Bangladesh to remove arsenic from groundwater. DPHE-Danida developed a 'Bucket Treatment Unit (BTU)' based on the principle of oxidation, co-precipitation, adsorption, sedimentation and filtration processes. The BTU uses alum dose of 200 mg/L and potassium permanganate dose of 2 mg/L. The units were reported to have very good performance in arsenic removal in both field and laboratory condition (Sarkar et al, 2000; Kohnhorst and Paul 2000). Several thousands BTUs were distributed in rural areas of Bangladesh. Evaluations of this technology under a DFID funded project "Rapid Assessment of Household level Arsenic Removal Technology" revealed that (i) it was generally not effective in reducing arsenic to below 50 ppb (Bangladesh Drinking Water Standard) if the feed water arsenic concentration was above approximately 120 ppb; (ii) manganese and aluminum contents of the treated water exceeded the Bangladesh Drinking Water Standards occasionally, and (iii) heavy microbiological contamination of the treated water (BAMWSP, DFID and WAB, 2001).

NGO Forum conducted an evaluation of the technology by setting 60 units in Putijani, Manikganj (Tahura et al, 2001). The results indicated that on average 4% of the units failed to produce arsenic safe water for feed water arsenic concentration in the range of 50-580 ppb. Aluminum and manganese concentrations exceeded the Bangladesh drinking water standards in 3% and 97% of all the cases, respectively. Bacterial contamination was also detected in 57% cases.

A laboratory study was conducted at BUET to evaluate arsenic removal by alum based on co-precipitation, adsorption, flocculation and sedimentation processes (Ali et al, 2001). It was found that an alum dose of 200 ppm removed arsenic above 90% for the feed water arsenate concentration from 500 to 1000 ppb. However, very high residual aluminum concentration in the treated water was found exceeding the Bangladesh drinking water standard by a wide margin. In another laboratory study (Razzaque, 2001), alum was used in place of ferric chloride in a "Ferric Chloride Based Arsenic Removal Unit" developed at BUET. The results showed that arsenic was very effectively removed by alum for feed water arsenic concentration up to 1000 ppb.

The above findings indicate that there is considerable debate on the effectiveness of alum in removing arsenic from water. Since alum is a common and cheap chemical, it is necessary to undertake a detail study to assess under what conditions, alum can remove arsenic from water to safe limit and how a sustainable household arsenic removal system based on alum can be developed. The present study aims at to answer these questions.

1.3 Objectives of the Research

The overall objective of the research is to evaluate the effectiveness of alum in removing arsenic from water under different water quality conditions and to design a sustainable household arsenic removal unit based on alum. The specific objectives are as follows:

- To construct an arsenic removal unit based on alum.
- To determine the arsenic removal efficiency of the unit and optimum alum dose.
- To determine the residual ions (aluminum, manganese and sulfate) in the treated water.

- To evaluate the effects of various parameters (i.e. initial concentration of arsenic, pH, alkalinity, iron, hardness, chloride, sulfate, phosphate, Nitrate, silicate) individually on arsenic removal efficiency.
- To study the synergistic effect of major anions on arsenic removal efficiency of the unit.
- To evaluate the effect of potassium permanganate dosing on removal efficiency.
- To determine the bacteriological performance of the arsenic removal unit and to study the performance of chlorination to eliminate the problem of bacterial pollution of the unit.
- To identify the cause(s) of poor performance of the BTU of DPHE-Danida.
- To study performance (both technical efficiency and social acceptability) of the arsenic removal unit at field.
- To develop operational and maintenance guidelines of the arsenic removal unit.

1.4 Scope of the Research

In many areas of Bangladesh, alum based arsenic removal unit is a very promising option, at least in the dry season. The researcher optimized the processes which were thought to be most suitable and easily applicable in the countryside of Bangladesh. The target users were the rural arsenic affected population who are unable to afford costly measures for arsenic free water. In the development of an optimum process for arsenic removal by alum, typical water requirements for drinking and cooking have been considered. During the process development, efforts were made to simulate field conditions as much as possible. No attempt was made to adjust the pH of groundwater in the field study, mixing was done by manual stirring; commercial grade chemicals and locally available raw materials were used. Any kind of complex machinery and sophisticated devices were avoided. Initial arsenic, pH range, alkalinity, iron, hardness, chloride, sulfate, phosphate, Nitrate and silicate concentrations of the groundwater of shallow hand tube wells were also taken into consideration during the research. Considering the time and resource constraints, field-testing was conducted in two arsenic affected districts only (Two villages in Munshigonj and two villages in Narayangonj)

1.5 Methodology

A brief description of the procedures followed in order to achieve the objectives of the research work is given below:

- As(V) stock solution was prepared by dissolving its sodium salts Na_2HAsO_2. $7H_2O$ in distilled water. As(III) stock solution was prepared by dissolving arsenic trioxide (As_2O_3) in distilled water containing sodium hydroxide (NaOH).
- Groundwater from a tap at the Environmental Engineering Laboratory of the Department of Civil Engineering, BUET was used to conduct all the laboratory experiments.
- Stock solutions of different chemicals were made as required. Synthetic groundwater of varying composition was prepared by adding the required amount of stock solution(s) to the tap water.
- 5 arsenic removal units were constructed following the same design of "Ferric Chloride Based Arsenic Removal Unit" developed at BUET. Alum was used in all the experiments in place of ferric chloride and potassium permanganate dosing was made when required.
- Synthetic groundwater containing 300, 500 and 1000 ppb As (V) and was used as feed waters of the arsenic removal units. Different alum doses were added to the feed waters and the same operational procedures of "Ferric Chloride Based Arsenic Removal Unit" was followed. However, sedimentation times were varied to determine its effect on arsenic removal efficiency.
- Feed water pH, alkalinity, iron, hardness, chloride, sulfate, phosphate, nitrate and silicate concentrations were varied individually with a particular dose of alum and As(V) and the ARU was operated to find the effect of the water quality parameters on arsenic removal efficiency.
- Synergistic effect of different ions was studied by adding, the ions to the tap water and running the ARU. A number of combinations were experimented to reveal whether the synergistic effect was present or not.
- Potassium permanganate dose were varied to reveal its effect on oxidation of trivalent As(III) to As(V).
- Treated water arsenic concentrations were measured by AAS methods. Other physical and chemical parameters were measured following standard methods.

- Bacteriological quality of the feed water and treated water were determined by counting TC and FC by the membrane filter technique.
- After completion of the laboratory work the data were grouped and presented according to the objectives of the research work.
- The available performance data of DPHE-Danida were investigated in the light of the experimental results of the present study.
- The units were tested at field by installing 5 units at 5 different households. The field-testing was conducted in Basgaon & Basail Bhog village of Srinagor thana of Munshigonj district and Echapara & Dolerbag village of Sonargaon thana of Narayangonj district. The units were operated and maintained for about one year by the householders under the close supervision of the researcher. The technical performances were evaluated on the basis of experimental data obtained from the field study. The social acceptability of the units was assessed through questionnaire survey.
- An operational and maintenance guideline was developed on the basis of results and work experience in the laboratory and field.

1.6 Organization of the Thesis

The thesis consists of six chapters. A short outline of the chapters is described below:

Chapter 1 presents the background, justification of the study, objectives, scope and methodology of works.

Chapter 2 presents the literature review concerning occurrence of arsenic, source of arsenic, arsenic in the environment, properties of arsenic, arsenic chemistry, arsenic in the soil, use of arsenic, methylation reaction and effects of arsenic on health and arsenic contamination in Bangladesh.

Chapter 3 reviews the arsenic removal processes, details of arsenic removal technologies and their merits & demerits of arsenic removal unit. This chapter also includes determination of arsenic by laboratory methods.

Chapter 4 describes the laboratory experimental works to determine the effect of source water composition and chemical dosing on arsenic removal. The results obtained from the experiments are also presented and discussed in this chapter.

Chapter 5 presents the field-testing of alum based household arsenic removal units carried out at the Munshigonj and Narayangonj district. Performance of the arsenic removal units was evaluated in terms effluent quality, user acceptance of the unit and operation & maintenance issues. The variation of raw water composition with time in different areas is also discussed here.

Finally chapter 6 presents concluding remarks and also provides recommendations for future study.

CHAPTER 2

ARSENIC IN ENVIRONMENT

2.1 Introduction

Arsenic is a naturally occurring element. Pure arsenic is a gray metal, which is usually found in the environment combined with other elements such as oxygen, sulfur and iron. Arsenic may be found in organic form when it is combined with carbon and hydrogen. Sometimes arsenic occurs naturally in the soil, from where it leaches into groundwater. Sometimes it may be found in effluents of different industries. This chapter presents a review of literature concerning occurrence, source, chemistry, uses and health effects of arsenic and its behavior in the environment.

Through the process of earth's materialization, the mantle was formed to contain the toxic metals in small quantities and in a way that does not affect our biosphere to any large extent. The toxic metals occurred only spot wise and mainly immobilized in geological formations. This allows for groundwater to migrate through the deep soil without dissolution at too high concentration levels. Like that, rainwater can pass through multiple geological layers of varied chemical compositions and contents of potentially toxic compounds. Yet it most often comes out in springs as fresh, enriched with tasty and healthy minerals and free of pathogenic micro-organism and toxic substances. There is no doubt that this immobilization of toxic components in the geosphere has been of significant importance for the development and survival of the biosphere as we know it today.

Like most of the toxic metals, arsenic occurs immobilized in the geosphere. However, arsenic is not a typical metal. It is also called metalloid, exhibiting metallic as well as non-metallic characters and corresponding chemical processes. It is due to this arsenic chemistry that mankind has developed the multiple uses and anthropogenic pollution. It is also due to this arsenic chemistry that arsenic is immobilized naturally to water bodies. Thus, arsenic is extremely toxic even carcinogenic, and yet estimated to be 12th most

abundant element in the human body (Katrien & Martin). Understanding of at least some of the arsenic chemistry may be most essential for the avoidance and the remediation of its environmental health problems, seriously faced in Bangladesh.

2.2 Arsenic in the Environment

Arsenic is the 20th most abundant element in the earth's crust and the 12th most abundant element in the biosphere, where it is said to be an essential element at least for some animal species, but not for human. Arsenic is the king of poisons and has plagued human beings since the days of antiquity. As a carcinogen, it has been well known since early times. In Asia, arsenic is both a cause of large-scale environmental contamination and a serious health-hazard. Arsenic is a toxic chemical and may pollute air, soil, sediments and water causing health hazards to both human and animal's life. Arsenic is found to occur in nature as mineral form which, by way of erosion and deposition, soil may be contaminated. Table 2.1 shows the approximate environmental concentration levels of arsenic and human exposure through the air, food and water.

Table 2.1: Approximate environmental concentration levels of arsenic and human exposure through the air, food and water (Data from WHO, 1996).

Medium	Concentration	Daily Intake	Daily exposure	Remarks
Air	0.4-30 ng/m^3	20m^3	0.01-0.6µg	May be much higher in industrial areas
Food	0.4-120µg/kg	1kg	0.4-120µg	70% is organic As and 25% is inorganic As
Water, Generally	1-2µg/L	2 L	2-4µg	Mainly inorganic As(III) most toxic
Water, up to	12000µg/L	2 L	24000µg	Causing endemic illnesses

At high concentrations (76 mg arsenite), arsenic can be lethal to human body. Arsenic is a dietary constituent and is present in many foods such as meat, fish, poultry, grain and cereals.

Arsenic is found in everywhere in the environment. It is found in atmosphere, biosphere, hydrosphere, pedosphere and geosphere and transferred from one to another by natural processes or human activities such as mining, agriculture, industrial processes etc. The environmental cycle of arsenic is shown in Figure 2.1.

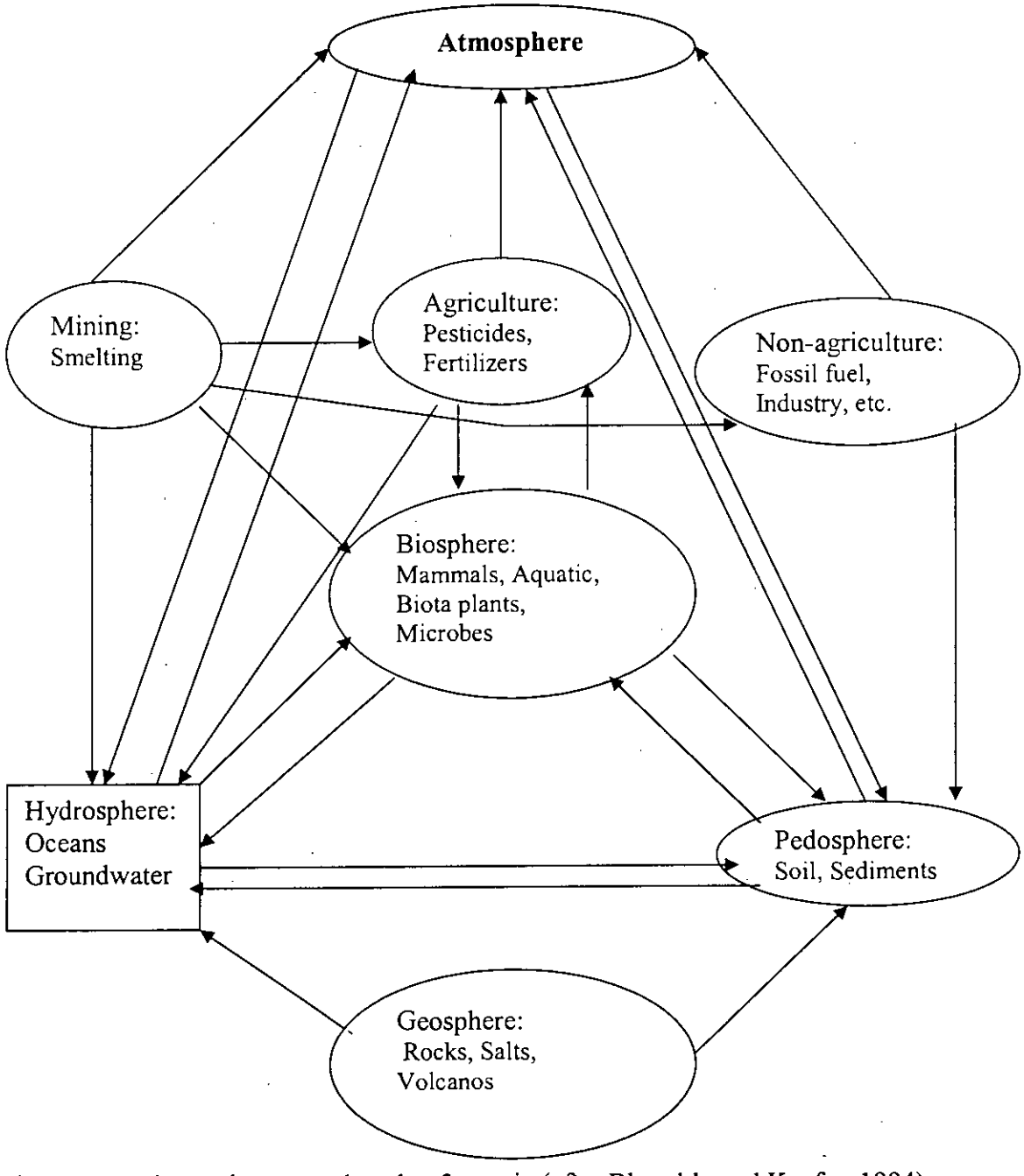

Figure 2.1: The environmental cycle of arsenic (after Bhumbla and Keefer, 1994)

Arsenic is mainly found in the form of its mineral compounds and widely distributed in air, water, soils, rocks and earth crust. It may be seen that rocks and minerals are the main reservoirs of arsenic, which is mobilized in the other media of the environment by natural weathering processes, biological activity, volcanic eruption and anthropogenic activities.

2.3 Use of Arsenic

2.3.1 Historical Uses

The use of arsenic is recorded 2000-3000 years ago in the orient. Orpiment and realger are occasionally cited in Akkadian texts as ingredients of paints and for ornamental or cosmetic purposes (Forbes, 1964). The yellow sulfide of arsenic was known to the classical painters as aurpigmentum and was a common ingredient in most of the colors in the middle ages for painting, and also for writing and in imitation of gold (Thompson, 1956). Arsenic bronzes were made by the Egyptians, who used it with it copper and tin in making metal mirrors (Derry and Williams, 1961). Arsenic is cited in the first treatises on glasses as on the fluxing ingredients in glass manufacture (Nriagu, 1994). Its effects are produced by crystallization during the cooling of the glass (Singer et al., 1957).

The main uses arsenic compounds in antiquity were pharmaceutical and medicinal. At the beginning of the sixteenth century, the revolutionary Paracelcus designated arsenic, along with opium, mercury, lead and copper sulfate as part of the modern pharmacopoeia (Hunter, 1978). Some arsenic compounds, mainly arsenate of potash, which was prepared by fusing the trioxide with saltpeter, seemed to be greatly favored as a medicine by Paracelcus, who named it arsenicum fixum (Meyer, 1975).

Until the nineteenth century, arsenic (As_2O_3) was the preferred poison of most homicidal practitioners, to the point where laws were passed against possession of it (Emsley, 1985). Despite this, Flower's solution (1%ptassium arsenate, discovered in 1786) became the most widely used medication for avariety of illness for 150 years (Frost, 1984). Donovan's solution (arsenic iodide) and devalagin's solution (arsenic trichloride) were also recommended to treat rheumatism, arthritis, asthma, malaria, trypanosome infections, tuberculosis and diabetes (Leonard, 1991). Several poisoning cases have been reported from the historical use of arsenical pigments for coloring artificial flowers, toys, wallpaper, and wrapping papers (Nriagu, 1994). A vast literature exists regarding the hypothesis that arsenic poisoning was the cause of Napoleon's death, due to its presence in the green pigments of the wallpaper (Jones, 1982; Richardson, 1974).

2.3.2 Modern Uses of Arsenic

Elemental arsenic has few uses, one of which is to impart more nearly spherical shape in the manufacture of lead shot. It is also used in certain alloys to increase strength at elevated temperatures, in bronzing and in pyrotechniqes. E-Pure arsenic elements are uses for hollow cathode lamp's filament in arsenic analysis. Arsenic compounds are used as components of pesticides and preservatives of electric poles and other wood, leather and like as shown below in Table 2.2.

Table 2.2: Principal modern uses of arsenic compounds (Azcue & Mrgagu, 1994)

Sector	Uses
Agriculture	Pesticides, insecticides, defoliants, wood preservatives, debarking trees, soil steriliant and disinfectant.
Livestock	Feed additives, disease prevention (swine dysentery, heart worm infections), cattle and sheep dips, algaecides
Medicine	Antisyphylitic, drugs, treatment of trypanosomiasis, amebiasis and sleeping sickness.
Electricity	Solar cells, optoelectronic devices, semiconductor applications, light- emitting diodes in digital instruments.
Industry	Glassware, electro-photography, catalysts, pyrotechnics, antifouling paints, dyes, soaps, ceramics, pharmaceutical substances.
Metallurgy	Alloys (automotive body solder and radiators), battery plates as hardening agents.

2.4 Sources of Arsenic

2.4.1 Natural Sources of Arsenic

Arsenic is a component of more than 245 minerals (Fredrick et al. 1994). These are mostly ores containing sulfide, along with copper, nickel, lead, cobalt or other metals. The most important ores are arsenopyrites or mispickel (FeS), realger (As_4S_4), orpiment (As_4S_6), Ioellignite ($FeAs_2$), nicoliote (NiAs), cobalt glance (CoAsS), Gersdroffite (NiAsS) and smaltite ($CoAs_2$). Within these minerals, arsenopyrite is probably the most common mineral in the environment. Table 2.3 shows some naturally occurring minerals containing arsenic.

Table 2.3: Naturally occurring minerals containing arsenic (NRCC, 1978)

Mineral	Chemical Formula	Mineral	Chemical Formula
Arsenite	As	Mutite	$Pb_5(PO_4,AsO_4)Cl$
Antimony arsenide	AsSb	Nicollite	NiAsS
Arsenopyrite	FeAsS	Orpiment	As_2S_3
Arsenogentite	Ag_3As	Olivenite	$Cu_2(AsO_4)OH$
Arsenolite	As_2O_3	Proustite	Ag_2AsS_3
Adamite	$Zn_2AsO_4(OH)$	Pearcite	$Ag_{16}As_2S_{12}$
Annabergite	$N_{13}(AsO_4)_2\ 8H_2O$	Pharmacosiderite	$Fe_3(AsO_4)_2OH_3$
Beaudanite	$PbFe_3(AsO_4)SO_4$	Realgar	AsS
Cobaltite	CoAsS	Rathite	$Pb_3As_5S_{10}$
Domeykite	Cu-As	Scorodite	$(FeAl)AsO_4\ 2H_2O$
Energite	Cu_3AsS_4	Smaltite	$(Co,Ni)As_x$
Erythrite	$Co_3AsO_4\ 8H_2O$	Safflorite	$(Co,Fe\ )As_2$
Gersdorffite	CoAsS	Skutteridite	$(Co,Ni)As_x$
Galucodote	(Co,Fe) As	Sperrylite	$PtAs_2$
Jordanite	$(Pb,Ti)_{13}As_7S_{23}$	Shloanthite	$(Ni,Co)As_{3-x}$
Loellingite	$FeAs_2$	Tennantite	$Cu_{12}As_4S_{13}$

Arsenic and its compounds are mobile in the environment. Weathering of rocks converts arsenic sulfides to arsenic trioxide, which enters the arsenic as dust or by dissolution in rain, rivers or groundwater (Clifford and Zhang, 1993). Volatile forms of arsenic e.g. arsine (AsH_3) and trimethyl arsine (CH_3As) enter the atmosphere from land and water, are returned by rain and atmospheric fallout. The oxidized forms of arsenic are converted back to sulfides by anaerobic processes occurring on land and water sediments (Tamaki, 1992). The concentrations of arsenic in natural reservoir with respect to soils have been shown in Table 2.4. Soils and oceans are the remaining major reservoirs that have much more inherent arsenic than do biota (plants, animals, man and microbes) and the atmosphere. The average concentration of arsenic in soils of the world is 7.2 ppm (Anonymous, 1978). Arsenic in the natural environment occurs in soils at an average concentration of about 5 to 6 ppm, but this varies among geographic regions (Peterson et al. 1981).

Table 2.4: Ratios of arsenic concentrations in natural reservoir with respect to soil (Mackenzie et al. 1979)

Reservoirs	Ratio with respect to soil
Rocks and Minerals	25,000
Oceans	4
Soils	1
Biota (Plant, animals, microbes)	0.0005
Atmosphere	0.000001

2.4.2 Anthropogenic Sources

Recent estimates have placed the ratio of natural to anthropogenic inputs of arsenic at 60:40 (Chilvers et al. 1985). The global production rates of arsenic compounds, determined in a recent survey are shown in Table 2.5:

Table 2.5: Production rates of the main arsenical compounds (Alloway, 1990)

Compound	Production (tons As/year)
Herbicides	8,000
Cotton desiccant	12,000
Wood preservatives	16,000

The anthropogenic influence on the level of arsenic in soils depends on the human activity, the distance from the pollution sources, and the pollution dispersion pattern (Yan-Chu, 1994). Arsenic may accumulate in soil through use of arsenical pesticides, application of fertilizers, irrigation, dusts from the burning fuels, and disposal of industrial and animal wastes (Sandberg and Allen, 1975). It is a natural contaminant in lead, zinc, gold and copper ores and can be released during the smelting process (Creelious et al. 1974; ragaini et al. 1977; O'toole et al. 1971; rosehart and Lee, 1973). The stack dust and flue gases from smelters often contaminate soils with arsenic downwind from the operation (Crecelcious et al. 1974; Ragaini et al. 1977). Arsenic is also commonly associated with phosphate minerals, in an average concentration of 7.7 ppb (Alloway, 1990).

2.4.3 Geological Sources of Arsenic in Bangladesh

Although the source and reason of arsenic contamination of groundwater in Bangladesh is said to be geological, extensive studies have not yet been conducted. However, having much geological similarity with West Bengal of India where most of the arsenic contaminated areas are in the region of alluvial formation and it has been recognized that the arsenic is of geological similarity origin, in Bangladesh similar problem may exist in the region of alluvial land. The studies carried out in West Bengal clearly indicated that in the region of alluvial sediment there is existence of pyrite and this pyrite is rich in arsenic. Due to heavy groundwater withdrawal and fluctuation of water table from pre-monsoon and also due to thousands of boreholes, the underground aquifer is aerated and the pyrite decomposes. The acid released due to this decomposition leaches out arsenic from pyrite. This may however, be one of the causes for arsenic contamination in Bangladesh. But there are many areas in south of Bangladesh where water levels remains always at high level and there is no irrigation from groundwater, the presence of arsenic in groundwater are also identified. However, it may be confirmed that the contamination of arsenic in groundwater is originated from the geological sources.

Previously a number of anthropogenic explanations had been made for the occurrence of arsenic in groundwater. While it is possible that some may explain isolated cases of arsenic contamination, none of the anthropogenic explanations can account for the regional extent of ground water contamination in West Bengal and Bangladesh. There is

no doubt that the source of arsenic is of geological in nature. The arsenic content of alluvial sediments in Bangladesh is usually in the range 2-10 mg/kg; only slightly greater than typical sediments (2-6mg/kg). However, it appears that an unusually large proportion of arsenic is present in a potentially soluble form. The high groundwater arsenic concentrations are associated with the gray sands rather than the brown sands.

The groundwater arsenic problem in Bangladesh arises because of an unfortunate combination of three factors:

- a source of arsenic (arsenic is present in aquifer sediments)
- mobilization (arsenic is released from the sediments to the groundwater)
- transport (arsenic is flushed away in the natural groundwater circulation)

2.5 Chemistry of Arsenic

2.5.1 Properties of Arsenic

Arsenic is a chemical element in the nitrogen family (group VA of the periodic table), existing in both grey and yellow crystalline forms. Although some forms of arsenic are metal-like, it is best classified as metalloid and non-metal. It can be manufactured in three allotropic forms, the yellow (α) form, the black (β) form and the steel grey (γ) form. These have different physical properties. The cubic α- form is made by condensing the vapor at very low temperatures; its metastable is soluble in CS_2 and consists of tetrahedral As_4 units. The black β- poiymorph is iso-structural with black phosphorous (II), also metastable. Both of these modifications revert to the stable γ form, grey or metallic, rhombohedral arsenic, on heating or exposure to light. Gray or metallic arsenic, which is more stable and more common than the softer yellow form, is very brittle, tarnishes in air and sublimes when heated at 610^{0C}, i.e., it passes directly into vapor form without melting and reverts to the crystalline solid without liquefying upon cooling the vapor (Encyclopaedia Britannica, 1994). Apart from the elementary arsenic, where the oxidation state by definition is 0, arsenic is stable in its states +5,+3 and -3. Some important properties of arsenic are listed in Table 2.6.

Table 2.6: Properties of arsenic (Encyclopedia Britannica, 1994)

Parameter	Value
Atomic number	33
Atomic weight	74.92158
Melting point (gray form)	814^0C at 36 atm
Boiling point	616^0C (sublimes)
Density (gray form)	5.73 g/cm^3 at 14^0C
Density (yellow form)	2.03 g/cm^3 at 18^0C
Specific gravity (α, β, γ)	2.026, 4.700, 5.727
Latent heat of fusion	27,740 J/(mol-K)
Latent heat of sublimation	31,974 J/(mol-K)
Oxidation number	-3,0,+3,+5
Electronic configuration	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^3$ (2-8-18-5)
Electrical resistivity	33.3 μohm cm (273 K)
Crystal system (grey form)	Hexagonal (rhombohedral)
Lattice constant at 26^0C	a = 0.376 nm, c = 1.0548 nm
Covalent radius	121 pm
Ionic radius (As^{+3})	69 pm
Metallic radius	139 pm
Hardness (Mohs' scale)	3.5

2.5.2 Principal Compounds of Arsenic

Because arsenic has a range of oxidation states from -3 to +5, it can form a variety of different kinds of compounds. Among the most important commercial compounds are oxides, the principal forms of which are arsenious oxide (As_2O_3) and arsenic pentoxide (As_2O_5). Arsenious oxide commonly known as white oxide is the material most widely used for the synthesis of arsenic compounds. It is produced as a by-product of the nonferrous metal industry, primarily from the smelting of copper ores. Naturally occurring metal arsenide's realgar and orpiment also convert to the trivalent oxide when

roasted in air. The formation of the trioxide by the roasting of a sulfide ore is illustrated in Eq. (2-1).

$$2\ FeAsS + 5\ O_2 \longrightarrow Fe_2O_3 + As_2O + 2\ SO_2 \qquad (2\text{-}1)$$

Elemental arsenic undergoes reaction with oxygen to yield the trioxide as follows:

$$4\ As + 3\ O_2 \longrightarrow 2\ As_2O_3 \qquad (2\text{-}2)$$

The trioxide is moderately soluble in water, but dissolves easily in aqueous alkali to produce a solution of arsenic, AsO^{2-}. It is slightly soluble in polar organic solvents such as alcohols and ethers and insoluble in benzene. The most useful reagent for the synthesis of pentoxide (As_2O_5) is concentrated nitric acid. The reaction between elemental arsenic and nitric acid gives H_3AsO_4. The controlled dehydration of this acid (Eq.3) gives the pentoxide.

$$4\ H_3AsO_4 \longrightarrow 6\ H_2O + As_4O_{10} \qquad (2\text{-}3)$$

Hypochlorous, hydrochloric and perchloric acids also oxidize the metal or As_2O_3 to the pentavalent state. Arsenic pentoxide dissolves readily in water to produce arsenic acid, H_3AsO_4. Arsine (AsH_3) is the best known of the hydrides of arsenic. It is a colorless poisonous gas composed of arsenic and hydrogen. The gas also called arsenic hydride is produced by the hydrolysis of metal arsenides and by the reduction by metals (e.g. zinc) of arsenic compounds in acidic solutions. Other hydrides of arsenic are diarsine (As_2H_4), diarsine hydride (As_2H_2), and polymeric diarsine monohydride $(As_2H)_x$.

Arsenic pentoxide, the anhydride of arsenic acid (H_3AsO_4) is very soluble in cold water and dissolves to form a solution of arsenic acid. The free acid can be obtained as a hydrate, H_3AsO_4. 0.5 H_2O, by the evaporation of a cold aqueous solution. Arsenic trioxide is the anhydride of arsenious acid. The solubility of arsenic trioxide in water at 25^{0C} is 21.6 g/L. The rate of dissolution of trioxide in water is painstakingly slow, sometimes requiring up to 50 h of continuous agitation. The solubility of arsenic trioxide increases greatly and occurs much more rapidly in both acid and alkaline media, Metal salts containing orthoarsenate (AsO_4^{3-}), monohydroarsenate ($HAsO_4^{2-}$), and dihydrogen arsenate ($H_2AsO_4^-$) are known. Diarsenic disulfide (As_2S_2), but more properly written as As_4S_4, exists in nature as mineral realgar. As_2S_4 is normally prepared as an impure material and must be purified by sublimation under an atmosphere of CO_2. Diarsenic trisulfide (As_2S_3), found in nature in orpiment, has been referred to as yellow arsenic sulfide. Diarsenic pentasulfide (As_2S_5), has been described as brownish-yellow, glassy, amorphous, and highly refractive. When suspended in water and heated, it decomposes

into the thermodynamically more stable As_2S_3 and free sulfur. Two binary As-P compounds have been reported. They are As_2P and AsP. Diarsenic phosphide is black and lustrous and turns brown on exposure to air. AsP is described as a lustrous and red brown powder.

Arsenic also forms numerous organic compounds, as for example, tetramethyldiarsine [$(CH_3)_2As\text{-}As(CH_3)_2$], used in preparing the common desiccant cacodylic acid. Several complex organic compounds of arsenic have been employed in the treatment of certain diseases, such as amebic dysentery, caused by microorganism. Some of the most important compounds and species of arsenic are shown in Table 2.7. Figure 2.2 (Dahi, 1997) shows a qualitative scale indicating that the toxicity of arsenic compounds varies to a large extent depending upon their chemical form.

2.5.3 Acid-Base Reaction

Apart from the elementary arsenic with oxidation state 0, arsenic is stable in the oxidation states of +5, +3, and -3 (see Table2.6), but generally found in water only in the trivalent and pentavalent states. The oxides of both As (III) and As(V) are soluble in water. The dissolution implies direct reaction with water, hydration, where the oxides behave like non-metals and exhibit acidic character. Arsenic (III) forms arsenious also called arsonic acid. Arsenic (V) forms the arsenic acid, also called arsinic acid. The two acids dissociate to form respectively arsenite and arsenate ions as shown in the following reactions.

Arsenious Acid Dissociation:

$$As_2O_3 + 3\ H_3O = 2\ H_3AsO_3 \qquad (2\text{-}4)$$

$$H_3AsO_3 = H^+ + H_2AsO_3^- \quad pKa=9.22 \qquad (2\text{-}5)$$

$$H_2AsO_3^- = H^+ + HAsO_3^{2-} \quad pKa=12.13 \qquad (2\text{-}6)$$

$$HAsO_3^{2-} = H^+ + AsO_3^{3-} \quad pKa=13.40 \qquad (2\text{-}7)$$

Arsenic Acid Dissociation:

$$As_2O_5 + 3\ H_2O = 2\ H_3AsO_4 \qquad (2\text{-}8)$$

$$H_3AsO_4 = H^+ + H_2AsO_4^- \quad pKa=2.2 \qquad (2\text{-}9)$$

$$H_2AsO_4^- = H^+ + HAsO_4^{2-} \quad pKa=7.08 \qquad (2\text{-}10)$$

$$HAsO_4^{2-} = H^+ + AsO_4^{3-} \quad pKa=11.5 \qquad (2\text{-}11)$$

Table 2.7: Arsenic species and their environmental importance in water

Compounds	Example	Environmental significance/ Dominant pH region
Arsine Oxidation state: -3	As^{3-}	Minor importance [Most toxic As species]
Elemental Arsenic Oxidation state: 0	As	Minor importance [Least toxic As species]
Trivalent Arsenic Oxidation state: +3	As(III)	Dominant under anaerobic condition [10 times more toxic than As(V)]
Arsenite, Inorganic	H_3AsO_3 $H_2AsO_3^{1-}$ $HAsO_3^{2-}$ AsO_3^{3-}	pH = 0 – 9 pH = 10 – 12 pH = 13 pH = 14 Important
Methylated As(III) MMAs(III) DMAs(III) TMAs(III) Organo-As(III)	$CH_3As(III)O_2^{2-}$ $(CH_3)_2As(III)O^{1-}$ $(CH_3)_3As(III)$	Minor importance [Less toxic than inorganic As(III)]
Pentavalent Arsenic Oxidation state: +5		Dominant under aerobic condition [10 times less toxic than As(III)]
Arsenate, Inorganic	H_3AsO_4 $H_2AsO_4^{1-}$ $HAsO_4^{2-}$ AsO_4^{3-}	pH = 0 – 2 pH = 3 – 6 pH = 7 - 11 pH = 12 - 14 Important
Methylated As(V) MMAs(V) DMAs(V) TMAs(V) Organo-As(V)	$CH_3As(V)O_3^{2-}$ $(CH_3)_2As(V)O_2^{1-}$ $(CH_3)_3As(V)O$	Minor importance [Less toxic than inorganic As(V)]

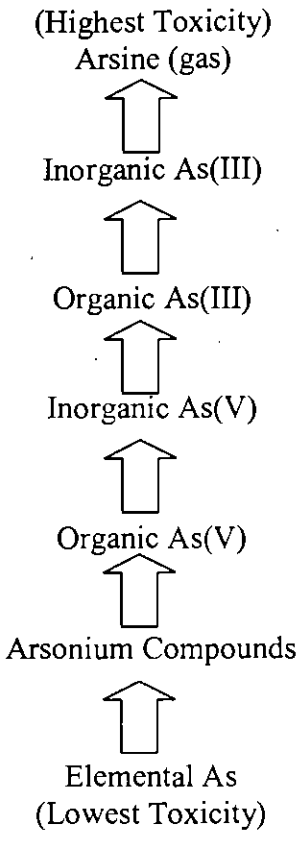

Figure 2.2: Arsenic toxicity scale (Dahi, 1997)

Figure 2.3 shows the predominance diagram of arsenic species as a function of pH. From figure 2.3 it is seen that arsenic acid is stronger than arsenious acid. Within the range of natural waters (particularly groundwater), where pH is usually between 6 to 9, the trivalent inorganic arsenic is found as non-dissociated arsenious acid (H_3AsO_3); while the pentavalent arsenic is primarily found as the ionized dihydrogen arsenate ($H_2AsO_4^-$) and mono-hydrogen arsenate ($HAsO_4^{2-}$). The relatively more mobile monomethylated and dimethylated forms are observed in ocean and lake waters, but seldom in groundwater.

As most treatment processes are more capable to remove ions, the trivalent arsenic is more difficult to remove from the water than the pentavalent (Kartinen and Martin, 1995). Probably this ionization of arsenic (V) is also important for the fate of arsenic in the human body. The reduced toxicity of the arsenic (V) may be, to a large extent, due to its ionization, which enables easier control of its intracellular transportation (Dahi, 1997).

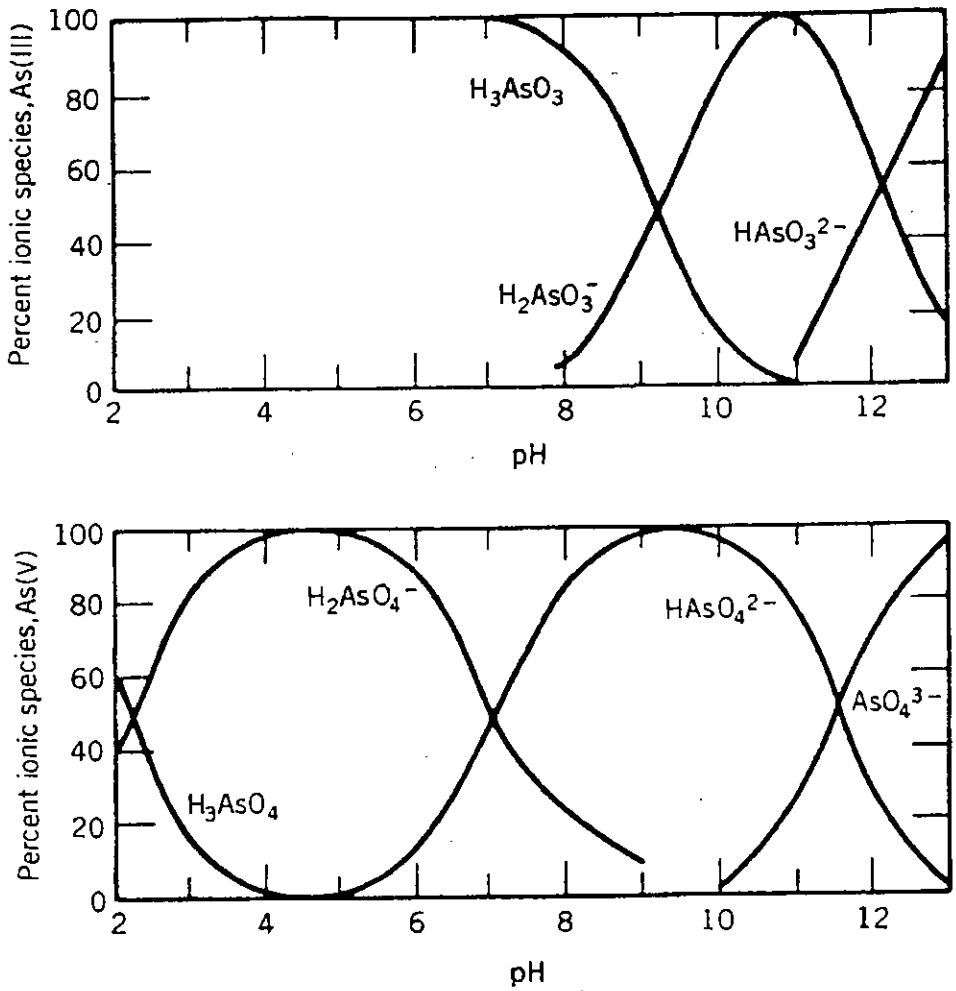

Figure 2.3: Predominance diagram of As(III) and As(V) as a function of pH (Montgomery, 1985)

2.5.4 Redox Reaction

Arsenic is a redox sensitive element. Arsenate [As(V)] and Arsenite [As(III)] are common oxidation states of arsenic in water. The mobility of arsenic is controlled, in large part, by the oxidation-reduction (redox) transformations. The valence in which arsenic exists is related to both pH and the redox potentials, *Eh*. The hypothetical electron activity at equilibrium, *pE*, is used interchangeably with *Eh*. These parameters are related by $pE = (F/2.3\ RT)\ Eh$, where T is the absolute temperature and F & R are the Faraday and Gas constants, respectively. Thus at 25^{0C}, 2.3 RT/F = 0.059 V and $pE = Eh/0.059$. The equation linking arsenic speciation to pH and *pE* are readily available, but Eh versus pH diagrams (Fig. 2.4), are the most concise way of presenting this information.

The Eh-pH diagram for arsenic (total concentration 10^{-5} mol/L) in a system including oxygen, H_2O and sulfur (total concentration 10^{-3} mol/L) is shown in Fig. 2.4. The diagram represents equilibrium conditions of arsenic under various redox potentials. Well-aerated surface waters would tend to induce high Eh values, therefore, any arsenic present should be in the arsenate [As(V)] form. Mildly reducing conditions, such as can be found in groundwater, should produce arsenite [As(III)]. By determining the pH and Eh of water, it is possible to determine which species of arsenic will be prevalent.

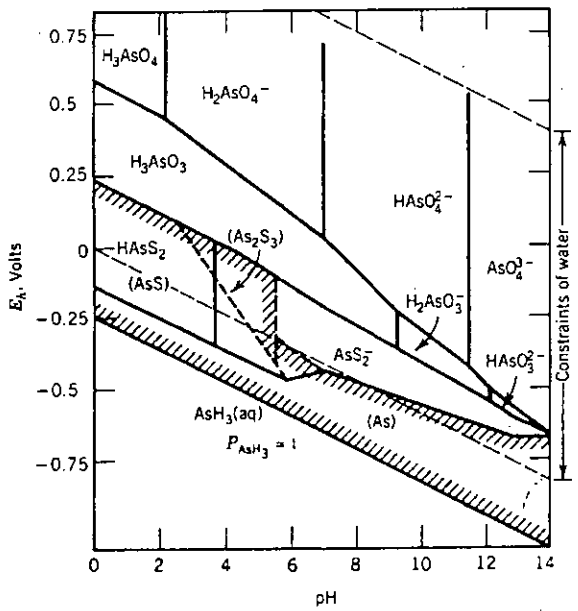

Figure 2.4: The Eh-pH diagram for As at 25^{oC} and 1 atm with total arsenic 10^{-5} M and total sulfur 10^{-3} M. Solid species are enclosed in parenthesis in cross-hatched area, which indicates solubility less than $10^{-5.3}$ M (Montgomery, 1985)

2.5.5 Oxidation Reaction

As stated earlier, arsenate is dominant in oxygenated water, while arsenite is dominant in non-oxygenated water. Although thermodynamics can provide an accurate prediction of possible changes in a given non-equilibrium conditions, they give no insight to the rate at which those changes will occur. While As(III) and As(V) acid-base reactions can be assumed to occur instantaneously, changes between oxidation states require indeterminate time periods in natural waters. For instance, the conversion of As(III) to As(V) in oxygenated water is thermodynamically favored, yet the transformation takes days, weeks or months depending on the specific conditions. The reduction of As(V) to As(III) is similarly kinetically constrained. This is the reason why arsenic (V) can be

found in some anoxic waters (Dahi, 1997). This process is however also known to be facilitated through catalysis and bacterial mediation.

In strongly acidic or alkaline solutions, the presence of copper salts, carbon, certain catalysts and higher temperatures can increase the arsenic oxidation rate (Ferguson and Davis, 1972). Catalytic oxidation of can be achieved by powered active carbon and dissolved oxygen in stirred reactions. The rate of oxidation can be described by the first-order equation.

The effective removal of arsenic from water requires the complete oxidation of As(III), especially if the drinking water standard is low. There are various means of oxidation available, but in drinking water treatment there are important considerations such as the limited list of safe chemicals, the residuals of oxidants, oxidation by-products and the oxidation of other inorganic and organic compounds. In the oxidation processes with dosing of chemicals, effective oxidants are free chlorine, hypochlorite, ozone, permanganate, and hydrogen peroxide/Fe^{2+} (Fenton's reagent), but not the chloramines (Frank and Clifford, 1986). These oxidants can directly transform As(III) to As(V) in the absence of oxygen. Chlorine is widly used for oxidation purpose, but may lead to chlorinated by-products, namely trihalomethenes (THMs), from reactions with natural organic matter. Ozone, widely used in surface water treatment for oxidation and disinfection, is quite effective but is not feasible for a specific application with As(III) oxidation. The most feasible oxidants are potassium permanganate and Fenton's reagent (H_2O_2/Fe^{2+}).Permanganate oxidizes As(III), Ferrous and manganese ions specifically and quickly. Chlorine and permanganate are able to oxidize As(III) to As(V) within a very short time, e.g., half an hour or even few minutes (Dahi, 1997).

Arsenious acid oxidations by most common oxidants are shown in the following reactions (Dahi, 1997):

$$H_3AsO_3 + \tfrac{1}{2}\, O_2 = H_2AsO_4^- + 2H^+ \quad (2\text{-}12)$$

$$H_3AsO_3 + HClO = H_2AsO_4^- + 2H^+ + Cl^- \quad (2\text{-}13)$$

$$H_3AsO_3 + 2/3\ MnO_4^- = H_2AsO_4^- + 2/3\ MnO_2 + 1/3\ H^+ + 1/3\ H_2O \quad (2\text{-}14)$$

Possible reaction with ferrous iron and permanganate is given bellow:

$$3\ Fe^{2+}(..) + KMnO_4 + 4\ H^+ \Rightarrow 3\ Fe^{3+}(..) + MnO_2 + H_2O + K^+(..) \quad (2\text{-}15)$$

2.5.5.1 Photochemical Oxidation of Arsenic

Besides oxidation with chemical dosing, photo-oxidation using either UV or solar light has been used for converting arsenite to arsenate. Khoe et al. (1997) developed and patened an As-removal procedure using addition of Fe(II, III) followed by exposure to UV or solar light to accelerate oxidation of As(III). Here iron is used both as photo-absorber and co-precipitator. This procedure was initially developed to treat acidic mining effluents. Efforts to enhance As(III) photo-oxidation at higher ph values are being made, e.g., by adding S(VI) (Khoe et al., 1999).

Another arsenic removal technology – SORAS (Solar Oxidation and Removal of Arsenic), is also based on photochemical oxidation of As(III) followed by precipitation or filtration of As(V) adsorbed on Fe(III) oxides. In this method water in transparent bottles are irradiated with sunlight for oxidation of As(III) to As(V). Lemon juice was found to be most effective in enhancing the photochemical oxidation of As(III). A small amount of lemon Juice is used in this process so that the pH of water (which is buffered by the presence of bicarbonate) is not changed (Wegelin et al., 1999).

UV irradiation for As(III) oxidation requires high-pressure mercury lamps with an emission spectrum between 190 and 254 nm; low-pressure mercury lamps, with their main line at 254nm, are ineffective. The rate of oxidation can also be described by a first order rate equation, but the rate constants are considerably higher compared to the activated carbon catalysis. Nearly complete oxidation can be achieved within 30 to 60 seconds but with a high –energy input of 3 to 4 kWh/m^3 treated water (Jekel, 1994).

2.5.6 Adsorption-Desorption

Adsorption-desorption reactions are very important in determining the mobility of arsenic in nature as well as its removal in many treatment systems. 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. Both arsenate and arsenite adsorb to surfaces of a wide range of solids including iron, aluminum and manganese oxides (e.g., iron oxyhydroxides), and clay minerals.

The strong adsorption characteristics of arsenic has been utilized in its removal from water by coagulation using alum, lime or ferric salts, where arsenic is removed primarily by adsorption onto solid flocs (e.g., aluminum hydroxide or ferric hydroxide) and subsequent precipitation. Arsenate is much more strongly adsorbed and removed than arsenite. Ferric salts have been found to be more effective in removing arsenic than alum on a weight basis and effective over a wider pH range. The strong adsorption of arsenic onto hydrous iron, aluminum and other solids has also been utilized in removing arsenic using a wide range of solid sorption media. These include activated alumina, iron coated sand, granular ferric hydroxide, and a wide range of other materials. Besides arsenic, a number of other ions present in natural water (e.g., phosphate, silicate, sulfate) also have strong affinity for solid surfaces and presence of high concentrations of these ions can reduce removal efficiency of arsenic in adsorption-based treatment systems.

Adsorption-desorption of arsenic onto iron oxide surfaces are important controlling reactions in the subsurface because iron oxides are widespread in the hydro-geologic environment as coatings on other solids, and because arsenate adsorbs strongly to iron oxide surfaces in acidic and near-neutral pH conditions. Desorption of arsenate is favored at higher (i.e., alkaline) pH values. The pH dependence of arsenate adsorption-desorption appears to be related to the change in net charge on iron-oxide surface with pH. The net charge on iron oxide surface changes from positive to negative as pH increases above the "zero-point-of-charge" (pH at which net surface charge is zero). The "zero-point-of-charge" is about 7.7 for goethite (crystalline iron oxide) and about 8.0 for ferrihydrite (amorphous iron oxide). Thus as pH increases above about 8, the net negative surface charge on iron oxides can repel the negatively charged ions such as arsenate. Compared to arsenate, arsenite is less strongly adsorbed by iron oxides. Arsenate and arsenite adsorption-desorption reactions onto other common surfaces are less well characterized.
In Bangladesh arsenic-rich iron oxyhydroxides present in aquifer materials appear to be the primary source of arsenic in groundwater. In the subsurface environment, adsorption-desorption of arsenic onto iron oxyhydroxides is an important mechanism controlling its mobility. As noted earlier, presence of ligands, which may compete with arsenic for adsorption sites on iron oxyhydroxides, e.g., phosphate, silicate and sulfate can also influence the mobility of arsenic in the subsurface, if present in large enough concentrations. Besides oxyanions of molybdenum, selenium and vanadium can also compete with arsenic for adsorption sites.

As a result of pH dependence of arsenic adsorption, changes in groundwater pH can promote adsorption or desorption of arsenic. Similarly, redox reactions can control aqueous arsenic concentration by their effect on arsenic speciation and hence on adsorption-desorption reactions. For example reduction of arsenate to arsenite can promote arsenic mobility because arsenite is less strongly adsorbed than arsenate. It should be noted that in nature bacteria often mediate oxidation-reduction reactions.

Finally, structural changes in solid phases at the atomic level can also affect arsenic adsorption-desorption (USGS, 1999). For example, conversion of amorphous ferrihydrite to crystalline goethite may occur gradually over time (Dzombak and Morel, 1990) and this can be accompanied by a decrease in adsorption site density. This reduction in site density may result in desorption of adsorbed arsenic. Structural changes in other solid phases may also affect arsenic mobility (USGS, 1999).

2.5.6.1 Adsorption-Desorption Reactions

Adsorption-desorption reactions on solid surfaces are usually modeled using surface complexation approach. The fundamental concepts upon which all surface complexation models are based are as follows (Dzombak and Morel, 1990):

- Sorption on oxides takes place at specific coordination sites.
- Sorption reactions on oxides can be described quantitatively via mass law equation.
- Surface charge (on oxides) results from the sorption reactions themselves.

The effect of surface charge on sorption can be taken into account by applying a correction factor derived from the theory to mass law constants for surface reactions.

A number of surface complexation models (SCMs) are available which basically differ in their description of the electrostatic component of sorption. Some important surface complexation models include: (i) constant capacitance model, (ii) diffuse layer model, (iii) triple-layer model, and (iv) generalized two-layer model.

According to the two-layer model, surface ionization reactions resulting in development of surface charge on iron oxide surfaces can be described by:

$$\equiv FeOH_2^+ = \equiv FeOH^0 + H^+ \quad ; K_{a1}^{app} \qquad (2\text{-}16)$$

$$\equiv FeOH^0 = \equiv FeO^- + H^+ \quad ; K_{a2}^{app} \qquad (2\text{-}17)$$

Here, K_{a1}^{app} and K_{a2}^{app} are "apparent" equilibrium constants, because they include surface charge effect and hence are dependent on extent of surface ionization. The mass law equations for the above reactions in terms of apparent equilibrium constants can be written as follows:

$$K_{a1}^{app} = (\equiv FeOH^0)\,(H^+) / (\equiv FeOH_2^+) \quad (2\text{-}18)$$

$$K_{a2}^{app} = (\equiv FeO^-)\,(H^+) / (\equiv FeOH^0) \quad (2\text{-}19)$$

Although it is impossible to separate experimentally the chemical and electrical contributions to total sorption energy (Dzombak and Morel, 1990), in SCMs these two are separated theoretically in order to obtain a specific (i.e., chemical) interaction term that does not vary with surface charge. A variable electrostatic interaction term is then added, resulting in a model that accounts for observed variations in effective mass law constants for sorption reactions. For the two layer model (Dzombak and Morel, 1990), we can write:

$$K^{app} = K^{int} \exp(-\Delta ZF\Psi/RT) \quad (2\text{-}20)$$

where, K^{int} is the intrinsic equilibrium constant that does not depend on surface charege, and K^{app} is the apparent equilibrium constant. Here Ψ is the surface potential, ΔZ is the change in charge of surface species due to sorption reaction, and the exponential term [exp $(-\Delta ZF\Psi/RT)$] is commonly referred to as electrostatic or coulombic correction factor. Thus the mass law equations given by Eqs. 2-18 and 2-19 can be written as:

$$K_{a1}^{int} \exp(F\Psi/RT) = (\equiv FeOH^0)\,(H^+) / (\equiv FeOH_2^+) \quad (2\text{-}21)$$

$$K_{a2}^{int} \exp(F\Psi/RT) = (\equiv FeO^-)\,(H^+) / (\equiv FeOH^0) \quad (2\text{-}22)$$

Fitting of the model to experimental data enables determination of intrinsic equilibrium constants for surface reactions. Adsorption-desorption reactions of arsenate and arsenite on hydrous ferric oxide modeled using the generalized two-layer model (Dzombak and Morel, 1990) is shown by the following reactions:

Arsenate Adsorption:

$$\equiv FeOH^0 + AsO_4^{3-} + 3\,H^+ = \equiv FeH_2AsO_4^0 + H_2O \quad (2\text{-}23)$$

$$\equiv FeOH^0 + AsO_4^{3-} + 2\,H^+ = \equiv FeHAsO_4^- + H_2O \quad (2\text{-}24)$$

$$\equiv FeOH^0 + AsO_4^{3-} + H^+ = \equiv FeAsO_4^{2-} + H_2O \quad (2\text{-}25)$$

$$\equiv FeOH^0 + AsO_4^{3-} = \equiv FeOHAsO_4^{3-} + H_2O \quad (2\text{-}26)$$

Arsenite Adsorption:

$$\equiv FeOH^0 + H_3AsO_3 \quad = \quad \equiv FeH_2AsO_3^{\circ} + H_2O \qquad (2\text{-}27)$$

Possible desorption of arsenate in the presence of phosphate ions are shown by the following reactions:

$$\equiv FeH_2AsO_4^{\circ} + PO_4^{3-} \quad = \quad \equiv FeH_2PO_4^{\circ} + AsO_4^{3-} \qquad (2\text{-}28)$$

$$\equiv FeHAsO_4^{-} + PO_4^{3-} \quad = \quad \equiv FeHPO_4^{-} + AsO_4^{3-} \qquad (2\text{-}29)$$

$$\equiv FeAsO_4^{2-} + PO_4^{3-} \quad = \quad \equiv FePO_4^{2-} + AsO_4^{3-} \qquad (2\text{-}30)$$

2.5.7 Precipitation and Dissolution Reactions

Precipitation-dissolution reactions are important mechanisms controlling mobility of arsenic in the subsurface. Arsenic contained within solid phases, either as a primary structural component of arsenic bearing minerals (e.g., arsenopyrite) or an impurity in any of a variety of solid phases (e.g., pyrite), is released to groundwater when these solid phases dissolve. Similarly, arsenic is removed from groundwater when solid phases containing arsenic precipitate from aqueous phase. As an example, because arsenic often coprecipitates with iron oxide, iron oxides may act as an arsenic source (case of dissolution) or a sink (case of precipitation) for groundwater (USGS, 1999). Besides, solid phase dissolution will contribute not only arsenic contained within that phase, but also any arsenic adsorbed to the solid-phase surface. In Bangladesh, reductive dissolution iron oxyhydroxides and consequent release of adsorbed arsenic could be an important mechanism of arsenic mobilization in the subsurface.

Oxidative dissolution reactions (Bhumba and Keefer, 1994) of arsenopyrite (FeAsS) (Eq. 2-31 & 32), Orpiment (As_2S_3), (Eq. 2-33) and Reagler (AsS) (Eq. 2-34) are shown below. Oxidative dissolution of pyrite (FeS_2) is shown in Eq. 2-35,36 & 37 (Chowdhury et al., 1998).

$$4FeAsS + 11O_2 + 6H_2O = 4FeSO_4 + 4H_2AsO_3^{-} + 4H^{+} \qquad (2\text{-}31)$$

$$4FeAsS + 13O_2 + 6H_2O = 4FeSO_4 + 4H_2AsO_4^{-} + 4H^{+} \qquad (2\text{-}32)$$

$$As_2S_3 + 7O_2 + 6H_2O = 2H_3AsO_4 + 6H^{+} + 3SO_4^{2-} \qquad (2\text{-}33)$$

$$4AsS + 11O_2 + 10H_2O = 4H_3AsO_4 + 8H^{+} + 4SO_4^{2-} \qquad (2\text{-}34)$$

$$2FeS_2 + 7O_2 + 2H_2O = 2Fe^{2+} + 4HSO_4^{-} \qquad (2\text{-}35)$$

$$4Fe^{2+} + O_2 + 4H^{+} = 4Fe^{3+} + 2H_2O \qquad (2\text{-}36)$$

$$FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^{+} \qquad (2\text{-}37)$$

The interplay of redox reactions and solid phase precipitation and dissolution may be particularly important with regard to aqueous arsenic and solid-phase iron oxides and sulfide minerals (USGS, 1999). High concentrations of arsenic often are associated with iron oxides and sulfide minerals. Iron oxides frequently dissolve under reducing conditions (e.g., in the presence of organic matter, as shown in Eq. 2-38), but often precipitate under oxidizing conditions. Sulfide minerals generally are unstable under oxidizing conditions, but may precipitate under reducing conditions (e.g., precipitation of As_2S_3, as shown in Eq. 2-39). Thus, as a result of redox sensitive nature of iron oxides and sulfide minerals, transfer of large amounts of arsenic between these solid phases and neighboring water may result from redox-facilitated precipitation and dissolution reactions (USGS, 1999).

$$Fe(OH)_3(s) + \tfrac{1}{4}\,CH_2O + 2H^+ = Fe^{2+} + \tfrac{1}{4}\,CO_2 + 11/4\,H_2O \quad (2\text{-}38)$$

$$2\,H_3AsO_3 + 6H^+ + 3\,S^{2-} = As_2S_3 + 6\,H_2O \quad (2\text{-}39)$$

Precipitation of arsenic has been utilized in the removal of arsenic from water. The insolubility of certain inorganic arsenic (V) compounds is the basis of many hydrometallurgical arsenic removal processes (Robins et al., 2001). The most common methods of removing arsenic from aqueous systems are by precipitation as arsenic (III) sulfide, calcium arsenate, or ferric arsenate. The sulfide As_2S_3 has its lowest solubility as pH 4, but this solubility is significantly higher than has been generally accepted (Robins et al., 2001). A number of calcium arsenates [e.g., $Ca_3(AsO_4)_2$] can be precipitated from As(V) solutions by lime addition to high pH. Arsenic (V) can also be precipitated from process solutions below about pH 2 with Fe(III) to form ferric arsenate, $FeAsO_4.2H_2O$. Other solids of interest include ferrous arsenate [$Fe_3(AsO_4)_2.xH_2O$], calcium-arsenate-phosphate [$Ca_{10}(AsO_4,PO_4)_6(OH)_2$], and ferric sulfide [$Fe_2S_2$]. Some other metal arsenates, such as those of Fe(II), Zn(II), Cu(II) and Pb(II) are less soluble and more stable in the neutral pH region than calcium arsenates and ferric arsenate, but these have not been seriously considered as disposal forms (Robins et al., 2001). Barium (II) arsenate was proposed to as being an extremely insoluble arsenate, but this was shown to be incorrect. More complex compounds, such as the apatite structured calcium phosphate-arsenate have recently been demonstrated to be of low solubility and of appropriate stability for disposal considerations. Ferric arsenite sulfate is also of recent interest and may prove to be useful in stabilizing arsenic (III) (Robins et al., 2001). A

number of mixed oxidation state materials [both Fe(II)-Fe(III) and As(III)-As(V)] are currently being studied (Robins et al., 2001).

2.6 Arsenic in Soil

In uncontaminated soils, average arsenic concentration varies from about 5 to 6 mg/kg, but this varies among geographic regions. However, significantly high arsenic concentrations have been found in agricultural soil irrigated with arsenic contaminated groundwater. Concentrations as high as 51 mg/kg and 83 mg/kg have been reported in soils of Faridpur and Comilla districts, respectively of Bangladesh (Ullah, 1998). A concentration varying from 1.5 to 19 mg/kg showing higher concentration in the top layers of soil has been found in Samta village in Jessore (Kubota, 1998).

2.6.1 Chemical Forms of Arsenic in Soils

The chemical forms of arsenic in soil have been illustrated in Figure 2.5 (Bhumba and Keefer, 1994). The reactions and processes involved in the transformation of different forms of arsenic include oxidation, reduction, adsorption dissolution, precipitation and volatilization. Bacteria and fungi play important roles in chemical transformation of arsenic to volatile arsine gases, which are extremely toxic. Limited data suggest presence of both As(III) and As(V) as well as organic arsenic in agricultural soil and the processes of transformation/bio-transformation of arsenic are not clearly understood. Soil components that contribute to arsenic sorption and retention include oxides of Al, Fe and Mn, soil mineralogy, and organic matter.

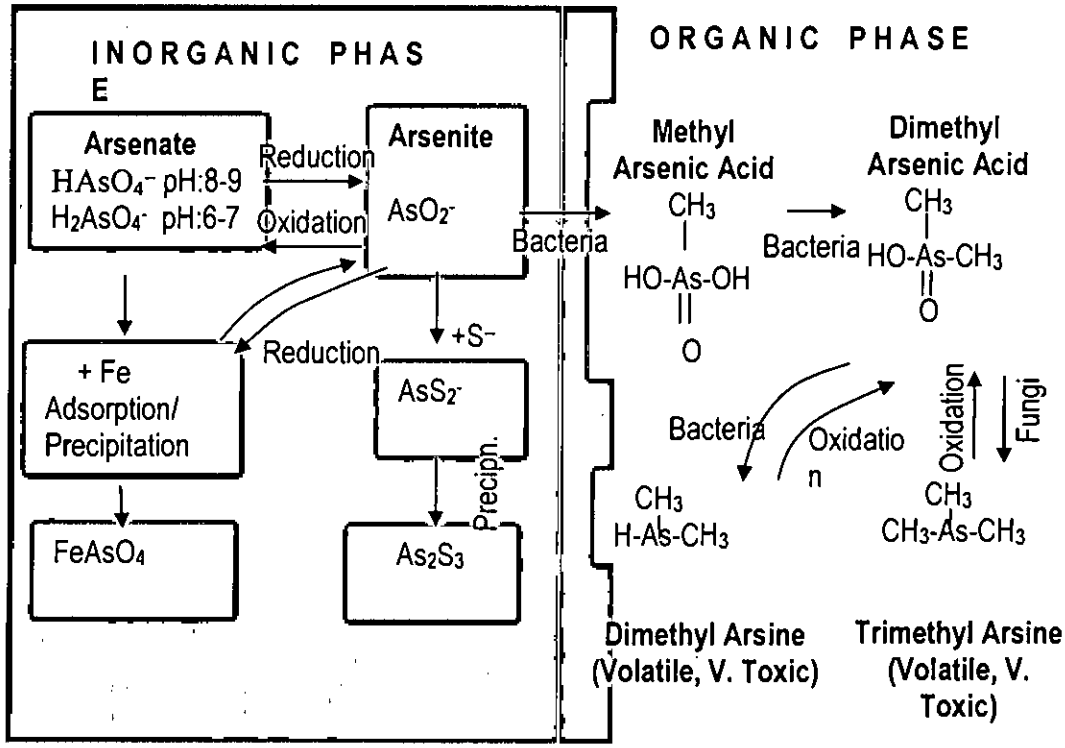

Figure 2.5: Chemical forms of arsenic and their transformations in soils (Bhumba and Keefer, 1994)

2.7 Arsenic in Atmosphere

Arsenic is widely distributed in nature. It enters into the atmosphere from natural sources that include volcanic activity, wind, erosion, sea spray, forest fires and low temperature volatilization (Cullen & Kenneth, 1989). Smelting operation and fossil fuel combustion contribute anthropogenic sources of arsenic (Eldestein, 1985). These inputs are lalanced by removal process such as dry deposition rainfall (Cullen & Kenneth, 1989). Most anthropogenic emissions, such as smelting operation and fossil fuel combustion, consist of As_2O_3 (Pacyna, 1987). It was suggested that sea spray would mainly contribute arsenate (Andreae, 1980) – the dominant species in water. However, arsenic speciation studies of rain and snow samples suggest that the ratio of inorganic oxidation states is not reflective of the arsenic source but is governed instead by redox changes in the atmospheric environment (Andreae, 1980). Using the lower arsenic content of rain, it is determined that 75% of the yearly global emissions of arsenic to the atmosphere were from pollution sources (Walsh et al., 1979).

On a global basis, 65% of airborne arsenic is derived from the smelting of base metal ores. Because arsenite, the main component of smelter flue dust, is volatile, a large fraction of the arsenic in the ores is often vented to the atmosphere. It has been estimated that the Ronnskar smelter in northern Sweden used to release 50-115 tonnes of arsenic per year, a gold smelter in Yellowknife, Canada released 19-2600 tonnes of arsenic per year, and the emission from the ASARCO smelter in Tacoma, Washington was about 7-152 tonnes. A pyrite roasting plant in Barreiro/Seixal, Portugal has been known to release 1000-2000 tones of arsenic annually to the atmosphere (Nriagu & Pacyna, 1988).

It has been estimated that coal combustion contributes about 11% of the arsenic emission to the atmosphere. The coal burning type of arsenic poisoning is caused by the domestic combustion of coal containing high levels of arsenic (90-2100 mg/kg). The coal is burned inside the home in open pits for daily cooking and corn drying. These practices result in high arsenic concentration in indoor air and arsenic accumulation on the corn. In southern China, these practices resulted in air arsenic concentration as high as 0.04-0.13 mg/m^3, i.e. 10-40 times higher than the standard. The water-arsenic concentration in that area was less than 0.005 mg/L. The arsenic content in the contaminated corn was in range from 1.5-110 mg/kg, which was 2-15 times higher than the proposed maximum limit value of 0.7 mg/kg (ren, 1993).

Most of the arsenic in the air is in the form of particulate matter (Cullen and Kenneth, 1989). Less than 10% is present in the vapor phase or on particles small than 0.2 μm (Walsh, 1987; Mackenzie et al., 1979). Analysis of these solids has revealed that they are often considerably enriched (10-1000 times) in arsenic in comparison to the continental crust (Mackenzie et al., 1979).

2.8 Methylation Reactions

Arsenic taken by mammals is subject to either direct excretion, direct accumulation in some parts of the body (e.g., nails, hair and skin tissue), or to biotransformation in the form of methylation. Besides microbial processes has also been utilized in the bioremediation of arsenic contaminated soils.

Humans are exposed to arsenic mostly in the forms of arsenate/arsenite and organic arsenosugars/arsenobetaines and marine products. The inorganic forms are more toxic

than organic forms. Methylation seems to be most important pathway of biotransformation of inorganic arsenic. The inorganic forms are metabolized by consecutive reduction and methylation reactions in humans and mammals to dimethylated arsenic (DMA) (see Figure 2.6), which is excreted into urine (Suzuki, 2002). The toxicity of arsenite is highly dependent on animal species, which in turn depends on the differences in the metabolism shown in Figure 2.6. The methylation process leading to DMA was believed to be the detoxification pathway, but recent studies document it as toxification pathway (Suzuki, 2002). Research works are being carried out to better understand these processes.

Several fungi and bacterial species have been demonstrated to methylate inorganic arsenic by an initially reducing arsenate fraction to arsenite, which then is methylated and released to the environment (Kartinen and Martin 1995). However, the concentration of methylated arsenic in the natural waters, whether ground or surface, is normally low. This is because the methylated arsenic is taken up by the biota where it undergoes metabolic conversion into organic arsenical. Compounds like arsenobetaine and arsenocholine, can thus be found in fish and crustaceans. These compounds do not have any toxicological significance. Upon consumption by man they are directly excreted through urine without any biotransformation (Vahter, 1994).

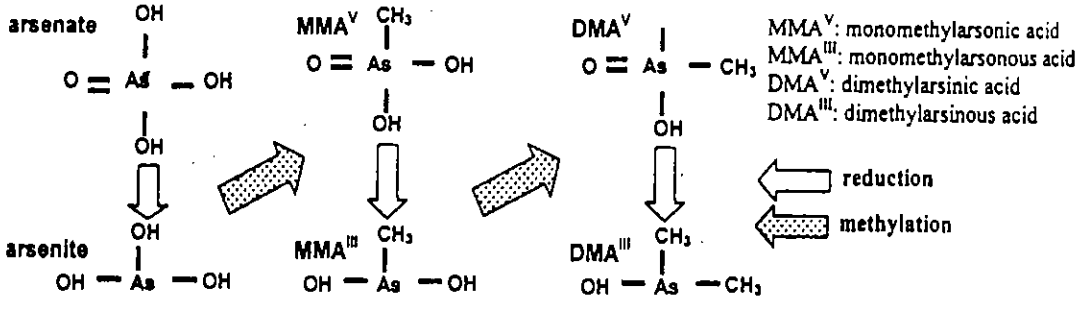

Figure 2.6: Reduction and methylation reactions in the metabolism of arsenic (Suzuki, 2002)

2.9 Health Effect of Arsenic

2.9.1 Introduction

Arsenic is called the king of all poisons. The fetal dose of arsenic is 125 mg. It means, one will die following acute poisoning if he or she takes such extent of arsenic. Arsenic is four the poisonous than mercury. The fetal dose of mercury is 500 mg. Arsenic enters in the human bodies through respiration from the air and through mouth from food and drink. The effect of arsenic after it entered by breathing or meals and drinks depends on the amount and physio-chemical states.

2.9.2 Toxicity of Arsenic

According to consumption of arsenic in human bodies, its toxicity can be divided in three categories:

- Acute toxicity
- Sub-acute toxicity
- Chronic toxicity

Chronic toxicity was observed in arsenic polluted area in Bangladesh.

2.9.2.1 Acute Toxicity

Acute arsenic poisoning in human being is usually homicidal, suicidal or accidental. Smallest recorded fetal dose is about 130 mg and death occurs after a fatal dose in 12 to 48 hours and symptoms appear within half an hour. Patient first of all complains of a feeling of faintness, nausea and sever burning pain in the throat and stomach with increased salivation, intense thirst and sever vomiting are constant symptom. There are may be severe cramps in calf muscles. Skin becomes cold and clammy, face become cyanosed, eyes are shrunken and pulse is feeble, irregular and frequent. The respiration becomes laboured and lastly convulsion and coma preceded death.

2.9.2.2 Sub-acute Toxicity

This is a condition where arsenic is administered in a small dose at repeated interval. The symptoms are at first dyspepsia, cough and tingling in the throat, then vomiting and purging with abdominal pain and tenesmus with foul tongue, dry and congested throat and a feeling of depression and languor. The motion is bloody. The symptoms of neuritis are pronounced. Severe cramps on the muscles which are tender on pressure. Patient become restless and cannot sleep, ultimately collapse sets in and results in death.

2.9.2.3 Chronic Toxicity

The clinical manifestation due to chronic arsenic toxicity develop very insidiously after six months to two years or more depending on the amount of arsenic intake. Chronic toxicity of arsenic is in terms of the organ and system affected, the skin, nervous system, liver, cardiovascular system and respiratory tract. Long-term effects of arsenic poisoning lead to malignancy.

2.9.3 Health Effects and Symptoms

In a population drinking arsenic contaminated water, a great variety of specific as well as non-specific symptoms may be observed. Table 2.8 lists some of the effects of arsenic reported to be due to exposure through drinking water.

Table 2.8: Toxicological effects due exposure to high arsenic concentration in drinking water (WHO, 1996, Khan, 1997)

Effect	Symptoms	Remarks
Blackfoot Disease Arsenical dermatosis	Dermal lesion, Peripheral neuropathy Keratosis, Hyperkeratosis, Hyperpigmentaion	May necessitate operation
None specific	Nausea, Abdominal Pain, Diarrhoea, Vomiting, Conjunctivitis, Oedema.	Mainly due to acute intoxication
Pregnancy disorders	Spontaneous abortions, miscarriages	-
Heart Disease	Coarctations of aorta, Cardiovascular disturb.	Among children
Cancer	Bladder, Kidney, Skin & Lungs, Liver & Colon	-
Mortality	-	Mainly due to cancer

2.10 Arsenic Contamination in Bangladesh

Presence of high concentrations of arsenic in tubewell water in excess of acceptable limit has become a major concern in Bangladesh. Arsenic contamination of groundwater was first detected in Bangladesh in 1993 by DPHE in Chapai Nawabganj in the far west of Bangladesh in a region adjacent to an area of West Bengal which has been found to be extensively contaminated since 1988. Extensive contamination in Bangladesh was confirmed in 1995 when additional surveys showed contamination of shallow and deep tubewells across much of southern and central Bangladesh. At the same time, cases of chronic arsenicosis were being recognized by health professionals.

The oldest known analyses in groundwater were for three municipal tubewells in Dhaka city in 1990. All were below detection limits, and did not attract attention. Recent analyses have confirmed the absence of arsenic contamination in Dhaka city. Since 1995, data pointing to the extensive contamination of Bangladesh groundwater have been collected by a large number of organizations. Extensive arsenic surveys carried out by Dhaka Community Hospital in association with in 1997 to 1999 were crucial in raising public awareness to the extent of contamination (DCH, 2000). These involved the analysis of water samples collected from homes of arsenic affected patients and confirmed the seriousness of arsenic problem. Classic symptoms of chronic arsenic exposure were becoming increasingly apparent and Bangladesh patients visited West Bengal in order to seek a 'cure' for their illness.

The study conducted by British Geological Survey (BGS), Department of Public Health Engineering (DPHE) and Mott MacDonald Limited (MML) in two phases examined 3534 distributed water samples from 61 districts out of 64 districts (DPHE, BGS and MML, 1999, BGS and DPHE, 2001). On an average 58 samples per district and 8 samples per upazila were analyzed. The study showed that arsenic concentration of 42% of all tubewell samples exceeded 10 ppb and 25% exceeded 50 ppb. When only shallow tubewells are considered, 46% and 27% exceeded 10 ppb and 50 ppb respectively. In case deep tubewell (>150m) samples, arsenic content 5% exceeded 10 ppb and 1% exceeded 50 ppb. The maximum acceptable level in Bangladesh as per requirement of Bangladesh Standards for Drinking Water is 50 ppb (GOB, 1997) and the provisional WHO guideline value for arsenic in drinking water is 10 ppb (WHO, 1993). A map

showing the intensity of arsenic contamination of groundwater in different parts of Bangladesh is shown in Figure 2.7.

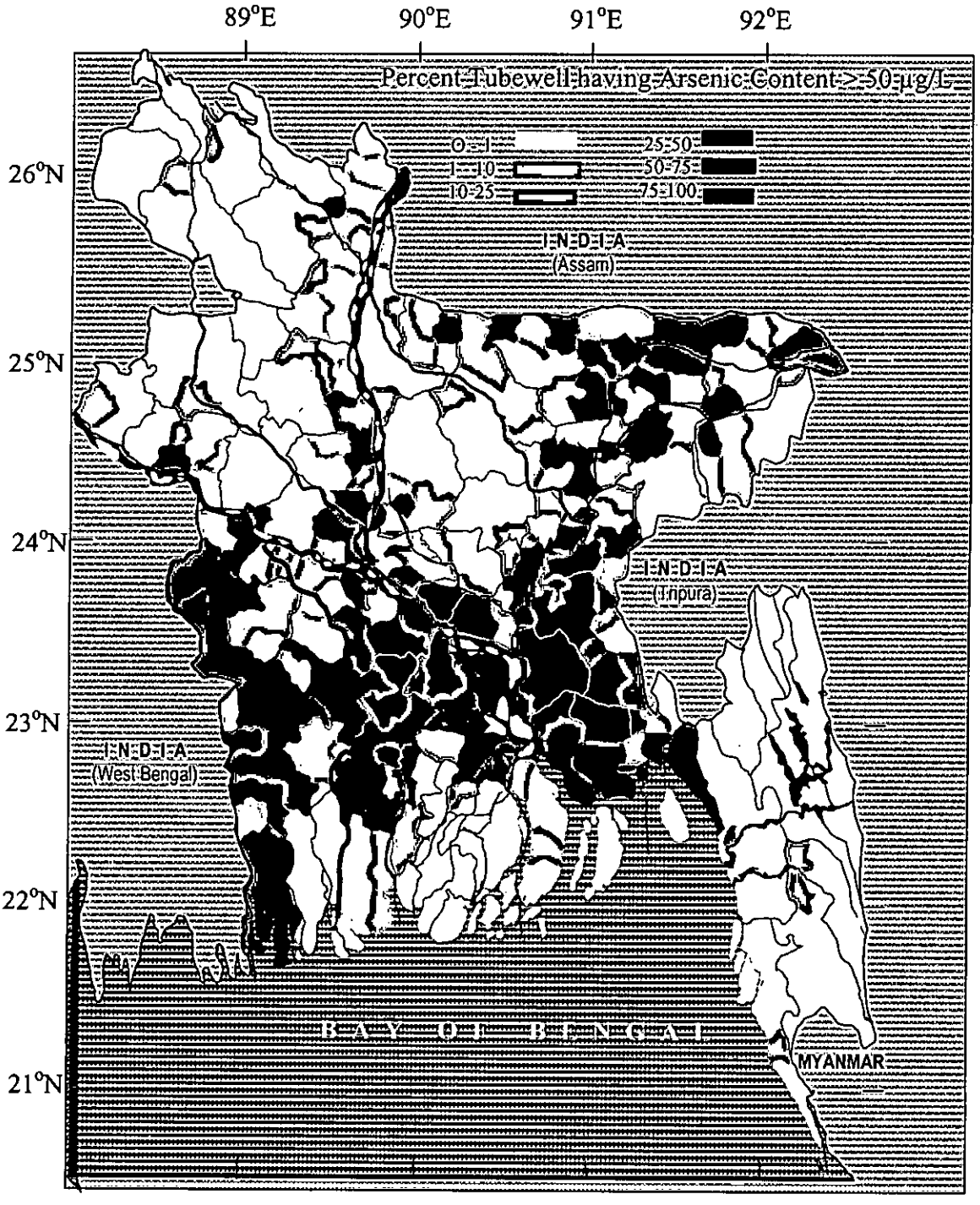

Figure 2.7: Intensity of arsenic contaminated (> 50 ppb) tubewell in Bangladesh

The map has been updated on the basis of information available from arsenic analysis conducted by BGS and DPHE (2001); DPHE, BGS and MML (1999); SOES and DCH, JU (2000) and BUET. The maps produced by other organizations based on field/laboratory test data more or less provide similar pictures of arsenic contamination. It may be observed that the central regions of Bangladesh are highly contaminated. The levels of arsenic in tubewell water as shown in BGS and DPHE study are also high in the central region (BGS and DPHE, 2001). The area of high arsenic concentration very well fit with the areas of Bangladesh submerged by flood (Ahmed, 2000).

There have been numerous reports of arsenic problem in the ground water sources in various part of Bangladesh with severe condition prevailing in the south, south west, north western and central zones. However until now, the ground water in the north-western zone of Bangladesh is relatively free of arsenic.

The numbers of patients showing symptoms of arsenic toxicity are increasing, as results from studies are available. The population exposed to arsenic contamination in excess of 50 ppb in Bangladesh Standard by the contaminated tubewells has been estimated as 29.05 million people. Department of Public Health Engineering, British Geological Survey and Mott MacDonald Ltd (MML) in Phase-1 studies estimated that the population exposed to arsenic contamination would lie in the range 185 - 22.7 million (DPHE, BGS, and MML, 1999). However, the BGS-DPHE studies finally gave two estimates of population exposure based on projected population of 125.5 million in 1999 (BGS and DPHE, 2001). The estimates of total population exposed to arsenic concentration above 50 and 10 ppb using kriging method were 35.2 million and 56.7 million respectively. Based on upazila statistics the exposure levels to arsenic concentration exceeding 50 and 10 ppb were 28.1 million and 46.4 million respectively. School of Environmental Studies, Jadavpur University (SOES, JU), Calcutta and Dhaka Community Hospital (DCH), Dhaka estimated that the populations exposed to above 50 and 10 ppb in 43 districts in Bangladesh were 25 million and 51 million respectively (SOES and DCH, 2000).

CHAPTER 3

ARSENIC REMOVAL TECHNOLOGIES

3.1 Introduction

Arsenic contamination of groundwater in the alluvial aquifer underlying Bangladesh has been recognized as a major problem of catastrophic proportions. Groundwater extracted by shallow tubewells from this aquifer has been found to contain high levels of arsenic, which is unsafe for drinking and cooking purpose. Thousands of people have already been under threat from drinking contaminated water. Provision of arsenic free water is urgently needed for immediate protection of health and well being of the people living in arsenic affected areas. For most situations, substitution of tube well water by an alternative safe and reliable source of water supply is not an easy task. Treatment of arsenic contaminated tubewell water is one prominent option in the acute arsenic affected areas of Bangladesh. There are several techniques and alum coagulation method has been found to be simpler, cheaper and more user friendly than any other methods of treatment.

3.2 Coagulation Theory

In water treatment plants, chemical coagulation is usually accomplished by the addition of trivalent metallic salts such as $Al_2(SO_4)_3$ (aluminum sulfate) or $FeCl_3$ (ferric chloride). Although the exact method by which coagulation is accomplished cannot be determined, four mechanisms are thought to occur. These include:

- Ionic layer compression
- Adsorption and charge neutralization
- Sweep coagulation
- Inter-particle bridging

3.2.1 Ionic Layer Compression

The quantity of ions in the water surrounding a colloid has an effect on the decay function of the electrostatic potential. High ionic concentration compresses the layers composed predominately of counter ions toward the surface of the colloid. If this layer is sufficiently compressed, then the vander waals force will be predominant across the entire area of influence, so that the net force will be attractive and no energy barriers will exit. Although coagulation such as aluminium and ferric salts used in water treatment ionize, at the concentration commonly used they would not increase the ionic concentration sufficiently to affect ion layer compression.

3.2.2 Adsorption Charge Neutralization

The nature and rather than the quantity of the ions of prime importance in the theory of adsorption and charge neutralization. Although aluminium sulphate (alum) is used as in the example below, ferric chloride behaves similarly. The ionization of aluminium sulfate in water produces sulfate anions (SO_4^{2-}) and aluminium cataions (Al^{3+}). The sulfate ion may remain in this from or combine with other cations. However, the Al^{3+} cations react immediately with to form a variety of aquometallic ions and hydrogen.

The aquometallic ions thus formed become part of the ionic cloud surrounding the colloid and, because they have a great affinity for surfaces, are adsorbed onto the surface of the colloid where they neutralize the surface charge. Once the surface charge has been netralized, the ionic cloud dissipater, and the electrostatic potential disappears so that contact occurs freely. Overdosing with coagulants can result in restabilizing the suspension. If enough aquometallic ions ate formed and adsorbed, the charges on the particles become reversed and the ionic clouds reform with negative ions being the counter ions.

3.2.3 Sweep Coagulation

The last product formed in the hydrolysis of alum is aluminium hydroxide, Al $(OH)_3$. The Al $(OH)_3$ forms in amorphous, gelatinous flocs as it is formed, or they may become enmeshed by it sticky surface as the flocs settle. The process by colloids are swept from suspension in this manner is known as sweep coagulation.

efficient removal. This can be achieved by addition of bleaching powder (chlorine) or potassium permanganate. The related chemical equations are as follows:

Oxidation of As(III) to As(V):

$$H_3AsO_3 + HClO = HAsO_4^{2-} + Cl^- + 3H^+ \quad (3\text{-}1)$$

$$3H_3AsO_3 + 2KMnO_4 = 3HAsO_4^{2-} + 2MnO_2^+ + 2K^+ + 4H^+ + H_2O \quad (3\text{-}2)$$

Alum dissolution:

$$Al_2(SO_4)_3.18H_2O = 2Al^{+++} + 3SO_4^{++} + 18H_2O \quad (3\text{-}3)$$

Aluminium precipitation (acidic):

$$2Al^{+++} + 6H_2O = 2Al(OH)_3 + 6H^+ \quad (3\text{-}4)$$

Co-precipitation (Non-stoichiometric, non-defined product):

$$H_2AsO_4^- + Al(OH)_3 = \text{Al-As (complex)} + \text{Other products} \quad (3\text{-}5)$$

pH adjustment:

$$6Ca(OH)_2 + 12H^+ = 6Ca^{2+} + 12H_2O \quad (3\text{-}6)$$

Adsorption of arsenic onto ferric hydroxides can be expressed by the following equations:

$$\equiv Fe\text{-}OH + H_2AsO^- + H^+ \longrightarrow \equiv Fe\text{-}H_2AsO_4 + H_2O \text{ (arsenate adsorption)} \quad (3\text{-}7)$$

$$\equiv Fe\text{-}OH + H_3AsO_3 \longrightarrow \equiv Fe\text{-}H_3AsO_3 + H_2O \text{ (arsenite adsorption)} \quad (3\text{-}8)$$

Arsenic adsorbed on ferric hydroxide flocs as Fe-As complex is removed by sedimentation. Filtration may be required to ensure complete removal of all flocs. Similarly, in case of alum coagulation, Al-As complex is removed by sedimentation and filtration (Eq. 3-3 to 3-5). Similar reactions take place in case of ferric chloride and ferric sulfate with the formation of Fe-As complex as end product, which is removed by the process of sedimentation and filtration. Arsenic removal efficiency by the coagulation process is dependent on the type of coagulant, coagulant dosage, pH of the raw water and the valency of the compounds such as As(III) or As(V) (Sorg & Logsdon, 1978). In alum coagulation, the removal is most effective in the pH range 7.2-7.5 and in iron coagulation; efficient removal is achieved in a wider pH range usually between 6.0 and 8.5 (Ahmed and Raham, 2000).

3.3.3 Alum and Iron Precipitation

It has been found that alum precipitation removes solids and dissolved metals. For the removal of arsenic, alum is most effective if an oxidizing agent, such as chlorine, is added ahead of the flocculator and clarifier and the pH is reduced to 7 or less. The effect of pH on arsenic removal efficiency by using alum is important. To use this process in treating drinking water, it would probably be necessary to use a number of chemicals. At the head end of the plant, chlorine would be needed to oxidize the arsenic. Acid would be added to reduce the pH and alum would of course, be needed. Post treatment of the clarified water by caustic (NaOH), for example, would be needed to increase the pH to an acceptable level. The arsenic removed from the water would be contained in the sludge from the clarifier.

It has also been seen that arsenic can be precipitated using iron. In this process, an iron compound such as ferric sulfate ($Fe_2 (SO_4)_3$), for example, is added to the untreated water. The arsenic combines with the iron to form a precipitate that settles out in the clarifier, a filter is employed which removes iron/arsenic particles not taken out in the clarifier. Adjustment of the pH does not appear to be as important as with alum. As with the alum process, the arsenic removed from the water comes out in the sludge that accumulates in the clarifier.

3.3.4 Lime Softening

Water treatment by the addition of fresh lime or calcium oxide is an efficient process for As(V) removal (Jakel, 1994). The precipitated calcium hydroxide acts as adsorbing flocculant for arsenic. Excess of lime would not be dissolved, but remains as a thickener and coagulant aid, which has to be removed along with the precipitated calcium hydroxide through a sedimentation/filtration process. The arsenic removal efficiency of the lime softening process is significantly affected by the pH and the presence of or absence of chlorine. The highest removals are achieved when the end pH of the water is as high as 10.6 to 10.4 (Dahi, 1997). Obviously this would require a secondary treatment in order to readjust the pH. Simple acidification may not be enough, buffering of the water may be required.

Sorg and Logsdon (1978) reported more than 90% removal of As(V) (initial concentration 400 μg/L) if the pH is above 10.5. As(III) removal could be about 75% at pH values above 11.0. The mechanism of removal may be adsorption onto the calcium carbonate and magnesium hydroxide, or it may a direct precipitation of calcium arsenates, similar to the phosphate precipitation that occurs under similar condition (Jekel, 1994). Previous studies recommended lime addition for the removal of arsenic in gold mine waste waters as the most economical treatment, provided careful control of the oxidation of As(III) to As(V), pH > 12 and effective filtration of the precipitate is exercised. If arsenic levels below 0.5 mg/dm^3 are required, a modification of the method by phosphate addition must be considered.

3.3.5 Passive Sedimentation

Passive sedimentation received considerable attention because of rural people's habit of drinking stored water from pitchers. Oxidation of water during collection and subsequent storage in houses may cause a reduction in arsenic concentration in stored water *(Bashi Pani*). Experiments conducted in Bangladesh showed zero to high reduction in arsenic content by passive sedimentation. Arsenic reduction by plain sedimentation appears to be dependent on water quality particularly the presence of precipitating iron in water. Ahmed et al. (2000) showed that more than 50% reduction in arsenic content is possible by sedimentation of tubewell water containing 380-480 mg/L of alkalinity as $CaCO_3$ and 8-12 mg/L of iron but cannot be relied to reduce arsenic to desired level. Most studies showed a reduction of zero to 25% of the initial concentration of arsenic in groundwater. In rapid assessment of technologies passive sedimentation failed to reduce arsenic to the desired level of 50 μg/L in any well (BAMWSP, DFID, WaterAid , 2001).

3.3.6 Chemical Oxidation

Arsenic is present in groundwater in As(III) and As(V) forms in different proportions. Most treatment methods are effective in removing arsenic in pentavalent form and hence include an oxidation step as pretreatment to convert arsenite to arsenate. Arsenite can be oxidized by oxygen, ozone, free chlorine, hypochlorite, permanganate, hydrogen peroxide and fulton's reagent but Atmospheric oxygen, hypochloride and permanganate are commonly used for oxidation in developing countries. Air oxidation of arsenic is very

slow and can take weeks for oxidation (Pierce and Moore, 1982) but chemicals like chlorine and permanganate can rapidly oxidize arsenite to arsenate under wide range of conditions.

3.3.6.1 Solar Oxidation

SORAS is a simple method of solar oxidation of arsenic in transparent bottles to reduce arsenic content of drinking water (Wegelin et al., 2000). Ultraviolet radiation can catalyze the process of oxidation of arsenite in presence of other oxidants like oxygen (Young, 1996). Experiments in Bangladesh show that the process on average can reduce arsenic content of water to about one-third.

3.3.7 Membrane Techniques

Membrane techniques like reverse osmosis, nanofiltration and electrodialysis are capable of removing all kinds of dissolved solids including arsenic from water. In this process water is allowed to pass through special filter media which physically retain the impurities present in water. The water, for treatment by membrane techniques, shall be free from suspended solids and the arsenic in water shall be in pentavalent form. Most membranes, however, can not withstand oxidizing agent. Two types of membranes process have been demonstrated to be effective in removing arsenic from water. Such as Reverse osmosis and electrodialysis.

The membrane processes, reverse osmosis and electrodialysis have been demonstrated to be capable of removing arsenic from water. For both processes removal rates for As(+5) is reportedly better than for As (+3). The use of an oxidizing agent such as chlorine is necessary. Unfortunately, oxidizing agents are, as a rule, harmful to reverse osmosis and electrodialysis membranes. They typically are more like a "shotgun" in that they remove portion of all the dissolved minerals in the feed water. This can result in product water that is too pure, post treatment may be necessary to obtain a product batter quality that meets drinking water standards. Whereas the precipitation processes result in arsenic contaminated sludge, that membrane processes produce arsenic contaminated wastewater. Disposal of either the sludge or the wastewater will probably pose a problem in most cases. However the wastewater from the membrane processes represents a loss of potentially useful water.

3.3.7.1 Reverse Osmosis

There are two types of reverse osmosis that can remove arsenic from water, Nano filtration and Hyper Filtration. Nanofiltration is a relatively low pressure reverse osmosis process that removes primarily the large dissolved solids as compared to Hyper-filtration. As with the precipitation processes discussed previously the literature indicates that reverse osmosis is more effective in removing pentavalent arsenic than trivalent arsenic. With trivalent arsenic removal rates using reverse osmosis of 40-80% have been reported and with pentavalent arsenic removal rate is greater than 97% have reported. Thus to achieve the best result, the feed water must be treated with an oxidizing agent to convert trivalent arsenic to pentavalent arsenic in order to achieve substantial arsenic reduction. The arsenic removed was concentrated in wastewater, there is no solid waste (sludge) produced by a reverse osmosis process.

3.3.7.2 Electrodialysis

Electrodialysis is another type of membrane water treatment process. As with other arsenic removal process, electrodialysis is more effective in removing pentavalent arsenic than trivalent arsenic. Therefore to achieve higher arsenic removal rates with electrodialysis, an oxidizing agent (chloride) should be injected in to the feed water. However, oxidizing agents are harmful to conventional ion exchange resins (from which the membranes are made) just as they are to most reverse osmosis membranes. Arsenic reductions of more than 95% have been reported. However it should be noted that there has been little work on the removal of arsenic using electrodialysis.

3.3.8 Sorptive Filter Media

Several sorptive media have been reported to remove arsenic from water. These are activated alumina, activated carbon, iron and manganese coated sand, kaolinite clay, hydrated ferric oxide, activated bauxite, titanium oxide, silicium oxide and many natural and synthetic media. The efficiency of all some sorptive media depends on the use of oxidizing agent as aids to sorption of arsenic. Saturation of media by different contaminants and components of water takes place at different times of operation depending on the specific sorption affinity of the medium to the given component. Saturation means that the efficiency in removing the desired impurities becomes zero.

3.3.8.1 Activated Alumina

Activated alumina has been shown to remove arsenic in a number of instances. While it has been fully characterized, it is believed the arsenic absorbs in to the surface of the activated alumina. Eventually, the alumina surface becomes sufficiently saturated with arsenic that adequate removal is no longer accomplished. It than becomes necessary to regenerate the alumina. This is done by subjecting the alumina to a caustic batch. Which appears to remove the surface layer of alumina, and the arsenic absorbed in to the layer. The alumina is the neutralized with a sulfuric acid rinse, and placed back into the service. Regeneration of alumina does not complete the alumina losses about 30-40% of its capacity with each regenerations, so that it must be replaced after only three to four regeneration. However, its low cost and relatively high capacity for arsenic keep costs at an acceptable level.

As with the arsenic removal processes discussed previously, better arsenic removal efficiencies are achieved if the arsenic is present in a (5+) oxidation state as compared to the efficiencies achieved if the arsenic is in a (3+) oxidation state. The use of chlorine, or some other oxidizing agent, is necessary to obtain the higher arsenic removal rates. The process is also more effective if the pH of the feed water is in the 5.5 to 6.0 range. At higher pH the arsenic removal efficiency of activated alumina is considerably less than that obtained at lower pH. In addition Higher pH even the use of chlorine to oxidize As (3+) to As (5+) is not too effective at increasing the bed volume of water that can be treated before regeneration of the alumina is needed.

3.3.8.2 Ion Exchange

Ion exchange is an adsorption process similar to activated alumina. Ion exchange has been used for many years to soften water, de-mineralize water, remove nitrate, and for other water treatment applications. For arsenic removal on ion exchange resin, usually loaded with chloride ions at the exchange sites, is placed in vessels. The arsenic containing water is passed through the vessels and the arsenic exchanged with the chloride ions. The water exiting the vessel is lower in arsenic but higher in chloride than the water entering the vessel.

Eventually, the arsenic becomes exhausted, that is all or most of the exchanged sites that were loaded with chloride ions become loaded with arsenic or other ions. The chloride ions that used to be on the resin were exchanged for the arsenic and other anions that were in the water being treated. As with the other processes discussed here, it is important that the arsenic have a (5+) oxidation state and the pH be at least 7.5 in order to achieve the best removal rates.

The arsenic removed from the water is removed from the ion exchanged resin when it is regenerated with salt (sodium chloride). Arsenic is dissolved in the wastewater. There are substantial concentrations of sodium and chloride in the wastewater and the arsenic. Experimental work has shown that ion exchange can achieve arsenic reductions of more than 95% and can produce treated water with an arsenic concentration of less than 2μg/L.

3.4 Naturally Occurring Iron in Groundwater

The use of naturally occurring iron precipitates in ground water in Bangladesh is a promising method of removing arsenic by adsorption. It has been found that hand tubewell water in 65% of the area in Bangladesh contains iron in excess of 2 mg/L and in many acute iron problem areas; the concentration of dissolved iron is higher than 15 mg/L. Although no good correlation between concentrations of iron and arsenic has been derived, iron and arsenic have been found to co-exist in ground water. Most of the tubewell water samples satisfying Bangladesh drinking water standard for iron (1 mg/L) also satisfy the standard for arsenic (50 mg/L). Only about 50% of the samples having iron content 1 - 5 mg/L satisfy the standard for arsenic while 75% of the samples having iron content > 5 mg/L are unsafe for having high concentration of arsenic.

The iron precipitates [$Fe(OH)_3$] formed by oxidation of dissolved iron [$Fe(OH)_2$] present in groundwater, as discussed above, have the affinity for the adsorption of arsenic. Only aeration and sedimentation of tubewell water rich in dissolved iron has been found to remove arsenic. The iron removal plants (IRP) in Bangladesh constructed on the principles of aeration, sedimentation and filtration in small units have been found to remove arsenic without any added chemicals. The conventional community type IRP, depending on the operating principles, more or less work as arsenic removal plants (ARP) as well. A study suggests that As(III) is oxidized to As(V) in the IRP to facilitate higher

efficiency in arsenic removal in IRP constructed in Noakhali (Dahi and Liang, 1998). The Fe-As removal relationship with good correlation in some operates. The IRP results shows that lower arsenic content of tubewell water to half to one-fifth of the original concentrations. The efficiency of these community type Fe-As removal plants can be increased by increasing the contact time between arsenic species and iron flocs. Community participation in operation and maintenance in the local level is absolutely essential for effective use of these plants.

Some medium scale Fe-As removal plants of capacities 2000-3000 m^3/d have been constructed for water supplies in district towns based on the same principle. The treatment processes involved in these plants include aeration, sedimentation and rapid sand filtration with provision for addition of chemical, if required. These plants are working well except that treated water requirement for washing the filter beds is very high. Operations of small and medium size IRP-cum-ARP in Bangladesh suggest that arsenic removal by co-precipitation and adsorption on natural iron flocs has good potential.

3.5 An Overview of Arsenic Removal Technologies

3.5.1 Introduction

In the context of prevalence of high concentrations of arsenic in tubewell water, a wide range of technologies has been tried for the removal of arsenic from drinking water. The most common technologies utilized the conventional processes of oxidation, co-precipitation and adsorption onto coagulated flocs, adsorption onto sorptive media, ion exchange and membrane techniques for arsenic removal. The conventional technologies have been scaled down to meet the requirements of households and communities and suit the rural environment. Some technologies utilized indigenous materials for arsenic removal. The last 5 – 6 years in our country several household and community based arsenic removal systems have been developed and most of them units have been testes either at bench scale or at field level This portion provides a brief description of the important principles used for arsenic removal in different household and community based arsenic removal plants, based on the detailed review of the technologies by Ahmed (2001).

3.5.2 Bucket Treatment Unit

The Bucket Treatment Unit (BTU), developed by DPHE-Danida Project is based on the principles of coagulation, co-precipitation and adsorption processes. It consists of two buckets, each 20 liter capacity, placed one above the other. Chemicals are mixed manually with arsenic contaminated water in the upper red bucket by vigorous stirring with a wooden stick for 30 to 60 seconds and then flocculated by gentle stirring for about 90 second. The mixed water is then allowed to settle for 1- 2 hours. The water from the top red bucket is then allowed to flow into the lower green bucket via plastic pipe and a sand filter installed in the lower bucket. The flow is initiated by opening a valve fitted slightly above the bottom of the red bucket to avoid inflow of settled sludge in the upper bucket. The lower green bucket is practically a treated water container.

The DPHE-Danida project in Bangladesh distributed several thousands BTU units in rural areas of Bangladesh. These units are based on chemical doses of 200 mg/L aluminum sulfate and 2 mg/L of potassium permanganate supplied in crushed powder form. The units were reported to have very good performance in arsenic removal in both field and laboratory conditions (Sarkar et al., 2000 and Kohnhorst and Paul, 2000). Extensive study of DPHE-Danida BTU under BAMWSP, DFID, WaterAid (2001) rapid assessment program showed mixed results. In many cases, the units under rural operating conditions fail to remove arsenic to the desired level of 0.05 mg/L in Bangladesh. Poor mixing and variable water quality particularly pH of groundwater in different locations of Bangladesh appeared to be the cause of poor performance in rapid assessment. Bangladesh University of Engineering and Technology (BUET) modified the BTU and obtained better results by using 100 mg/L of ferric chloride and 1.4 mg/L of potassium permanganate in modified BTU units. The arsenic contents of treated water were mostly below 20 ppb and never exceeded 37 ppb while arsenic concentrations of tubewell water varied between 375 to 640 ppb. The BTU is a promising technology for arsenic removal at household level at low cost. It can be built by locally available materials and is effective in removing arsenic if operated properly.

3.5.3 BCSIR Filter Unit

Bangladesh Council of Scientific and Industrial Research (BCSIR) have developed an arsenic removal system, which uses the process of coagulation/co-precipitation with an iron based chemical followed by sand filtration. The unit did not take part in a comprehensive evaluation process.

3.5.4 Stevens Institute Technology

This technology also uses two buckets, one to mix chemicals (reported to be iron sulphate and calcium hypochloride) supplied in packets and the other to separate flocs by the processes of sedimentation and filtration. The second bucket has a second inner bucket with slits on the sides to help sedimentation and keeping the filter sand bed in place. The chemicals form visible large flocs on mixing by stirring with stick. Rapid assessment showed that the technology was effective in reducing arsenic levels to less than 50 ppb in case of 80 to 95% of the samples tested (BAMWSP, DFID, WaterAid, 2001). The sand bed used for filtration is quickly clogged by flocs and requires washing atleast twice a week. Figure 3.1 shown bellow the Stevens Institute Technology.

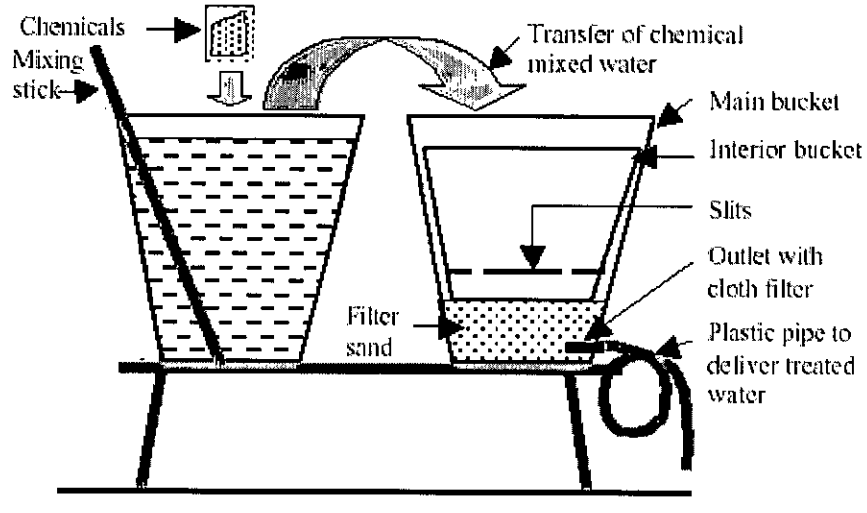

Figure 3.1: Stevens institute technology

3.5.5 DPHE-Danida Fill and Draw Arsenic Removal Unit

It is a community type treatment unit designed and installed under DPHE-Danida Arsenic Mitigation Pilot Project. It is 600 L capacity (effective) tank with slightly tapered bottom for collection and withdraws of settled sludge. The tank is fitted with a manually operated mixer with flat-blade impellers. Figure 3.2 shown bellow the DPHE-Danida Fill and Draw arsenic removal unit.

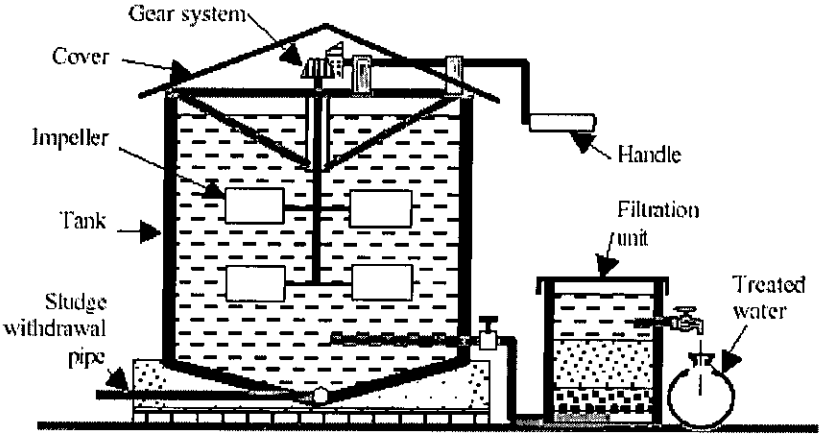

Figure 3.2: DPHE-Danida fill and draw arsenic removal unit

The tank is filled with arsenic contaminated water and required quantity of oxidant and coagulant are added to the water. The water is then mixed for 30 seconds by rotating the mixing device at the rate of 60 rpm and left overnight for sedimentation. The water takes some times to become completely still which helps flocculation. The flocs formation is caused by the hydraulic gradient of the rotating water in the tank. The settled water is then drawn through a pipe fitted at a level, few inches above the bottom of the tank and passed through a sand bed and finally collected through a tap for drinking purpose. The mixing and flocculation processes in this unit are better controlled to effect higher removal of arsenic. The experimental units installed by DPHE-Danida project are serving the clusters of families and educational institutions.

3.5.6 Arsenic Removal Unit Attached to Tubewell

The principles of arsenic removal by alum coagulation, sedimentation and filtration have been employed in a compact unit for water treatment in the village level in West Bengal, India. The arsenic removal plant attached to hand tubewell has been found effective in removing 90 percent arsenic from tubewell water having initial arsenic concentration of 300 ppb. The treatment process involves addition of sodium hypochloride (Cl_2), and aluminum alum in diluted form, mixing, flocculation, sedimentation and up flow filtration in a compact unit. Figure 3.3 shown bellow the arsenic removal plants attached to the tubewell.

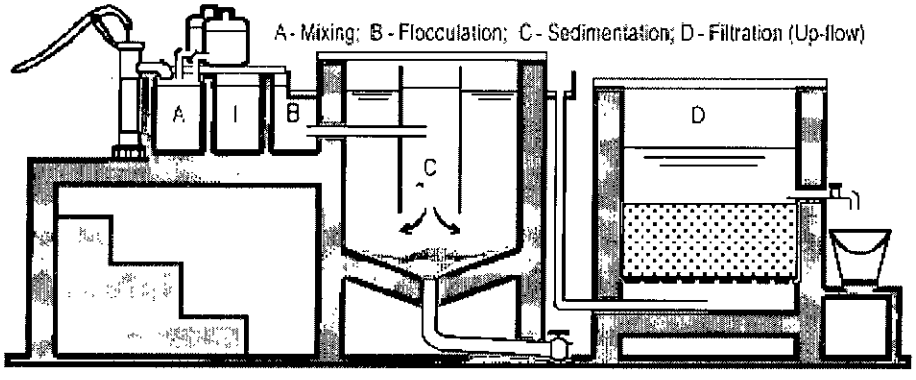

Figure 3.3: Arsenic Removal Plants Attached to Tubewell

The iron precipitates [$Fe(OH)_3$] formed by oxidation of dissolved iron [$Fe(OH)_2$] present in groundwater, as discussed above, have the affinity for the adsorption of arsenic. Only aeration and sedimentation of tubewell water rich in dissolved iron has been found to remove arsenic. The Iron Removal Plants (IRP) in Bangladesh constructed on the principles of aeration, sedimentation and filtration in a small units have been found to remove arsenic without any added chemicals. The conventional community type IRP, depending on the operating principles, more or less work as Arsenic Removal Plants (ARP) as well. A study suggests that As(III) is oxidized to As(V) in the IRP to facilitate higher efficiency in arsenic removal in IRP constructed in Noakhali (Dahi and Liang, 1998). The efficiency of these community type Fe-As removal plants can be increased by increasing the contact time between arsenic species and iron flocs. Community participation in operation and maintenance in the local level is absolutely essential for effective use of these plants.

Some medium scale Fe-As removal plants of capacities 2000-3000 m^3/d have been constructed for water supplies in district towns based on the same principle. The treatment processes involved in these plants include aeration, sedimentation and rapid sand filtration with provision for addition of chemical, if required. These plants are working well except that treated water requirement for washing the filter beds is very high. Operations of small and medium size IRP-cum-ARP in Bangladesh suggest that arsenic removal by co-precipitation and adsorption on natural iron flocs has good potential.

3.5.7 Chemical Packages

In Bangladesh, different types of chemical packages have been distributed in the form of tea bags, small packets and powder or tablet form for the removal of arsenic from drinking water. The principles involved in arsenic removal by these chemicals involve oxidation, sorption and co-precipitation. Application methodology and efficiency of any of these chemicals have not been fully optimized by long experimentation. Quality assurance and dose control in rural condition are extremely difficult. The residuals of added chemicals in water after treatment can do equal harm. The use of unknown chemicals and patented process without adequate information should be totally discouraged.

3.5.8 Activated Alumia

Activated alumia, Al_2O_3, having good sorptive surface is an effective medium for arsenic removal. When water passes through a packed column of activated alumina, the impurities including arsenic present in water are adsorbed on the surfaces of activated alumina grains. Eventually the column becomes saturated, first at its upstream zone and later the saturated zone moves downstream towards the bottom end and finally the column get totally saturated.

Regeneration of saturated alumina is carried out by exposing the medium to 4% caustic soda, NaOH, either in batch or by flow through the column resulting in high arsenic contaminated caustic waste water. The residual caustic soda is then washed out and the medium is neutralized with a 2% solution of sulfuric acid rinse. During the process about 5-10% alumina is lost and the capacity of the regenerated medium is reduced by 30-40%.

The activated alumina needs replacement after 3-4 regeneration. Like coagulation process, pre-chlorination improves the column capacity dramatically. Some of the activated alumina based sorptive media used in Bangladesh include:

- ❖ BUET Activated Alumina
- ❖ Alcan Enhanced Activated Alumina
- ❖ ARU of Project Earth Industries Inc.,USA
- ❖ Apyron Arsenic Treatment Unit

The BUET and Alcan activated alumina have been extensively tested in field condition in different areas of Bangladesh under rapid assessment and found very effective in arsenic removal (BAMWSP, DFID, WaterAid, 2001). The Arsenic Removal Units (ARU) of Project Earth Industries Inc. (USA) used hybrid aluminas and composite metal oxides as adsorption media and were able to treat 200-500 Bed Volume (BV) of water containing 550 μg/L of arsenic and 14 mg/L of iron (Ahmed et al., 2000). The Apyron Technologies Inc. (ATI) also uses inorganic granular metal oxide based media that can selectively remove As(III) and As(V) from water. The Aqua-Bind TM arsenic media used by ATI consist of non-hazardous aluminium oxide and manganese oxide for cost-effective removal of arsenic. The proponents claimed that the units installed in India and Bangladesh consistently reduced arsenic to less than 10μg/L. Figure 3.4 shown bellow the schematic diagram of Alcan Enhanced Activated Alumina.

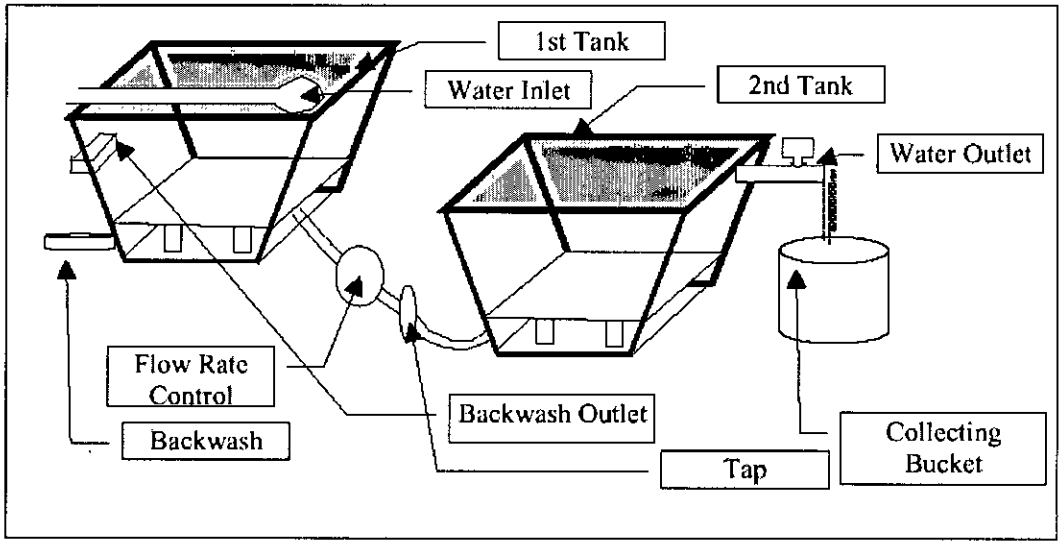

Figure 3.4: Schematic diagram of Alcan enhanced activated alumina

3.5.9 GARNET Filter

Garnet filter relies on passive coagulation with iron and or adsorption to sand matrix and filtration process. It consists of two chambers (bucket, pitche or other container), the unit placed one under the other. Each bucket contains at least one layer of brick chips, one layer of sand and more than one piece of nylon cloths. The production capacity of this system is about 0.40-0.70 L/h depending on the turbidity of feed water. Removal efficiency of 70-100% cited in GARNET's own literature depending on the presence of arsenic and iron in the feed water. But recent field test concluded that arsenic removal efficiency of GARNET filter is unpredictable and it is not clear why this should be (Wateraid Phase II, 2001).

3.5.10 Granular Ferric Hydroxide

M/S Pal Trockner (P) Ltd, India and Sidko Limited, Bangladesh installed several Granular Ferric Hydroxide based arrsenic removal units in India and Bangladesh. The Granular Ferric Hydroxide (AdsorpAs ®) is arsenic selective adsorbent developed by Technical University, Berlin, Germany. The unit requires ironremoval as pre-treatment to avoid clogging of filter bed. The proponents of the unit claim to have very high arsenic removal capacity and produces non-toxic spent granular ferric hydroxide.

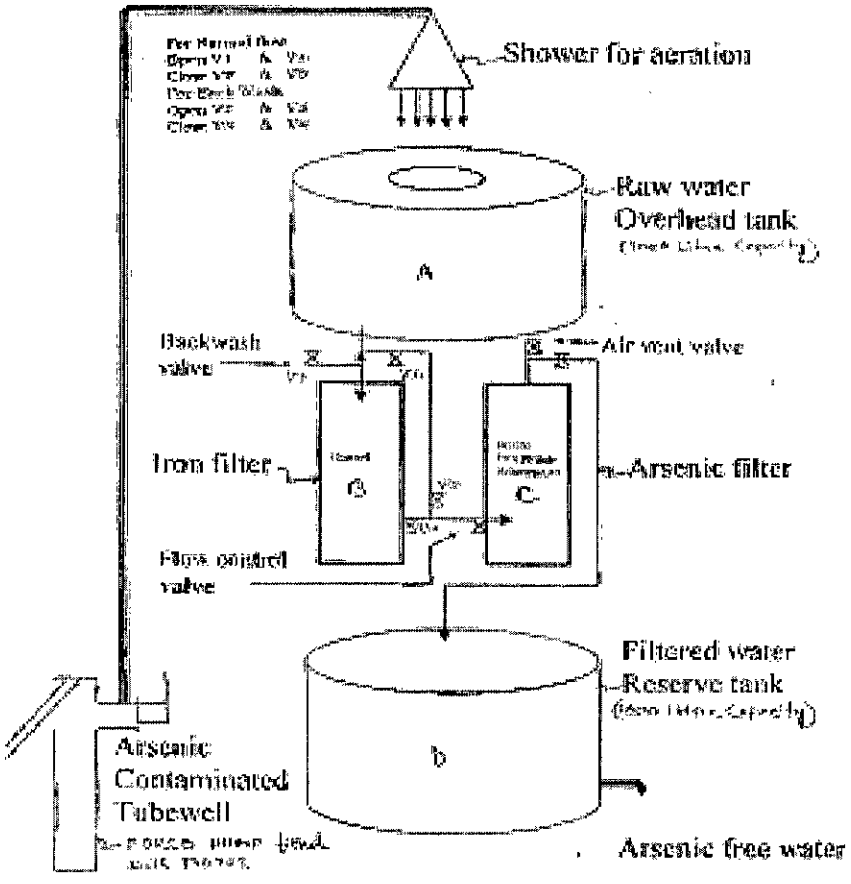

Figure 3.5: Schematic diagram of Sidko arsenic removal plant

3.5.11 Read-F Arsenic Removal Unit

Read-F is an adsorbent produced and promoted by Shin Nihon Salt Co. Ltd, Japan for arsenic removal in Bangladesh. Read-F displays high selectivity for arsenic ions under a broad range of conditions and effectively adsorbs both arsenite and arsenate without the need for pretreatment. The Read-F is Ethylene-vinyl alcohol copolymer (EVOH)-borne hydrous cerium oxide in which hydrous cerium oxide (CeO_2. n H_2O), is the adsorbent. The material contains no organic solvent or other volatile substance and is not classified as hazardous material. Laboratory test at BUET and field testing of the materials at 4 sites under the supervision of BAMWSP showed that the adsorbent is highly efficient in removing arsenic from groundwater (SNSCL, 2000).

3.5.12 Iron Coated Sand

BUET has constructed and tested iron coated sand based small scale unit for the removal of arsenic from groundwater. Iron coated sand has been prepared following a procedure similar to that adopted by Joshi and Choudhuri (1996). The iron content of the iron coated sand was found to be 25 mg/g of sand. Raw water having 300 μg/L of arsenic when filtered through iron coated sand becomes essentially arsenic-free. It was found that 350 bed volumes could be treated satisfying the Bangladesh drinking water standard of 50 ppb. The saturated medium is regenerated by passing 0.2N sodium hydroxide through the column or soaking the sand in 0.2N sodium hydroxide followed by washing with distilled water. No significant change in bed volume (BV) in arsenic removal was found after 5 regeneration cycles. It was interesting to note that iron coated sand is equally effective in removing both As(III) and As(V). Iron coated brick dust has also been developed in Bangladesh for arsenic removal from drinking water.

3.5.13 Indigenous Filters

There are several filters available in Bangladesh that use indigenous material as arsenic adsorbent. Red soil rich in oxidized iron, clay minerals, iron ore, iron scrap or fillings and processed cellulose materials are known to have capacity for arsenic adsorption. Some of the filters manufactured using these materials include:

- Sono 3-Kolshi Filter
- Granet Home-made Filter
- Chari Filter
- Adarsha Filter
- Shafi Filter
- Bijoypur Clay/Processed Cellulose filter

The Sono 3-Kolshi filter uses zero valent iron fillings and coarse sand in the top Kolshi, wood coke and fine sand in the middle Kolshi while the bottom Kolshi is the collector of the filtered water (Khan et al., 2000). Earlier Nikolaidis and Lackovic (1998) showed that 97 % arsenic can be removed by adsorption on a mixture of zero valent iron fillings and sand and recommended that arsenic species could have been removed through formation

of co-precipitates, mixed precipitates and by adsorption onto the ferric hydroxide solids. The Sono 3-Kolshi unit has been found to be very effective in removing arsenic but the media habour growth of microorganism (BAMWSP, DFID and WaterAid, 2000). The one-time use unit becomes quickly clogged, if groundwater contains excessive iron. Figure 3.6 shown bellow the schematic diagram and Picture of a Sono 3-kolssi filter.

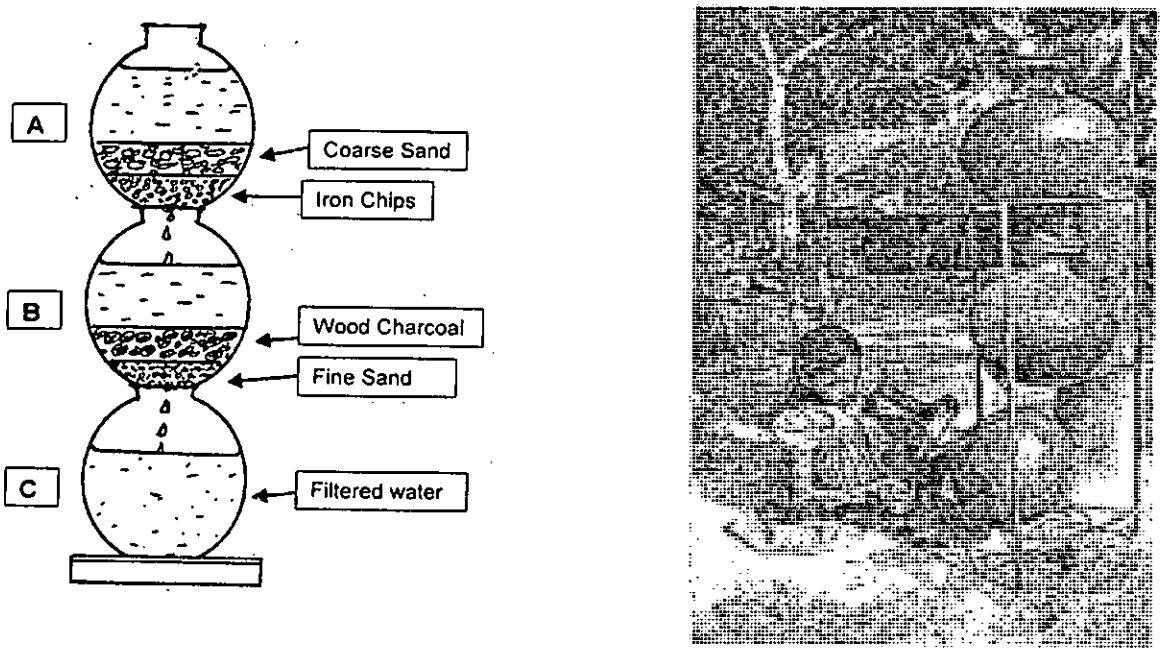

Figure 3.6: Schematic diagram and picture of a Sono 3-kolssi filter

The Garnet home-made filter contains relatively inert materials like brick chips and sand as filtering media. No chemical is added to the system. Air oxidation and adsorption on iron-rich brick chips and flocs of naturally present iron in groundwater could be the reason for arsenic removal from groundwater. The unit produced inadequate quantity of water and did not show reliable results in different areas of Bangladesh and under different operating conditions. The Chari filter also uses brick chips and inert aggregates in different Charis as filter media. The effectiveness of this filter in arsenic removal is not known.

The Shafi and Adarsh filters use clay material as filter media in the form of candle. The Shafi filter was reported to have good arsenic removal capacity but suffered from clogging of filter media. The Adarsha filter participated in the rapid assessment program but failed to meet the technical criterion of reducing arsenic to acceptable level (BAMWSP, DFID and WaterAid, 2000). Bijoypur clay and treated cellulose were also found to adsorb arsenic from water (Khair, 2000).

3.5.14 Cartridge Filters

Filter units with cartridges filled with soptive media or ion-exchange resins are readily available in the market. These units remove arsenic like any other dissolved ions present in water. These units are not suitable for water having high impurities and iron in water. Presence of ions having higher affinity than arsenic can quickly saturate the media requiring regeneration or replacement. Two household filters were tested at BUET laboratories, these are:

- ❖ Chiyoda Arsenic Removal Unit, Japan
- ❖ Coolmart Water Purifier, Korea

The Chiyoda Arsenic Removal Unit could treat 800 BV meeting the WHO guideline value of 10μg/L and 1300 BV meeting the Bangladesh Standard of 50μg/L when the feed water arsenic concentration was 300μg/L. The Coolmart Water Purifier could treat only 20 L of water with a effluent arsenic content of 25 μg/L (Ahmed et al., 2000). The initial and operation costs of these units are high and beyond the reach of the rural people.

The process is similar to that of activated alumina; just the medium is a synthetic resin of more well defined ion exchange capacity. The process is normally used for removal of specific undesirable cation or anion from water. As the resin becomes exhausted, it needs to be regenerated. The arsenic exchange and regeneration equations with common salt solution as regeneration agent are as follows:

Arsenic exchange:

$$2R\text{-}Cl + HAsO_4^{--} = R_2HAsO_4 + 2Cl^- \quad (3\text{-}9)$$

Regeneration:

$$R_2HAsO_4 + 2N^+ + 2Cl^- = 2R\text{-}Cl + HAsO_4^{--} + 2Na^+ \quad (3\text{-}10)$$

Where R stands for ion exchange resin

The arsenic removal capacity is dependent on sulfate and nitrate contents of raw water as sulfate and nitrate are exchanged before arsenic. The ion exchange process is less dependent on pH of water. The efficiency of ion exchange process is radically improved by pre-oxidation of As(III) to As(V) but the excess of oxidant often needs to be removed before the ion exchange in order to avoid the damage of sensitive resins. Development of ion specific resin for exclusive removal of arsenic can make the process very attractive.

3.5.15 Tetrahedron Ion Exchange Resin Filter

Tetrahedron ion exchange resin filter tested under rapid assessment program in Bangladesh (BAMWSP, DFID and WaterAid, 2000) showed promising results in arsenic removal. The system needs pre-oxidation of arsenite by sodium hypochloride. The residual chlorine helps to minimize bacterial growth in the media. The saturated resin requires regeneration by recirculating NaCl solution. The liquid wastes rich in salt and arsenic produced during regeneration require special treatment. Some other ion exchange resins were demonstrated in Bangladesh but sufficient field test results are not available on the performance of those resins. Figure 3.7 shown bellow the schematic diagram of Tetra Hedron filter unit.

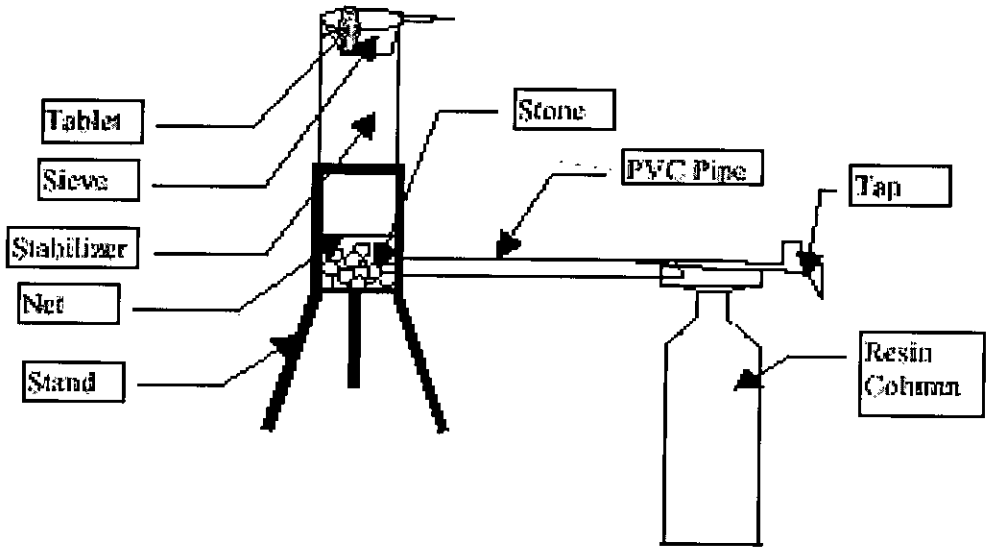

Figure 3.7: Schematic diagram of Tetra Hedron filter unit

3.5.16 MRT-1000 and Reid System Ltd.

Jago Corporation Limited promoted a household reverse osmosis water dispenser MRT-1000 manufactured by B & T Science Co. Limited, Taiwan. This system was tested at BUET and showed arsenic (III) removal efficiency more than 80%. A wider spectrum reverse osmosis system named Reid System Limited was also promoted in Bangladesh. Experimental results showed that the system could effectively reduce arsenic content along with other impurities in water. The capital and operational costs of the reverse osmosis system would be relatively high.

3.5.17 Low-pressure Nanofiltration and Reverse Osmosis

Oh et al. (2000) applied reverse osmosis and nanofiltration membrane processes for the treatment of arsenic contaminated water applying low pressure by bicycle pump. A nanofiltration membrane process coupled with a bicycle pump could be operated under condition of low recovery and low pressure range from 0.2 to 0.7 MPa. Arsenite was found to have lower rejection than arsenate in ionized forms and hence water containing higher arsenite requires pre-oxidation for reduction of total arsenic acceptable level. In tubewell water in Bangladesh the average ratio of arsenite to total arsenic was found to be 0.25. However, the reverse osmosis process coupled with a bicycle pump system operating at 4 Mpa can be used for arsenic removal because of its high arsenite rejection. The study concluded that low-pressure nanofiltration with pre-oxidation or reverse osmosis with a bicycle pump device could be used for the treatment of arsenic contaminated groundwater in rural areas (Oh et al., 2000).

3.5.18 Solar Oxidation and Removal of Arsenic (SORAS)

The process is based on photochemical oxidation of As^{3+} to As^{5+} followed by flocculation, precipitation and possibly filtration of As^{5+} adsorbed on $Fe(OH)_3$ particles. Photochemical oxidation is accelerated and enhanced by the addition of a few drops (6-8 drops per liter) of lemon juice (citrate) and exposed to sunlight for 5-6 hours to form Fe^{3+} complexes. SORAS require at least 2 mg/L iron in the groundwater and UV-A radiation dose of about $50Wh/m^2$. Removal efficiency achieved in laboratory is more than 90% but in the field it is about 50-80%. SORAS is a simple process that can be used at household level to reduce arsenic in ground water (containing an arsenic concentration of less than 100-150 μg/L) with available resources (Wegelin et al, 2001). But availability of sunlight and lemon juice throughout the year may be a concern. The effects of excess iron in the raw water are not considered. The picture of a SORAS system is presented in the figure 3.8 below.

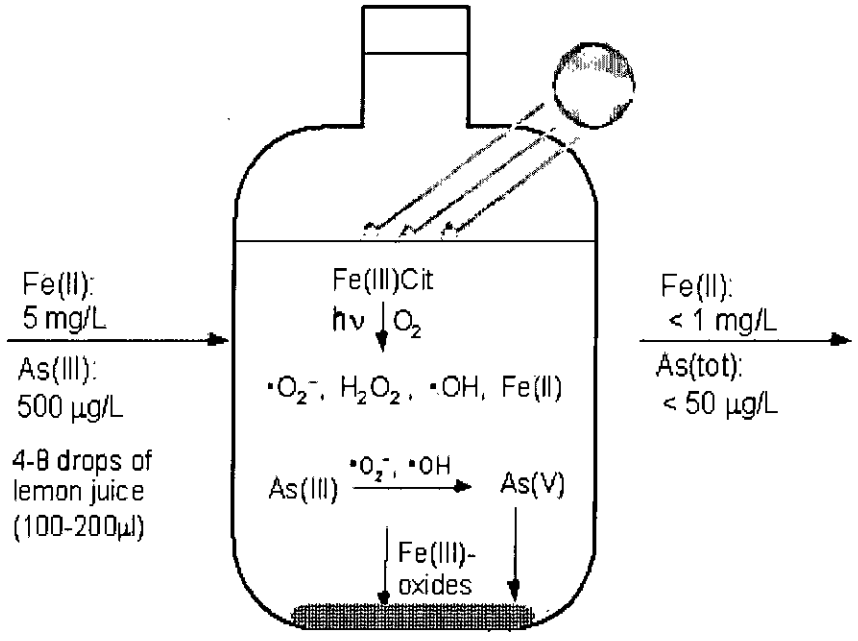

Figure 3.8: Picture of a solar oxidation and removal of arsenic system

3.6 Comparison among the Technologies

A remarkable technological development in arsenic removal from rural water supply based on conventional arsenic removal processes has been taken place during last 5-6 years. A comparison of different arsenic removal processes is shown in Table 3.1. All the technologies have their merits and demerits and are being refined to make them suitable in rural condition with the objectives to:

- improve effectiveness in arsenic removal
- reduce the capital and operation cost of the systems
- make the technology user friendly
- overcome maintenance problems
- resolve sludge and arsenic concentrates management problems.

Arsenic removal technologies have to compete with other technologies in which cost appears to a major determinant in the selection of a treatment option by the users. The rural people habituated in drinking tubewell water may find arsenic removal from tubewell water as a suitable option for water supply. In many arsenic affected areas, arsenic removal may be the only option in the absence of an alternative safe source of water supply.

The technologies found effective and safe for arsenic removal from tubewell water need promotion for wider implementation in the acute arsenic problem areas to avoid ingestion of excessive arsenic through tubewell water. The arsenic removal technologies are expected to improve further through adaptation in rural environment.

Table 3.1: A comparison of main arsenic removal technologies (Ahmed, 2001)

Technologies	**Advantages**	**Disadvantages**
Oxidation/ Precipitation ▪ Air Oxidation ▪ Chemical oxidation	• Relatively simple, low-cost but slow process • Relatively simple and rapid process • Oxidizes other impurities and kills microbes	• The processes remove only a part of arsenic
Coagulation Coprecipitation • Alum Coagulation • Iron Coagulation	• Relatively low capital cost, • Relatively simple operation • Common Chemicals available	• Produces toxic sludges • Low removal of As(III) • Pre-oxidation may be required
Sorption Techniques • Actvated Alumina • Iron Coated Sand • Ion Exchange Resin • Other Sorbents	• Relatively well known and commercially available • Well defined technique • Plenty possibilities and scope of development	• Produces toxic solid waste • Replacement/regeneratin required • High tech operation and maintenance • Relatively high cost
Membrane Techniques • Nanofiltration • Reverse osmosis • Electrodialysis	• Well defined and high removal efficiency • No toxic solid wastes produced • Capable of removal of other contaminants	• Very high capital and running cost • High tech operation and maintenance • Toxic wastewater produced

3.7 Analytical Methods for Measurement of Arsenic

Analytical methods for measuring arsenic may be categorized as follows:

- ❖ Inductively Coupled Plasma (ICP) method
- ❖ Graphite Furnace Atomic Absorption Spectrophotometry (GFAAS)
- ❖ Flame Atomic Absorption Apectrophotometry (FAAS)
- ❖ Hydride Heneration Atomic Absorption Apectrophotometry
- ❖ Silver Diethyl Dithio Carbamate (SDDC) Colorimetric method
- ❖ Field kit method

The first four methods involve high-cost equipment and provide more accuracy and lower detection limit (in the range of 1 μg/L). The last two methods are relatively low cost methods. Briefly discuss here Graphite Furnace Atomic Absorption Spectrophotometry (GFAAS) analytical method, Silver Diethyl Dithio Carbamate (SDDC) Colorimetric method and field kit method.

3.7.1 Graphite Furnace Atomic Absorption Spectrophotometry (GFAAS)

Electro-thermal atomic absorption spectroscopy is based on the same principle as direct flame atomization but an electrically heated atomizer or graphite furnace replaces the standard burner head. A discrete sample volume is dispensed into the graphite sample tube (or cup). Typically, determinations are made by heating the sample in three or more stages. First, a low current heats the tube to dry the sample. The second, or charring, stage destroys organic matter and volatilizes other matrix components at an intermediate temperature. Finally, high current heats the tube to incandescence and, in an inert atmosphere, atomizes the element being determined. Additional stages frequently are added to aid in drying and charring, and to clean and cool the tube between samples. Figure 3.9 shown bellow the Atomic Absorption Spectrophotometer (AAS) with graphite furnace.

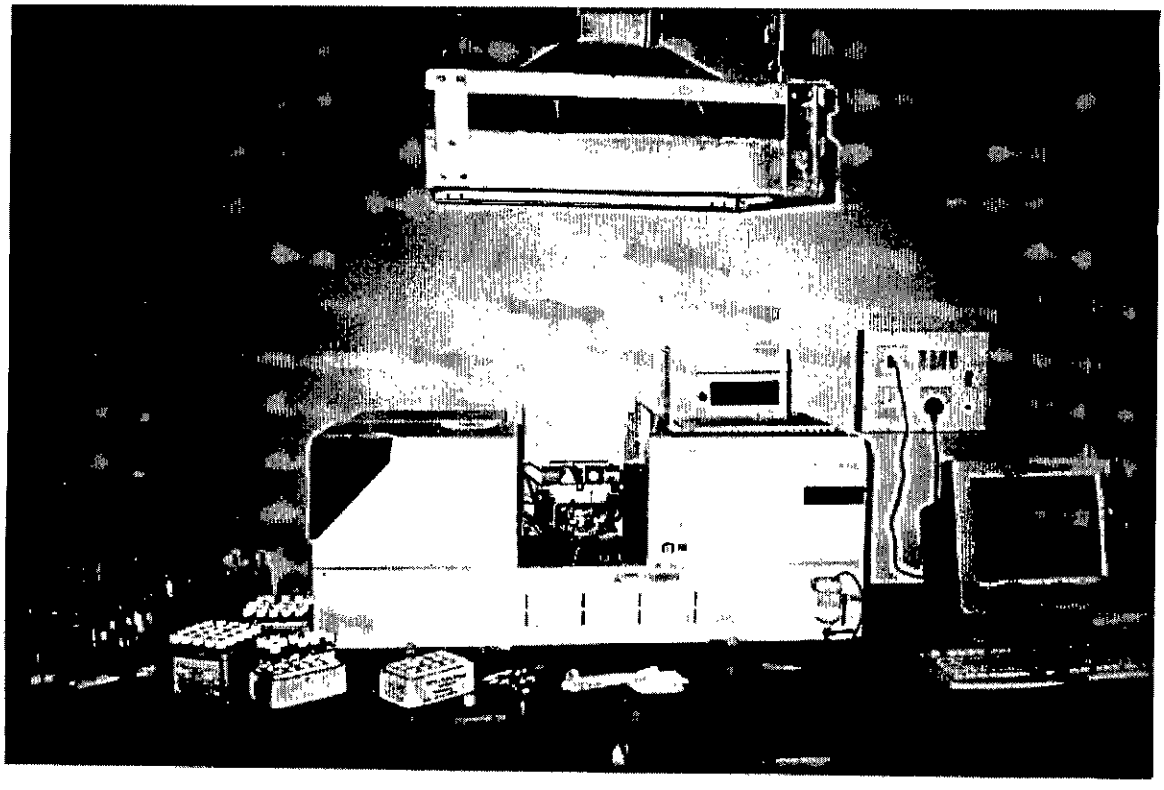

Figure 3.9: A photograph shows an atomic absorption spectrophotometer (AAS) with graphite furnace

3.7.1.1 The Basic Parts, Working Principle and Analysis of Arsenic by AAS Parts:

1. Graphite furnace: Creating temperature
2. Monochromatic source (HC Lamp): Monochromatic radiation (For Arsenic, wave length 193.70 nm)
3. Graphite tube: For inject the sample
4. Photoelectric detector: Measure the transmitted radiation
5. Out put: Concentrations of the element
6. Operating software: WizAArd
7. Auto sampler: Use for auto sampling (10 μl sample)

3.7.1.2 Working Principle:

Atomic vapor absorbs monochromatic radiation from the source. A photoelectric detector measures the intensity of transmitted radiation. The inverse of the transmittance is related logarithmically to absorbance; which is directly proportional to the number density of vaporized atoms (Beer-Lambert Law) over a limited concentration range.

4.2.3 Analysis of Arsenic:

Sample prepare: 9 ml sample + 1 ml $Ni(NO_3)_2$ solution (Con. =1560 ppm)

Matrix modifier: $Ni(NO_3)_2$ solution uses for minimize the interference of other elements, as like as masking substance for Arsenic.

Sample inject: 20 µl samples inject in the Graphite tube.

Standard solution: Mother solution strength 1000 ppm. Take 10 µl and make 100 ml. So the concentration of new solution is 100 ppb (10000 times dilution). Then make the other standard concentration 10, 20, 30 and 40 ppb use this solution.

Standard curve: Inject the standard concentration 0, 10, 20, 30 and 40 ppb respectively. So the standard curve (concentration vs absorbance) is prepared.

Minimum detection limit (MDL): 1 ppb

3.7.2 Silver Diethyl Dithio Carbamate (SDDC) Colorimetric method

Arsine Generation

Organic arsenic-containing compounds are decomposed by adding acids and repeatedly evaporating the sample. The arsenic(V) so produced, together with inorganic arsenic originally present, is subsequently reduced to arsenic(III) by potassium iodide and stannous chloride. By adding zinc to this solution, the arsenic is reduced more to arsine (arsenic hydride). Hydrogen is produced by the reaction of hydrochloric acid on zinc. By this nascent hydrogen arsenic is reduced and finally becomes gaseous AsH_3.

Arsenic Detection and Measurement

The resulting mixture of gases is passed through a scrubber containing borosilicate wool impregnated with Lead acetate solution to remove hydrogen sulfide and other sulfide which interfere with the result. Then the gases passed into an absorption tube containing a solution of Silver Diethyl Dithio Carbamate (SDDC) in Pyridine or chloroform. Arsenic react with this reagent to form a red coloured silver solution having maximum absorbency at about 535-540 nm. The absorbency of the solution is measured photometrically and arsenic determined by reference to an analytical curve prepared from standards.

Apparatus

The arsenic apparatus is composed of major three parts:

(a) Arsenic generator (250 ml flask)

(b) Scrubber, and

(c) Absorber (U-neck glass tube)

Moreover a Spectrophotometer suitable for use at 535-540 nm and providing a light path of at least 10 mm is required.

3.8 Arsenic Measurement by Field Kit

The Field kit Technique is based on the hydride generation system as mentioned in the SDDC method. In the Ground Water arsenic usually occurs as arsenite (As-III) and arsenate (As-V). To determine the arsenic in water arsenate is reduced to arsenite by the reducing agents potassium iodide and stannous chloride. The As-III is then reacted with Zinc and HCl to produce arsine gas. Colour change (Yellow to Reddish brown) produced by reaction of Arsine gas with the specially treated Mercury bromide paper indicates the presence of arsenic in water. In absence of Arsenic in the water sample no colour is produced on the paper. To avoid interference with Hydrogen sulfide cotton ball impregnated with lead acetate may be used.

CHAPTER 4

EFFECT OF SOURCE WATER COMPOSITION ON ARSENIC REMOVAL BY ALUM

4.1 Introduction

Coagulation is a well known technique to remove inorganic contaminants from water when the constituent metal of the coagulant precipitates as an amorphous metal hydroxide with which the inorganic contaminants become associated (e.g., by adsorption) and removed by sedimentation and filtration. By addition of a coagulant (such as alum), soluble arsenic can be removed through adsorption, occlusion (entrapment of adsorbed contaminants in the interior of the growing particle) and solid-solution formation (Benefield and Morgan, 1990). The behavior of arsenic in adsorption and coagulation (using alum as coagulant) studies indicates that adsorption is a dominant mechanism for arsenic removal by coagulants (Hering et al., 1996) when alum is added to water. Arsenic is primarily removed by adsorption onto coagulated flocs of amorphous aluminium hydroxide, which is formed upon addition of alum ($Al_2(SO_4)_3.18H_2O$) to water.

This chapter presents materials and methods of arsenic (both arsenate and arsenite) removal from groundwater by coagulation with alum in laboratory (batch experiments). The effects of initial arsenic concentration, coagulant dose, and pre-oxidation of arsenite (with potassium permanganate) on arsenic removal have been examined. The results obtained from the experiments are discussed in detail. Based on these results, alum required for achieving Bangladesh standard for arsenic have been determined for different initial concentrations of arsenic.

4.2 Experimental Setup

The arsenic removal unit (ARU) based on ferric chloride coagulation developed at BUET (Ali et al., 2001) has been used for the present study. The ARU is described below:

The ARU is constructed using locally available materials and accessories. It has the following components:

3-legged iron frame:	1. No.
Bucket (25 litre):	2 Nos of different colour with cover
Water tap:	2 Nos
Jam nut:	4 Nos
Washer:	8 Nos
Transparent pipe:	1 feet length (1/4" diameter)
Filtering cloth:	1/2 yards
Strainer (37 mm diameter):	1 feet length
Strainer Cap:	4 Nos
Coarse sand:	1 bag (40 kg)
Steel rod:	5 m (10 mm ϕ MS bar)
Thread tape:	1 Nos
Piping glue:	1 Nos

The Construction Procedure of the ARU is as follows:

- The iron frame made of mild steel rod, is prepared so that two buckets can be set easily one over another in the frame.
- In each bucket, a hole 2 inches above the bottom is made to set a water tap.
- In the top bucket one water tap is fitted, making it watertight and strong using thread tape, washer and jam nut.
- In the lower bucket, another tape is fitted and it is connected with strainer of required length placed in the bucket. The bucket is then filled with sand to make sand filter of 20 cm deep.
- The lower bucket is covered with the filter cloth and the cover of the bucket is placed on it.

- The transparent pipe is then connected with the top water tap and the other end is inserted through the hole of the lower bucket cover.

5 sets (A, B, C, D & E) of ARUs were constructed for the study. The assembled ARU is shown in Fig. 4.1

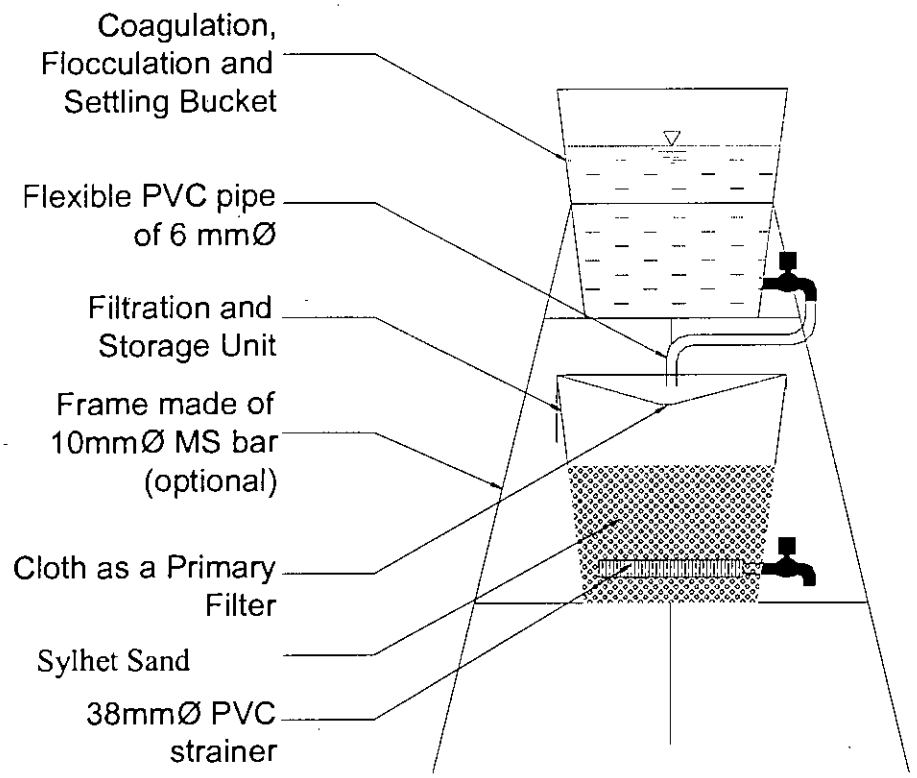

Figure 4.1: Arsenic removal unit based on alum

4.2.1 Operation of the ARU

The following steps are needed to operate the ARU:

- Raw or spiked water (20 L) is put in the top bucket of the arsenic removal unit.
- Required quantity of chemical is added to the water in the top bucket.
- The water stirred for about 10 -12 turns vigorously (for mixing) and then 40 - 45 turns slowly (for flocculation of alum precipitates).
- About one hour settling time is then allowed to settle the flocs produced in the water.
- After one hour, both water taps are opened.
- The supernatant of the top bucket passes through the sand filter and is collected from the bottom tap.

4.3 Experimental Procedure

The efficiency of alum in removing arsenate and arsenite from groundwater was evaluated in of laboratory batch experiments. All experiments were conducted in 25 L plastic buckets (containing 20 L of water) using arsenic-free groundwater spiked with As(V) and/or As(III) standard solutions. The procedures followed are described in the following sub-section.

4.3.1 Preparation of Synthetic Water

The arsenic free groundwater was collected from environmental engineering research laboratories, BUET and pump house of BUET. As(V) stock was prepared by dissolving its sodium salt Na_2HAsO_4 $7H_2O$ in deionized water, while As(III) stock solution was prepared by dissolving arsenic trioxide (As_2O_3) in deionized water containing sodium hydroxide. Required quantity of As(V) or As(III) stock solution was added to the beakers to achieve the desired initial arsenic concentrations. For when As(III) was used, potassium permanganate ($KMnO_4$) was added for oxidation of As(III) to improve removal efficiency. A potassium permanganate ($KMnO_4$) dose twice that required from stoichiometric consideration was used in these experiments. Alum stock solution (prepared by dissolving $Al_2(SO_4)_3$. $18H_2O$ to distilled water) was then added to the buckets. No attempt made to adjust pH of the waters.

The composition of arsenic-free groundwater used in this study is reported in Table 4.1. The water was collected from Environmental laboratories, BUET. Iron concentration of the groundwater was found to be very low (0.01 ppm or Nil), which is typical of groundwater in this region of Dhaka. The aluminum concentration is also below detection limit (0.01 ppm). In this study aluminum sulfate (Alum) doses used ranged from 25 to 200 ppm, for which corresponding aluminum concentrations were 2.03 to 16.22 ppm, respectively. The raw water pH varied from 6.1 to 6.6.

Table 4.1: Detailed characterization of groundwater used in laboratory experiments

Parameters	Unit	Concentration
pH	-	6.1 - 6.6
Alkalinity (as CaCO3)	ppm	210
Iron	ppm	<0.01
Hardness (as CaCO3)	ppm	310
Chloride	ppm	200
Sulfate	ppm	36.7
Phosphate	ppm	0.05
Nitrate	ppm	5.3
Silicate (Silica)	ppm	30
Aluminum	ppm	<0.01
Manganese	ppm	0.01
TDS	ppm	260
Arsenic	ppb	<1
Color	Pt-Co	Nil
Turbidity	NTU	1
Conductivity	μs/cm	648

4.3.2 Experimental Conditions and Operations

The first set of experiments were conducted to determine the effect of alum dosing in removing arsenic from water having different initial arsenic [As(V)] concentrations under vigorous mixing (12-15 turns strongly). Natural sylhet sand was used in the sand filters. The experimental conditions are given in Table 4.2.

Synthetic groundwater containing 300, 500 and 1000 ppb As (V) was used as feed waters of the arsenic removal units. Different alum doses 0, 25, 50, 100, 150, and 200 ppm were added to the feed waters. The contents of the buckets was mixed to different mixing variation such as standard mixing (10-12 vigorous mixing, 40-50 slow mixing), Medium mixing (12-15 vigorous mixing) and little mixing (3-5 vigorous mixing). In this study, wooden stick was used for mixing to simulate the field condition in rural Bangladesh. The effect of mixing on floc formation was evaluated by varying mixing energy. Then the flocs were allowed to settle for one hour, after which the water was allowed to pass through the sand bed. The experiment setup shown in Fig. 4.1. Treated water was collected and preserved by adding 1 mL concentrated HCl in 500 mL of sample to lower the pH below 2 for analysis.

Table 4.2 Experimental conditions for As(V) removal study using natural Sylhet sand filter.

As(V) Concentration (ppb)	Alum dose, (mg/L)	ARU
300	0	A, B, C, D & E
	25	
	50	
	100	
	150	
	200	
500	0	
	25	
	50	
	100	
	150	
	200	
1000	0	
	25	
	50	
	100	
	150	
	200	

Table 4.3: Composition of water for parametric study of arsenic removal (DW = Distilled water, TW = Tap Water, PW = Pond water.)

Parameter	Unit	Salts Used	Tap water	Variation-1	Variation-2	Variation-3	Variation-4	Variation-5
pH		HCl/NaOH	6.5	5	6	7	7.5	8
Alkalinity	ppm	$NaHCO_3$	210	50	PW,100	TW	350	500
Iron	ppm	$Fe(NO_3)_39H_2O$	00	TW	2.5	5	10	20
Hardness	ppm	$CaCl_2$	306	DW	PW,100	TW	400	500
Chloride	ppm	NaCl	200	DW	PW,40	TW	400	600
Sulfate	ppm	Na_2SO_4	36.7	DW		TW	50	100
Phosphate	ppm	$NaH_2PO_42H_2O$	0.05	TW		1	10	20
Nitrate	ppm	$Ni(NO_3)_26H_2O$	5.3	TW	1	5	10	20
Silicate	ppm	$Na_2SiO_39H_2O$	30	DW	TW	50	75	100

The effects of different parameters such as feed water pH, alkalinity, iron, hardness, chloride, sulfate, phosphate, nitrate and silicate concentrations on arsenic removal were studied by varying each parameter individually (Table 4.3) with a particular dose of alum (100 and 50 ppm) and As (V) concentration of 300 ppb. Different salts and water were used to vary these parameters. The ARU was operated to find the effect of the water quality parameters on arsenic removal efficiency. The synergistic effects of different ions

were studied by adding the ions in three different combinations as shown in Table 4.4 (Low, Moderate and High ion concentration) to groundwater. The arsenic concentrations and alum dose applied are presented in Table 4.5. Potassium permanganate dose was varied to assess its effect on oxidation of trivalent As (III) to As (V) for the condition as shown in Table 4.6. The effects of ferrous iron and potassium permanganate on arsenite removal with phosphate and without phosphate were studied (Tables 4.7 and 4.8). The effect of different combinations of arsenate and arsenite were studied on arsenic removal with particular doses of alum, potassium permanganate, ferrous iron and phosphate and the conditions are presented in Table 4.9.

Table 4.4: Composition of water used to study the synergistic effect of dissolved constituents on arsenic removal

Parameter	Unit	Low	Moderate	High
pH	-	6.0	6.5	7.0
Alkalinity	ppm	210	350	500
Iron	ppm	2.5	10	20
Hardness	ppm	306	400	500
Chloride	ppm	200	400	600
Sulfate	ppm	36.7	50	100
Phosphate	ppm	1	10	20
Nitrate	ppm	5.3	10	20
Silicate	ppm	50	75	100
Ionic Strength	M	0.0511	0.0816	0.1061

Table 4.5: Arsenic concentration and alum dose used in the "synergistic effect" study

As(V) ppb	Alum ppm	Ionic Strength
100	100	Low(0.0500 M), Moderate(0.0816 M) and High(0.1061 M)
200	100	
300	100	

Table 4.6: Experimental conditions to study the effect of permanganate dose on As(III) removal at low iron concentration

Permanganate	Iron Condition	As(III) ppb	Alum ppm
00	Fe(II)=1 ppm	300	100
0.5	Fe(II)=1 ppm	300	100
1.0	Fe(II)=1 ppm	300	100
2.0	Fe(II)=1 ppm	300	100

Table 4.7: Experimental conditions to study the effect of permanganate dose on As(III) removal at moderate phosphate and iron concentration

As(III) ppb	Phosphate ppm	Alum ppm	Fe(II) ppm	Permanganate ppm
350	3.0	100	5.0	00
350	3.0	100	5.0	1.0
350	3.0	100	5.0	1.5
350	3.0	100	5.0	2.0

Table 4.8: Experimental conditions to study the effect of ferrous iron on As(III) removal

As(III) ppb	Alum ppm	Fe(II) ppm	Phosphate Condition (ppm)	
300	100	00	X	3.0
300	100	2.5	X	3.0
300	100	5.0	X	3.0
300	100	10	X	3.0
300	100	20	X	3.0

Table 4.9: Experimental conditions to study the effect of arsenic species on arsenic removal

As Total ppb	As(V)	As(III)	Fe(II) ppm	PO_4 ppm	$KMnO_4$ ppm
350	0%	100%	5.0	3.0	0.0
	0%	100%	5.0	3.0	1.0
	71%	29%	5.0	3.0	1.0
	57%	43%	5.0	3.0	1.0
	50%	50%	5.0	3.0	1.0
	43%	57%	5.0	3.0	1.0
	29%	71%	5.0	3.0	1.0

4.3.3 Testing of Water Sample

The water samples collected during the experimental investigation were analyzed for a number of water quality parameters following standard methods (Ref. AWWA). Arsenic concentrations were measured by Graphite Furnace Atomic Absorption Spectrophotometer (Model AA-6800, Shimadzu) Thiocyanate method was used to measure iron content of water samples. pH was determined using pH meter (Ehamp pH tester, HANA). Mohr method was followed to measure the chloride content of water samples. Titration method was used to measure the alkalinity and hardness was measured by EDTA titration method. Total and fecal coliform rerere measured following standard membrane filtration method. Conductivity measured by conductivity meter and other parameters were measure by Spectrophotometer (HACH DR/4000U and DR/2010).

4.4 Results and Discussions

Laboratory experiments were conducted to evaluate the arsenic removal efficiency using 5 alum based arsenic removal units under a wide variety of conditions. The effects of feed water concentrations of arsenic, pH, alkalinity, sulfate, hardness, chloride, phosphate, silicate, iron, and nitrate as well as the synergistic effect of these ions were studied in detail. The effects of alum dose, permanganate dose, mixing, settling time, and filtration was also studied. The results are presented and discussed in the following sub-sections.

4.4.1 Residual Arsenic in the Treated Water using Natural Sylhet Sand

All the 5 units were operated using natural groundwater spiked with arsenic standard solution under 3 different mixing conditions (slow, medium and strong) was varying alum dose from 0 to 200 ppm and As(V) dose from 300 to 1000 ppb. Initially sylhet sand without acid treatment was used in the sand filters. The results are presented in Table 4.10.

The experimental results were both encouraging and interesting. Although excellent removal was obtained for a good number of cases, no consistent correlation was obtained between either alum dose and residual arsenic concentration or between initial and residual arsenic concentrations. Chemical dosing was not applied in a sequential order and the filter sands contained iron. Analysis of the filter sands for iron content and particle size revealed that the sands contained 12.5 to 13.2 mg iron per gm of sand and the fineness modulus varied from 1.99 to 2.47. It appears that the iron of the sands adsorbed arsenic and the adsorptive capacity of same filters was greatly reduced due to passing of large volume of arsenic contaminated water. These were the reasons for not getting consistent results all the time.

To obtain consistent results, iron was removed from the filter sands by acid treatment (by soaking the sands in 20% HCl acid solution for 11 days). About 50% iron was removed in this way. Finally all the sands were mixed uniformly and then were placed in the filters to obtain same graded sand in each filter. All the subsequent experiments were conducted using these units only.

Table 4.10: Residual As concentration in treated water (Original Sylhet sand)

Alum/As	Unit	200 ppm	150 ppm	100 ppm	050 ppm	025 ppm	000 ppm
300 ppb	A	3	0	0	-	0	0
500 ppb	A	0	0	0	-	3	34
1000 ppb	A	0	-	0	-	11	41
300 ppb	B	87	63	38	24	42	76
500 ppb	B	78	26	47	35	50	162
1000 ppb	B	17	21	-	57	425	204
300 ppb	C	24	30	50	12	38	20
500 ppb	C	6	-	12	11	25	62
1000 ppb	C	-	9	27	-	47	158
300 ppb	D	-	6	3	7	3	0
500 ppb	D	4	3	-	5	11	19
1000 ppb	D	-	19	5	-	12	9
300 ppb	E	0	-	0	0	0	0
500 ppb	E	0	-	0	0	0	0
1000 ppb	E	0	0	-	5	0	0

4.4.2 Effects of Alum Dose, Initial Arsenic Concentration and Mixing

To study the effects of alum dose, initial arsenic concentration and mixing, alum dose was varied from 25 ppm to 200 ppm, initial arsenic concentration was fixed at 300 ppb, 500 ppb and 1000 ppb, and little mixing (3 – 5 strong turns by wooden stick), medium mixing (12 – 15 strong turns) and standard mixing (10 – 12 strong turns and then 40 – 45 slow turns) were applied. The results in terms of percent removal of arsenic are presented in Figs. 4.2(a), 4.2(b) and 4.2(c) for standard mixing, medium mixing and little mixing, respectively. The same results in terms of residual arsenic in the treated water are presented in Figs. 4.3(a), 4.3(b) and 4.3(c).

From Fig. 4.2(a) it is seen that for standard mixing, the removal efficiency increase with alum dose for all the three initial arsenic concentrations, but the rate of increase was not very significant for alum dose over 50 ppm. Higher initial arsenic concentrations yielded better removal. The arsenic removal efficiency was excellent, 90% - 97% for alum dose over 50 ppm. As higher alum dose produced more precipitates and standard mixing provided greater chances for coprecipitation and adsorption of arsenic, excellent arsenic removal was obtained. This finding is in agreement with the results of previous researchers (Cheng, *et al.*, 1994; Edwards, 1994; Gulledge and O'Conner, 1973).

At medium mixing (Fig. 4.2(b)) it is seen that the arsenic removal efficiency was 88% - 95% and the maximum removal was corresponding to alum dose of 100 ppm. But at little mixing (Fig. 4.2(c)), 73% - 87% arsenic was removed and the optimum alum dose was again 100 ppm. Hence, it can be concluded that mixing has a prominent role in arsenic removal by alum coagulation and standard mixing should be practiced to obtain excellent results. Considering the arsenic removal efficiencies under the different mixing conditions, it appears that the optimum alum dose is 100 ppm for any water arsenic concentration in the range of 300 ppb to 1000 ppb.

From Fig. 4.3(a), it is seen that, for As(V) concentration of 300 ppb, the residual arsenic concentrations were around 25 ppb, much below the Bangladesh standard at the applied alum dose of 100 ppm for standard and medium mixing conditions but not below the WHO guide line value. But the residual arsenic concentration was close to 50 ppb in case of little mixing. In case of feed water As(V) concentration of 500 ppb, the residual arsenic concentrations in the treated water were around 30 ppb for standard and medium mixing conditions at the applied dose of 100 ppm, but it was around 65 ppb for little mixing (Fig. 4.3(b)).

Even for feed water As(V) concentration of 1000 ppb, the residual arsenic concentrations were below 50 ppb for standard and medium mixing at 100 ppm alum dose (Fig. 4.3(c)). But the corresponding residual arsenic concentration for little mixing was about 130 ppb. It is to be also noted that for medium mixing only the alum dose of 100 ppm was able to produce effluent containing less than 50 ppb arsenic but not below the WHO guideline value (10 ppb). Hence, it can be concluded that alum dose of 100 ppm is the optimum for producing arsenic safe water (Bangladesh standard) from feed water containing arsenic upto 1000 ppb provided at least medium mixing is ensured.

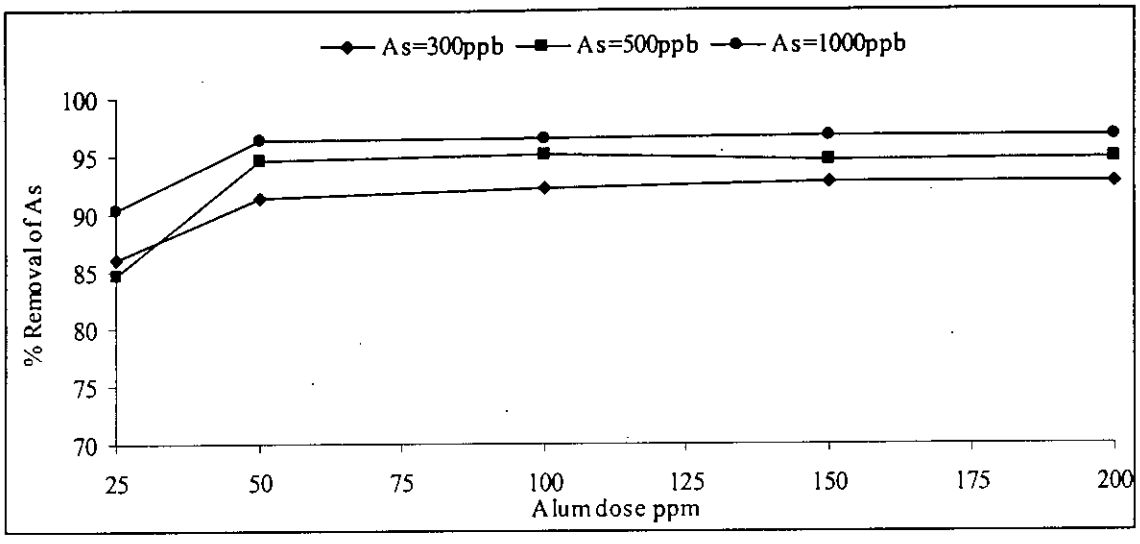

Figure 4.2(a) Variation of As(V) removal with alum dose (standard mixing)

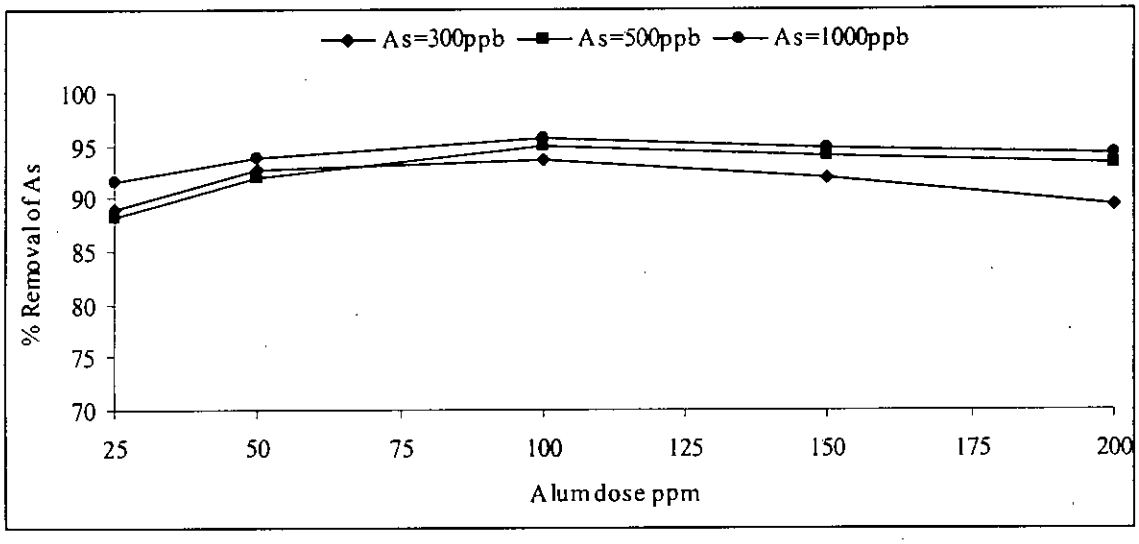

Figure 4.2 (b) Variation of As(V) removal with alum dose (medium mixing)

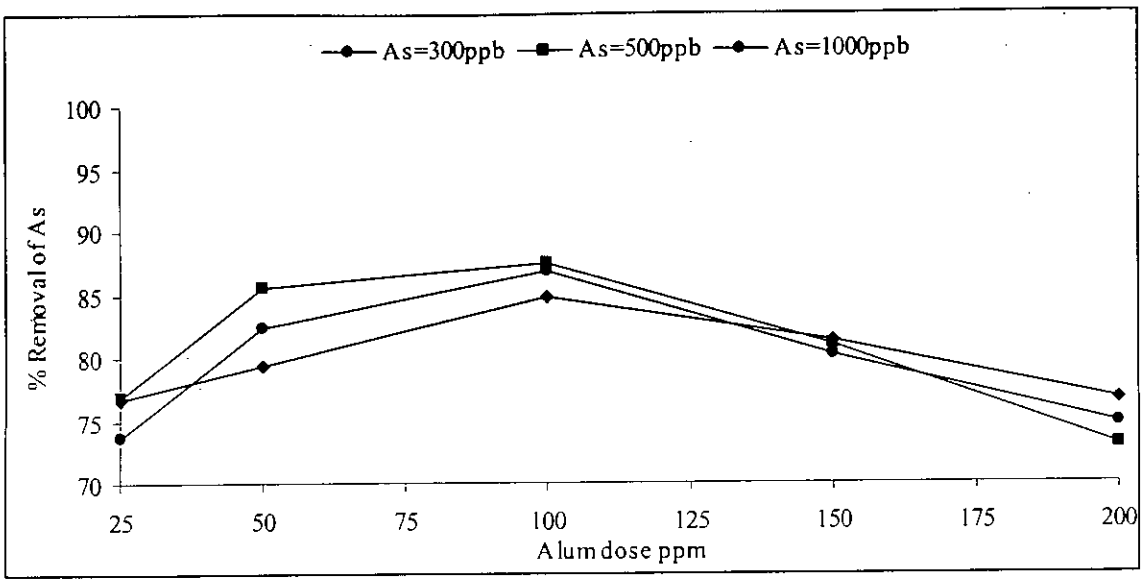

Figure 4.2 (c) Variation of As(V) removal with alum dose (little mixing)

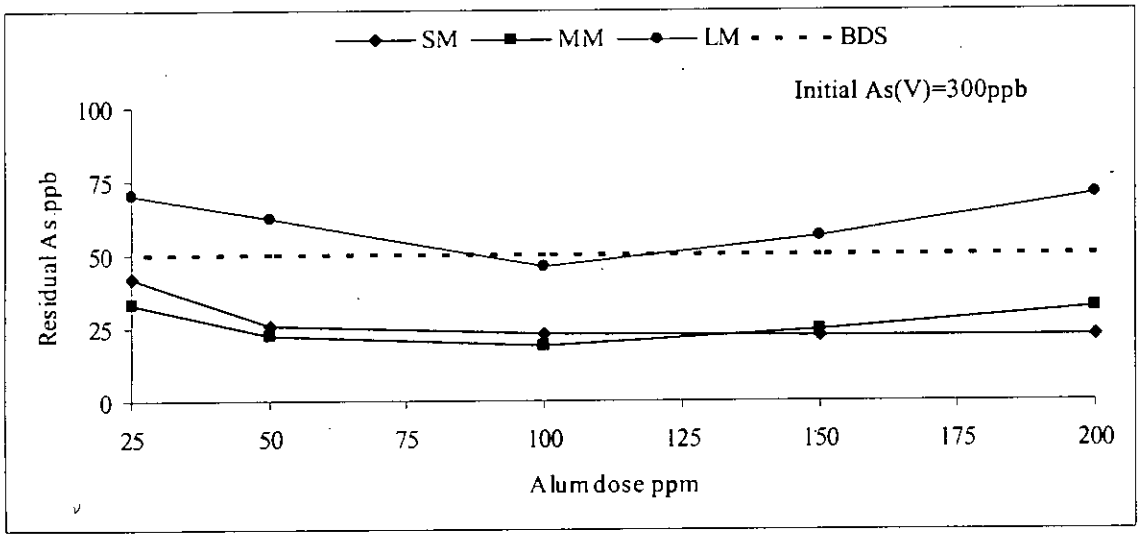

Figure 4.3 (a) Effect of mixing on residual As [As(V) = 300 ppb] (SM=Standard mixing, MM=Medium mixing & LM=Little mixing)

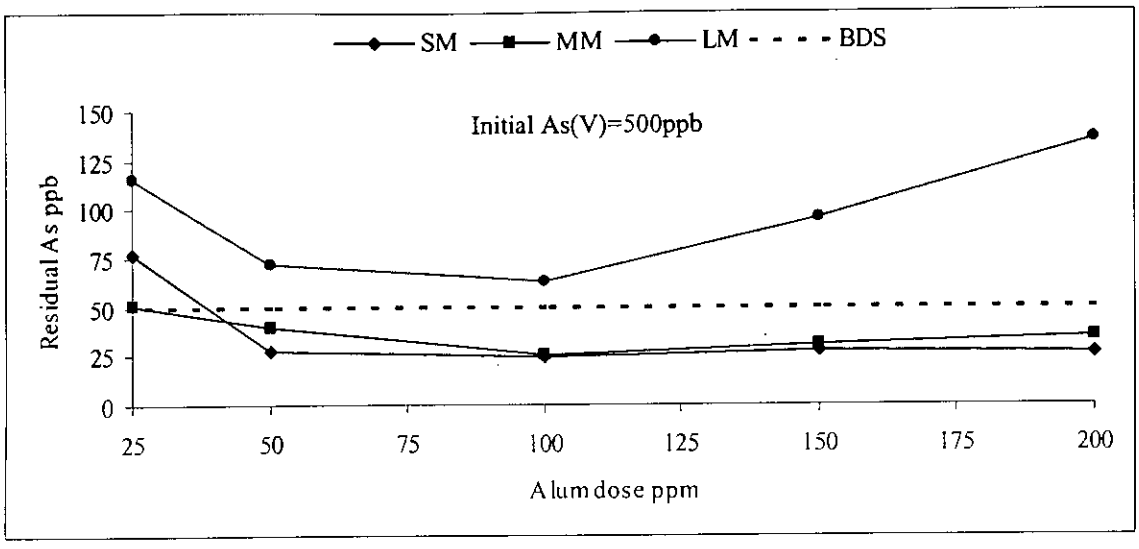

Figure 4.3 (b) Effect of mixing on residual As [As(V) = 500 ppb] (SM=Standard mixing, MM=Medium mixing & LM=Little mixing)

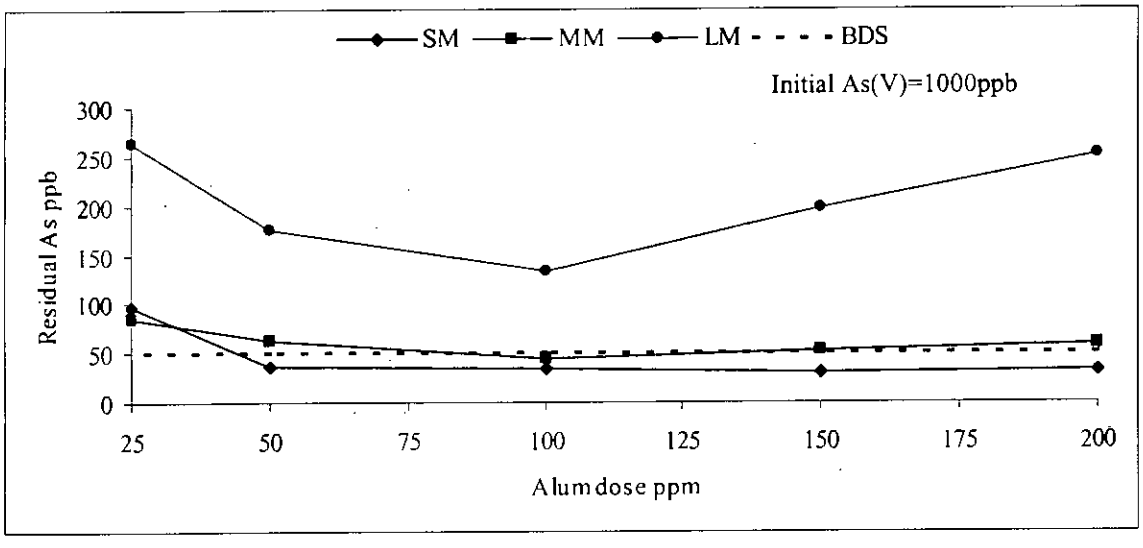

Figure 4.3 (c) Effect of mixing on residual As [As(V) = 1000 ppb] (SM=Standard mixing, MM=Medium mixing & LM=Little mixing)

4.4.3 Arsenic Removal as a Function of Sorbate / Sorbent Ratio

Fig. 4.4 (a) shows removal efficiency of As(V) as a function of sorbate/sorbent ratio (expressed as μg As/mg Al).From Fig. 4.4 (a) it appears that the removal efficiency decreases with the increase of sorbate/sorbent ratio and for sorbate/sorbent ratio of about 75 or less, removal efficiencies exceeding 91 percent can be achieved, irrespective of the

initial As(V) concentration. It is also seen that for sorbate/sorbent ratio of 150, removal efficiency exceeding 90 percent can be achieved for initial As(V) concentration of 1000 ppb. This result in effect gives the adsorption capacity of aluminium hydroxide flocs (formed upon coagulation with aluminium sulfate) at the optimum sorbate/sorbent ratio. In other words, this result suggests that at the optimum sorbate/sorbent ratio (which is 75), 1 ppm of aluminium (in the form of aluminium hydroxide flocs) can effectively remove about 75 ppb dissolved As(V). In an earlier research work (Chowdhury, 1999) obtained the optimum sorbate/sorbent ratio as 50 in case of ferric chloride coagulation.

Figure 4.4 (b) shows adsorption density (expressed as μg As / mg Al)) as a function of aluminium (added as aluminium sulfate) dose for three different As(V) concentrations. From Figure 4.4 (b), it is clear that higher adsorption is achieved with lower aluminium concentration (i.e., lower adsorption sites) and higher arsenic concentration. For a fixed arsenic concentration, as aluminium concentration increases adsorption density decreases. With increasing aluminium concentration, adsorption density is decreased because of the increasing number of adsorbent site. In other words, for a fixed aluminium concentration, when arsenic concentration is increased, adsorption density also increases.

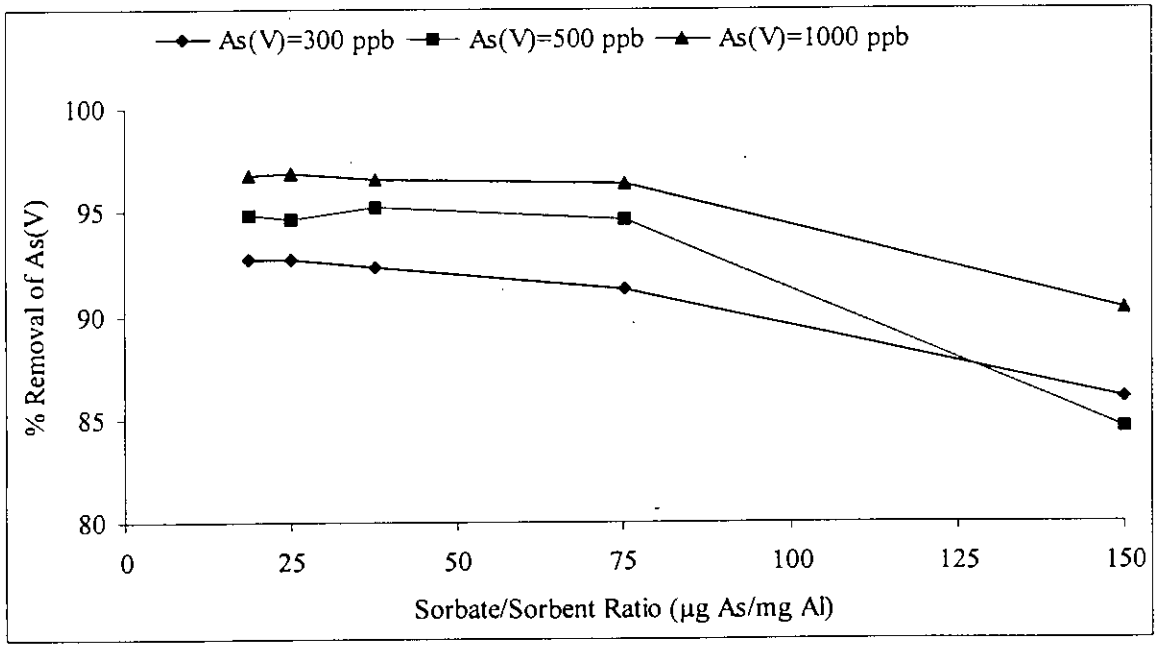

Figure 4.4 (a) Removal of As(V) as a function of Sorbate/Sorbent ratio for standard mixing

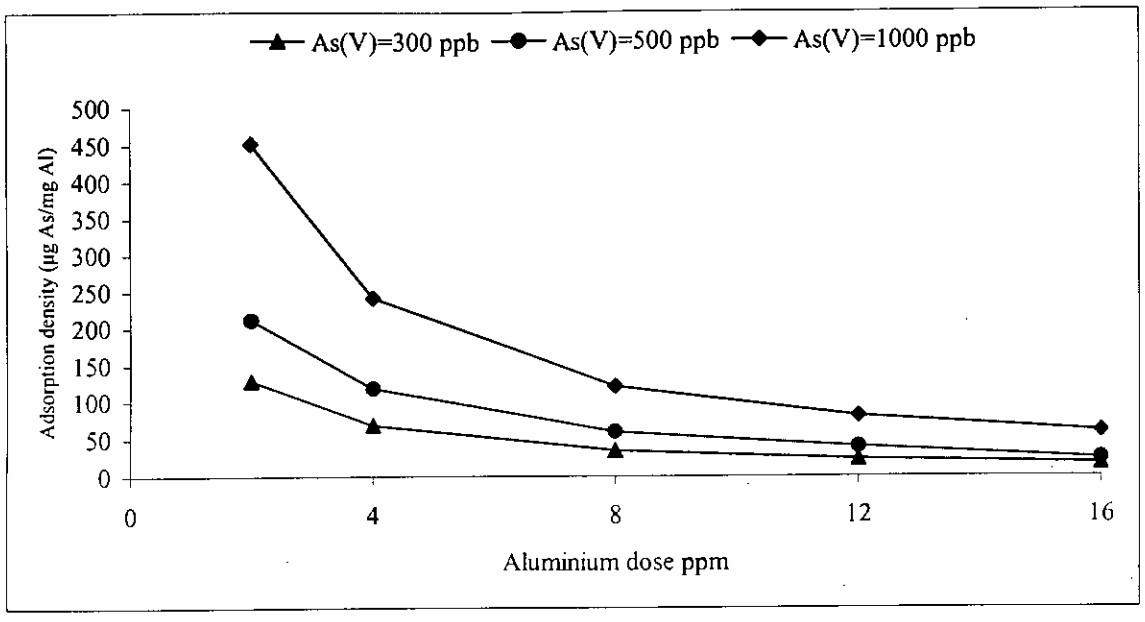

Figure 4.4 (b) Calculated adsorption density as a function of aluminium dose for three different initial As(V) concentration for standard mixing

4.4.4 Effects of Source Water Composition

The effect of pH on arsenic removal by alum is very significant. The pH alkalinity hardness, cations and anion of field water may affect the arsenic removal efficiency of an alum arsenic removal unit. The cations may compete for surface binding onto oxide surfaces and influence the adsorption of arsenate. The effects of anions are very important in arsenic removal by alum. The anions effects are also attributed to the competition of the anions with arsenate for aluminum hydroxide sorption sites. The phosphate, which has the high affinity for metal oxides is most likely to compete with arsenic.

The ground water compositions vary widely in Bangladesh. Table 4.3 shows the water quality parameters used in the parametric study of arsenic removal. The name of the salts used to vary concentration of a particular constituent is also shown. The following sub-sections describe effects of pH, alkalinity, hardness, Iron, chloride, sulfate, phosphate, nitrate and silicate on arsenic removal by alum.

4.4.4.1 Effect of pH

The effect of pH on arsenic removal by alum is shown in Fig. 4.5 for feed water arsenic concentration of 300 ppb and alum doses of 50 ppm and 100 ppm. PH was varied from 5 to 8 it appears that as the pH is increased, the residual arsenic increased and the rate of increase was higher for 50 ppm alum dose. When the alum is added to water, it immediately dissociates to aluminium and sulfate ions. The aluminium ion immediately starts reacting with water to form large aluminium complexes depending on the pH value of water. These aluminium complexes adsorb As(V) species. The distribution of As(V) species also depends on pH. It is likely that at higher pH, the adsorption is reduced by competition from hydroxyl ions. It appears that due to these reasons, the arsenic removal efficiency decreased with the increase of pH value of feed water. (Sorg and Logsdon (1978) demonstrated that arsenic removal with alum coagulation is most effective at pH 5 to 7. Edwards (1994) summarized that at significant coagulant dosages, As(V) removal was similar for both alum and ferric coagulants at pH 7.6 or lower.)

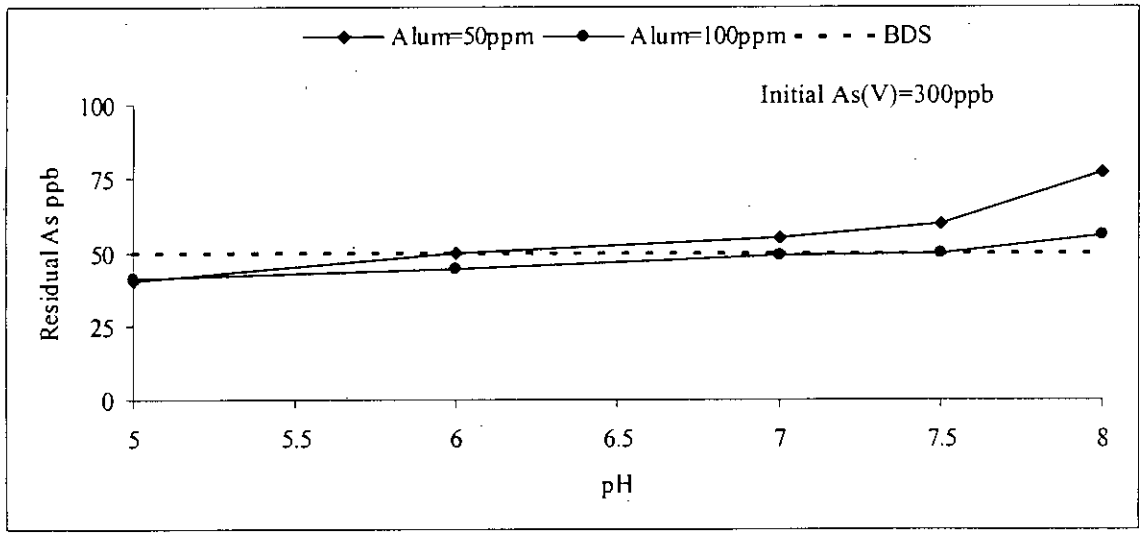

Figure 4.5 Effect of pH on As(V) removal

4.4.4.2 Effect of Alkalinity

Alkalinity of the feed water was varied from 100 ppm to 500 ppm by adding $NaHCO_3$ as required. The effect of alkalinity on arsenic removal is presented in Fig. 4.6. It is observed that the residual arsenic increase with the increase of alkalinity and the rate of increase is higher for 50 ppb alum dose compared to that for 100 ppm. When the alkalinity is high, it acts as a buffer to stop decrease the pH of water due to addition of alum to water HCO_3^- as competing ions with As ions. Since As(V) is removed better at lower pH, the higher the alkalinity, the higher the residual arsenic was obtained. Higher dose of alum increased the amount of aluminium flocs produced resulting in greater adsorption of As(V). Hence the role of alkalinity became insignificant at higher alum dose and for alum dose of 100 ppm arsenic-safe effluent was obtained for feed water arsenic concentration of 300 ppb, irrespective of the feed water alkalinity concentration.

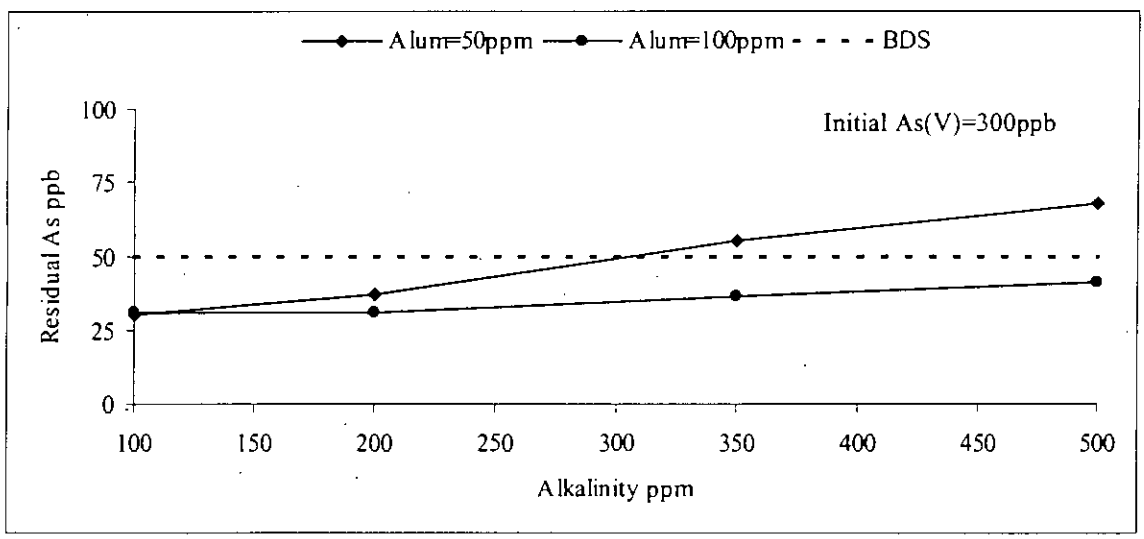

Figure 4.6 Effect of alkalinity on As(V) removal

4.4.4.3 Effect of Iron

Figure 4.7 presents the effect of iron on arsenic removal by alum. It appears that the residual arsenic slowly increased with the increase of iron dose and then decreased with further increase of the iron dose. The arsenic removal efficiency was the lowest corresponding to 10 ppm iron dose. The Fig. 4.7 also shows that the alum dose of 50 ppm was more effective than alum dose 100 ppm in the presence iron. In this study $FeCl_3$ was used as the source of iron. Ferric iron is also used as a very effective coagulant for arsenic removal.

Addition of ferric chloride to water may result in a drop of pH of the water, especially for groundwater with low alkalinity (i.e., low buffer capacity). Also, the addition of alum to water drops pH of the water. Possible greater solubility of amorphous iron (III) at lower pH values may result in lower removal efficiency. Hence lower efficiency for higher alum dose was observed. Since very high amount of iron produces large quantity of flocs, the arsenic removal efficiency is increased at higher iron dose.

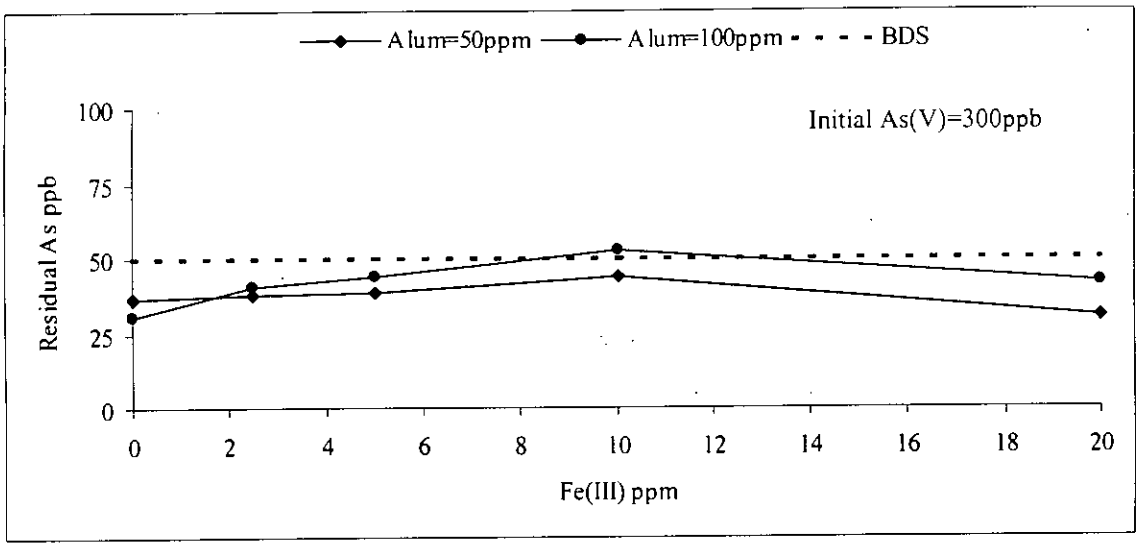

Figure 4.7 Effect of iron on As(V) removal

4.4.4.4 Effect of Hardness

Figure 4.8 shows the effect of hardness on arsenic removal efficiency by alum. It appears that, hardness has not any significant effect on arsenic removal. Alum dose 100 ppm is more effective than 50 ppm when hardness is zero, the residual arsenic 20 ppb and 34 ppb respectively. But for hardness varying from 100 ppm to 600 ppm (as $CaCO_3$), no significant effect on arsenic removal was observed for both alum doses of 50 ppm and 100 ppm.

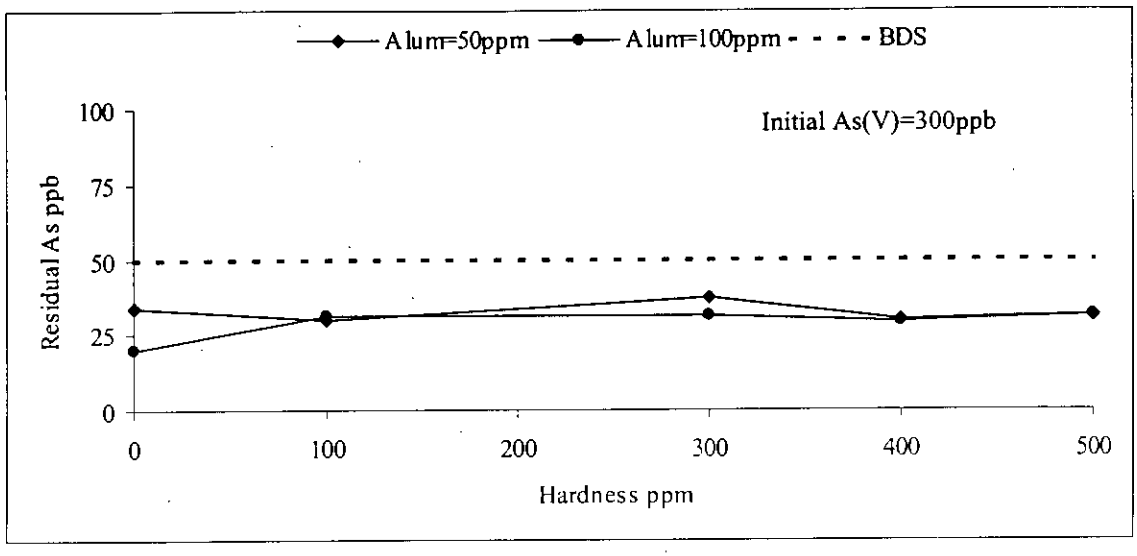

Figure 4.8 Effect of hardness on As(V) removal

4.4.4.5 Effect of Chloride

Figure 4.9 shows the influence of chloride on As(V) removal by alum. It is seen that chloride has no effect upto 400 ppm of chloride. At higher concentrations, the removal efficiency decreases with the increase of chloride concentration. The residual arsenic concentration was below of 50 ppb upto chloride concentration of 600 ppm.

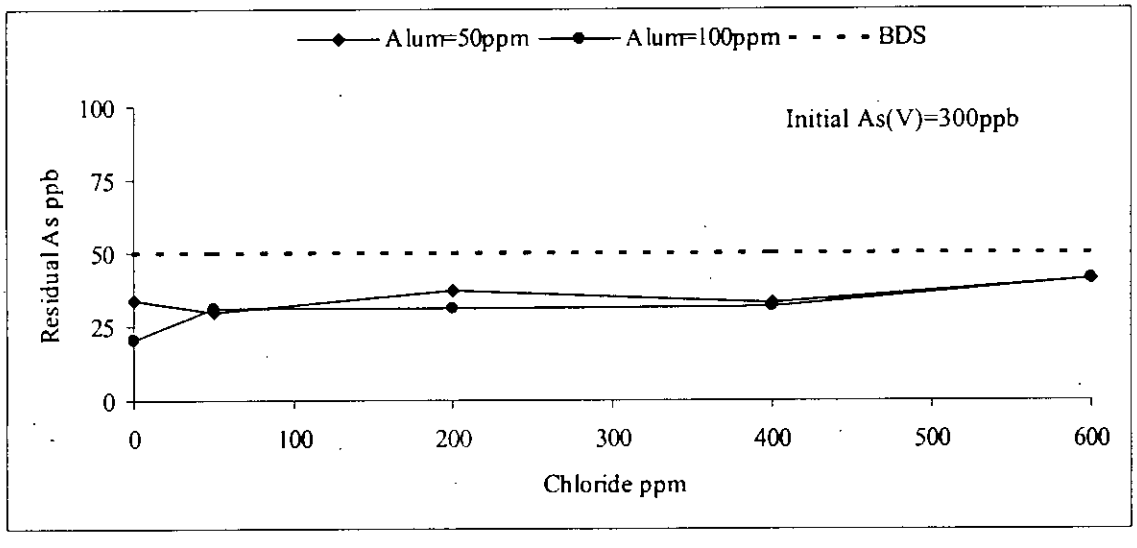

Figure 4.9 Effect of chloride on As(V) removal

4.4.4.6 Effect of Sulfate

Figure 4.10 shows the influence of sulfate on As(V) removal by alum. It is seen that sulfate has no significant effect upto 100 ppm of sulfate. The residual arsenic concentration is below the Bangladesh standard for sulfate concentration up to (100 ppm + 43 ppm = 143 ppm) 143 ppm for alum dose of 100 ppm, where the As(V) concentration is 300 ppb. It appears that increasing the sulfate dose no significant effect on arsenic removal. The residual arsenic concentration slowly increases with increasing sulfate content of the source water. It is likely that sulfate ions compete for adsorption site onto aluminum flocs. Meng and Korfiatis (2001) also reported that little effect of sulfate on arsenate removal.

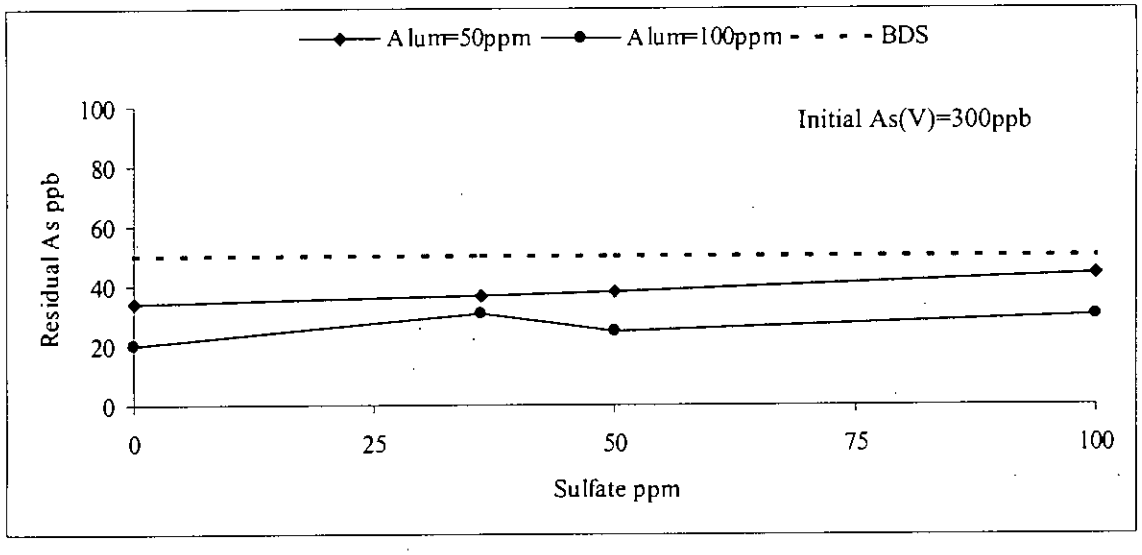

Figure 4.10 Effect of sulfate on As(V) removal

4.4.4.7 Effect of Phosphate

Figure 4.11 Shows the influence of phosphate on removal of As(V) by alum. It is clear that the residual arsenic increases with increasing phosphate concentration and the rate of increase is dependent on alum dose. The higher the alum dose, the lower is the residual arsenic concentration. The residual arsenic concentration is below the Bangladesh standard for phosphate concentration up to 7.5 ppm for alum dose 100 ppm, where the As(V) concentration is 300 ppb. But for alum dose of 50 ppm, the corresponding limit of phosphate concentration is only about 1.25 ppm. The affinity of phosphate for sorption site of $Al(OH)_3$ is grater than arsenic. The effects of certain anion are very important in

arsenic removal by coagulation. Anions compete with arsenic for sorptive sites and lower the removal rates. Manning and Goldberg (1996) indicated the theoretical affinity at neutral pH for anions sorption on metal oxides as:

$$PO_4 > SeO_3 > AsO_4 > AsO_3 >> SiO_4 > SO_2 > F$$

PO_4 has the highest affinity for metal oxides and is most likely to compete with arsenic for adsorption sites. The presence of more than one anion can have synergistic effect on arsenic removal.

The effect of phosphate on As(V) removal observed in this study are much more significant than those observed by Hering et al. (1996) and McNeill and Edwards (1997) using ferric chloride as coagulant. The primary reason for this is the fact that both Hering et al. (1996) and McNeill and Edwards (1997) used very low concentration of phosphate (0.076 ppm and 0.032 ppm respectively); while phosphate concentration used in this study ranged from 1.0 to 20.0 ppm. Relatively high concentrations of phosphate, reaching as high as 22.47 ppm, have been found in some places of Bangladesh (BAMWSP/DFID/Water Aid Bangladesh, 2001) and that was the main reason behind using higher concentration of phosphate in this study. Nibedita (1999) obtained dramatic effect of phosphate on As(V) removal efficiency for ferric chloride coagulation.

Results from this study suggest that in determining alum doses for arsenic removal, due concentration should be given to the phosphate concentration of the raw water. Alum dose determined from laboratory batch studies without the presence of phosphate can significantly underestimate the actual dose requirement.

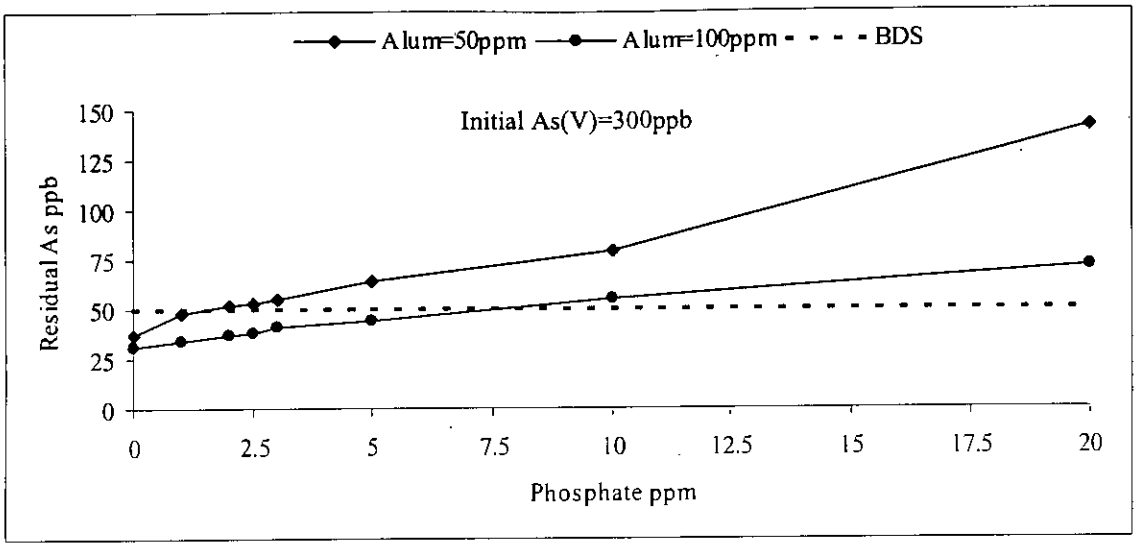

Figure 4.11 Effect of phosphate on As(V) removal

4.4.4.8 Effect of Nitrate

Figure 4.12 shows the effect of nitrate on arsenic removal by alum. It appears that the residual arsenic varies significantly with nitrate and the maximum residual arsenic is at 10 ppm of nitrate. It is also seen that the effect of nitrate is more significant in case of alum dose of 100 ppm than alum dose of 50 ppm. In deionized water removal efficiency was over 93 percent but in the groundwater (Environmental laboratory water, BUET, nitrate concentration 5.3 ppm) removal efficiency was 88 percent. In this study, $Ni(NO_3)_2$ $6H_2O$ was used for variation of nitrate anion. Co-occurring inorganic solutes may compete for surface binding sites onto oxide surfaces and influence the adsorption of trace contaminants, such as arsenic. In presence of phosphate and one or more anion may have grater effect on arsenic removal by coagulation process.

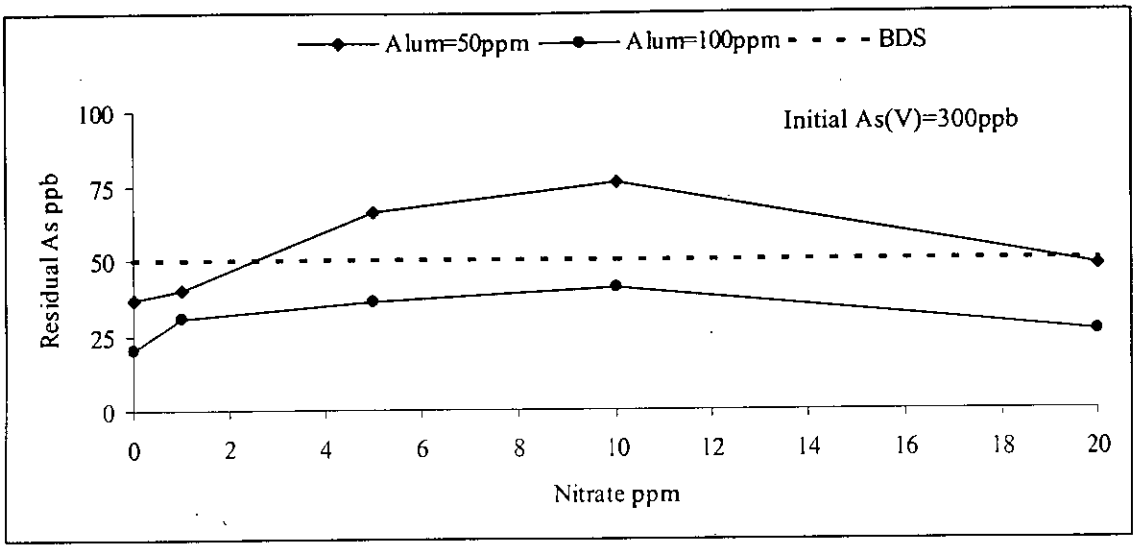

Figure 4.12 Effect of nitrate on As(V) removal

4.4.4.9 Effect of Silicate

Fig. 4.13 presents the influence of silicate on As(V) removal by alum. It is seen that the residual arsenic increases slowly with silicate up to 50 ppm of silicate and then the residual arsenic increases at increasingly higher rate with the increase of silicate concentration. In this study alum dose of 100 ppm was better than 50 ppm in removing As(V). Residual arsenic was below Bangladesh standard for silicate concentration up to 75 ppm when alum dose was 100 ppm. Alum dose 50 ppm reduced the safe limit of silicate concentration to 60 ppm. In deionized water arsenic removal efficiency was grater than 93%. The affinity of silicate is lower than the arsenic and hence the effect at lower concentration of silicate was not very significant in removing As(V).

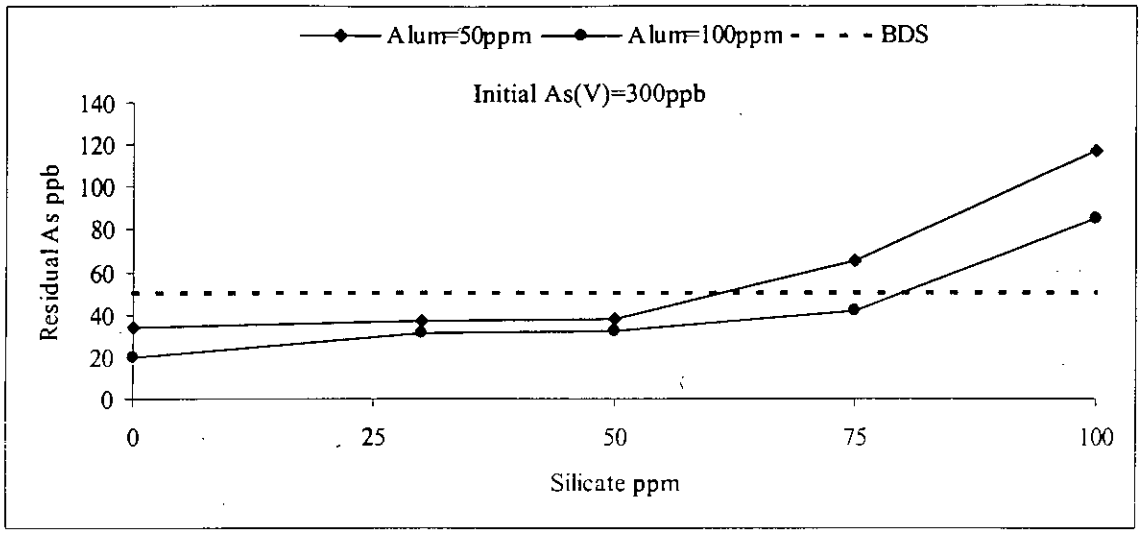

Figure 4.13 Effect of silicate on As(V) removal

4.5 Synergistic Effect of Ions on Arsenic Removal

The simultaneous effect of a number of ions present concurrently in water on arsenic removal is depicted in Figs. 4.14 (a) and 4.14 (b). Both the Figures show that the residual arsenic increases with the increase of ions concentrations. In presence of iron [Fig. 4.14 (a)], the arsenic removal was higher than that without iron. So it appear anions have synergistic effect on the arsenic removal efficiency by alum. Figure 4.14 (b) shows the synergistic effect for different initial arsenic concentrations. It is clear that even for 100 ppb of As(V), alum dose of 100 ppm could not bring the residual arsenic concentration below 50 ppb in the presence of medium and high anions concentrations. The presence of more than one anion can have synergistic effect on arsenic removal (Meng et al., 2000). Meng and Korfiatis (2001) reported that elevated levels of phosphate and silicate in Bangladesh well water dramatically decreased the adsorption of arsenic by ferric hydroxides. From Fig. 4.14 (b), it is clear that the synergistic effect of anions is very significant.

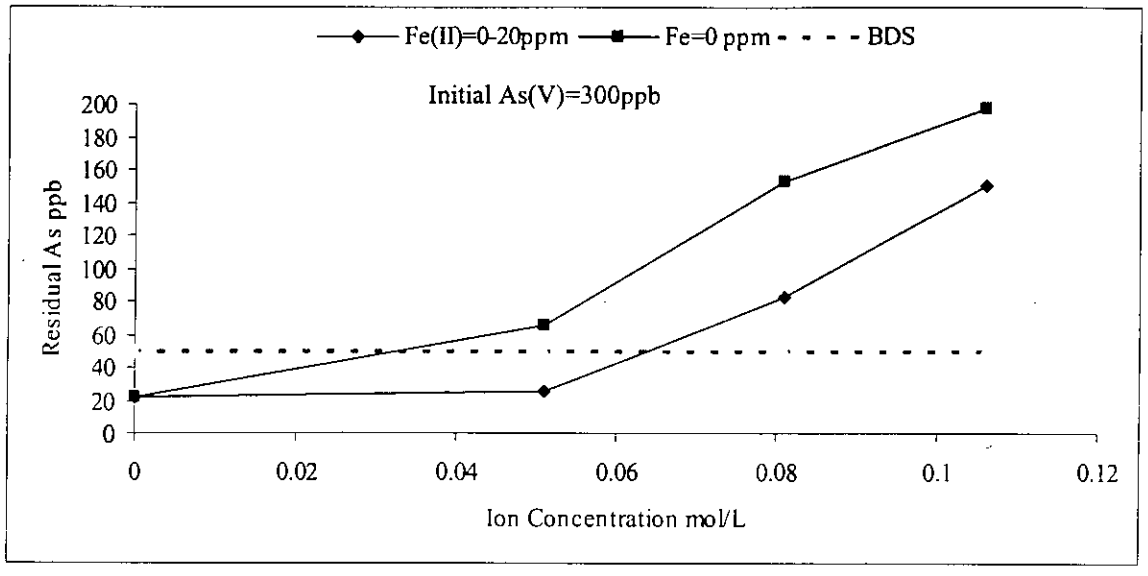

Figure 4.14 (a) Synergistic effect of ion on As(V) removal, arsenic concentration 300 ppb (Alum=100 ppm, standard mixing and proper washing, 0=Distilled)

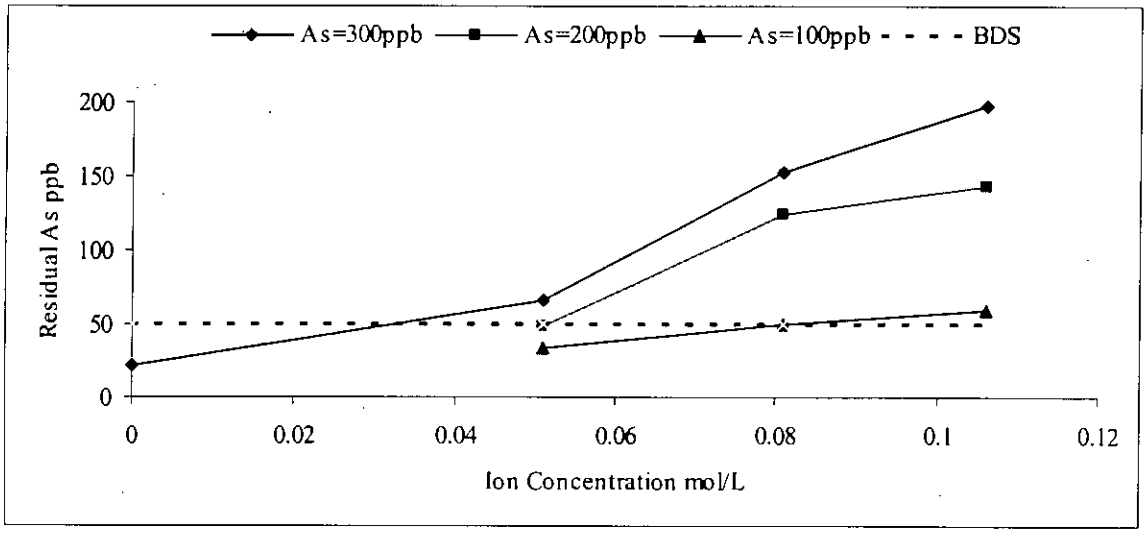

Figure 4.14 (b) Synergistic effect on As(V) removal, arsenic concentration 100 to 300 ppb (Alum=100 ppm, standard mixing and proper washing, 0=Distilled)

4.6 Effect of Potassium Permanganate Dose on Residual Color

The effect of permanganate dose on the color of water is presented in Fig. 4.15. It is seen that both the color of the raw and treated water increased with higher dose of potassium permanganate but lower color values were obtained in the presence of Fe(II). When the potassium permanganate dose was 2 ppm, residual color satisfied the Bangladesh standard (15 Pt-Co unit) in the presence of 1 ppm Fe(II). But in the absence of Fe(II), the residual color value exceed the Bangladesh standard. Potassium permanganate oxidizes both As(III) and Fe(II), hence in the presence of Fe(II), lower residual color values weres obtained.

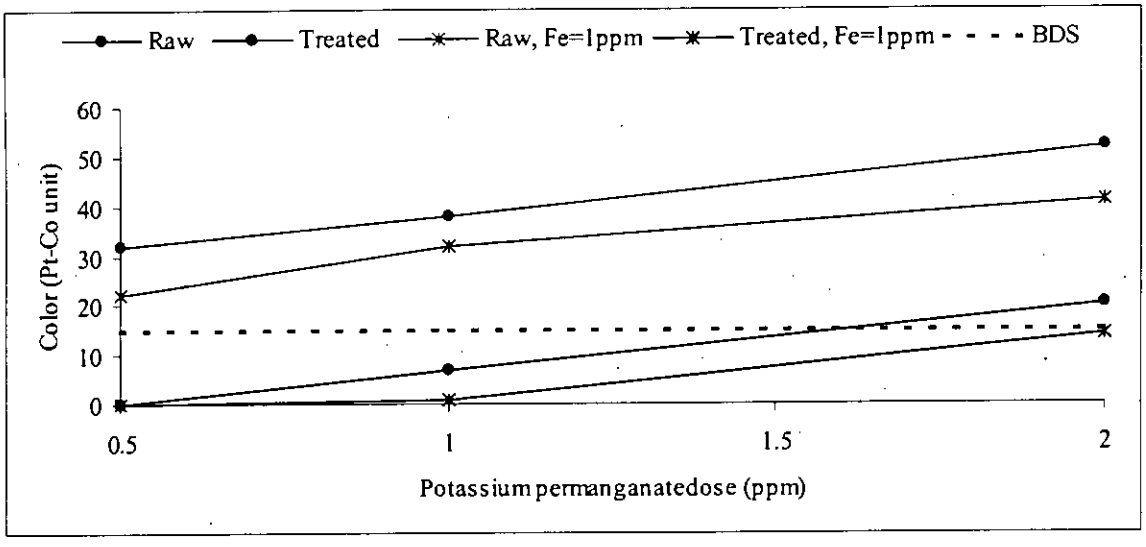

Figure 4.15 Color effect of raw & treated water on Fe(II) and $KMnO_4$ (Alum=100ppm, As(V)=300 ppb, Fe=1 ppm, Standard mixing and Proper washing)

4.7 Effect of Filter Bed on Arsenic Removal

The effect of sand filter on arsenic removal by alum is presented in Table 4.11. From the Table, it is seen that a major portion (61% - 90%) of the raw water arsenic was removed by coprecipitation-sedimentation in the upper bucket of the treatment unit. The sand filter of the lower bucket removed 5% - 32% of the raw of arsenic. In the upper bucket, due to coprecipitation-adsorption-flocculation, large alum flocs were formed and settled easily and substantial removal of arsenic was achieved. But macro-flocs could not be settled and these were removed in the filter bed. Since the amount of macro and micro-

flocs varied significantly with the applied alum dose, the removal by coprecipitation-adsorption-flocculation-sedimentation and filtration varied greatly. The higher the alum dose, the greater was the amount of floc formation resulting in higher removal efficiency in the upper bucket of the treatment unit. Sand filter was more effective in arsenic removal for lower dose of alum.

The variations of residual arsenic concentrations of the effluent of the upper bucket with alum dose are depicted in Fig. 4.16. It is clear from the Figure that although the residuals decreased with the increase of alum dose, without sand filtration, the treated water did not satisfy the Bangladesh standard for arsenic for most of the cases. But in association with sand filter, excellent arsenic removal was obtained for all the cases (Table 4.11). Hence sand filtration is a must for reliable performance of alum based arsenic removal unit.

Table 4.11 As(V) Removal due to Precipitation and Filtration.

Raw As(V) ppb	Alum ppm	Residual As (final) ppb	Total Removal	Residual As (after coprecipitation-sedimentation) ppb	Removal by coprecipitation - sedimentation	Removal by Filtration
300	200	29	90%	44	85%	5%
500		32	93%	70	86%	7%
1000		44	96%	100	90%	6%
300	150	22	93%	45	85%	8%
500		27	94%	69	86%	8%
1000		41	96%	145	86%	10%
300	100	22	93%	81	73%	20%
500		24	95%	141	72%	23%
1000		34	97%	272	73%	24%
300	050	20	93%	117	61%	32%
500		26	95%	154	69%	26%
1000		35	96%	328	67%	29%

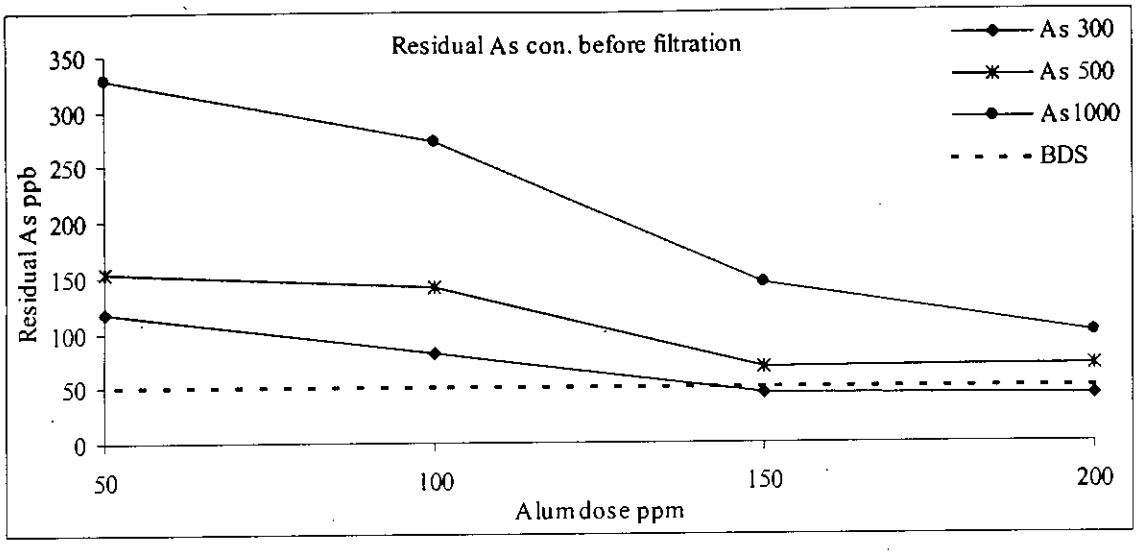

Figure 4.16 Variations of As(V) removal due to coprecipitation-adsorption-flocculation-sedimentation with alum dose.

4.8 Permanganate Dose Requirement

It is well known that As(III) is poorly removed by alum coagulation. As(III) is to be oxidized to As(V) for efficient removal of arsenic by alum. Potassium permanganate was tried for this oxidation. But the presence of iron and phosphate in raw water affects the removal efficiency. The variation of residual arsenic with potassium permanganate dose for raw water As(III) concentration of 300 ppb is shown in Fig. 4.17. It is seen that the residual arsenic decreases slowly with the increase of permanganate dose but lower arsenic removal efficiency was obtained in presence of 1 ppm Fe(II). In the absence of Fe(II), the applied permanganate dose was used to oxidize As(III) to As(V) and hence better removal was achieved. In the presence of Fe(II), potassium permanganate oxidized both Fe(II) and As(III), resulting in lower arsenic removal efficiency by alum coagulation. Stoichiometrically, 0.844 ppm potassium permanganate is required to oxidize 300 ppb As(III) to As(V) and 0.944 ppm potassium permanganate is required to oxidize 1 ppm Fe(II) to Fe(III) (see appendix B.12). Hence at least 1.788 ppm potassium permanganate is required for effective removal of arsenic when the raw water arsenic concentration is 300 ppb and Fe(II) concentration is 1 ppm. From Fig. 4.17, it is seen that potassium permanganate dose requirement was 1 ppm to bring the residual arsenic to 50 ppb corresponding to these arsenic and iron concentration of the raw water.

For raw water containing 350 ppb As(III) and 5 ppm Fe(II), the variation of residual arsenic with alum dose is depicted in Fig. 4.18 (a). From the Figure, it is seen that over 1.5 ppm permanganate dose was required to satisfy the Bangladesh standard for arsenic. Hence it can be concluded that higher dose of permanganate is required for treating water containing higher amount of As(III) and Fe(II).

For a particular dosing combination (Alum=100 ppm and $KmnO_4$=1.0 ppm) and in presence of 3 ppm phosphate and 350 ppb As(III) in the raw water, the variation of residual arsenic with Fe(II) dose is presented in Fig. 4.18 (b). It is clear that the residual arsenic increases significantly with increasing Fe(II) dose and when the Fe(II) dose exceeded about 2 ppm, the treated water could not satisfy the Bangladesh standard for arsenic. When Fe(II) concentration was increased, the applied permanganate was mainly used for oxidation of Fe(II). The oxidation of As(III) was poor resulting in lower arsenic removal efficiency. Hence the presence of high amount of Fe(II) in water can significantly reduce the arsenic removal efficiency of the ARU.

Fig. 4.19 show the effect of Fe(II) on residual arsenic in absence and in presence of phosphate in the raw water, respectively. From the Figures, it is clear that when phosphate is absent, the residual arsenic decreases with Fe(II) dose. Fe(II) acted as coagulant and hence higher dose resulted in higher removal but could not bring the residual arsenic below 50 ppb for raw water containing 300 ppb arsenic even at Fe(II) dose of 20 ppm.

Table 4.12 presents the effect of arsenic species on arsenic removal by alum in presence of medium iron and phosphate concentrations (5.0 ppm and 3.0 ppm respectively) when the applied permanganate dose is 1.0 ppm. This Table also presents the result when no permanganate was added. When 100% arsenic existed as As(III), 72% arsenic was removed in the absence of the oxidant. But at the permanganate dose of 1.0 ppm, the combinations of As(III) and As(V) had little effect and the removal efficiency varied from 82.6% to 86.3%, the higher efficiency was corresponding to the higher proportion of As(V). A portion of Fe(II) was oxidized and formed iron flocs and ferric phosphate precipitates enhancing the arsenic removal efficiency, Hence at medium iron and phosphate concentrations, arsenic removal efficiency varies a little with the forms of arsenic in the presence of a oxidant.

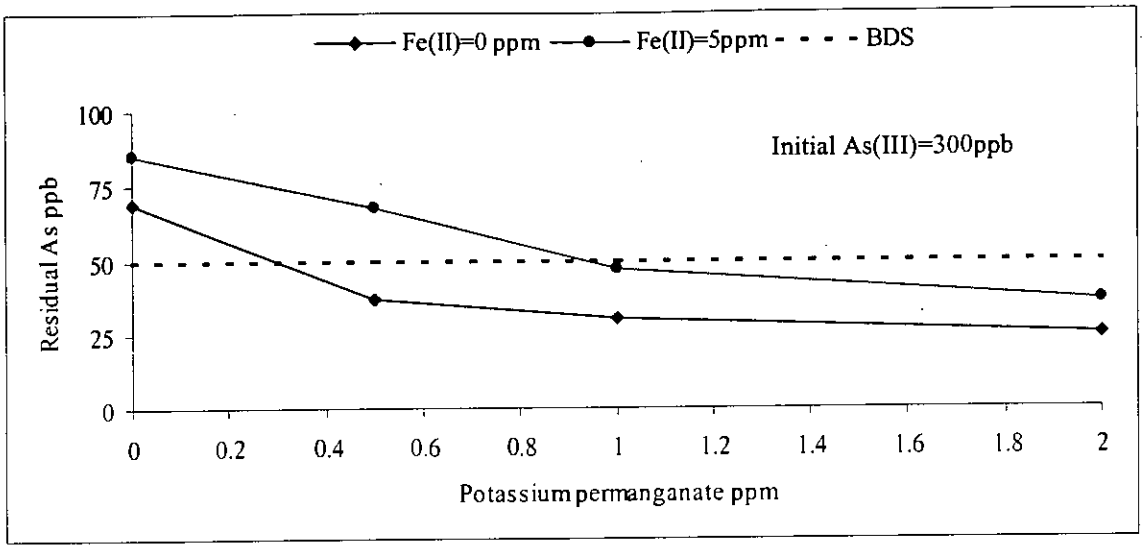

Figure 4.17 Effect of $KMnO_4$ on As(III) removal (Alum=100 ppm, As(III)=300 ppb and Fe(II)=1 ppm, Standard mixing and Proper washing)

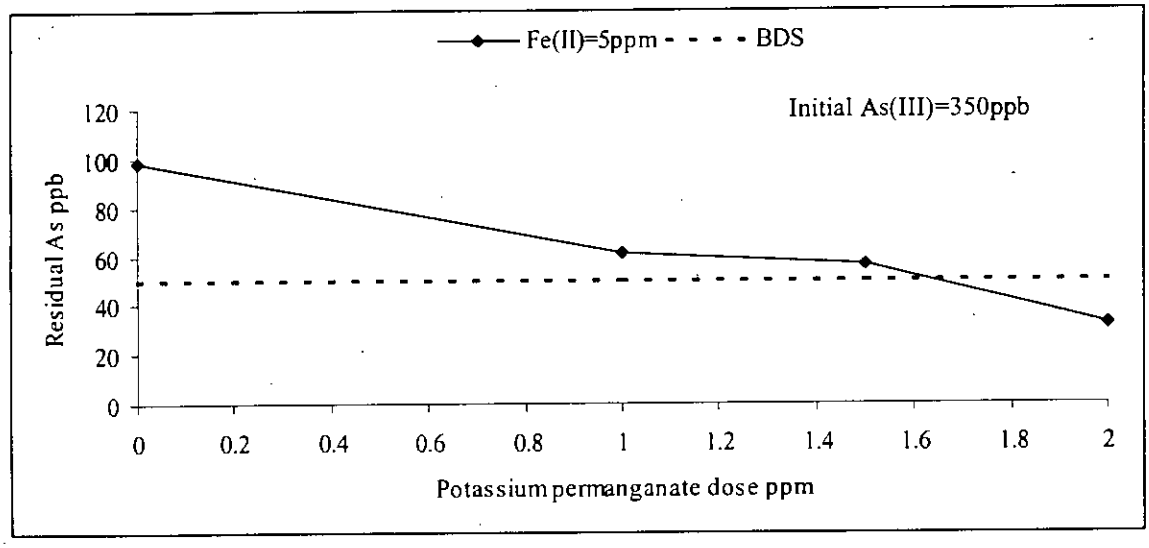

Figure 4.18 (a) Effect of $KMnO_4$ on As(III) removal in presence of Fe(II) (Alum=100 ppm, As(III)=350 ppb, Fe(II)=5 ppm and Phosphate=3 ppm, Standard mixing and Proper washing)

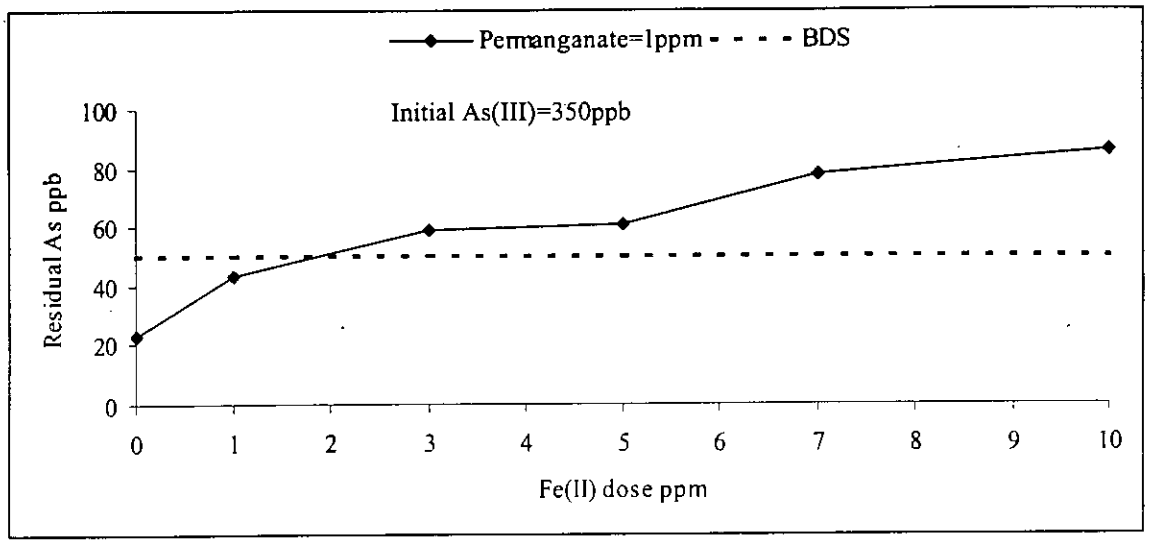

Figure 4.18 (b) Effect of Fe(II) on As(III) removal for particular dose of $KMnO_4$ (Alum=100 ppm, As(III)=350 ppb, $KMnO_4$=1 ppm & Phosphate=3 ppm, Standard mixing and Proper washing)

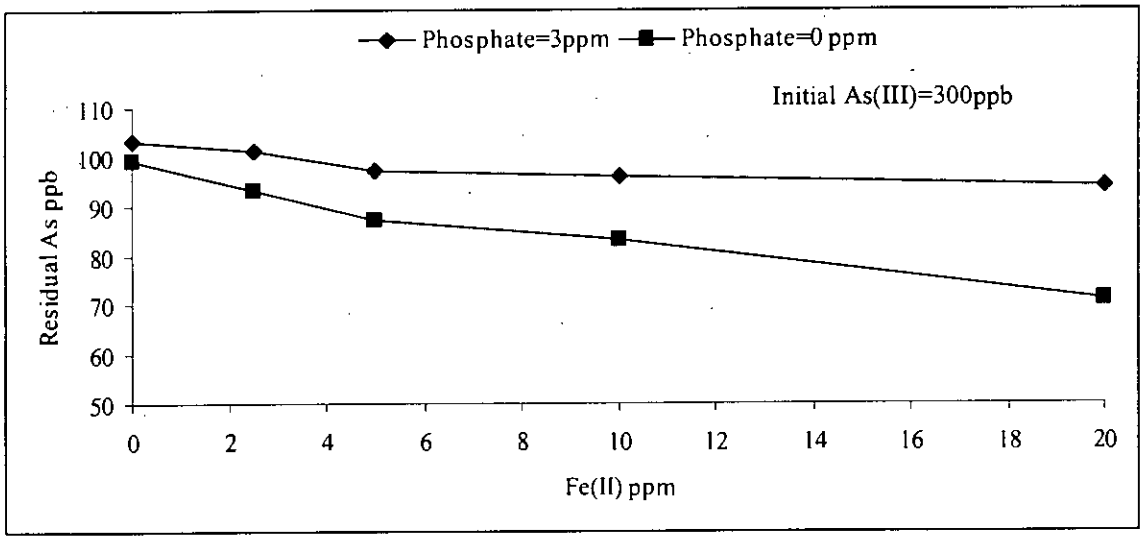

Figure 4.19 Effect of Fe(II) on As(III) removal without potassium permanganate (Alum=100 ppm, As(III)=300 ppb, Standard mixing and Proper washing)

Table 4.12 Arsenic removal on different concentration As(V) and As(III) with Fe(II) and phosphate

As Total ppb	As(V)	As(III)	Fe(II) ppm	PO_4 ppm	$KMnO_4$ ppm	Residual As ppb	% Removal
350	0%	100%	5.0	3.0	0.0	98	72%
	71%	29%	5.0	3.0	1.0	48	86.3%
	57%	43%	5.0	3.0	1.0	52	85.1%
	50%	50%	5.0	3.0	1.0	50	85.7%
	43%	57%	5.0	3.0	1.0	58	83.4%
	29%	71%	5.0	3.0	1.0	60	82.9%
	0%	100%	5.0	3.0	1.0	60	82.6%

4.9 Effect of Settling Time

The effect of settling time on arsenic removal efficiency is shown in Figs. 4.20 (a) and 4.20 (b). It appears that the removal efficiency increases with increasing settling time but the rate varies with time. Fig. 4.20 (a) shows that upto 60 minutes settling, the residual arsenic decreases rapidly and then the rate slowly decreases. But the residual arsenic was not below the Bangladesh standard when initial arsenic concentration was 500 and 1000 ppb and alum dose was 50 ppm even for two hour settling time. For initial As(V) concentration of 300 ppb, residual arsenic was below the Bangladesh standard. For alum dose of 100 ppm better results were obtained. Fig. 4.20 (b) shows that using paper filter for initial arsenic concentration of 300 ppb, settling time of half an hour to one hour was enough to decrease the residual arsenic below the Bangladesh standard. The removal efficiency increased upto settling time of one and half hour, but the there was no significant effect on arsenic removal and alum dose of 100 ppm was more effective than 50 ppm.

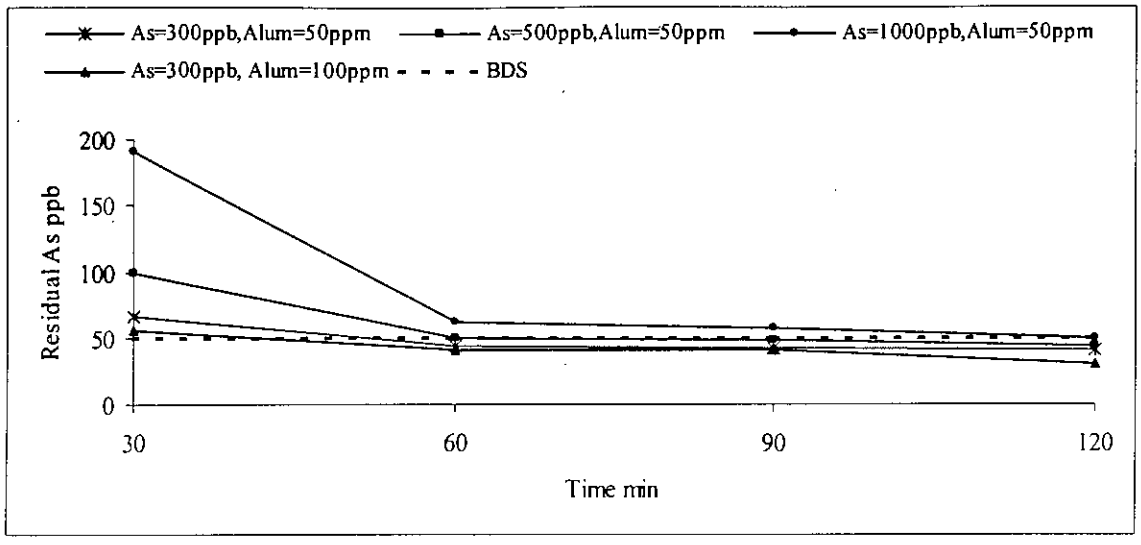

Figure 4.20 (a) Effect of Settling time on As(V) removal

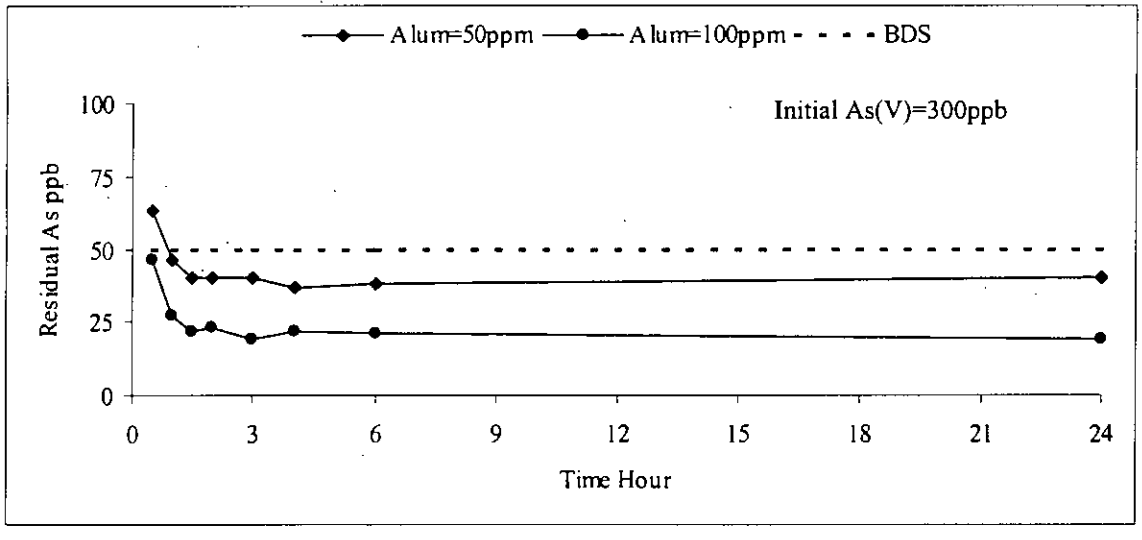

Figure 4.20 (b) Effect of Settling time on As(V) Removal [As(V) = 300 ppb]

4.10 Summary and Conclusions

Based on the laboratory results of the present study, the following conclusions can be drawn:

1. Natural sylhet sand contained 12.5 to 13.2 mg iron per gm of the sand. When it was used as filter sand in the alum based arsenic removal unit, the arsenic removal efficiency was greatly influenced by the arsenic adsorption capacity of the sand due to the iron content. No consistent result obtained until the adsorption capacity was exhausted.

2. A moderate mixing of the coagulant required for satisfactory performance of the arsenic removal units resulting from effective coagulation.

3. Optimum alum dose for As(V) removal was found to be 100 ppm and 88% - 97% As(V) was removed at this dose for initial arsenic concentrations of 300 ppb – 1000 ppb.

4. Removal of As(V) was found to decrease with the increase of sorbate/sorbent ratio. The optimum sorbate/sorbent ratio was 75 (expressed as μg As / mg Al). Adsorption density was also found to decrease with higher aluminium dose.

5. The effect of pH on removal was insignificant within the pH range 5 to 8. The As(V) removal efficiency decreased slowly with the increase of pH value.

6. The As(V) removal efficiency decreased slowly with higher alkalinity. The HCO_3^- as competing ions with As ions. Fe(III) reduced the As(V) removal efficiency slowly upto 10 ppm but at higher dosing, the efficiency slowly increased.

7. Hardness had no effect on As(V) removal efficiency and chloride decreased the efficiency only at concentrations grater than 400 ppm.

8. The As(V) removal efficiency decreased slowly with increase sulfate concentrations.

9. Phosphate had significant effect on As(V) removal efficiency, higher concentration of phosphate reduced the removal efficiency markedly.

10. Fe(II) increased slightly the As(III) removal efficiency. In the presence of constant dose of potassium permanganate and phosphate, Fe(II) reduced the As(III) removal efficiency significantly.

11. As(III) was relatively poor removed by alum coagulation (66%). In the presence of medium iron and phosphate concentrations (5.0 ppm and 3.0 ppm respectively) the removal efficiency varied little (83% - 86%) with the form of arsenic even at low permanganate dose (1.0 ppm).

12. The effect of nitrate on arsenic removal was significant at 10 ppm of nitrate. The residual arsenic increases slowly with silicate up to 50 ppm of silicate and then the residual arsenic increases at increasingly higher rate with the increase of silicate concentration.

13. Anions had significant synergistic effect on As(V) removal efficiency at medium (0.0816M) to high (0.1061M) concentrations.

14. Sand filtration was very effective to remove color and to bring down the As(V) concentrations below Bangladesh standard. Without it, reliable performance could not be guaranteed.

15. The required potassium permanganate dose for effective removal of As(III) depended on the concentration of Fe(II). Higher concentrations of Fe(II) required higher dose of potassium permanganate.

16. One hour settling time was found optimum for settling of aluminium flocs in the upper bucket of the arsenic removal unit.

CHAPTER 5

FIELD TESTING OF ALUM BASED HOUSEHOLD ARSENIC REMOVAL UNIT

5.1 Introduction

Based on the findings of the laboratory experiments described in chapter four which showed good arsenic removal by alum coagulation, it was decided to install household arsenic removal units (ARUs) in rural areas. These ARUs utilized alum coagulation and filtration processes. Natural groundwater may contain both arsenite and arsenate. So it was decided that potassium permanganate would be used as an oxidizing agent for oxidation of arsenite to arsenate for effective arsenic removal. This chapter describes the detailed design considerations of the household arsenic removal unit. It also describes the field testing of the ARUs in Basgaon and Basail Bhog villages of Srinagor thana of Munshigonj district and Echapara and Dolerbag villages of Sonargaon thana of Narayangonj district. On the basis of field test results, chemical dosing was also varied for three units during the field testing to obtains satisfactory performance of the units. In the light of the findings of the laboratory and field investigatons, the causes of poor performance of DPHE-Danida BTU were evaluated. Estimated cost of the ARU, including its operation and maintenance cost, has also been provided. This chapter also provides a detailed assessment of the performance of the arsenic removal unit in the field, including users' acceptance.

5.2 Design of Household ARU

5.2.1 Physical Design of the ARU

Three issues need to be considered in the design of the household arsenic removal unit. Firstly, it should be affordable to the poor people and the materials should be available in the local market. Secondly, it should efficiently remove arsenic and should also be safe with respect to other chemical and microbiological water quality parameters. Thirdly, the

design of the unit should be such that people, especially women in rural Bangladesh, can use and maintain it without any difficulty and that it should be replicated easily at the rural level. These issues were considered in the design of the household arsenic removal units (ARU) based on alum (aluminium sulfate) coagulation.

It was decided that the physical design of the arsenic removal unit would be similar to that developed at BUET for ferric chloride coagulation (Ali et al., 2001). The ARU to be designed would consist of two buckets, one placed over the other. Untreated tubewell water would be placed in the upper bucket. Chemicals (coagulant and oxidant) would be added to the groundwater in the top bucket, mixed and then allowed to flow to the lower bucket. In the lower bucket, it would flow through a sand filter and finally treated water would be collected from a tap connected to the bottom of the lower bucket. In the rural areas of Bangladesh women are generally responsible for fetching and storing water for drinking and cooking. Average height of the village women in Bangladesh is below 5 feet (152.4 cm). Therefore, the arsenic removal unit to be designed should be of such a height that average women could easily pour water and chemicals in the upper bucket and mix its contents. Beside, the collection point (i.e., tap) in the lower bucket should be high enough to have space for a pitcher or jug for collection of treated water for drinking and cooking. In view of the relatively small size of average rural household, the ARU should not occupy much space and should have an aesthetically pleasing appearance.

The average size of households in rural area of Bangladesh is 4.8 persons per family according to Bangladesh population census 2001 (BBS, 2001). Therefore, 40 liters of water should be sufficient to meet drinking and cooking demand of an average family (Ahmed and Rahman, 2000). It was decided that two 25-liter plastic buckets with lids would be used in the ARUs. About 20 liters of water would be placed in the upper bucket and design output (i.e., treated water) per batch of the unit was taken to be 17 liters. Thus, each unit would require three runs per day for an average family in the rural area of Bangladesh. Larger buckets were selected to provide a dead volume at the bottom for sludge to settle as well as some freeboard at the top to prevent water spilling off the bucket during stirring.

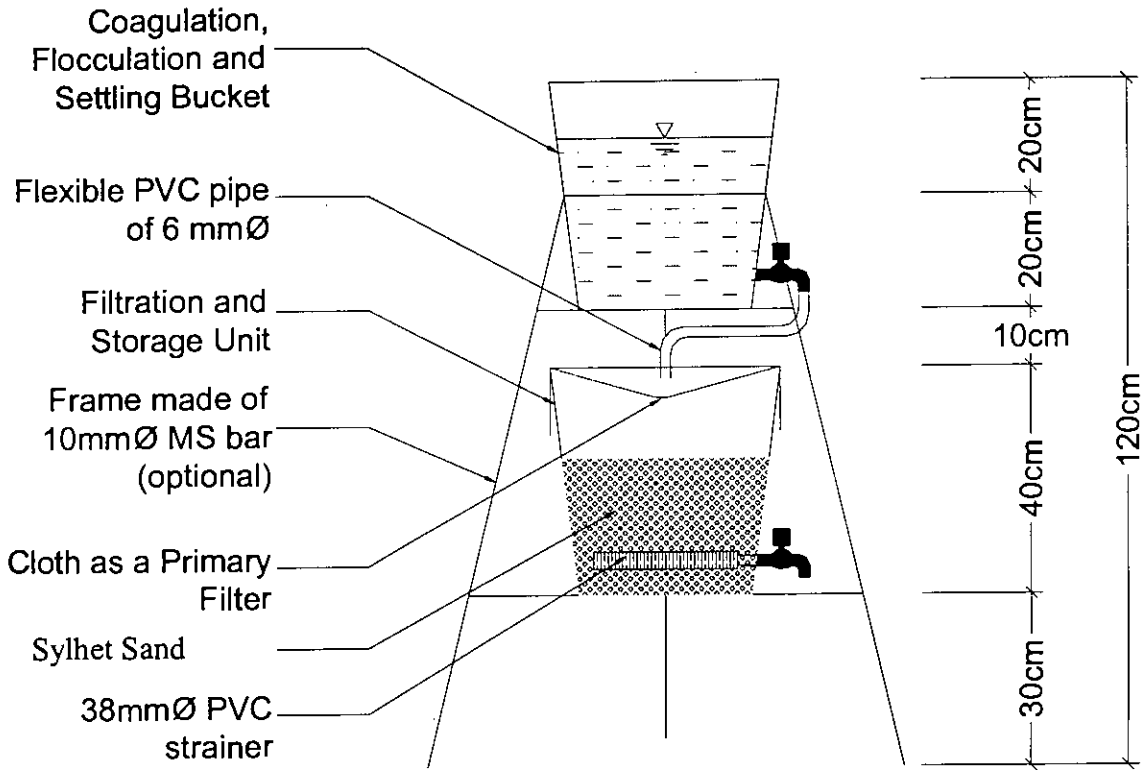

Figure 5.1: Arsenic removal unit based on alum

Figure 5.1 shows a schematic representation of the designed arsenic removal unit. The upper bucket of ARU can be called as the coagulation-flocculation-settling unit. In this bucket a filling mark is provided to indicate 20 liters volume. A plastic tap (bibcock) placed 4 cm from the bottom provides approximately a 2.5-litre dead volume for accumulation of settled sludge. A flexible pipe of 1 cm diameter carries the effluent to the lower bucket through a small hole at its lid.

The lower bucket acts as a filtration unit, which is intended to remove any aluminum hydroxide flocs (with adsorbed arsenic on it) that would come from the upper bucket and also to remove the color produced by potassium permanganate. Just below the lid of this bucket a piece of cloth is placed to aid in removing the unsettled flocs coming from the upper bucket. A 20-cm deep sand bed (Sylhet sand) is provided in the lower bucket to filter out micro flocs and color. Through the sand filter, the water flows into a piece of PVC strainer (slot # 30) laid horizontally at the bottom of the lower bucket (Fig. 5.1). Both ends of the strainer are closed with appropriate PVC stoppers. A 1 cm diameter

flexible pipe connects the strainer with a tap (bibcock), fixed 4 cm from the bottom of the bucket. Treated water is collected from this tap.

Both the buckets are placed in an iron frame, made of 10 mm mild steel bars. The lower bucket sits 30 cm above the ground. This clearance is provided for the collection vessel. The top bucket is placed above the lower one. A 10-cm gap is provided between the buckets to facilitate easy operation/functioning of the connecting pipe (Figure 5.1).

5.2.2 Chemical Dose for the ARU

Analysis of the past data on arsenic concentration in tubewell water all over Bangladesh (BGS, 2000) revealed that about 99.6% tubewells have arsenic concentration below 1000 ppb, 98.7% tubewells have arsenic concentration below 700 ppb and 92.6% tubewells have arsenic concentration below 500 ppb. In the design of the ARU, 500 ppb is taken as the design concentration of arsenic in the groundwater. Results of the batch experiments, presented in chapter four, showed that Alum concentrations of 100 ppm (added as aluminum sulfate) along with a potassium permanganate dose of 1.0 ppm is sufficient to remove As(III) well below 50 ppb (the Bangladesh standard) from an initial concentration of 300 ppb. The alum and permanganate theoretical dose was shown in appendix B.12. Thus the required dose of aluminum sulfate ($Al_2SO_4.18H_2O$) was 100 ppm. During the field-testing it was assess that the ARUs become contaminated with coliforms (total and fecal coliforms). Then it was decided that commercial bleaching powder (CaOCl) would be used as disinfectant, which contained 5% chlorine (Cl_2). It was found that Cl_2 concentration of 0.45 ppm was sufficient to free the water from coliforms. Therefore, the total chemical requirements per batch were as follows:

Aluminum sulfate (commercial grade) = 100 mg/L * 20 L = 2000 mg = 2 gm
Potassium Permanganate = 1mg/L *20 L = 20 mg
Bleaching Powder (as Cl_2) = 0.45 mg/l * 20 L = 9 mg
Bleaching Powder (5% strength) = 9/0.05 mg = 180 mg

5.3 Installations and Operation of the Household ARUs

Five arsenic removal units were installed at Basgaon & Basail Bhog villages of Srinagor thana of Munshigonj district and Echapara & Dolerbag villages of Sonargaon thana of Narayangonj district for field testing. Different districts were selected for a wider variation of water quality parameters. There were a few deep tubewells in that locality. For installation of the ARUs, tubewells were selected on the basis of water quality, mainly the arsenic, iron and phosphate concentrations. General information about the tubewells are describe in Table 5.1

Table 5.1 General information about the selected tubewells

Name of the Owner	Village	Upazila	District	Depth	Platform Condition	Unit ID
S.M. Khalil	Basgaon	Srinagor	Munshiganj	160 ft	Well	Unit - A
M.Riaz Uddin	Basail Bhog	Srinagor	Munshiganj	150 ft	Well	Unit - B
M. Abu Mia	Echapara	Sonargaon	Narayanganj	110 ft	No Platform	Unit - C
M.Faroque Ahmed	Dolerbag	Sonargaon	Narayanganj	70 ft	Well	Unit - D
M. Nuruddin	Dolerbag	Sonargaon	Narayanganj	90 ft	Well	Unit - E

The field testing started on 9th June 2002 with installation of the five units in the five households. The arsenic concentrations and other parameters of raw water are presented in Table 5.2. It is evident that the range of variation for arsenic, iron and phosphate concentrations among the five tubewells' water is very high. The performance of all the ARUs was closely monitored for one year for a wide range of parameters. In operation guidline was supplied to each household with the unit. The operation of the ARUs basically consisted of the following steps:

- Filling the top red bucket upto the mark with tubewell water.

- ❖ Adding 1mL potassium permanganate (Pink solution) and 1.5 mL bleaching powder solution and mixing with water vigorously.
- ❖ After 5 min. then addition of one-full spoon alum
- ❖ Stirring the water with the wooden stirrer vigorously for 10~12 turns to mix the alum.
- ❖ Then slowly stirring the water for 40~50 turns.
- ❖ Covering the top bucket with lid and wait for an hour.
- ❖ Opening the two taps simultaneously to collect water.
- ❖ Closing both the taps after the water collection.
- ❖ Disposing the sludge to the drain or cow dung pit.
- ❖ Washing the filter cloth.

Table 5.2 Detailed characterization of raw water quality of the selected tubewells

Parameter	Unit	Unit-A	Unit-B	Unit-C	Unit-D	Unit-E
Arsenic	ppb	190	278	432	455	280
pH		7.01	7.11	7.02	7.17	7.05
Alkalinity	ppm	444	456	390	388	290
Iron	ppm	05	04	20	10	09
Hardness	ppm	408	416	418	332	292
Chloride	ppm	30	32	34	28	36
Sulfate	ppm	0.0	0.0	0.5	0.3	0.5
Phosphate	ppm	4.84	5.54	0.38	0.48	0.65
Nitrate	ppm	00	1.33	1.33	2.27	1.34
Silicate	ppm	24	19.8	15.2	11.2	15.7
Manganese	ppm	0.063	0.127	1.01	1.747	0.264
Aluminium	ppm	0.028	0.011	0.045	0.019	0.029
Color	Pt-Co	407	390	1350	734	726
FC	/100 ml	65	TNTC	50	10	60
Conductivity	μs/cm	542	615	450	477	369
TS	ppm	474	523	456	407	320
TDS	ppm	404	486	415	390	302

The alum and permanganate dosing combinations for all the units are presented in Table 5.3.

Table 5.3: Chemical dosing combinations for the field units

Unit	Dosing Combination
A	Combination 1: Alum 100 ppm & Permanganate 1 ppm
	Combination 2: Alum 200 ppm & Permanganate 1 ppm
	Combination 3: Alum 200 ppm & Permanganate 2 ppm
	Combination 4: Alum 100 ppm & Permanganate 3 ppm
B	Combination 1: Alum 100 ppm & Permanganate 1 ppm
	Combination 2: Alum 200/300/400/500 ppm & Permanganate 1 ppm
	Combination 3: Alum 500 ppm & Permanganate 2 ppm
	Combination 4: Alum 100 ppm & Permanganate 3 ppm
	Combination 5: Alum 100 ppm & Permanganate 4 ppm
	Combination 6: Alum 100 ppm & Permanganate 5 ppm
	Combination 7: Alum 100 ppm & Permanganate 6 ppm
C	Alum 100 ppm & Permanganate 1 ppm
D	
E	

Users were given spot training on the operation and maintenance. They were briefed about the technique of stirring and the importance of proper mixing and waiting period before collecting treated water. They were advised to throw away the sludge collected at the bottom of the top bucket to cow dung pit. All the field units were started with alum dose of 100 ppm and permanganate dose 1 ppm. Later it was revealed that those dose were not enough for units A and B to bring down the treated water arsenic concentrations consistently below 50 ppb. Hence various combinations of alum and permanganate doses were tried for those units to obtain optimum dosing for the particular water compositions. They recorded the amount of treated by the units and collecteds treated water sample for laboratory tests. Samples of both raw and treated were also collected during field visits. All collected samples (raw and treated) were tested for total arsenic, pH, iron, manganese, aluminium, alkalinity, hardness, chloride, sulfate, phosphate, nitrate, silicate, conductivity, TS, TDS, TSS and coliforms (total and fecal). Besides discussion with the users about the performance of the ARUs, a questionnaire survey was conducted to gather users' opinion about the ARUs.

Treated water samples were tested for arsenic to determine the arsenic removal efficiency of the units in the field conditions. The samples were preserved in low pH (1~2) conditions before testing by adding about 1 ml of concentrated HCl to 500 ml of sample. The dilution of the sample due to this acidification was insignificant and therefore ignored. For arsenic and iron test needed acidified samples and non-acidified samples for other parameters.

5.4 Raw Water Quality Variation with Time

From the laboratory experiments, it was revealed that the most significant water quality parameters affecting the arsenic removal efficiency of alum based ARU were arsenic concentrations, oxidation state of arsenic, iron content and phosphate concentration. Arsenic, iron and phosphate concentrations of the raw waters were monitored for a period of one year. The variations of arsenic and phosphate concentrations with time were found significant but the iron content did not change appreciably.

5.4.1 Variation of Raw Water Arsenic Concentration

The results of monitoring the arsenic contents of all the 5 ARUs for one year are presented in Figs. 5.2 to 5.6. It is found that the ranges of variations for units A, B, C, D and E are 157-235 ppb, 225-340 ppb, 247-518 ppb, 376-508 ppb and 180-334 ppb respectively. All though the variations were high, no trend in the variations could be detected and could not be correlated with the availability of surface water and rain water or abstraction of large amount of groundwater for irrigation.

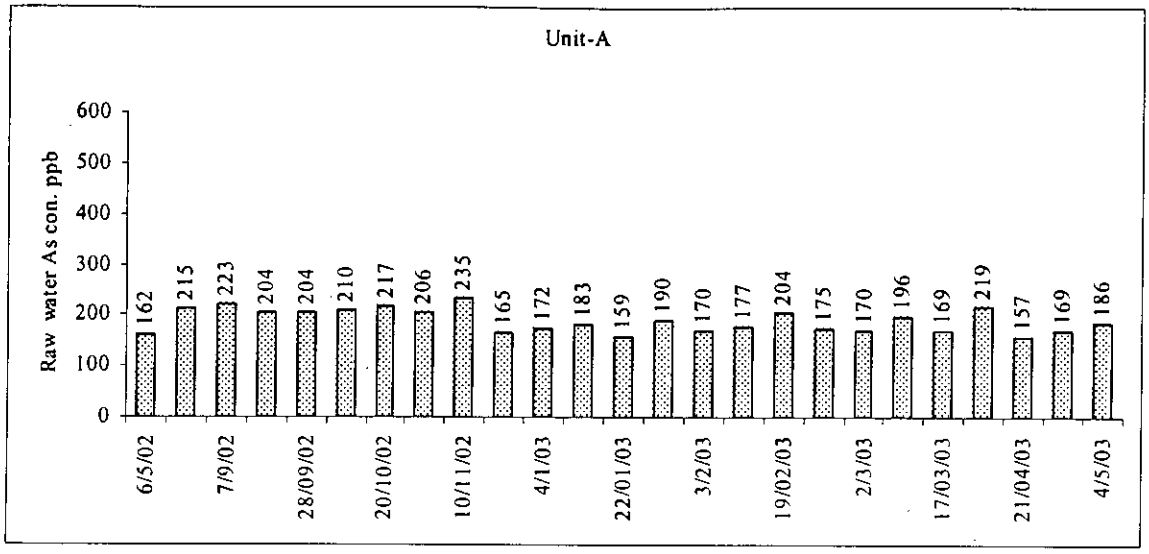

Figure 5.2 Raw water arsenic concentration variations with time for unit A

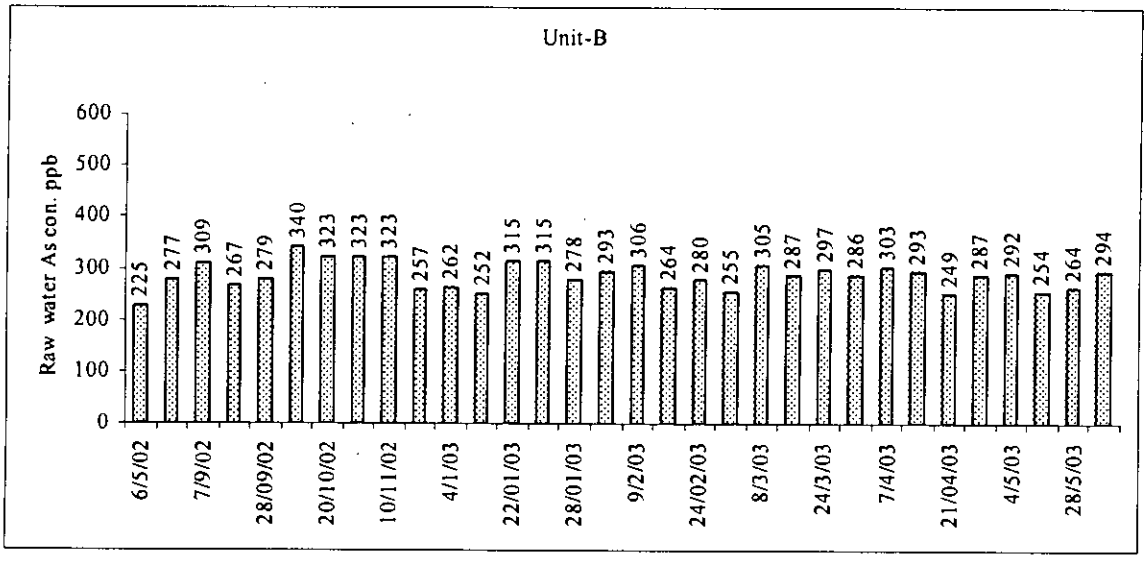

Figure 5.3 Raw water arsenic concentration variations with time for unit B

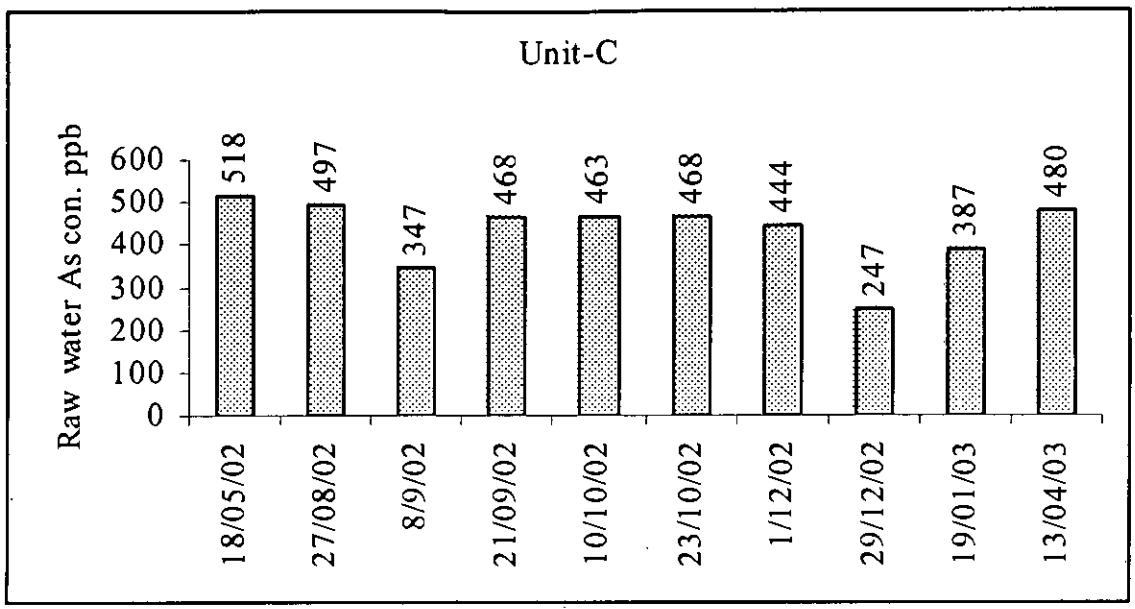

Figure 5.4 Raw water arsenic concentration variations with time for unit C

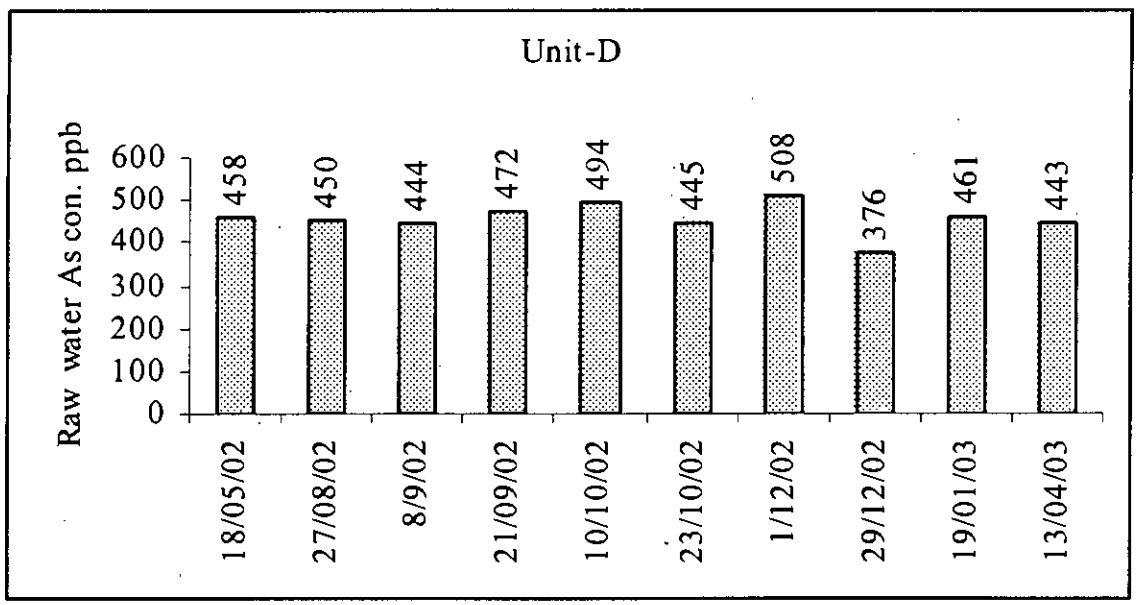

Figure 5.5 Raw water arsenic concentration variations with time for unit D

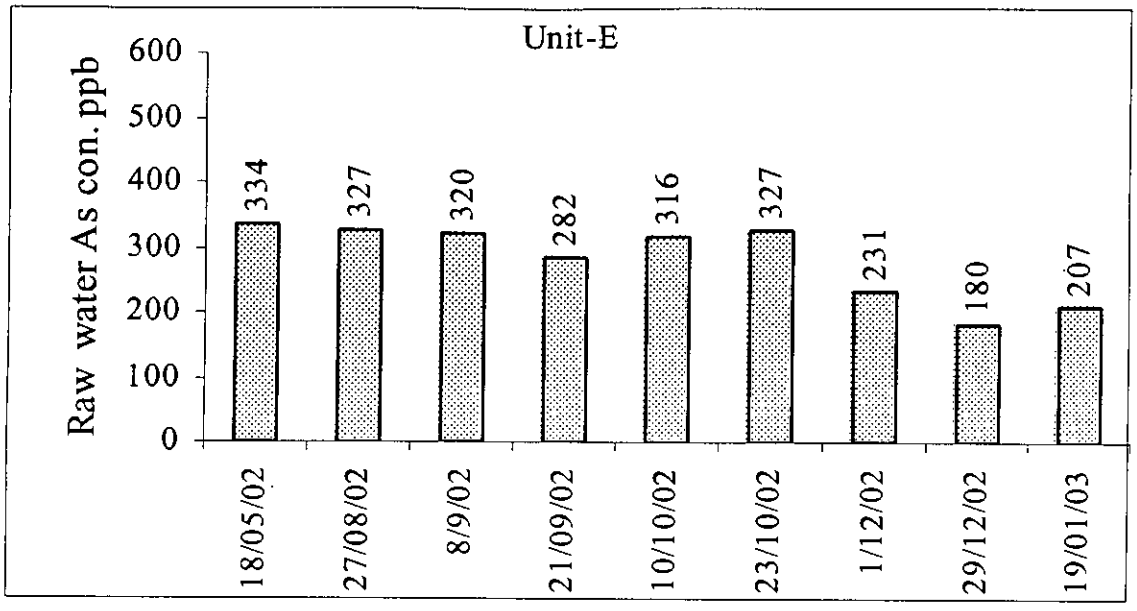

Figure 5.6 Raw water arsenic concentration variations with time for unit E

5.4.2 Variation of Raw Water Phosphate Concentration

The change of raw water phosphate concentrations of all the field units with time are depicted in Fig. 5.7 to 5.11. The phosphate concentrations varied in the ranges of 2.37 - 5.92 ppm, 2.01 – 8.35 ppm, 0.21 – 0.57 ppm, 0.34 – 0.61 ppm and 0.40 – 0.86 ppm for units A, B, C, D and E respectively. From the Figures, it clear that the variations of phosphate concentrations with time did not follow any particular trend, although the variations were quite high. Application of phosphate fertilizer could be the reason of such high variations.

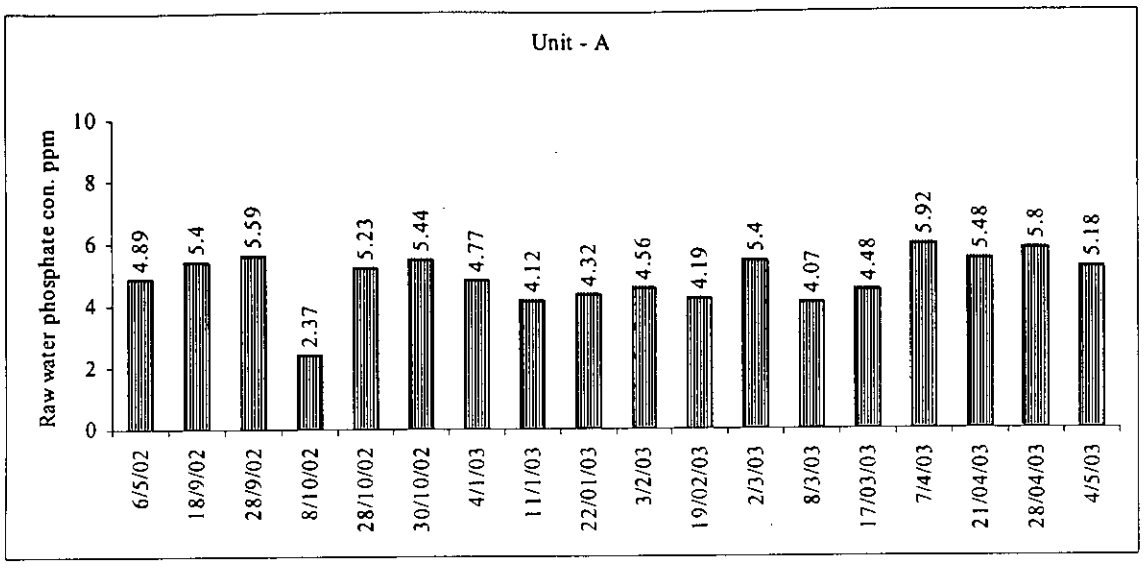

Figure 5.7 Raw water phosphate concentration variations with time for unit A

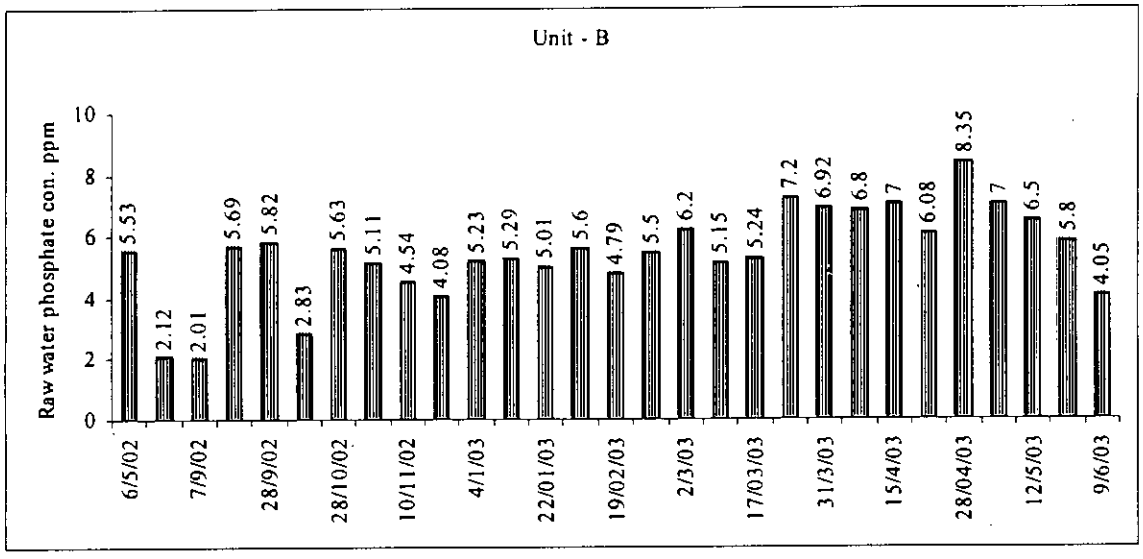

Figure 5.8 Raw water phosphate concentration variations with time for unit B

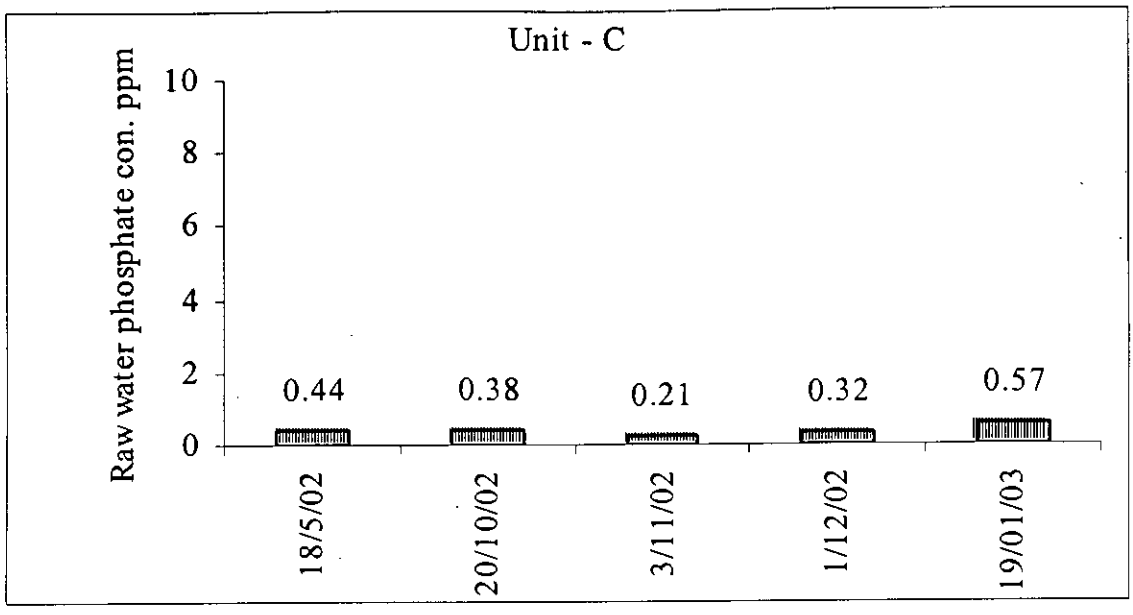

Figure 5.9 Raw water phosphate concentration variations with time for unit C

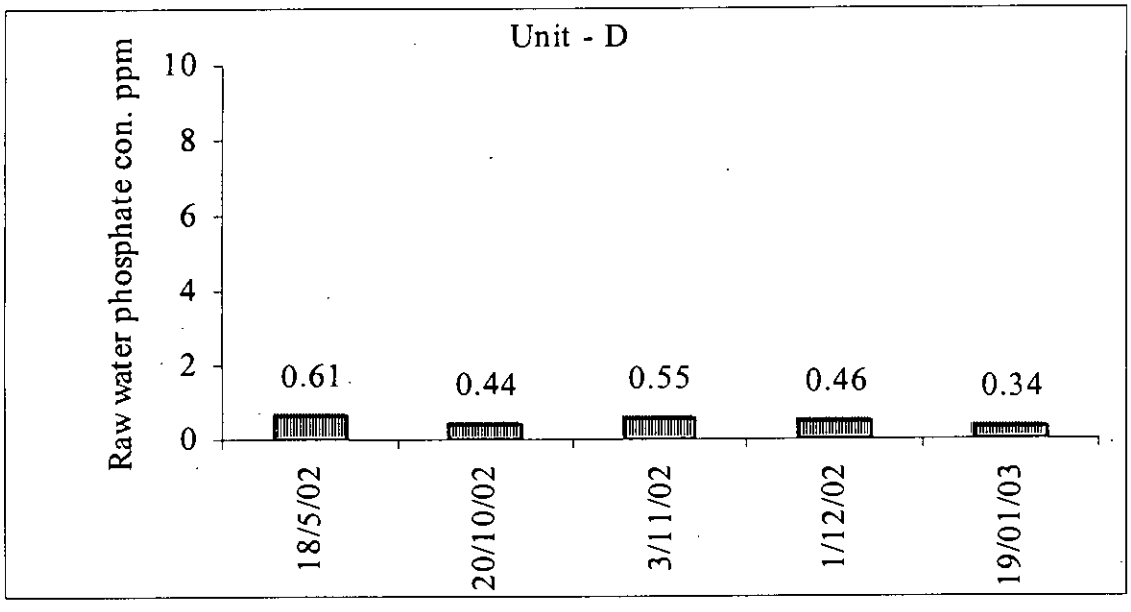

Figure 5.10 Raw water phosphate concentration variations with time for unit D

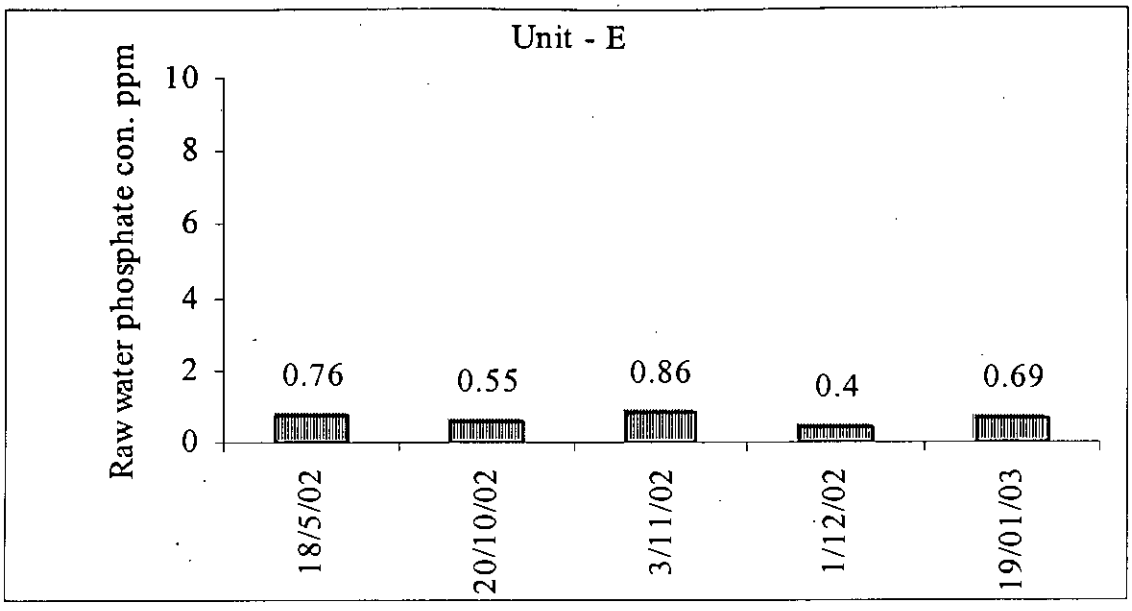

Figure 5.11 Raw water phosphate concentration variations with time for unit E

5.5 Arsenic Removal Efficiency of the Field Units

The detailed results concerning the arsenic removal by all the five field units presented in Appendix B. The performance of the units mainly depended on iron and phosphate concentrations of raw waters. The infiltration rates of the field units were presented in appendix B.11. For units A and B, the iron concentrations were moderate (4.0 ~ 5.0 ppm) and the phosphate concentrations were high (4.89 ~ 5.53 ppm). For units C, D & E, the iron concentrations were high (9.0 ~ 20.0 ppm) and the phosphate concentrations were low (0.44 ~ 0.76 ppm). The arsenic removal efficiency of the fild units are discussed below for the two different combinations of iron and phosphate concentrations of raw waters.

5.5.1 High Phosphate and Moderate Iron Concentration (units A and B)

For unit A, the average arsenic, iron and phosphate concentrations of the raw water were 162 ppb, 4.0 ppm and 4.89 ppm respectively. The arsenic removal efficiency of the unit A under different combinations of chemical dosing is shown in Fig. 5.12. For alum dose of 100 ppm and $KMnO_4$ dose of 1 ppm the residual arsenic concentration slowly increased upto 10 ppb corresponding to 2280 L of treated water. Then the residual arsenic concentration increased rapidly and exceeding 50 ppb corresponding to treated water

volume of about 3000 L. Al the first step, arsenic mainly removed by co-precipitation and adsorption on alum and iron flocs in the top bucket. Subsequently, when the settled water from the first bucket passed through the sand filter, arsenic was also removed. As the filter sand contained iron it adsorbed arsenic. But with accumulative treated water volume, the adsorption capacity of the sand filter decreased resulting in progressively higher arsenic concentrations in the effluent. Since the adsorption capacity of the filter sand would eventually be exhausted, higher chemical dosing was required to bring down the residual arsenic concentration below 50 ppb in the presence of high phosphate concentration. Alum dose of 200 ppm and permanganate dose 1 ppm reduced the residual arsenic content to increased to 34~48 ppb. When the permanganate dose was increased to 2 ppm, the effluent arsenic concentration was in the range of 27~32 ppb. For alum dose of 100 ppm and permanganate dose of 3 ppm, the residual arsenic varied in between 23~34 ppb. Phosphate interferes in the arsenic removal by competing for adsorption sites of alum and iron flocs. At the same time phosphate is also removed as $AlPO_4$ and $FePO_4$ precipitates in the presence of Al^{3+} and Fe^{3+}. Hence increased dosing of alum enhanced the arsenic removal by the unit A. When permanganate dose was increased, it enhanced the oxidation of both As(III) and Fe(II) of natural water. Hence the removal of phosphate as $FePO_4$ precipitates increased resulting in higher rate of arsenic adsorption on alum and iron flocs, thereby reducing the treated water arsenic concentrations. The variation of arsenic concentrations in the effluent for a particular combination of chemical dosing after exhausting of adsorption capacity of sand filters is mainly due to the changes in the raw water arsenic and phosphate concentrations.

The average arsenic, iron and phosphate concentrations in the feed water of unit B were 225 ppb, 4.0 ppm and 5.53 ppm respectively. The variations of effluent arsenic concentration for different combinations of chemical dosing are applied in Fig. 5.13. For alum dose of 100 ppm and permanganate dose of 1 ppm, it is seen that the effluent arsenic concentration increased slowly upto the treated water volume of 360 L, then increased rapidly to 42 ppb at treated water volume of 540 L and crossed the 50 ppb level at the volume of 1200 L. Due to high arsenic and phosphate concentrations and lower iron concentration of the raw water as compared to those of unit A, the arsenic removal efficiency was relatively low in comparison with unit A. It is evident that the dosing combination was not enough for running the unit. Increased alum doses decreased the residual arsenic concentration as expected but 500 ppm alum dose was required to bring

down the residual arsenic concentration below 50 ppb. When this dose was contained, it was found that the effluent arsenic concentration progressively increased and exceeded 50 ppb. This was due to the depletion of the adsorption capacity of the sand filter with higher volume of treated water. Increasing the permanganate dose to 2 ppm, it was observed that the effluent arsenic concentration remained below 50 ppb. Higher permanganate dose enhanced the oxidation of As(III) and Fe(II), the precipitation increased and arsenic was better adsorbed on the alum/iron flocs resulting in higher removal of arsenic.

For alum dose of 100 ppm and permanganate dose 3 ppm, the effluent arsenic concentration initially was below 50 ppb but gradually exceeded the 50 ppb level. Increasing the permanganate dose of 4 ppm showed that the similar results. Further increase of the permanganate dose to 5 ppm improved the situation with effluent arsenic concentrations close to 50 ppb. For alum dose of 100 ppm and permanganate dose of 6 ppm, the arsenic concentrations of the effluent were in the range of 31 – 36 ppb, much below the 50 ppb level. Hence higher permanganate dose is required for satisfactory arsenic removal when the raw water arsenic and phosphate concentrations are high.

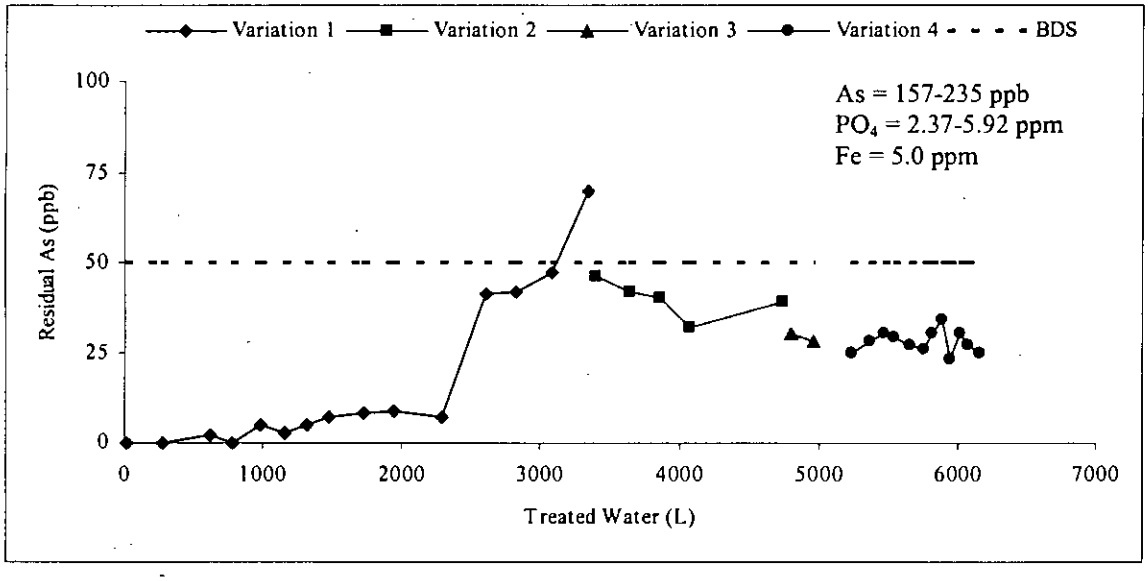

Figure 5.12 Variation of residual As with varying chemical dosing for unit A

(Cl_2 = 0.45ppm, Variation 1: alum 100 ppm & $KMnO_4$ 1 ppm, Variation 2: alum 200 ppm & $KMnO_4$ 1 ppm, Variation 3: alum 200 ppm & $KMnO_4$ 2 ppm and Variation 4: alum 100 ppm & $KMnO_4$ 3 ppm)

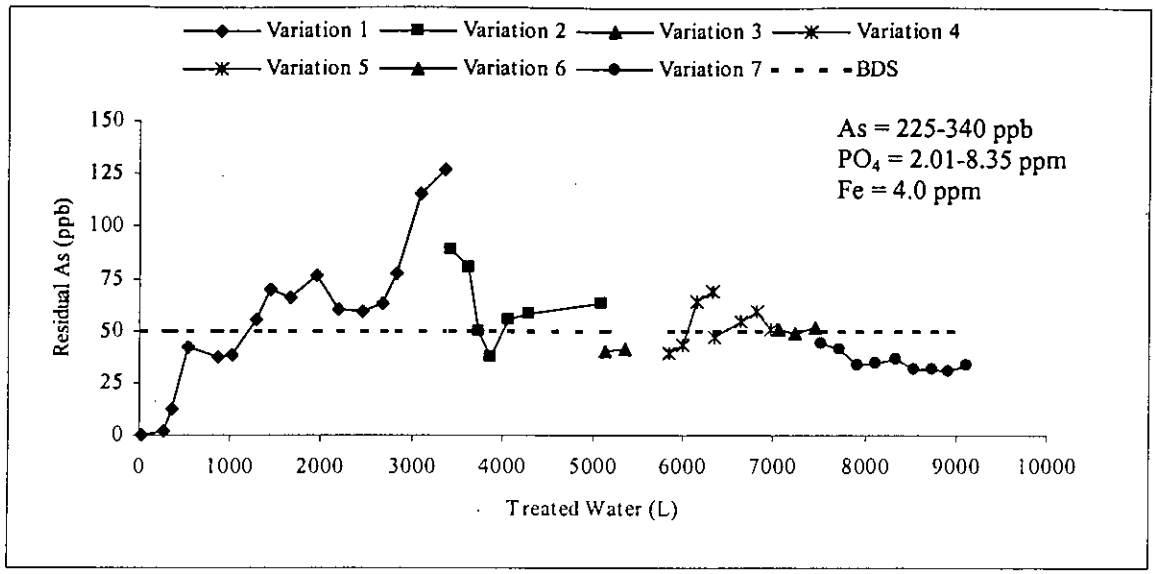

Figure 5.13 Variation of residual As with varying chemical dosing for unit B

(Cl2 =0.45ppm, Variation 1: alum 100 ppm & $KMnO_4$ 1 ppm, Variation 2: 1st 3 points alum 200, 300, 400 ppm respectively & $KMnO_4$ 1 ppm, others alum 500 ppb & $KMnO_4$ 1 ppm, Variation 3: alum 500 ppm & $KMnO_4$ 2 ppm, Variation 4: alum 100 ppm & $KMnO_4$ 3 ppm, Variation 5: alum 100 ppm & $KMnO_4$ 4 ppm, Variation 6: alum 100 ppm & $KMnO_4$ 5 ppm and Variation 7: alum 100 ppm & $KMnO_4$ 6 ppm)

5.5.2 Low Phosphate and High Iron Concentrations

The feed waters of unit C, D and E contain low phosphate and high arsenic and iron concentrations. The average arsenic, iron and phosphate concentrations in the feed waters of units C, D and E are shown in Table 5.4.

Table 5.4: Arsenic, iron and phosphate concentrations in feed waters of units C, D and E.

Unit	Average Arsenic Concentration (ppb)	Average Iron Concentration (ppm)	Average Phosphate Concentration (ppm)
C	432	20.00	0.38
D	455	10.00	0.48
E	280	9.00	0.65

All these units were operation with only one combination of chemical dosing namely alum dose of 100 ppm and permanganate dose of 1 ppm. The variations of treated water arsenic concentration for units C, D and E are depicted in Fig. 5.14, 5.15 and 5.16

respectively. From the Figures, it is evident that the effluent arsenic concentrations were consistently much below the 50 ppb level for all the units except one or two data points exceeding 50 ppb. Due two improper operations of the units such as non-addition of chemicals, insufficient stirring of water in the top bucket and providing enough settling time were the reasons for exceeding the 50 ppb level. For unit C, D and E, the arsenic removal performance is summarized in Table 5.5.

Table 5.5: Arsenic removal efficiency of units C, D and E

Unit	Raw Water Arsenic Concentration (ppb)	Effluent Arsenic Concentration (ppb)	
		Average Value	Range
C	518	7.5	0 - 17
D	458	5.0	0 - 22
E	334	11.0	2 - 34

For unit C, although the arsenic concentration was very high, presence of high amount of iron contributed in co-precipitation and adsorption of arsenic on iron flocs appreciably to reduce the residual arsenic concentrations to very low values. Since iron concentration in the feed water of unit D was about half as compared to unit A, and the phosphate concentration was relatively high, the average effluent arsenic concentration of the unit D was close to that of unit C although unit C had higher influent arsenic concentration. With lower influent arsenic concentration, unit E showed a higher mean value of effluent arsenic concentration as compared to units C and D, because of relatively lower iron concentration and higher phosphate concentration. However, it is clear that irrespective of the feed water arsenic concentration, the ARU perform very well if the feed water phosphate concentration is low. The variation in the effluent arsenic concentration of each unit can be attributed to the changes of the arsenic and phosphate concentrations in the feed water with time and the variability in the operation of the unit.

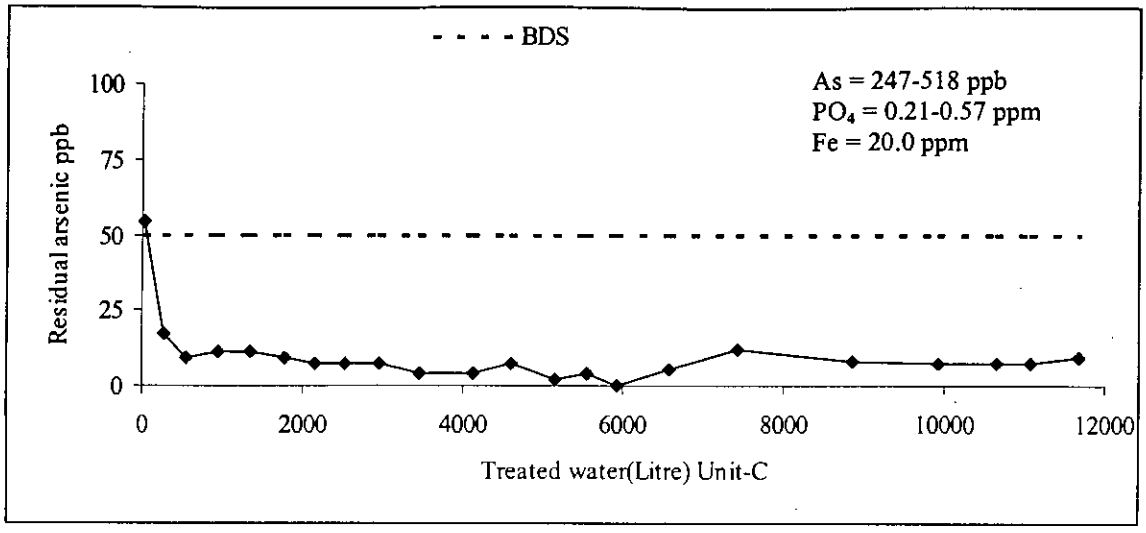

Figure 5.14 Variation of residual As with volume of treated water for Unit C

(alum 100 ppm, $KMnO_4$ = 1 ppm, Cl_2 = 0.45 ppm)

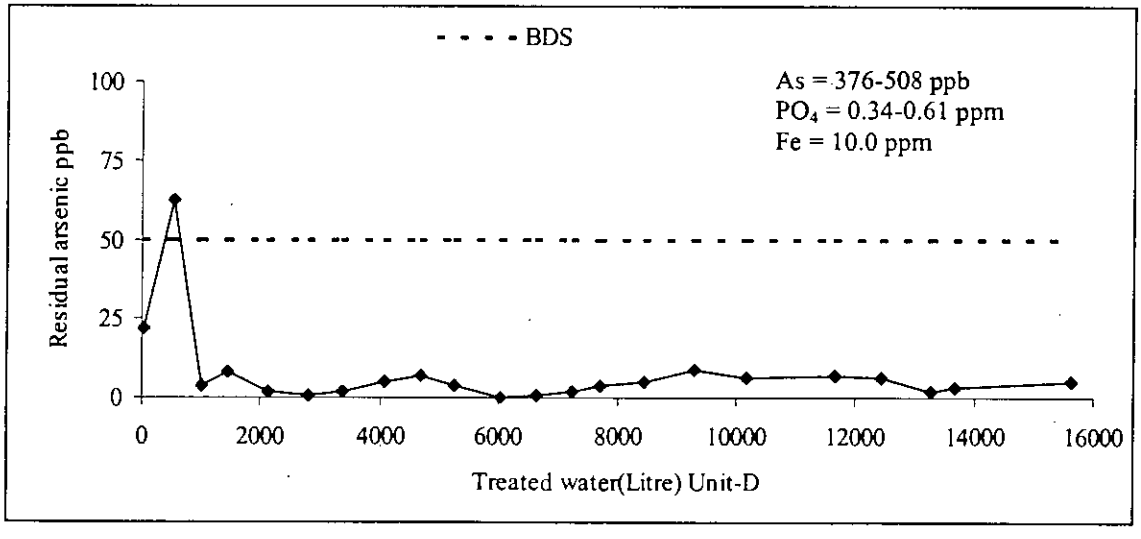

Figure 5.15 Variation of residual As with volume of treated water for Unit D

(alum 100 ppm, $KMnO_4$ = 1 ppm, Cl_2 = 0.45 ppm)

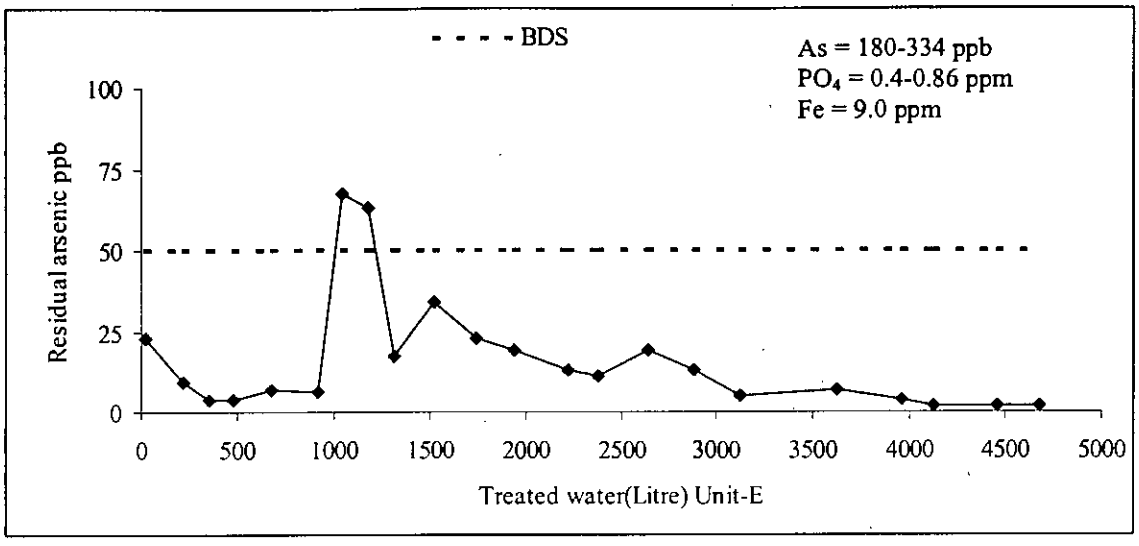

Figure 5.16 Variation of residual As with volume of treated water for Unit E (Alum 100 ppm, $KMnO_4$ = 1 ppm, Cl_2 = 0.45 ppm)

5.6 Quality of Treated Waters

In addition to arsenic, a number of water quality parameters (e.g., pH, alkalinity, hardness, iron, chloride, sulfate, phosphate, nitrate, silicate, manganese, color, aluminium, residual Cl_2 and FC) of the treated waters were measured of the field units under different chemical doses. Table 5.6 shows the results of treated waters of all the units at a particular chemical dosing. These results show excellent removal of iron, phosphate and color concentrations and complete destruction of FC. Although the sulfate concentration increased, it remained much below the Bangladesh drinking water standard. Compared to raw water concentrations (Table 5.2), others parameters of the treated water did not change significantly. Due to chemical dosing, aluminium, manganese, sulfate and Cl_2 were added to the raw water by 8.103 ppm, 0.348 ppm, 43.2 ppm and 0.45 ppm respectively. But the residual were much below the Bangladesh standards. Thus, it appears that along with arsenic, aluminium and manganese are also very effectively removed from water by alum coagulation. The apparent colors of all the raw waters of the units were very high, but the treated water color values were nil. The treated water quality at alum doses of 200 and 500 ppm is presented in Table 5.7. The sulfate concentration of the treated water exceeded the Bangladesh drinking water standard for obvious reason.

Table 5.6: Treated water quality of the field units

(Alum=100 ppm, $KMnO_4$ = 1 ppm, Cl_2 = 0.45 ppm)

Parameters	unit	Unit-A	Unit-B	Unit-C	Unit-D	Unit-E	BDS
pH	-	7.24	7.23	7.04	7.44	7.20	6.5-8.5
Iron	ppm	0.03	0.02	<0.01	<0.01	<0.01	0.3-1.0
Alkalinity	ppm	380	460	286	312	250	-
Hardness	ppm	360	400	320	306	224	200-500
Chloride	ppm	28	29	29	24	23	150-600
Sulfate	ppm	27.1	31.7	36.7	17.9	18.0	400
Phosphate	ppm	0.54	1.23	0.36	0.58	0.62	6.0
Nitrate	ppm	1.772	0.883	1.380	0.542	1.420	10
Silicate	ppm	21.3	20.0	14.3	12.5	14.6	-
Manganese	ppm	0.013	0.018	0.016	0.063	0.012	0.1
Color	Pt-Co	Nil	Nil	1	Nil	Nil	15
Aluminium	ppm	0.027	0.007	0.014	0.024	0.002	0.2
Residual Cl_2	ppm	0.10	0.09	0.11	0.14	0.12	0.2
FC	/100	Nil	Nil	Nil	Nil	Nil	Nil

Table 5.7: Treated water quality of the field units A & B

($KMnO_4$ = 1 ppm, Cl_2 = 0.45 ppm)

Parameters	Unit	Unit – A Alum = 200 ppm	Unit – B Alum = 500 ppm	Bangladesh Drinking Water Standard
pH	-	7.19	6.82	6.5 – 8.5
Alkalinity	ppm	280	236	-
Hardness	ppm	360	430	200 - 500
Chloride	ppm	24	22	150 - 600
Iron	ppm	0.02	0.02	0.3 – 1.0
Sulfate	ppm	152	302	400
Phosphate	ppm	1.21	1.48	6.0
Nitrate	ppm	6.2	5.76	10
Silicate	ppm	16.5	17	-
Aluminum	ppm	0.16	0.18	0.20

5.7 Bacteriological quality of water

All the 5 tubewells were bacteriologicaly contaminated and presence of coliform were also detected in the treated waters (Table 5.8). The tubewells were used for domestic purposes and all of them here close to latrines. It was observed that hand washing and anal cleansing of children after defecation at the tubewell sites were the common practice. Hence contaminated water was added to the upper bucket of the arsenic removal units. The sand beds did not remove coliforms satisfactorily as was evidenced from continued presence of these organisms in all the units. This problem was tried to eliminate by addition of bleaching powder in the feed water. The commercial bleaching powder contained 5% Cl_2. First 0.30 ppm Cl_2 was added to the water. But fecal coliforms were not completely removed from the water of all the units. Then 0.45 ppm Cl_2 was tried and the fecal coliform faced complete destruction for all the units but the removal of TC was not fully satisfactory.

Table 5.8 Bacteriological quality of raw & treated water

Unit	Date	Cl_2	Raw TC	Raw FC	Treated TC	Treated FC
			N/100ml	N/100ml	N/100ml	N/100ml
A	24/08/02	0.00	80	65	80	90
B	24/08/02	0.00	TNTC	TNTC	60	45
C	27/08/02	0.00	40	50	65	54
D	27/08/02	0.00	30	10	13	2
E	27/08/02	0.00	50	60	27	16
A	07/09/02	0.30	60	45	7	2
B	07/09/02	0.30	275	300	13	10
C	08/09/02	0.30	70	60	2	4
D	08/09/02	0.30	30	20	25	Nil
E	08/09/02	0.30	45	30	2	Nil
A	18/09/02	0.45	55	24	15	Nil
B	18/09/02	0.45	300	125	3	Nil
C	21/09/02	0.45	60	45	1	Nil
D	21/09/02	0.45	20	15	Nil	Nil
E	21/09/02	0.45	35	18	Nil	Nil
A	22/01/03	0.45	25	2	10	Nil
B	22/01/03	0.45	30	5	Nil	Nil
C	19/01/03	0.45	40	2	15	Nil
D	19/01/03	0.45	325	4	240	Nil
E	19/01/03	0.45	35	Nil	10	Nil

5.8 Effect of Potassium Permanganate dosing on Residual Manganese and Color

The results of residual color and manganese concentrations at the various doses of potassium permanganate are presented in Table 5.9. It is seen that the residual color was always within the Bangladesh standard irrespective of the applied permanganate dose. The Table also shows that although high content of manganese was added through permanganate addition, the residual manganese concentration was very low. Hence the ARU was very effective in removing both the color and manganese.

Table 5.9 Residual manganese and color for different potassium permanganate dosing (Alum = 100 ppm Cl_2 = 0.45 ppm)

Date	Res. Color	$KMnO_4$ ppm	Mn ppm	Residual Mn ppm
11/01/03	13	0	0	0.017
11/01/03	14	1	0.353	0.013
13/01/03	15	2	0.706	0.014
13/01/03	15	3	1.059	0.016
08/03/03	02	5	1.76	0.004
17/03/03	04	6	2.12	0.003
24/03/03	02	6	2.12	-
31/03/03	09	6	2.12	0.004
07/04/03	13	6	2.12	0.004
15/04/03	10	6	2.12	0.005
28/04/03	14	6	2.12	0.004
05/05/03	13	6	2.12	0.005

5.9 Comparison on Arsenic Removal by Co-precipitation-adsorption-sedimentation and Filtration

In the study, arsenic was removed by co-precipitation-adsorption-sedimentation and filtration processes. The filter bed played an important role on arsenic removal. The infiltration rate was also varying 2.44 to 3.46 ml/min/cm^2 (see appendix-B.11). The presence of high iron concentration (≥9 ppm) and low phosphate concentration (<1 ppm) for the feed waters of unit C, B and E, from Fig. 5.17, it is evident that 39 to 49% arsenic was removed by the filter beds. But presence of high concentrations of phosphate (>2 ppm) and moderate concentration of iron (≥4 ppm) in case of units A and B, arsenic was removed by 13% and 25% by filtration process respectively. The performances of those units were poor because low dose of permanganate was not effective to precipitate the

high phosphate content. In presence of phosphate oxidation required more potassium permanganate to increase the removal efficiency.

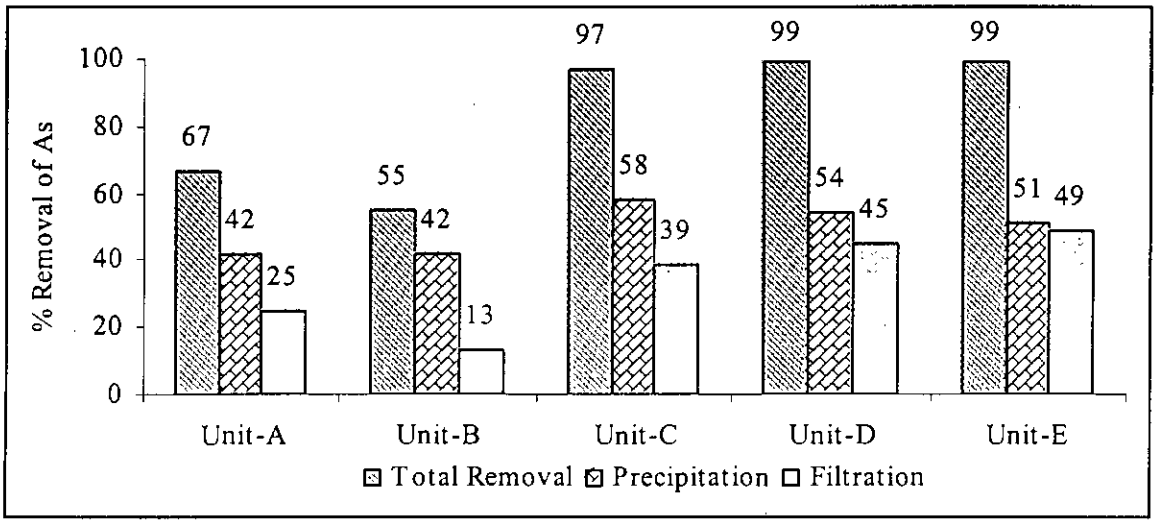

Figure 5.17 Removal of arsenic due co-precipitation and filtration
(Alum=100 ppm, MnO_4 = 1 ppm, Cl_2 =0.45 ppm)

5.10 Arsenic Removal Efficiency Under Various Combinations of Different Chemicals

The effect of chemical dosing combinations on arsenic removal is presented in Fig. 5.18. It shows that when no chemical was used, the treated water arsenic concentrations for units C, D and E were below 50 ppb. This was possible become the water contained high iron concentration (≥ 9.0 ppm) and low phosphate concentration (< 1.0 ppm). But for the units A and B, even though the feed water arsenic concentrations were relatively low, the treated water arsenic concentration were higher than 50 ppb at no chemical dosing because of the presence of high phosphate concentrations (> 4.5 ppm) and moderate iron concentration (≥ 5.0 ppm). Addition of chlorine, chlorine plus potassium permanganate, alum plus permanganate, alum plus permanganate plus chlorine increased the arsenic removal efficiency progressing. However, for unit A all these combinations produced arsenic safe water but not for unit B.

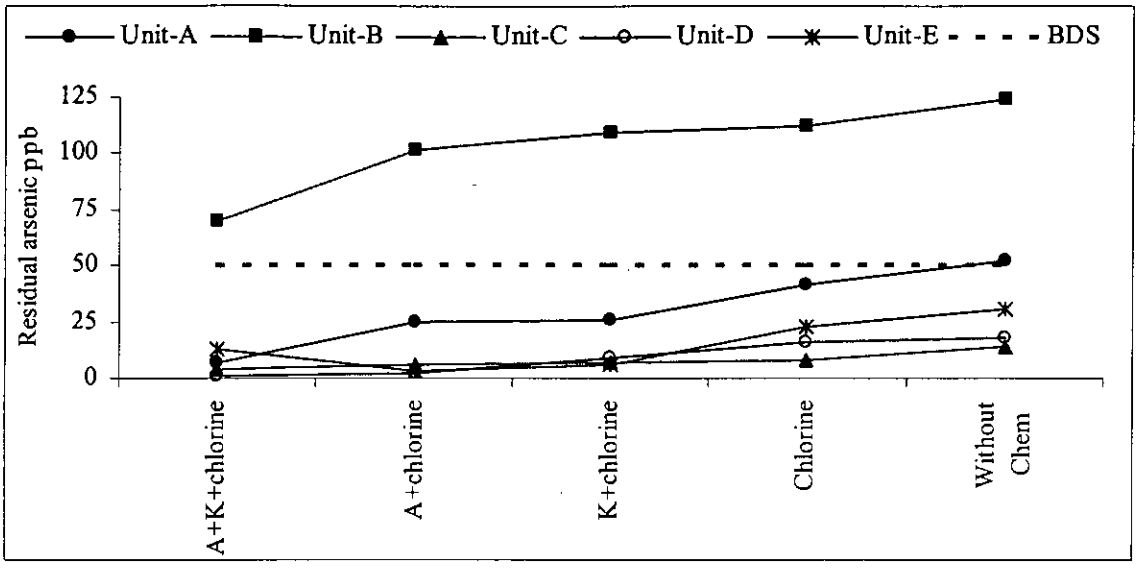

Figure 5.18 Effect of chemical dosing combination on arsenic removal

(A = Alum 100 ppm, K = $KMnO_4$ = 1 ppm, Cl_2 = 0.45 ppm)

5.11 Cost of water treatment

The total cost of constructing the unit was about Tk. 875/-. The cost of chemical per liter was around Tk. 0.02/-. Detailed breakdown of the cost is provided in Table 5.10 and Table 5.11.

Table 5.10 Estimated cost of the household arsenic removal unit

Items	Quantity	Price (Tk.)	Remarks
25 liter bucket+ lid	2 pc.	260.00	Depending on the quality or type of the materials
Collection bucket	1 pc.	50.00	
Tap	2	20.00	
Cloth	¼ yard	5.00	
Spoon	1 pc.	5.00	
Jam Nut	2 pc.	12.00	
Washer	4 pc.	4.00	
Strainer	1 ft	15.00	
Stopper Cap	2 pc.	12.00	
Connecting Pipe (1 cm dia)	2 ft	12.00	
Sand (Sylhet sand)	1 cft	15.00	
Wooden Stirrer	1 pc.	10.00	
Others	L.S.	30.00	
Sub-total		450.00	
Stand		425.00	
Total		875.00	

Table 5.11 Cost of chemical per liter of treated water

Items	Quantity	Price (Tk.)	Remarks
Alum (commercial grade)	2.0 gm	0.20	450 times per 1000 gm.
Potassium permanganate	20 mg	0.15	
Bleaching powder	180 mg	0.01	
Total		0.36	17.5 liter of treated water

The operating cost of treated water was Tk. 0.02 per liter

5.12 User acceptance

Information about user acceptance was gathered from discussion with the users and from the questionnaire survey conducted among the users. The questionnaire is presented in Annex C along with the responses of the users. Five units were supplied but during the testing of the units many people requested for supply additional units. About one year of operation, many people become very interested about these units who were more aware about the adverse effects of arsenic in drinking water. Many people showed their willingness to pay for the chemicals (which were being supplied free of cost by the research project) and some of them wanted to buy these units and were interested to learn about the operation and maintenance procedure. The easy operation and maintenance was one aspect that appeared to have made these units popular.

Apart from the arsenic removal efficiency of these units, the aspect that impressed people most was the clarity of water produced by these units. Many households identified this aspect as the primary reason for using the unit. With high iron content (upto 20 ppm), raw water from many tubewells in the villages showed high turbidity (resulting from precipitated iron flocs). The units were very effective in removing the iron content of water and the clear water was very attractive aesthetically. One of the householder informed that they did not use the treated water for drinking during winter because the water was very cold. They used tubewell water directly, which was not cold. And another householder informed that they used the unit only in the rainy season because in the dry season they collected the arsenic free water easily from other sources. Some people opted for that type of technology, which would not require any chemical.

Based on the survey reports and one year of field experience, it is clear that relatively poor and concious people were interested in these units. Rich people wanted better and expensive solution for arsenic free water such as deep tubewell. Some of them considered daily operation and maintenance of the ARUs as a difficult task. This was mainly due to lack of awareness about the adverse health effects of arsenic. This reveals that awareness about the ill effects of arsenic on human health is necessary to make any option acceptable to the community. One user initially complained about the smell of bleaching powder in the treated water. But it appeared that they got habituated with that smell after using the unit for some days and never complained about it again. Some other drawbacks were reported by the users; such as height of the unit and insufficient yield. This can be corrected by some minor modification of the unit.

5.13 Reasons for Poor Performance of DPHE-Danida BTU

Based on the results of the laboratory and field study the following reasons can be attributed for poor performance of DPHE-Danida BTU:

Major reasons:

- Small quantity of sand in the filter
- High phosphate content in the raw water.
- Moderate iron content (4~5 ppm) in the raw water in presence of high phosphate.

Minor reasons:

- Insufficient permanganate dose.
- Presence of high arsenic content in the raw water.
- Improper operation.

Small cylindrical sand beds provided low area for filtration. The micro flocs easily clogged the bed thereby decreasing the flow rate within a short period of time. The water quality parameters are not same over the country. So high concentration of phosphate required more permanganate dose for efficient arsenic removal. High arsenite and ferrous ions needed more permanganate dose for oxidation. Improper operation such as mixing and less settling time also caused poor performance of DPHE-Danida bucket treatment units.

5.14 Summary and Conclusions

Performance of arsenic removal unit was evaluated in the field in order to determine their suitability at household levels in the rural area of Bangladesh. Field testing of 5 arsenic removal units was carried out in Basgaon & Basail Bhog villages of Srinagor thana of Munshigonj district and Echapara & Dolerbag villages of Sonargaon thana of Narayangonj district for about one year.

1. The variations of raw water arsenic and phosphate concentrations with time were found significant but the iron content did not change appreciably.

2. The residual arsenic concentrations in the treated water of 3 field units were found to be mostly below 20 ppb, much below the Bangladesh standard at alum dose of 100 ppm and permanganate dose of 1 ppm. These doses were enough to remove arsenic effectively from natural groundwater if its iron content was high ($\geq$ 9 ppm) and phosphate content was low (<1.0 ppm) irrespective of the raw water arsenic concentration.

3. Alum dose of 100 ppm and permanganate dose of 1 ppm could not produce arsenic-safe water in the remaining two field units because of the presence of moderate amount of iron (4.0 ~ 5.0 ppm) and high concentration of phosphate (4.84 ~ 5.54 ppm) in the raw water. Higher permanganate dose was required for effective arsenic removal by the field units. For arsenic and phosphate concentrations of 190 ppb and 4.84 ppm respectively, the required permanganate dose was 3 ppm. When the arsenic and phosphate concentrations were 278 ppb and 5.54 ppm respectively, 6.0 ppm permanganate was needed to produce arsenic-safe water.

4. Excellent iron removal (>99%) was achieved by all the field units.

5. Proper operation of the system was essential to obtain satisfactory performance. Under favorable conditions (low phosphate concentration and high iron concentration), the system removed arsenic satisfactorily without addition of any chemical.

6. All the five tubewells were bacteriologically contaminated. So chlorine dose was introduced and it was found that 0.45 ppm was satisfactory for disinfection.

7. Filtration removed a substantial amount (39-49%) of arsenic when natural iron content was very high.

8. Residual color, aluminium and manganese content remained within allowable limits where proper dosing was applied.

9. Presence of moderate to high concentrations of iron and phosphate in raw water, small cross-sectional area of sand filter and improper operation were the main reasons for poor performance of Danida-DPHE Bucket Treatment Unit.

10. The chemical cost of the treated water was about Tk. 0.02 per liter.

11. Users' acceptability of the units was found to be satisfactory especially among the poor and conscious people. The minor drawbacks from the user point of view were the height and low yield of the units.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 General

The present study focussed on removal of arsenic from groundwater by on alum based arsenic removal unit. In order to simulate the field conditions in Bangladesh as closely as possible, synthetic groundwater was used in all laboratory experiments in this study. Arsenic concentrations used in this study were typical of those reported for groundwater of Bangladesh. Field testing of the unit was also carried out to make them suitable in natural condition.

The main objectives of this study were (i) to evaluate the efficiency of alum in removing As(V) & As(III) from groundwater (arsenic removal efficiency of the unit), (ii) to determine the effect of oxidation of arsenite to arsenate (effect of potassium permanganate dosing on removal efficiency), (iii) to evaluate the effect of source water compositions (i.e. initial concentration of arsenic, pH, alkalinity, iron, hardness, chloride, sulfate, phosphate, Nitrate and silicate), (iv) to determine the residual ions (aluminum, manganese and sulfate) in treated water, (v) to evaluate the synergistic effect of major anions, (vi) to determine the bacteriological performance and (vii) to develop operational and maintenance guidelines of the arsenic removal unit.

6.2 Conclusions

The flowing conclusions are drawn on the basis of the results:

1. Natural sylhet sand contained 12.5 to 13.2 mg iron per gm of the sand. When it was used as filter sand in the alum based arsenic removal unit, the arsenic removal efficiency was greatly influenced by the arsenic adsorption capacity of the sand due to the iron content. No consistent result obtained until the adsorption capacity was exhausted.

2. A moderate mixing of the coagulant required for satisfactory performance of the arsenic removal units resulting from effective coagulation.

3. Optimum alum dose for As(V) removal was found to be 100 ppm and 88% - 97% As(V) was removed at this dose for initial arsenic concentrations of 300 ppb – 1000 ppb.

4. Removal of As(V) was found to decrease with the increase of sorbate/sorbent ratio. The optimum sorbate/sorbent ratio was 75 (expressed as μg As / mg Al). Adsorption density was also found to decrease with higher aluminium dose.

5. The effect of pH on removal was insignificant within the pH range 5 to 8. The As(V) removal efficiency decreased slowly with the increase of pH value.

6. The As(V) removal efficiency decreased slowly with higher alkalinity. The HCO_3^- as competing ions with As ions. Fe(III) reduced the As(V) removal efficiency slowly upto 10 ppm but at higher dosing, the efficiency slowly increased.

7. Hardness had no effect on As(V) removal efficiency and chloride decreased the efficiency only at concentrations grater than 400 ppm.

8. The As(V) removal efficiency decreased slowly with increase sulfate concentrations.

9. Phosphate had significant effect on As(V) removal efficiency, higher concentration of phosphate reduced the removal efficiency markedly.

10. Fe(II) increased slightly the As(III) removal efficiency. In the presence of constant dose of potassium permanganate and phosphate, Fe(II) reduced the As(III) removal efficiency significantly.

11. As(III) was relatively poor removed by alum coagulation (66%). In the presence of medium iron and phosphate concentrations (5.0 ppm and 3.0 ppm respectively) the removal efficiency varied little (83% - 86%) with the form of arsenic even at low permanganate dose (1.0 ppm).

12. The effect of nitrate on arsenic removal was significant at 10 ppm of nitrate. The residual arsenic increases slowly with silicate up to 50 ppm of silicate and then the residual arsenic increases at increasingly higher rate with the increase of silicate concentration.

13. Anions had significant synergistic effect on As(V) removal efficiency at medium (0.0816M) to high (0.1061M) concentrations.

14. Sand filtration was very effective to remove color and to bring down the As(V) concentrations below Bangladesh standard. Without it, reliable performance could not be guaranteed.

15. The required potassium permanganate dose for effective removal of As(III) depended on the concentration of Fe(II). Higher concentrations of Fe(II) required higher dose of potassium permanganate.

16. One hour settling time was found optimum for settling of aluminium flocs in the upper bucket of the arsenic removal unit.

17. The variations of arsenic and phosphate concentrations with time were found significant but the iron content did not change appreciably.

18. The residual arsenic concentrations in the treated water of 3 field units were found to be mostly below 20 ppb, much below the Bangladesh standard at alum dose of 100 ppm and permanganate dose of 1 ppm. These doses were enough to remove arsenic effectively from natural groundwater if its iron content was high ($\geq$ 9 ppm) and phosphate content was low (<1.0 ppm) irrespective of the raw water arsenic concentration.

19. Alum dose of 100 ppm and permanganate dose of 1 ppm could not produce arsenic-safe water (Bangladesh standard) in the remaining two field units because of the presence of moderate amount of iron (4.0 ~ 5.0 ppm) and high concentration of phosphate (4.84 ~ 5.54 ppm) in the raw water. Higher permanganate dose was required for effective arsenic removal by the field units. For arsenic and phosphate concentrations of 190 ppb and 4.84 ppm respectively, the required permanganate dose was 3 ppm. When the arsenic and phosphate concentrations were 278 ppb and 5.54 ppm respectively, 6.0 ppm permanganate was needed to produce arsenic-safe water.

20. Excellent iron removal (>99%) was achieved by all the field units.

21. Proper operation of the system was essential to obtain satisfactory performance. Under favorable conditions (low phosphate concentration and high iron concentration), the system removed arsenic satisfactorily without addition of any chemical.

22. All the five tubewells were bacteriologically contaminated. So chlorine dose was introduced and it was found that 0.45 ppm was satisfactory for disinfection.

23. Filtration removed a substantial amount (39-49%) of arsenic when natural iron content was very high.

24. Residual color, aluminium and manganese content remained within allowable limits where proper dosing was applied.

25. Presence of moderate to high concentrations of iron and phosphate in raw water, small cross-sectional area of sand filter and improper operation were the main reasons for poor performance of Danida-DPHE Bucket Treatment Unit.

26. The chemical cost of the treated water was about Tk. 0.02 per liter.

27. Users' acceptability of the units was found to be satisfactory especially among the poor and conscious people. The minor drawbacks from the user point of view were the height and low yield of the units.

6.3 Recommendations

Based on the result of laboratory and field investigation conducted in this study, the following recommendations can be made to future study.

1. Potassium permanganate oxidizes both As(III) and Fe(II) of raw water. As Fe(II) can be easily oxidized by aeration, this can be tried before alum and permanganate dosing to reduce the requirement of permanganate.

2. If the raw water contains high amount of iron, arsenic removal by coprecipitation should be tried first. If satisfactory results are not obtained, only then minimum chemical dosing shall be determined.

3. Potassium permanganate dosing shall be optimized for groundwaters containing different combinations of moderate to high phosphate and iron concentrations.

4. Bleaching powder shall be tried to replace potassium permanganate as this will act as both oxidant and disinfectant.

5. The arsenic removal unit will have to be modified to decrease the height and increase the flow rate. With minor modifications, these can be achieved.

6. Once the modifications are made, the arsenic removal unit may be submitted for technology verification by appropriate authority.

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Appendix – A

Laboratory Data

Table A.1 Synthetic water As(V) concentration at different time

Given	300 ppb	500 ppb	1000 ppb	300 ppb	500 ppb	1000 ppb
Calculated	295	490	960	267	446	883
Calculated	310	500	1000	233	417	846
Calculated	280	488	923	293	481	969
Calculated	269	417	793	287	476	973
Calculated	270	507	981	291	485	980
Calculated	282	440	938	264	438	823
Calculated	308	468	944	275	445	882
Calculated	295	494	1060	282	471	917
Calculated	312	506	1057	291	479	943
Calculated	290	465	947	274	432	869
Calculated	252	385	782	281	447	851
Calculated	271	437	879	268	445	833

Table A.2 Residual As Concentration in Treated (Water Average data)
(Original Sylhet sand)

As(v) ppb	Unit	Alum 200 ppm	Alum 150 ppm	Alum 100 ppm	Alum 050 ppm	Alum 025 ppm	Alum 000 ppm
300	A	3	0	0	-	0	0
500	A	0	0	0	-	3	34
1000	A	0	-	0	-	11	41
300	B	87	63	38	24	42	76
500	B	78	26	47	35	50	162
1000	B	17	21	-	57	425	204
300	C	24	30	50	12	38	20
500	C	6	-	12	11	25	62
1000	C	-	9	27	-	47	158
300	D	-	6	3	7	3	0
500	D	4	3	-	5	11	19
1000	D	-	19	5	-	12	9
300	E	0	-	0	0	0	0
500	E	0	-	0	0	0	0
1000	E	0	0	-	5	0	0

Table A.3 Arsenic removal by ferric chloride, Standard mixing

As(V) ppb	$FeCl_3$ ppm	Mixing	Settling time hour	Residual As ppb	Avg. As ppb
300	100	Standard	1.0	37	33
300	100	Standard	1.0	34	
300	100	Standard	1.0	28	

Table A.4 Residual As concentrations treated by acid wash Sylhet sand variation with alum doses (Standard mixing and settling time one hour)

Unit	Raw As(V) ppb	Alum ppm	1st set		2nd set	
			Residual As ppb	Avg. As ppb	Residual As Ppb	Avg. As ppb
A	300	200	14	22	20	22
A	300	200	26		24	
A	300	200	26		23	
A	300	150	16	24	19	22
A	300	150	23		27	
A	300	150	32		21	
A	300	100	13	21	21	23
A	300	100	22		28	
A	300	100	27		19	
A	300	050	16	22	24	26
A	300	050	23		31	
A	300	050	28		23	
A	300	025	31	32	36	42
A	300	025	29		46	
A	300	025	34		43	
B	500	200	07	20	28	26
B	500	200	28		24	
B	500	200	26		22	
B	500	150	07	19	25	27
B	500	150	21		34	
B	500	150	30		23	
B	500	100	10	20	20	24
B	500	100	21		31	
B	500	100	28		21	
B	500	050	18	27	20	27
B	500	050	25		32	
B	500	050	39		26	
B	500	025	53	55	79	77
B	500	025	43		76	
B	500	025	68		76	
C	1000	200	09	22	30	33
C	1000	200	23		35	
C	1000	200	33		33	
C	1000	150	09	29	30	32
C	1000	150	27		37	
C	1000	150	50		29	
C	1000	100	15	26	29	34
C	1000	100	28		42	
C	1000	100	28		31	
C	1000	050	17	30	32	36
C	1000	050	29		39	
C	1000	050	44		36	
C	1000	025	72	83	100	97
C	1000	025	73		88	
C	1000	025	105		104	

Table A.5 Residual As concentrations treated by acid wash Sylhet sand variation with alum doses (medium & little mixing and settling time one hour)

Unit	Raw As(V) ppb	Alum ppm	Medium mixing		Little mixing	
			Residual As ppb	Avg. As ppb	Residual As ppb	Avg. As ppb
A	300	200	35	32	93	70
A	300	200	31		61	
A	300	200	30		55	
A	300	150	20	24	48	56
A	300	150	27		64	
A	300	150	24		59	
A	300	100	18	19	47	46
A	300	100	20		46	
A	300	100	18		44	
A	300	050	26	22	59	62
A	300	050	20		65	
A	300	050	21		61	
A	300	025	23	33	66	70
A	300	025	41		74	
A	300	025	36		71	
B	500	200	38	34	171	135
B	500	200	35		121	
B	500	200	28		114	
B	500	150	27	30	85	95
B	500	150	34		117	
B	500	150	28		83	
B	500	100	22	25	61	63
B	500	100	27		65	
B	500	100	26		63	
B	500	050	42	40	70	72
B	500	050	37		78	
B	500	050	41		68	
B	500	025	38	51	101	116
B	500	025	60		122	
B	500	025	54		126	
C	1000	200	57	59	241	252
C	1000	200	63		260	
C	1000	200	56		256	
C	1000	150	52	52	185	198
C	1000	150	56		263	
C	1000	150	47		147	
C	1000	100	42	44	124	132
C	1000	100	43		133	
C	1000	100	48		140	
C	1000	050	58	62	193	176
C	1000	050	63		193	
C	1000	050	66		143	
C	1000	025	69	85	237	264
C	1000	025	100		254	
C	1000	025	85		302	

Table A.6 Residual As concentrations treated by acid wash Sylhet sand variation with alum doses and its water quality parameters. (As = 300 ppb, ST = 1.0 H, Standard mixing, Proper washing)

Parameters	Alum ppm	Variation - 1 ppb	Variation - 2 ppb	Variation - 3 ppb	Variation - 4 ppb	Variation - 5 ppb
pH	100	46	46	47	48	59
pH	100	40	43	45	47	52
pH	100	37	42	46	51	55
Alkalinity	100		34	35	36	40
Alkalinity	100		26	27	38	45
Alkalinity	100		30	31	33	37
Iron	100	35	49	41	58	43
Iron	100	27	37	48	55	35
Iron	100	31	38	44	50	45
Hardness	100	19	33	35	34	38
Hardness	100	22	30	27	27	28
Hardness	100	18	29	31	25	25
Chloride	100	19	33	35	34	43
Chloride	100	22	30	27	33	39
Chloride	100	18	29	31	30	41
Sulfate	100	19		35	18	35
Sulfate	100	22		27	33	25
Sulfate	100	18		31	21	29
Phosphate	100	35		32	55	68
Phosphate	100	27		38	58	75
Phosphate	100	31		35	53	69
Nitrate	100	35	32	38	49	30
Nitrate	100	27	29	36	37	25
Nitrate	100	31	31	33	36	23
Silicate	100	19	35	29	36	78
Silicate	100	22	27	31	41	88
Silicate	100	18	31	36	51	88

Table A.7 Residual As concentrations treated by acid wash Sylhet sand variation with alum doses and its water quality parameters. (As = 300 ppb, ST = 1.0 H, Standard mixing, Proper washing)

Parameters	Alum ppm	Variation - 1 ppb	Variation - 2 ppb	Variation - 3 ppb	Variation - 4 ppb	Variation - 5 ppb
pH	50	37	51	58	63	73
pH	50	40	47	53	60	80
pH	50	43	53	54	57	79
Alkalinity	50		36	35	49	66
Alkalinity	50		28	37	55	73
Alkalinity	50		26	39	60	65
Iron	50	35	41	42	43	28
Iron	50	37	35	39	45	31
Iron	50	39	37	35	44	35
Hardness	50	33	36	35	34	37
Hardness	50	36	28	37	27	28
Hardness	50	32	26	39	27	29
Chloride	50	33	36	35	34	45

Parameters	Alum ppm	Variation - 1 ppb	Variation - 2 ppb	Variation - 3 ppb	Variation - 4 ppb	Variation - 5 ppb
Chloride	50	36	28	37	32	33
Chloride	50	32	26	39	32	46
Sulfate	50	33		35	41	50
Sulfate	50	36		37	34	42
Sulfate	50	32		39	40	41
Phosphate	50	35		50	80	146
Phosphate	50	37		50	75	133
Phosphate	50	39		45	82	144
Nitrate	50	35	40	63	83	45
Nitrate	50	37	39	66	70	41
Nitrate	50	39	41	71	74	50
Silicate	50	33	35	35	61	70
Silicate	50	36	37	37	70	149
Silicate	50	32	39	41	63	133

Table A.8 Residual As concentrations treated by acid wash Sylhet sand variation with alum doses and its water quality parameters. (As = 300 ppb, ST = 1.0 H, Standard mixing, without washing)

Parameters	Alum ppm	Variation - 1 ppb	Variation - 2 ppb	Variation - 3 ppb	Variation - 4 ppb	Variation - 5 ppb
pH	100	60	54	67	89	156
pH	100	47	45	57	75	147
pH	100	37	42	65	85	128
Alkalinity	100		51	40	61	55
Alkalinity	100		46	37	58	53
Alkalinity	100		48	31	58	60
Iron	100	40	51	99	172	60
Iron	100	37	61	91	151	48
Iron	100	31	52	75	122	46
Hardness	100	42	51	40	55	63
Hardness	100	40	46	37	47	54
Hardness	100	42	48	31	41	48
Chloride	100	42	51	40	43	40
Chloride	100	40	46	37	41	42
Chloride	100	42	48	31	38	38
Sulfate	100	42		40	69	107
Sulfate	100	40		37	74	95
Sulfate	100	42		31	63	89
Phosphate	100	40		32	150	250
Phosphate	100	37		38	172	253
Phosphate	100	31		35	156	262
Nitrate	100	40	55	73	149	49
Nitrate	100	37	49	62	94	38
Nitrate	100	31	40	57	68	34
Silicate	100	42	40	39	73	270
Silicate	100	40	37	43	61	231
Silicate	100	42	31	36	84	236

Table A.9 Residual As concentrations treated by acid wash Sylhet sand variation with alum doses and its water quality parameters. (As = 300 ppb, ST = 1.0 H, Medium mixing, without washing)

Parameters	Alum ppm	Variation - 1 ppb	Variation - 2 ppb	Variation - 3 ppb	Variation - 4 ppb	Variation - 5 ppb
pH	50	95	114	91	95	102
pH	50	77	90	85	113	89
pH	50	64	89	82	111	101
Alkalinity	50		12	42	69	24
Alkalinity	50		61	37	74	40
Alkalinity	50		79	41	87	63
Iron	50	42	115	106	134	26
Iron	50	37	84	94	124	24
Iron	50	41	67	84	126	24
Hardness	50	20	12	42	52	79
Hardness	50	62	61	37	55	69
Hardness	50	67	79	41	56	70
Chloride	50	20	12	42	08	08
Chloride	50	62	61	37	12	15
Chloride	50	67	79	41	14	21
Sulfate	50	20		42	52	43
Sulfate	50	62		37	50	42
Sulfate	50	67		41	48	46
Phosphate	50	42		64	120	164
Phosphate	50	37		74	180	224
Phosphate	50	41		82	206	240
Nitrate	50	42	103	121	167	23
Nitrate	50	37	84	99	139	25
Nitrate	50	41	72	88	126	28
Silicate	50	20	42	125	153	161
Silicate	50	62	37	128	101	197
Silicate	50	67	41	107	212	258

Table A.10 Residual As concentration chart variation of settling time on As(V) Removal (Alum 50 ppm & Alum 100 ppm, standard mixing and Sand Filter)

Settling time hour	Alum 50 ppm			Alum 100 ppm
	Residual As ppb Unit-A	Residual As ppb Unit-B	Residual As ppb Unit-C	Residual As ppb Unit-A
0.5	77	109	212	57
0.5	67	103	192	53
0.5	53	88	170	56
01	43	53	58	45
01	47	49	63	40
01	42	47	66	39
1.5	41	45	59	42
1.5	44	50	55	38
1.5	40	49	57	40
02	39	42	50	26
02	42	45	47	30
02	38	41	49	33

Table A.11 Residual As concentration chart variation of settling time on As(V) Removal
[As(V) = 300 ppb, Alum 50 ppm & Alum 100 ppm, standard mixing and filter paper]

Settling time hour	Unit	Alum ppm	Residual As ppb	Unit	Alum ppm	Residual As ppb
0.5	A	50	63	B	100	47
0.5	A	50	59	B	100	43
0.5	A	50	66	B	100	48
01	A	50	45	B	100	24
01	A	50	48	B	100	27
01	A	50	44	B	100	29
1.5	A	50	40	B	100	25
1.5	A	50	37	B	100	20
1.5	A	50	42	B	100	22
02	A	50	39	B	100	25
02	A	50	43	B	100	23
02	A	50	38	B	100	22
03	A	50	35	B	100	17
03	A	50	43	B	100	20
03	A	50	41	B	100	19
04	A	50	41	B	100	18
04	A	50	37	B	100	26
04	A	50	32	B	100	21
06	A	50	39	B	100	17
06	A	50	34	B	100	25
06	A	50	40	B	100	21
24	A	50	37	B	100	20
24	A	50	43	B	100	18
24	A	50	39	B	100	18

Table A.12 Synergistic effect on As(V) removal
(Alum 100 ppm, Standard mixing and Proper washing)

Raw As(V) ppb	Iron	Residual As ppb Tap Water	Residual As ppb Low Con.	Residual As ppb Medium Con	Residual As ppb High Con
300	With Fe	19	29	57	86
300	With Fe	24	26	85	178
300	With Fe	23	24	105	188
300	Without Fe	19	56	75	109
300	Without Fe	24	70	187	231
300	Without Fe	23	72	198	252
200	Without Fe		44	98	112
200	Without Fe		48	124	144
200	Without Fe		52	155	174
100	Without Fe		26	33	44
100	Without Fe		36	53	62
100	Without Fe		40	65	74

Table A.13 Color effect of raw & treated water on Fe(II) and $KMnO_4$
[As(III)=300 ppb, Alum=100 ppm, Fe=1 ppm, Standard mixing and Proper washing]

$KMnO_4$ ppm	Color Raw Pt-Co.	Color Trea Pt-Co.	Residual As ppb	Iron (ferrous) 1 ppm		
				Color Raw Pt-Co.	Color Trea Pt-Co.	Residual As ppb
00	01	00	60	01	00	60
00	01	00	67	01	00	67
00	01	01	81	01	01	81
0.5	32	00	39	22	01	60
0.5	32	00	35	22	00	71
0.5	32	00	36	22	00	73
1.0	38	07	28	32	00	51
1.0	38	06	32	32	00	48
1.0	38	09	30	32	02	44
2.0	52	21	23	41	12	42
2.0	52	17	26	41	15	36
2.0	52	22	25	41	17	32

Table A.14 Residual Mn concentration of different $KMnO_4$ doses
[As(III)=300 ppb, Alum=100 ppm, Standard mixing]

$KMnO_4$ ppm	Mn ppm	Mn of Raw water ppm	Iron Fe(II) = 0 ppm	Iron Fe(II) = 1 ppm
			Residual Mn ppm	Residual Mn ppm
0.5	0.179	0.104	0.009	0.013
0.5	0.179	0.104	0.007	0.015
0.5	0.179	0.104	0.013	0.018
1.0	0.348	0.174	0.017	0.015
1.0	0.348	0.174	0.011	0.025
1.0	0.348	0.174	0.025	0.016
2.0	0.693	0.351	0.070	0.049
2.0	0.693	0.351	0.066	0.045
2.0	0.693	0.351	0.088	0.042

Table A.15 Residual As on phosphate variation 1.0, 2.0, 2.5, 3.0 & 5.0 ppm
(Alum=100 ppm, P= PO_4)

As(III)	Original Sylhet sand (Residual As ppb)					Acid wash Sylhet sand (Residual As ppb)				
	P=1.0	P=2.0	P=2.5	P=3.0	P=5.0	P=1.0	P=2.0	P=2.5	P=3.0	P=5.0
300	20	18	18	19	22	26	35	40	42	48
300	18	15	15	19	23	28	39	38	41	41
300	19	18	16	20	21	18	37	37	41	42
350	18	18	17	17	22	36	42	50	40	43
350	16	17	18	18	23	42	38	41	48	45
350	16	16	18	21	23	44	39	44	40	51
400	19	18	16	17	22	46	42	46	48	53
400	17	17	16	17	20	42	44	43	47	48
400	16	16	18	19	22	42	41	49	44	51

Table A.16 Arsenic removal on different concentration As(V) & As(III) with Fe(II)
[As(Total) =350 ppb, PO_4 =3 ppm]

As(V)	As(III)	Fe(II) ppm	$KMnO_4$ ppm	Resi. As ppb	As(V)	As(III)	Fe(II) ppm	$KMnO_4$ ppm	Resi. As ppb
0%	100%	0.0	1.0	27	0%	100%	7.0	1.0	73
0%	100%	0.0	1.0	21	0%	100%	7.0	1.0	76
0%	100%	0.0	1.0	22	0%	100%	7.0	1.0	85
0%	100%	1.0	1.0	49	0%	100%	10.0	1.0	84
0%	100%	I.0	1.0	44	0%	100%	10.0	1.0	78
0%	100%	1.0	1.0	37	0%	100%	10.0	1.0	96
0%	100%	3.0	1.0	55	71%	29%	5.0	1.0	48
0%	100%	3.0	1.0	60	71%	29%	5.0	1.0	44
0%	100%	3.0	1.0	61	71%	29%	5.0	1.0	51
0%	100%	5.0	0.0	99	57%	43%	5.0	1.0	52
0%	100%	5.0	0.0	110	57%	43%	5.0	1.0	60
0%	100%	5.0	0.0	86	57%	43%	5.0	1.0	44
0%	100%	5.0	1.0	61	50%	50%	5.0	1.0	51
0%	100%	5.0	1.0	56	50%	50%	5.0	1.0	38
0%	100%	5.0	1.0	65	50%	50%	5.0	1.0	59
0%	100%	5.0	1.5	55	43%	57%	5.0	1.0	58
0%	100%	5.0	1.5	55	43%	57%	5.0	1.0	59
0%	100%	5.0	1.5	57	43%	57%	5.0	1.0	57
0%	100%	5.0	2.0	33	29%	71%	5.0	I.0	72
0%	100%	5.0	2.0	31	29%	71%	5.0	1.0	50
0%	100%	5.0	2.0	32	29%	71%	5.0	1.0	58

Table A.17 Effect of Fe(II) ($FeSO_4$ $7H_2O$) on As(III) removal without & phosphate
[As(III) =300 ppb, Alum =100 ppm]

Fe(II) ppm	Without phosphate		With phosphate	
	Residual As ppb	Avg. As ppb	Residual As ppb	Avg. As ppb
0	94	99	99	
0	99		100	103
0	103		110	
2.5	92	93	103	
2.5	89		97	101
2.5	97		101	
5	86	87	97	
5	86		93	97
5	87		100	
10	80	83	98	
10	83		93	96
10	85		96	
20	71	71	91	
20	70		96	94
20	73		94	

Appendix – B

Field Data

Table B.1 Raw water arsenic and phosphate concentration variation with time

Date	Unit-A		Unit-B		Unit-C		Unit-D		Unit-E	
	As ppb	PO_4 ppm	As ppb	PO_4 ppm	As ppb	PO_4 ppm	As ppb	PO_4 ppm	As ppb	PO_4 ppm
06/05/02	162	4.89	225	5.53						
18/05/02					518	0.44	458	0.61	334	0.76
24/08/02	215	-	277	2.12						
27/08/02					497	-	450	-	327	-
07/09/02	223	-	309	2.01						
08/09/02					347	-	444	-	320	-
18/09/02	204	5.40	267	5.69						
21/09/02					468	-	472	-	282	-
28/09/02	204	5.59	279	5.82						
10/10/02					463	-	494	-	316	-
08/10/02	210	2.37	340	2.83						
20/10/02	217	-	323	-						
23/10/02					468	0.38	445	0.44	327	0.55
28/10/02	206	5.23	323	5.63						
30/10/02	-	5.44	-	5.11						
15/11/02					-	0.21	-	0.55	-	0.86
10/11/02	235	-	323	4.54						
01/12/02					444	0.32	508	0.46	231	0.40
24/12/02	165	-	257	-						
29/12/02					247	-	376	-	180	-
04/01/03	172	4.77	262	5.23						
11/01/03	183	4.12	252	5.29						
19/01/03					387	0.57	461	0.34	207	0.69
22/01/03	159	4.31	315	5.00						
28/01/03	190	-	278	-						
03/02/03	170	4.56	293	5.60						
09/02/03	177	-	306	-						
19/02/03	204	4.19	264	4.79						
24/02/03	175	-	280	5.50						
02/03/03	170	5.40	255	6.20						
08/03/03	196	4.07	305	5.15						
17/03/03	169	4.48	287	5.24						
24/03/03	-	-	287	7.20						
31/03/03	-	-	286	6.92						
07/04/03	219	5.92	303	6.80						
13/04/03					480	-	443	-	-	-
15/04/03	-	-	293	7.00						
21/04/03	157	5.48	249	6.08						
28/04/03	169	5.80	287	8.35						
04/05/03	186	5.18	292	7.00						
12/05/03	-	-	254	6.50						

Table B.2 Effects on chemical combination in the field unit
(F=Filtered, BF=Before filtered A=Alum 100 ppm, K=$KMnO_4$= 1 ppm, Cl_2= 0.45 ppm.)

Chemical	Unit-A ppb	Unit-B ppb	Unit-C ppb	Unit-D ppb	Unit-E ppb
A+K+Cl_2	07	70	04	01	13
A+Cl_2	11	132	05	01	01
A+Cl_2	31	83	07	01	02
A+Cl_2	23	89	05	05	07
K+Cl_2	21	120	05	11	05
K+Cl_2	29	101	07	06	05
K+Cl_2	27	107	09	09	09
Cl_2	36	111	07	09	10
Cl_2	45	105	07	15	35
Cl_2	41	121	11	25	23
Without che	51	118	11	17	28
Without che	54	126	15	18	34
Without che	51	128	16	19	31

Table B.3 Residual As without chemical before filtration in the field unit

Chemical	Unit-A	Unit-B	Unit-C	Unit-D	Unit-E
Raw As	204	267	468	472	252
Without che	195	246	440	409	239
Without che	199	258	444	470	231
Without che	198	249	446	386	234
Raw As	243	279	463	494	316
Without che	227	267	426	443	291
Without che	211	263	440	435	297
Without che	226	271	433	437	300

Table B.4 Effects on color residual manganese and residual arsenic on the $KMnO_4$ variation in the field
(Alum =100 ppm, Cl_2 = 0.45 ppm)

$KMnO_4$ ppm	Household unit A				Household unit B			
	Resi. As (f) ppb	Resi. As (bf) ppb	Color Pt-Co	Residual Mn	Resi. As (f) ppb	Resi. As (bf) ppb	Color Pt-Co	Residual Mn
0.0	54	146	09	0.013	68	130	09	0.017
0.0	55	141	12	0.016	72	158	12	0.018
0.0	61	145	11	0.015	75	143	10	0.015
1.0	48	86	11	0.014	56	102	12	0.013
1.0	41	78	10	0.017	53	95	15	0.015
1.0	43	58	11	0.012	57	93	12	0.010
2.0	25	54	10	0.021	45	57	12	0.022
2.0	25	55	12	0.013	47	59	08	0.010
2.0	32	58	10	0.014	49	50	14	0.010
3.0	31	30	15	0.018	24	42	09	0.016
3.0	31	29	13	0.021	33	40	08	0.020
3.0	28	23	16	0.017	35	42	10	0.011

Table B.5 Residual arsenic in the field unit (Cl_2 = 0.45 ppm)

Date	Household unit A				Date	Household unit B			
	Alum ppm	$KMnO_4$ ppm	Treated water(L)	Residua As(f) ppb		Alum ppm	$KMnO_4$ ppm	Treated water(L)	Residua l As(f) ppb
09/06/02	100	1.0	20	00	09/06/02	100	1.0	20	00
18/06/02	100	1.0	280	00	18/06/02	100	1.0	260	02
01/07/02	100	1.0	620	02	23/06/02	100	1.0	360	12
07/07/02	100	1.0	780	00	01/07/02	100	1.0	540	42
15/07/02	100	1.0	980	05	14/07/02	100	1.0	860	37
21/07/02	100	1.0	1160	03	21/07/02	100	1.0	1020	38
27/07/02	100	1.0	1320	05	28/7/02	100	1.0	1280	55
02/08/02	100	1.0	1480	07	04/08/02	100	1.0	1440	70
09/08/02	100	1.0	1720	08	12/08/02	100	1.0	1660	66
16/08/02	100	1.0	1940	09	22/08/02	100	1.0	1940	76
24/08/02	100	1.0	2280	07	24/08/02	100	1.0	2180	60
07/09/02	100	1.0	2600	41	07/09/02	100	1.0	2460	59
18/09/02	100	1.0	2820	42	18/09/02	100	1.0	2680	63
28/09/02	100	1.0	3080	47	28/09/02	100	1.0	2840	77
08/10/02	100	1.0	3340	70	08/10/02	100	1.0	3100	116
08/10/02	200	1.0		45	20/10/02	100	1.0		120
08/10/02	200	1.0		48	20/10/02	100	1.0		134
08/10/02	200	1.0	3400	44	20/10/02	100	1.0	3360	128
20/10/02	200	1.0		45	20/10/02	200	1.0		89
20/10/02	200	1.0		38	20/10/02	200	1.0		92
20/10/02	200	1.0	3640	43	20/10/02	200	1.0	3420	85
28/10/02	200	1.0		41	28/10/02	300	1.0		79
28/10/02	200	1.0		38	28/10/02	300	1.0		77
28/10/02	200	1.0	3860	42	28/10/02	300	1.0	3620	85
10/11/02	200	1.0		32	30/10/02	400	1.0		45
10/11/02	200	1.0		32	30/10/02	400	1.0		48
10/11/02	200	1.0	4080	31	30/10/02	400	1.0	3740	58
24/12/02	200	1.0	4740	39	03/11/02	500	1.0		45
24/12/02	200	2.0		27	03/11/02	500	1.0		33
24/12/02	200	2.0		30	03/11/02	500	1.0	3880	34
24/12/02	200	2.0	4800	32	10/11/02	500	1.0		57
04/01/03	200	2.0		29	10/11/02	500	1.0		50
04/01/03	200	2.0		26	10/11/02	500	1.0	4080	58
04/01/03	200	2.0	4960	30	18/11/02	500	1.0		59
					18/11/02	500	1.0		63
					18/11/02	500	1.0	4300	53
					24/12/02	500	1.0	5080	63
					24/12/02	500	2.0	5140	40
					04/01/03	500	2.0		44
					04/01/03	500	2.0		44
					04/01/03	500	2.0	5360	34

Table B.6 Residual arsenic in the field unit (Alum = 100 ppm, Cl_2 = 0.45 ppm)

Date	Household unit A			Date	Household unit B		
	$KMnO_4$ ppm	Residual As(f)	Residual As(bf)		$KMnO_4$ ppm	Residual As(f)	Residual As(bf)
22/01/03	3.0	25		22/01/03	3.0	39	67
28/01/03	3.0	28		28/01/03	3.0	42	
28/01/03	3.0	32		28/01/03	3.0	44	
28/01/03	3.0	26		03/02/03	3.0	62	63
28/01/03	3.0	29		03/02/03	3.0	65	69
28/01/03	3.0	27		09/02/03	3.0	70	
28/01/03	3.0	29		09/02/03	3.0	68	
03/02/03	3.0	32		09/02/03	4.0	55	
03/02/03	3.0	33		09/02/03	4.0	39	
03/02/03	3.0	29		19/02/03	4.0	54	69
03/02/03	3.0	31		19/02/03	4.0	52	72
03/02/03	3.0	27		19/02/03	4.0	55	57
09/02/03	3.0	30	35	19/02/03	4.0	54	61
09/02/03	3.0	27	31	24/02/03	4.0	63	
09/02/03	3.0	31	25	24/02/03	4.0	66	
19/02/03	3.0	32		24/02/03	4.0	52	
19/02/03	3.0	28		24/02/03	4.0	56	
19/02/03	3.0	22		02/03/03	4.0	48	
24/02/03	3.0	25		02/03/03	4.0	53	
24/02/03	3.0	27		02/03/03	5.0	48	
24/02/03	3.0	26		02/03/03	5.0	52	
02/03/03	3.0	28	27	02/03/03	5.0	51	
02/03/03	3.0	30	34	02/03/03	5.0	52	
02/03/03	3.0	31	29	08/03/03	5.0	58	
08/03/03	3.0	36		08/03/03	5.0	48	
08/03/03	3.0	37		08/03/03	5.0	50	
08/03/03	3.0	30		08/03/03	5.0	41	
17/03/03	3.0	23		17/03/03	5.0	55	78
17/03/03	3.0	20		17/03/03	5.0	53	65
17/03/03	3.0	27		17/03/03	5.0	51	71
07/04/03	3.0	30	33	17/03/03	6.0	48	46
07/04/03	3.0	29	28	17/03/03	6.0	41	79
07/04/03	3.0	32	37	17/03/03	6.0	42	49
21/04/03	3.0	27					
21/04/03	3.0	26					
21/04/03	3.0	29					
28/04/03	3.0	28					
28/04/03	3.0	23					
28/04/03	3.0	24					
04/05/03	3.0	27	32				
04/05/03	3.0	24	41				
04/05/03	3.0	26	29				

Table B.7 Residual As after wash the sand bed unit-B (Alum =100 ppm, $KMnO_4$ =6 ppm, Cl_2 =0.45 ppm)

Date	Residual As(f) ppb	Residual As(bf) ppb	Date	Residual As(f) ppb	Residual As(bf) ppb
24/03/03	114	47	28/04/03	29	20
24/03/03	54	45	28/04/03	37	16
24/03/03	43	44	04/05/03	38	29
24/03/03	39	35	04/05/03	26	34
31/03/03	35	32	04/05/03	33	17
31/03/03	32	33	04/05/03	27	20
31/03/03	31	44	12/05/03	33	36
31/03/03	35	33	12/05/03	36	28
07/04/03	34	41	12/05/03	31	29
07/04/03	35	40	Change	sand	bed
07/04/03	31	61	12/05/03	0.01	
07/04/03	35	45	12/05/03	0.12	
15/04/03	41	33	12/05/03	0.11	
15/04/03	34	37	28/05/03	0.55	27
15/04/03	32	28	28/05/03	1.39	25
15/04/03	36	34	28/05/03	0.19	28
21/04/03	38	20	28/05/03	0.14	35
21/04/03	31	09	09/06/03	0.77	41
21/04/03	31	17	09/06/03	1..27	43
21/04/03	28	18	09/06/03	0.11	48
28/04/03	33	22	09/06/03	0.05	37
28/04/03	30	30			

Table B.8 Residual arsenic on the treated volume of water
(Alum = 100 ppm, $KMnO_4$ = 1 ppm, Cl_2 = 0.45 ppm)

Date	Household unit C		Household unit D		Household unit E	
	Treated water(L)	Residual As(f)	Treated water(L)	Residual As(f)	Treated water(L)	Residual As(f)
09/06/02	20	54	20	22	20	23
15/06/02	280	17	540	62	220	09
20/06/02	540	09	1020	04	360	04
28/06/02	940	11	1460	08	480	04
06/07/02	1360	11	2120	02	680	07
12/07/02	1780	09	2780	01	920	06
19/07/02	2140	07	3380	02	1040	67
27/07/02	2520	07	4060	05	1180	63
05/08/02	2960	07	4680	07	1320	17
15/08/02	3460	04	5240	04	1520	34
27/08/02	4120	04	6020	00	1740	23
08/09/02	4600	07	6640	01	1940	19
16/09/02	5140	02	7240	02	2220	13
21/09/02	5560	04	7720	04	2380	11
29/09/02	5920	00	8440	05	2640	19
10/10/02	6580	05	9280	09	2880	13
23/10/02	7420	12	10180	06	3120	05
15/11/02	8840	08	11640	07	3620	07
01/12/02	9920	07	12440	06	3960	04
18/12/02	10640	07	13280	02	4120	02
29/12/02	11080	07	13660	03	4460	02
19/01/03	11680	09	15640	05	4680	02
13/04/03	-	10	-	06	-	-
13/04/03	-	10	-	06	-	-

Table B.9 Oxidizing agent oxidize As(III) to As(V) in the field unit A & B

Unit	Raw As ppb	$KMnO_4$ ppm	Cl_2 ppm	As(III) ppb	As(V) ppb	Total As ppb
A	165	0	0	114	9	157
A	165	1	0.45	110	21	139
A	165	2	0.45	98	27	150
B	257	0	0	209	29	234
B	257	1	0.45	156	37	210
B	257	2	0.45	148	40	216

Table B.10 Effects on color and residual manganese on the $KMnO_4$ variation in the field unit-B (Alum = 100 ppm Cl_2 = 0.45 ppm)

Date	$KMnO_4$ ppm	Color Pt-Co	Residual Mn ppm	Date	$KMnO_4$ ppm	Color Pt-Co	Residual Mn ppm
11/01/03	0	14	0.017	07/04/03	6	17	0.003
	0	14	0.018		6	14	0.009
	0	12	0.015		6	07	0.002
11/01/03	1	15	0.013		6	12	-
	1	13	0.015	15/04/03	6	11	0.007
	1	13	0.010		6	14	0.003
13/01/03	2	12	0.022		6	10	0.008
	2	16	0.010		6	06	0.001
	2	18	0.010	28/04/03	6	17	0.009
13/01/03	3	13	0.016		6	09	0.001
	3	18	0.020		6	16	0.002
	3	15	0.011		6	14	0.005
08/03/03	5	00	0.008	05/05/03	6	15	0.004
	5	05	0.001		6	11	0.005
	5	00	0.004		6	14	0.005
17/03/03	6	07	0.002		6	10	0.004
	6	03	0.003	09/06/03	6	14	
	6	03	0.002		6	15	
24/03/03	6	02	-		6	13	
	6	00	-		6	13	0.004
	6	00	-				
31/03/03	6	13	0.008				
	6	07	0.001				
	6	04	0.005				

B.11 Infiltration rate of the field unit

Unit	A	B	C	D	E
X-section area (cm^2)	780	780	780	780	780
Treated volume of water (L)	17.5	17.5	17.5	17.5	17.5
Flow rate (L/min)	2.50	2.30	1.90	2.70	2.60
Infiltration (ml/min/cm^2)	3.20	2.95	2.44	3.46	3.33
Strainer surface area (cm^2)	215	215	215	215	215
Opening area (cm^2) 15%	32.5	32.5	32.5	32.5	32.5
Infiltration (ml/min/cm^2)	76.9	70.8	58.5	83.1	80.0

B.12 Chemical required on As removal

Oxidant for As(III) and Fe(II)	As(III)=300 ppb	Fe(II)=1ppm	F(II)=5 ppm
$KMnO_4$	0.844 ppm	0.954 ppm	4.72 ppm
Coagulant for PO_4	-	PO_4=1 ppm	PO_4=5 ppm
Alum	-	3.50 ppm	17.50 ppm

Appendix – C

Questionnaire Survey Information

QUESTIONNAIRE SURVEY ON USERS' ACCEPTANCE OF BUET ARU AT SONARGAON/SRINAGOR

HOUSEHOLD QUESTIONNAIR SURVEY: UNIT – A

General Information:

Name of the Respondent: M. Khalil Shaik
Father's Name: M. Waz Uddin Shaik
Educational Qualification: S.S.C.
Occupation: Business
Village: Basgaon
Union: Pata Bhog
Upazila: Srinagor
District: Munshiganj
Number of Men in the household: 3
Number of Women in the household: 5
Number of Children in the household: 0
Date of Interview: 11/08/2002

Question and Answers:

01. What is your opinion about the treated water quality in respect to:
    Taste: a) Good √ b) Bad
    Smell: a) Yes b) No √
    Color: a) Yes b) No √
02. How much water do you treat in a day?
    20 – 40 L (two buckets)
03. Can this ARU meet your demand for water?
    a) Yes √ b) No

04. How much time do you spend to operate the Unit (one time)?
    15 minutes
05. What is the condition of effluent flow rate with cumulative treated water volume?
    a) Increases b) No change c) Decreases √

06. For what purposes the treated water is used?
    a) Drinking √ b) Cooking c) Washing d) Others

07. W□□v is the distance of the tubewell from the Unit?
    30 ft.
08. What is the distance of the Arsenic free water source from the Unit?
    1500 ft.
09. How many turns do you rotate the wooden stick to mix the red solution in the bucket water?
    6 – 8 turns

10. How many turns do you rotate the wooden stick to mix the white powder in the bucket water?
    40 – 50 turns
11. What is the time gap between mixing of the red solution in the bucket water and mixing the white powder?
    5 minutes
12. What is the time gap between starting time of the Unit and collection of water?
    60 minutes
13. Who mixes the red solution in the bucket water?
    a) Self b) Another member of the family √ c) Supervisor

14. Where do you dispose the residue/sludge of the bucket?
    a) Cow dung bed b) Drain c) Pond d) Land √ e) Other places

15. How much money you are willing to spend for buying the ARU?
    400 – 500 Tk.
16. What should be the mode of use of the Unit?
    a) Individually √ b) Collectively

17. How much money you are willing to spend monthly for chemical to run the Unit?
    25 – 30 Tk.
18. Who maintains the Unit?
    a) Self b) Another member of the family √ c) Supervisor

19. Do you want to always use this Unit?
    a) Yes √ b) No

20. Do you discus the villager's about this Arsenic Removal Unit?
    a) Yes √ b) No

21. If the questio□□□o. 20 is yes, are the villager's willing to buy the Unit?
    a) Yes √ b) No

22. Do you know the Arsenicosis problem?
    a) Yes √ b) No

23. Do you use the other type of ARU before use this Unit?
    a) Yes √ b) No

24. If the question no. 23 is yes, is this Unit works better than that?
    a) Yes √ b) No

25. List the problems you faced in using this Unit.
    Chemical use
    Plastic Container
    Water collection

QUESTIONNAIRE SURVEY ON USERS' ACCEPTANCE OF BUET ARU AT SONARGAON/SRINAGOR

HOUSEHOLD QUESTIONNAIR SURVEY: UNIT – B

General Information:

Name of the Respondent: M. Riaz Uddin
Father's Name: M. Ophaz Uddin
Educational Qualification: Class VIII
Occupation: Farmer
Village: Basail Bhog
Union: Pata Bhog
Upazila: Srinagor
District: Munshiganj
Number of Men in the household: 5
Number of Women in the household: 4
Number of Children in the household: 2
Date of Interview: 11/08/2002

Question and Answers:

01. What is your opinion about the treated water quality in respect to:
    Taste: a) Good √ b) Bad
    Smell: a) Yes b) No √
    Color: a) Yes b) No √
02. How much water do you treat in a day?
    20 – 40 L (two buckets)
03. Can this ARU meet your demand for water?
    a) Yes √ b) No

04. How much time do you spend to operate the Unit (one time)?
    12 – 15 minutes
05. What is the condition of effluent flow rate with cumulative treated water volume?
    a) Increases b) No change c) Decreases √
06. For what purposes the treated water is used?
    a) Drinking √ b) Cooking c) Washing d) Others

07. What is the distance of the tubewell from the Unit?
    15 ft.
08. What is the distance of the Arsenic free water source from the Unit?
    200 ft.
09. How many turns do you rotate the wooden stick to mix the red solution in the bucket water?
    6 – 8 turns

10. How many turns do you rotate the wooden stick to mix the white powder in the bucket water?
    50 turns
11. What is the time gap between mixing of the red solution in the bucket water and mixing the white powder?
    5 minutes
12. What is the time gap between starting time of the Unit and collection of water?
    60 minutes
13. Who mixes the red solution in the bucket water?
    a) Self b) Another member of the family √ c) Supervisor

14. Where do you dispose the residue/sludge of the bucket?
    a) Cow dung bed √ b) Drain c) Pond d) Land e) Other places
15. How much money you are willing to spend for buying the ARU?
    500 – 600 Tk.
16. What should be the mode of use of the Unit?
    30 – 35 Tk.
    a) Individually √ b) Collectively

17. How much money you are willing to spend monthly for chemical to run the Unit?

18. Who maintains the Unit?
    a) Self b) Another member of the family √ c) Supervisor

19. Do you want to always use this Unit?
    a) Yes √ b) No

20. Do you discus the villager's about this Arsenic Removal Unit?
    a) Yes √ b) No

21. If the question no. 20 is yes, are the villager's willing to buy the Unit?
    a) Yes √ b) No

22. Do you know the Arsenicosis problem?
    a) Yes √ b) No

23. Do you use the other type of ARU before use this Unit?
    a) Yes b) No √

24. If the question no. 23 is yes, is this Unit works better than that?
    a) Yes b) No

25. List the problems you faced in using this Unit.
    Time
    Height of the unit
    Chemical Use

QUESTIONNAIRE SURVEY ON USERS' ACCEPTANCE OF BUET ARU AT SONARGAON/SRINAGOR

HOUSEHOLD QUESTIONNAIR SURVEY: UNIT – C

General Information:

Name of the Respondent: m. Abu Mia
Father's Name: M. Kazem Ali Munsi
Educational Qualification: Class VIII
Occupation: Business
Village: Echapara
Union: Aminpur
Upazila: Snargaon
District: Narayanganj
Number of Men in the household: 12
Number of Women in the household: 8
Number of Children in the household: 3
Date of Interview: 18/08/2002

Question and Answers:

03. What is your opinion about the treated water quality in respect to:
    Taste: a) Good √ b) Bad
    Smell: a) Yes b) No√
    Color: a) Yes b) No√
04. How much water do you treat in a day?
    40 – 60 L
03. Can this ARU meet your demand for water?
    a) Yes √ b) No

04. How much time do you spend to operate the Unit (one time)?
    15 minutes
05. What is the condition of effluent flow rate with cumulative treated water volume?
    a) Increases b) No change c) Decreases √

06. For what purposes the treated water is used?
    a) Drinking √ b) Cooking c) Washing d) Others

07. What is the distance of the tubewell from the Unit?
    20 ft.
08. What is the distance of the Arsenic free water source from the Unit?
    600 ft.
09. How many turns do you rotate the wooden stick to mix the red solution in the bucket water?
    5 – 7 turns

10. How many turns do you rotate the wooden stick to mix the white powder in the bucket water?
    45 – 50 turns
11. What is the time gap between mixing of the red solution in the bucket water and mixing the white powder?
    5 minutes
12. What is the time gap between starting time of the Unit and collection of water?
    60 minutes
13. Who mixes the red solution in the bucket water?
    a) Self b) Another member of the family √ c) Supervisor

14. Where do you dispose the residue/sludge of the bucket?
    a) Cow dung bed b) Drain c) Pond d) Land √ e) Other places

15. How much money you are willing to spend for buying the ARU?
    300 – 400 Tk.
16. What should be the mode of use of the Unit?
    a) Individually b) Collectively √

17. How much money you are willing to spend monthly for chemical to run the Unit?
    20 – 25 Tk.
18. Who maintains the Unit?
    a) Self b) Another member of the family √ c) Supervisor

19. Do you want to always use this Unit?
    a) Yes √ b) No

20. Do you discus the villager's about this Arsenic Removal Unit?
    a) Yes √ b) No

21. If the question no. 20 is yes, are the villager's willing to buy the Unit?
    a) Yes √ b) No

22. Do you know the Arsenicosis problem?
    a) Yes √ b) No

23. Do you use the other type of ARU before use this Unit?
    a) Yes b) No √

24. If the question no. 23 is yes, is this Unit works better than that?
    a) Yes b) No
25. List the problems you faced in using this Unit.
    Chemical Use
    Water Collection
    Height of the unit

QUESTIONNAIRE SURVEY ON USERS' ACCEPTANCE OF BUET ARU AT SONARGAON/SRINAGOR

HOUSEHOLD QUESTIONNAIR SURVEY: UNIT – D

General Information:

Name of the Respondent: Masuda Faroque
Husbend's Name: M. faroque Ahmed
Educational Qualification: H. S. C.
Occupation: Teacher
Village: Dolerbag
Union: Udobganj
Upazila: Sonargaon
District: Narayanganj
Num`gr of Men in the household: 4
Number of Women in the household: 7
Number of Children in the household: 5
Date of Interview: 27/08/2002

Question and Answers:

05. What is your opinion about the treated water quality in respect to:
    Taste: a) Good √ b) Bad
    Smell: a) Yes b) No √
    Color: a) Yes b) No √
06. How much water do you treat in a day?
    60 – 80 L
03. Can this ARU meet your demand for water?
    a) Yes √ b) No
04. How much time do you spend to operate the Unit (one time)?
    12 – 15 minutes
05. What is the condition of effluent flow rate with cumulative treated water volume?
    a) Increases b) No change √ c) Decreases

06. For what purposes the treated water is used?
    a) Drinking √ b) Cooking √ c) Washing √ d) Others

07. What is the distance of the tubewell from the Unit?
    25 ft.
08. What is the distance of the Arsenic free water source from the Unit?
    400 ft.
09. How many turns do you rotate the wooden stick to mix the red solution in the bucket water?
    5 – 7 turns

10. How many turns do you rotate the wooden stick to mix the white powder in the bucket water?
    40 – 45 turns
11. What is the time gap between mixing of the red solution in the bucket water and mixing the white powder?
    5 minutes
12. What is the time gap between starting time of the Unit and collection of water?
    60 minutes
13. Who mixes the red solution in the bucket water?
    a) Self √ b) Another member of the family c) Supervisor
14. Where do you dispose the residue/sludge of the bucket?
    a) Cow dung bed b) Drain c) Pond d) Land √ e) Other places
15. How much money you are willing to spend for buying the ARU?
    400 – 500 Tk.
16. What should be the mode of use of the Unit?
    a) Individually b) Collectively √
17. How much money you are willing to spend monthly for chemical to run the Unit?
    20 – 25 Tk.
18. Who maintains the Unit?
    a) Self √ b) Another member of the family c) Supervisor
19. Do you want to always use this Unit?
    a) Yes √ b) No
20. Do you discus the villager's about this Arsenic Removal Unit?
    a) Yes √ b) No
21. If the question no. 20 is yes, are the villager's willing to buy the Unit?
    a) Yes √ b) No
22. Do you know the Arsenicosis problem?
    a) Yes √ b) No
23. Do you use the other type of ARU before use this Unit?
    a) Yes √ b) No
24. If the question no. 23 is yes, is this Unit works better than that?
    a) Yes √ b) No
25. List the problems you faced in using this Unit.
    Water Collection
    Height of the unit

QUESTIONNAIRE SURVEY ON USERS' ACCEPTANCE OF BUET ARU AT SONARGAON/SRINAGOR

HOUSEHOLD QUESTIONNAIR SURVEY: UNIT – E

General Information:

Name of the Respondent: M. Nuruddin
Father's Name: M. Tazim Uddin
Educational Qualification: H. S. C.
Occupation: Business
Village: Dolerbag
Union: Udobganj
Upazila: Sonargaon
District: Narayanganj
Number of Men in the household: 4
Number of Women in the household: 2
Number of Children in the household: 0
Date of Interview: 18/08/2002

Question and Answers:

07. What is your opinion about the treated water quality in respect to:
    Taste: a) Good √ b) Bad
    Smell: a) Yes b) No √
    Color: a) Yes b) No √
08. How much water do you treat in a day?
    20 L
03. Can this ARU meet your demand for water?
    a) Yes √ b) No

04. How much time do you spend to operate the Unit (one time)?
    10 – 12 minutes
05. What is the condition of effluent flow rate with cumulative treated water volume?
    a) Increases b) No change √ c) Decreases

06. For what purposes the treated water is used?
    a) Drinking √ b) Cooking c) Washing d) Others

07. What is the distance of the tubewell from the Unit?
    20 ft.
08. What is the distance of the Arsenic free water source from the Unit?
    200 ft.
09. How many turns do you rotate the wooden stick to mix the red solution in the bucket water?
    5 – 7 turns

XXX

10. How many turns do you rotate the wooden stick to mix the white powder in the bucket water?
    40 – 50 turns
11. What is the time gap between mixing of the red solution in the bucket water and mixing the white powder?
    5 minutes
12. What is the time gap between starting time of the Unit and collection of water?
    60 minitues
13. Who mixes the red solution in the bucket water?
    a) Self b) Another member of the family √ c) Supervisor

14. Where do you dispose the residue/sludge of the bucket?
    a) Cow dung bed √ b) Drain c) Pond d) Land e) Other places

15. How much money you are willing to spend for buying the ARU?
    300 – 400 Tk.
16. What should be the mode of use of the Unit?
    a) Individually √ b) Collectively

17. How much money you are willing to spend monthly for chemical to run the Unit?
    25 – 30 Tk.
18. Who maintains the Unit?
    a) Self b) Another member of the family √ c) Supervisor

19. Do you want to always use this Unit?
    a) Yes √ b) No

20. Do you discus the villager's about this Arsenic Removal Unit?
    a) Yes √ b) No

21. If the question no. 20 is yes, are the villager's willing to buy the Unit?
    a) Yes √ b) No

22. Do you know the Arsenicosis problem?
    a) Yes √ b) No

23. Do you use the other type of ARU before use this Unit?
    a) Yes b) No √

24. If the question no. 23 is yes, is this Unit works better than that?
    a) Yes b) No

25. List the problems you faced in using this Unit.
    Water Collection
    Chemical Use
    Plastic Container