Dearsenation of Drinking Water by Means of Coagulation in Bangladesh

Master Thesis

for

Qin Liang (C958419)

at

Institute of Environmental Science and Engineering

Copenhagen 1998

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Title: *Dearsenation of Drinking Water by Means of Coagulation in Bangladesh*

Background: In recent years, occurrence of arsenic at high levels in the ground water has increasingly been acknowledged in West Bengal and Bangladesh. Due to limitations in capacity of epidemiological and chemical testing, the arsenic problems are yet not precisely sized. However, the information gained so far confirms that the region accommodates a vast arsenic belt inhabited by more than 70 millions of people. It seems no doubt that the West Bengal-Bangladesh arsenic problem is the largest arsenic calamity for now in the world. The occurrence of arsenic in water is mainly confined to shallow and intermediate depth It is therefore to a large extent related to the use of hand pumps in the rural areas.

Objective: The purpose of the project is to test and optimize a proper method for arsenic removal, which is suitable for use in Bangladesh. Selection and optimization of the method are first to be carried out in a laboratory, and then to be tested in a bucket system

Contents: The contents of the project are as follows:

1. Literature survey on arsenic removal.

2. Selection of a most promising method for testing, e.g. coagulation / co-precipitation method.

3 Optimization of the removal process through the following steps:

   - Analyzing arsenic and iron concentrations in the water samples from Iron Removal Units (IRU) in Noakhali and finding out if the IRU can remove some of arsenic and the relation, if any, between iron removal and arsenic removal.

   - In the laboratory, water from one of the IRU will be used for testing Arsenic removal process by means of Jar Test Apparatus (JTA). Different chemicals will be added either separately or in combination into the water samples. These chemicals include ferric chloride ($FeCl_3 \cdot 6H_2O$), alum ($Al_2(SO_4)_3 \cdot xH_2O$) and rice husk, which are available in the local market. Different dosages will be used. The initial and residual concentrations of arsenic, iron and pH will be measured. Since it has been proved that arsenic removal efficiency is higher when arsenic is in the form of arsenate, the tested water will be oxidized in advance by adding sodium hypochloride ($NaClO$) / beaching powder.

- Selecting an appropriate speed and duration for mixing, and estimating the production of obtained sludge and the yield of treated water.

- Testing of a simple filtration to assure a complete sedimentation of the sludge.

4. Applying the optimal method to a bucket system in laboratory in Noakhali.

5. Evaluation of the MERCK Arsenic Test kit.

Duration of the project: August 1997 - January 1998, in which three months were spent for field work in Bangladesh.

Evaluation: 13 scale based report and oral presentation.

Supervision: In Denmark, Assoc. Professor Jens Christian Tjell. In Bangladesh Assoc. Professor Eli Dahi and Dr. Jens Thøgersen.

PREFACE

The present report is the result of my master thesis project carried out in the period from August 1997 to January 1998. The project is consisted of a research work on dearsenation by means of coagulation. The results of this project may help solving the serious problem related with drinking water contaminated by arsenic.

All the experiment work was performed in a 3 month stay in Bangladesh. The jar test experiments were done in the laboratory at BUET (Bangladesh University of Environment Engineering) and most of the analyses and bucket test experiments were done in a newly established laboratory for DPHE - Danida Urban Water and Sanitation Project (UWASP) in Noakhali, Bangladesh.

The Technical University of Denmark (DTU), which covered the travel expense for this study trip, and UWASP, which financially supported this project with accommodation in Noakhali, cost of chemicals and laboratory facilities etc. for the experimental work, are sincerely appreciated.

I would also like to express my sincere appreciations to all staff at UWASP who offered me a lot of help and with whom I enjoyed my stay in Noakhali

Many thanks are given to BUET and its staff members who allowed me to use their laboratory and helped me a lot with my work during my stay in Bangladesh.

In carrying out the field work, great help was offered by Poul, Arne, Kaj, Henrik, and Palle, Danida consultants in Bangladesh

The supervisors of this project were Assoc. Prof. Jens Christian Tjell (in Danmak), and Assoc. Prof Eli Dahi and Dr. Jens Thøgersen (in Bangladesh), to whom I owe a great deal for their advice and assistance through the whole period of this project.

SUMMARY

Arsenic

Arsenic has been called the "King of Poisons". Yet it is found in drinking water spot wise all over the world The natural arsenic problems are related to its chronic toxicity and to the fact that it is tasteless, odorless and colorless.

As in Bangladesh

During the recent years arsenic is measured in the groundwater and arsenosis is observed increasingly among communities of Bangladesh, thus adding one more serious calamity and creating a new major health concern in the country. A simple, affordable, technically feasible and socially acceptable arsenic removal method for safe drinking water treatment at household level is very much on demand.

IRU

25 iron removal plants attached to hand pumps in Noakhali are studied with respect to iron and arsenic removal. It is found that the arsenic removal, on an average, is about 65 % , at great variation though.

Methods of Removal

From the literature survey it is found that coagulation using ferric chloride and alum may be the most appropriate methods for removing arsenic from drinking water in rural Bangladesh. Experiments on Noakhali water have demonstrated that both methods are able to remove arsenic to acceptable levels. Formulas are derived for calculation of an appropriate dosage according to normal sorption modeling. Furthermore, mixing is found to be an important operation parameter. The required mixing and corresponding resulting water quality criteria are specified.

Rice Husk

The rice husk method recommended by UNICEF in Bangladesh is tested and found quit good in its ability to remove arsenic. However, this method results in treated water of repelling appearance.

Combination with use of alum and ferric chloride in order to improve the method has been tested and found to be feasible, but still insufficient to allow for expected successful implementation.

Sludge Disposal

It is noticed that the three studied methods result in considerable amounts of sludge, which has to be disposed. Appropriate solutions to the sludge problems are yet to be elaborated upon.

Analysis Method

As a part of the project the most recent Standard Method for laboratory testing of arsenic was developed in Denmark and set up in Bangladesh for first time. The method was used to obtain the study results Furthermore, a field test kit was tested and calibrated with the standard method. It was found that the kit hits the right value as estimated spectrophotometrically in the laboratory standard method, at a significant level of 5 %. The variation is considerable though.

LIST OF SYMBOLS

$Al_2(SO_4)_3\ xH_2O$	Alum
As	Arsenic
As(III)	Arsenite
As(V)	Arsenate
SDDC	Silver DiethylDithioCarbamate
RH	Rice Husk
F. C.	Ferric Chloride
BP	Bleaching Powder
BD	Bed Volume
BT	Bucket Test
BUET	Bangladesh University of Environment Engineering
WHO	World Health Organization
UWASP	DPHE - Danida Urban Water and Sanitation Project
NIPSON	National Institute of Preventive and Social Medicine
EBD	Empty Bed Volume
EQS	the proposed Environmental Quality Standards
IRU	Iron Removal Unit
MCL	Maximum Contaminant Level
JT	Jar Test
JTA	Jar Test Apparatus
RPM	Rotation per Minute
V	Volume
bgl	Below Ground Level
Conc.	Concentration
Fe_{Raw}	Iron concentration in the raw water
As_{Raw}	Arsenic concentration in the raw water
$Fe_{Residual}$	Iron concentration in the treated water
$As_{Residual}$	Arsenic concentration in the treated water
St. Dev	Standard Deviation
sec	Second
min	Minute
Set.	Settling
Abs	Absorbence

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1. INTRODUCTION

1.1. Background

Arsenic is a silvery-white very brittle crystalline semi-metallic element. Its chemical symbol is As, having the atomic number 33 Arsenic is the 20th most abundant element in the Earth's crust, approximately 2-5 mg/kg, and the 12th most abundant element in the human body / Viraraghavan et al., 1994; WHO Vol. 1, 1993; WHO Vol. 2. 1996; WHO, 1981; Robert et al., 1986; Ernest & Christopher, 1995; Parker, 1992/. Though arsenic is believed to be an essential element for some animals, and proved to be beneficial for the growth of some livestock /Emsley, 1985/, it has never been scientifically proved as an essential element in humans. On the contrary, arsenic is proved to cause several adverse health effects, both acute and chronic. Animal studies have not shown any significant relationship between intake of arsenic and increase in the incidence of cancer. However, data from Taiwan show clearly that arsenic in drinking water is responsible for an increased cancer incidence /WHO vol. 1, 1993; WHO vol. 2, 1996/.

The exposure to arsenic through drinking water can be more significant than through food, even in situations where more arsenic is consumed through the food. This is because arsenic in water is predominantly in its most toxic inorganic form. Thus the health hazard from arsenic in nature is mainly a function of the arsenic concentration in the drinking water /Liang & Sharma, 1997/.

Groundwater, in general, is the preferred water resource. This is because the groundwater quality is normally acceptable without any treatment, and because of the availability at the user sites, without long distance transportation. However spot wise, in many places all over the world, arsenic is leaching from anoxic geological materials and occurring in the ground waters at too high concentrations. Thus the arsenic contamination of drinking water supplies is, spot wise, a world-wide problem of increasing dimensions and public health concern. The presence of arsenic at elevated level and the resulting harm effects on the health have been reported in many areas, e. g. in the United States, Chile, Bangladesh, Taiwan, Mongolia, Xinjiang (China), West Bengal (India).

In Bangladesh, traditionally, the surface water is the principal source for drinking. However, during the recent decades, and due to intensive development programmers, the groundwater is utilized for drinking potential in most rural areas. Today, the water supply in rural Bangladesh is primarily based on groundwater sources. During the last decade there has been considerable tapping of the groundwater not only for drinking but also for irrigation purposes /Quadiruzzaman, 1997/. At present, Bangladesh has a total of 2.5 millions of hand tube wells working in the rural areas. 95 % of the rural population in Bangladesh has today access to tube well water. Traditionally these water supplies used to be thought of as "safe". Unfortunately, recent investigations have demonstrated an almost country wide occurrence of too high arsenic levels in the tube well waters. Today Bangladesh seems to be one of the most arsenic affected countries in the world /Bhattacharya et al., 1997/.

Compared to other arsenic affected countries, the arsenic problem in Bangladesh has been discovered very recently. The first samples of arsenic contaminated water were analyzed as late as 1993. Much work has been carried out since. Today it can be stated that at least 34 districts out of the 64 districts of Bangladesh do have arsenic problems The prevalence of arsenic illnesses has been detected by NIPSOM (National Institute of Preventive and Social Medicine), so far concerning 2300 cases in 25 districts. Similar data are also reported by Dhaka Community Hospital /Dahi, 1997b/.

Groundwater in the deeper aquifers in Bangladesh, i e 150 - 300 m bgl, show acceptable concentrations of arsenic, below 0.05 mg/l. Thus extraction of water from such tube wells is considered to be an appropriate health promotion measure with respect to as well microbiological as chemical parameters. The use of the deep aquifers remains to be the most viable alternative to safeguarding the drinking water supply. However the extraction of drinking water from the deep aquifers by hand pumps is quit expensive in installation costs and the risk of future intrusion of arsenic to these aquifers can not be neglected This could be due to leaching and downward movement of soluble arsenic from the overlying sediments resulting from forced extraction of ground water /Bhattacharya et al., 1997/

Bangladesh is already a poor disaster prone country. It is particularly subjected to calamities like epidemics, flood and cyclone. Considering the abject poverty in Bangladesh (the GNP is US $230 per capita) and the high illiteracy, efficient removal of arsenic from drinking water in high-cost, full-scale treatment plants is not a viable solution to the arsenic problem, especially in rural areas. Because of the dependence of the rural population on groundwater, there is an urgent need to develop suitable treatment methods for removal of arsenic from the groundwater A simple, affordable, technically feasible and socially acceptable arsenic removal method for safe drinking water treatment at household level in rural and semi - urban areas of Bangladesh is very much on demand

1.2. Project Aim

The aim of this project is to elaborate on a suitable method to remove excessive arsenic from groundwater in rural Bangladesh One of the most promising methods is the traditional coagulation process using locally available coagulants It is here of particular interest to find out how the process can be run in house hold buckets, which chemicals could be used, which dosage may be required, how mixing should be performed and what are the water quality implications.

As rural Bangladesh is already burdened with the problems of occurrence of iron in the ground water, this project aims furthermore on investigating the relation between simultaneous emerging of iron and arsenic, and on the arsenic removal along with iron in Iron Removal Units (IRUs) as installed in Noakhali district.

Furthermore, because the arsenic testing is not yet standardized in Bangladesh and several methods are used, this project evolved an elaboration on analysis techniques which may be useful for field and laboratory testing of arsenic in raw and treated water.

2. LITERATURE SURVEY

2.1. Occurrence of Arsenic in Groundwater

Arsenic is found widely distributed in nature, in igneous rocks and in ores in earth crust. It is ranked as the 20th most abundant element in the earth's crust, where it is found as a components of more than 245 naturally occurring minerals, some of which are listed in Table 1. /Kartinen & Martin, 1995; Cullen & Reimer, 1989; Azcue & Nriagu, 1994/.

Table 1. The most common naturally occurring arsenic-bearing minerals /Azcue & Nriagu, 1994/.

Name	Formula
Arsenargentite	Ag_3As
Chloanthite	$(Ni, Co)As_{3-x}$
Domeykite	(Cu_3As)
Loellingite	$FeAs_2$
Niccolite	NiAs
Safflorite	$(Co, Fe)As_2$
Sperrylite	$PtAs_2$
Skutterudite	$(Co, Ni)As_3$
Orpiment	As_2S_3
Realgar	AsS
Arsenopyrite	FeAsS
Cobaltite	CoAsS
Enargite	$Cu_3As\ S_4$
Tennantite	$(Cu, Fe)_{12}As_4S_{13}$
Pearceite	$Ag_{16}As_2S_{11}$
Proustite	Ag_3AsS_3
Gersdorffite	NiAsS
Glaucodote	(Co, Fe)AsS
Arsenolite	As_2O_3
Adamite	Zn_2AsO_4OH
Olivenite	Cu_2AsO_4OH
Scorodite	$(Fe, Al)(AsO_4) \cdot 2H_2O$
Pharmacosiderite	$Fe_3(AsO_4)_2(OH)_3 \cdot 5H_2O$

The source of arsenic in the natural water is generally related to the process of leaching from geological materials and sediments derived from the arsenic bearing minerals, inputs from geothermal sources, mining wastes and landfills /Welch et al., 1988; Korte & Fernando, 1991; Robertson, 1989/. Uncontrolled anthropogenic activities such as smelting of metal ores, use of arsenical pesticides, wood preservative agents, and other various arsenicals (see Table 2) may release arsenic directly to the environment /Bhattacharya et al., 1997/.

Table 2. Some uses of arsenic within different sectors /Azcue & Nriagu, 1994/.

Sector	Uses
Agriculture	pesticides, insecticides, defoliants, wood preservatives, debarking trees, soil sterilant
Livestock	Feed additives, disease prevention (swine dysentery, heart worn infection), cattle and sheep dips, algaecides.
Medicine	Antisyphilitic drugs, treatment of trypanosomiasis, amebiasis, sleeping sickness.
Electronics	Solar cells, optoelectronic devices, semiconductor applications, light-emitting diodes (digital watches).
Industry	Glassware, electrophotography, catalysts, pyrotechnics, antifouling paints, dyes and soaps, ceramics, pharmaceutical substances.
Metallurgy	Alloys (automotive body solder and radiators), battery plates (hardening agents).

In the Bengal delta plains, mineralogical investigations have revealed that arsenic occurs in the silty clay as well as in the sandy ground layers, as a coating on the mineral grains Probably arsenopyrite is a main compound in the alluvial underground of the delta plain /Bhattacharya et al., 1996; Bhattacharya et al , 1997/.

Occurrence of arsenic in the natural water depends on the local geology, hydrology and geochemical characteristics of the aquifer materials Furthermore the organic contents as well as the land-use pattern may be important factors in controlling the natural mobility of arsenic in the alluvial underground Under anoxic conditions the mobilization of arsenic is the reason for the overall greater risk for contamination of groundwater as compared to surface water

In the West Bengal-Bangladesh arsenic contaminated belt, groundwater occurs in both confined and unconfined aquifers Broadly the aquifers are classified in three groups:

- The shallow aquifers, less than 50 m bgl
- The intermediate aquifers, between 50 and 150 m bgl
- The deep aquifers, more than 150 m bgl.

The experiences gained in West Bengal shows, in general, that the arsenic is detected in shallow and intermediate aquifers. As a rule, the arsenic contents decreases with increasing depth. Excessive withdrawal of ground water and the seasonal groundwater draw down during dry months, are speculated to facilitate mobilization of arsenic from the underground formations to the aquifer water. The exposure of these formations, which contain arsenic immobilized as e.g. arsenopyrite, to atmospheric or dissolved oxygen, results in an oxidation which would lead to the arsenic contamination of the groundwater /Dahi, 1997e/.

According to /Bhattacharya et al., 1997/ the arsenic contained in pyrite or asenopyrite has been deposited in the sediments and partly redistributed there. The part contained in clays may have remained in its initial form while in the sandy sediments it has been oxidezed and adsorbed onto ferric coatings of the sand grains. The arsenic is mobilized mainly by two processes:

- Oxidation of pyrite and /or arsenopyrite in clay intercalations.
- Reduction of ferric coatings on sand releasing arsenic and adsorbed phosphate.

Anaerobic conditions leading to reduction of ferric iron seems to be the most plausible mechanism for the formation of the observed hydrochemical conditions in the UDP /Bhattacharya et al., 1997/.

The oxidation processes of arsenopyrite and the arsenic sulfides realgar and orpiment may be described by the following equations /Mok & Wai, 1994; Bhumbla & Keefer, 1994/:

$$4FeAsS + 13O_2 + 6H_2O \rightarrow 4FeSO_4 + 4H_3AsO_4 \qquad \text{eq. 1}$$

$$4AsS + 11O_2 + 10H_2O \rightarrow 4H_2SO_4 + 4H_3AsO_4 \qquad \text{eq. 2}$$

$$As_2S_3 + 7O_2 + 6H_2O \rightarrow 3H_2SO_4 + 2H_3AsO_4 \qquad \text{eq. 3}$$

2.2. Arsenic Chemistry

Arsenic is an element of group Va in the periodic table along with N, P, Sb and Bi, and is characterised by its outer $4s^24p^3$ electronic configuration with its half-filled 4p sub-shell. This configuration gives arsenic tremendous range of chemistry, with oxidation states -3, 0, +3, +5 /Viraraghavan et al., 1994, Robert et al., 1986; Kotz & Purcell, 1991; Parker, 1992; O'Neill, 1990; O'Neill, 1995/.

2.2.1. Aquatic Chemistry

As mentioned above, arsenic occurs in 4 oxidation states. The most common oxidation states in the natural water are +3 and +5. Though both organic and inorganic forms of arsenic are present in natural water systems, the inorganic arsenic is dominant, whereas the organic species are rarely present at concentration > 0.001 mg/l /Cheng et al., 1994; Edwards, 1994; Hering, 1996; Kartinen &Martin, 1995; Viraraghavan et al., 1994, Mariner et al., 1996/.

The presence of different arsenic species in aquatic systems depends largely upon the pH and the oxidation potential of the water. The stability and the predominance of arsenic species in the aquatic environments at different pH ranges are shown in Table 3 and Figure 1 /Edwards, 1994; Kartinen &Martin, 1995; Viraraghavan et al., 1994; Mariner et al., 1996, O'Neill, 1990, O'Neill, 1995/.

Table 3. Stability and predominance of arsenic species in varying pH ranges in the aquatic environments /Viraraghavan et al., 1994/.

PH	0-9	10-12	13	14
As(III)	H_3AsO_3	$H_2AsO_3^-$	$HAsO_3^{2-}$	AsO_3^{3-}
PH	0-2	3-6	7-11	12-14
As(V)	H_3AsO_4	$H_2AsO_4^-$	$HAsO_4^{2-}$	AsO_4^{3-}

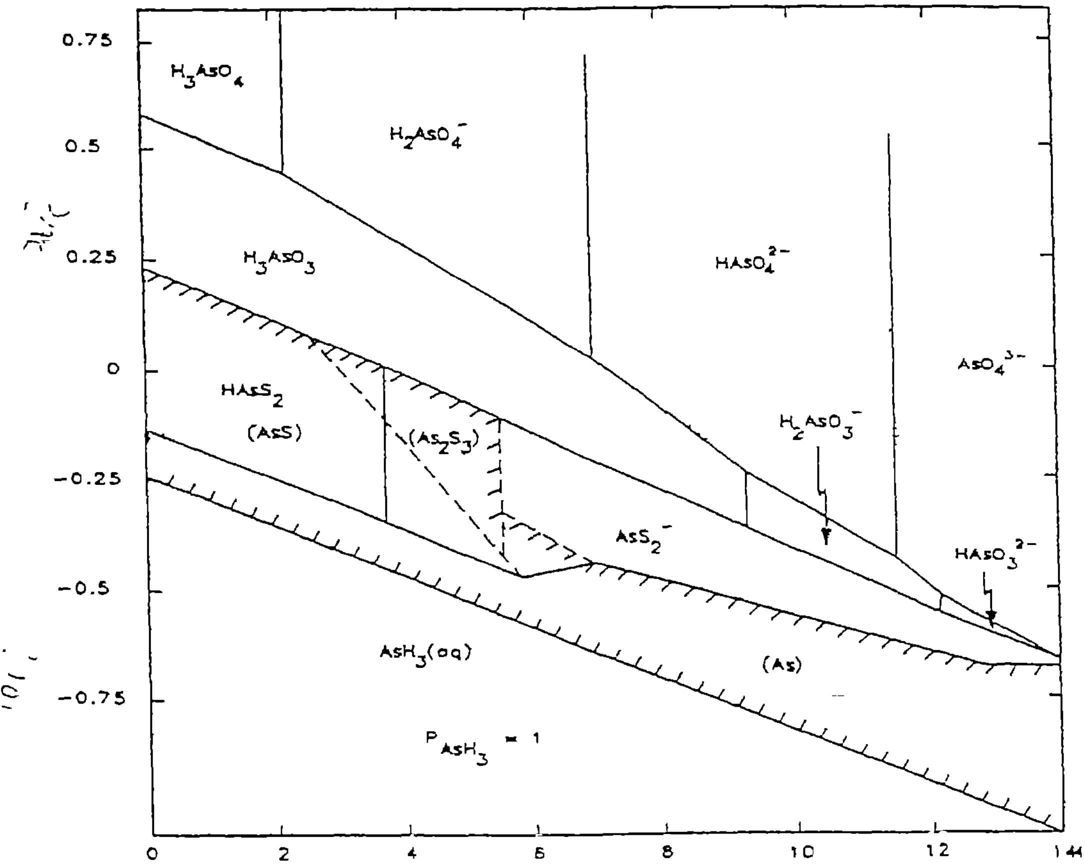

Figure 1. Speciation of arsenic as a function of pH and Eh /Korte & Fernando, 1991/.

Generally speaking, *arsenate (V)* is the thermodynamically stable and dominating form of the inorganic arsenic species in *oxic* waters, whereas *arsenite (III)* is the stable and dominating form of the inorganic arsenic species under *unoxic* conditions. Under strictly unaerobic conditions, the arsenic sulfides are thermodynamically most probable.

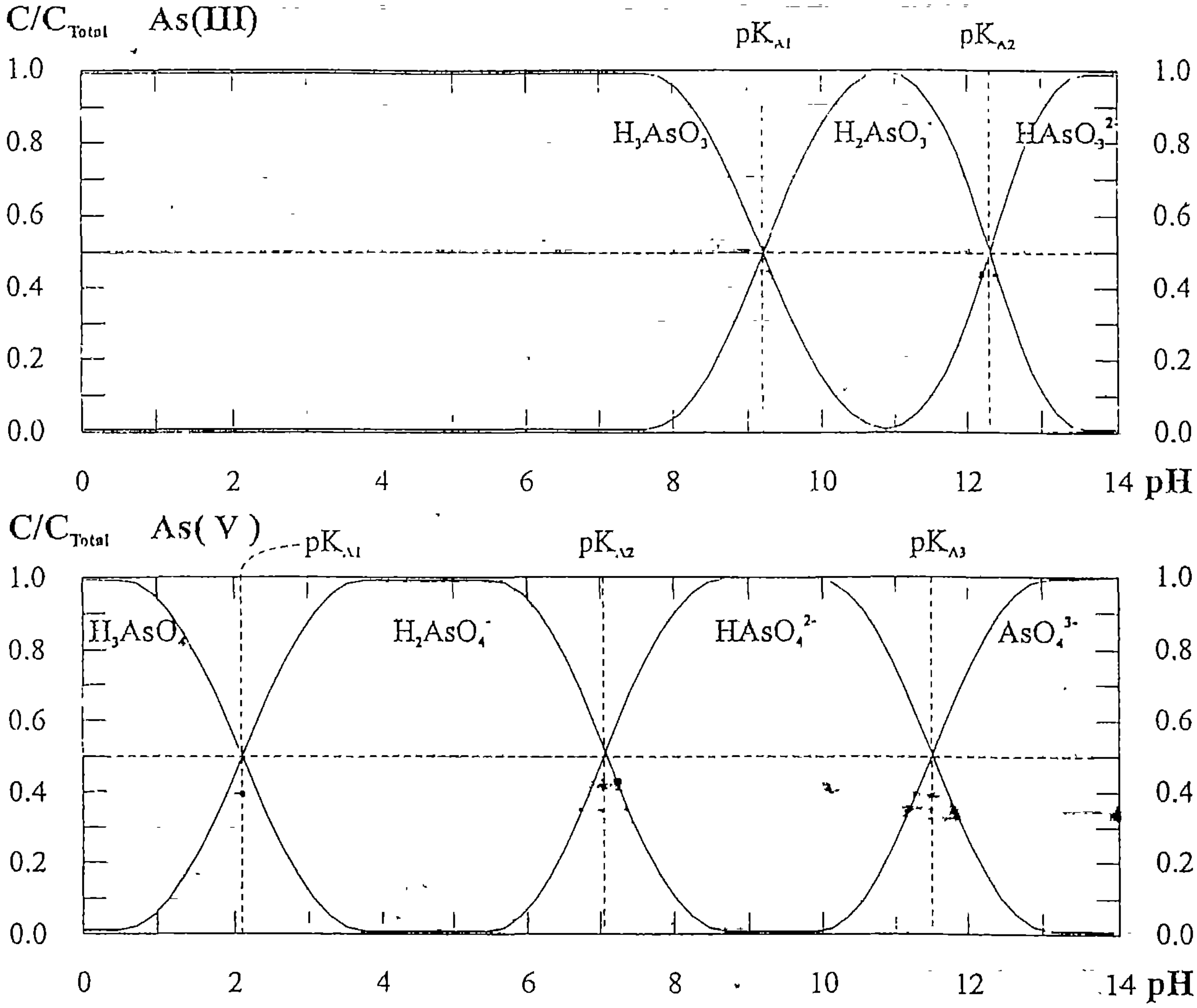

Figure 2. The dissociation of arsenious and arsenic acids as a function of pH /Dahi, 1997c/.

The redox reaction of the As(III)/As(V) system can be described by the following equation /Jekel, 1994/:

$$H_3AsO_4 + 2H^+ + 2e \rightarrow H_3AsO_3 + H_2O \qquad E_O = +0.56V \qquad \text{eq. 4}$$

The equilibria for arsenic acid, As(V), and arsenous acid, As(III), in aqueous solutions are given below /Kartinen & Martin, 1995; O'Neill, 1990/.

Arsenic acid, As(V):

$$H_3AsO_4 \rightarrow H^+ + H_2AsO_4^- \qquad pK_a = 2.20 \qquad \text{eq. 5}$$

$$H_2AsO_4^- \rightarrow H^+ + HAsO_4^{2-} \qquad pK_a = 6.97 \qquad \text{eq. 6}$$

$$HAsO_4^{2-} \rightarrow H^+ + AsO_4^{3-} \qquad pK_a = 11.53 \qquad \text{eq. 7}$$

Arsenous acid, As(III):

$$H_3AsO_3 \rightarrow H^+ + H_2AsO_3^- \qquad pK_a = 9.22 \qquad \text{eq. 8}$$

$$H_2AsO_3^- \rightarrow H^+ + HAsO_3^{2-} \qquad pK_a = 12.23 \qquad \text{eq. 9}$$

$$HAsO_3^{2-} \rightarrow H^+ + AsO_3^{3-} \qquad pK_a = 13.4 \qquad \text{eq. 10}$$

The above equilibria, Figure 1, Figure 2 , and Table 3 indicate that within the range of pH in natural waters, i. e. when pH is between 6 and 9, the trivalent inorganic arsenic is found primarily as none-dissociated arsenious acid, while the pentavalent arsenic is primarily found as the ionised di-hydrogen arsenate and mono-hydrogen arsenate. As most treatment processes are most capable to remove ions, the trivalent arsenic is more difficult to remove from the water than the pentavalent /Kartinen & Martin, 1995/.

2.2.2. Geochemistry

The geochemistry of Arsenic is generally dominated by the redox processes, the sulphide precipitation, the co-precipitation-adsorption to iron and manganese hydroxides, and the competition between arsenic and phosphorus for sorption sites /Cheng et al., 1994; Mariner et al., 1996; Parker, 1992/.

Arsenic can be immobilised through co-precipitation-adsorption with iron and manganese hydroxides, or mobilised when such solids are dissolved under low redox potential conditions. Arsenic may also be released from the oxide surfaces due to competition for sorptive surface sites in the presence of orthophosphate and natural organic matter. The latter mechanism may explain why the concentration of arsenic can be correlated to occurrence of divalent manganese, Mn(II), ferrous iron, Fe(II), and orthophosphate.

This concept of occurrence and dissolution is generalised to the groundwater source depth as shown in Table 4 /Edwards, 1994/. Each water source is divided into three zones, namely aerobic, anoxic without Sulphides and anoxic with sulphides.

Within the *oxygenated zones,* As(V) is stable and may remain soluble or sorb-coprecipitated with iron and manganese oxides. These oxides have a very high specific surface area ($Fe(OH)_3$ has around 600 m^2/g) and thus a very high adsorption capacity.

High concentrations of orthophosphate may compete with As(V) for adsorption sites, increasing soluble arsenic concentrations and mobility in the aquifer. Phosphate is known to displace sorbed arsenic from soils. This has been used to ameliorate the toxic effects of As in some soils /Onken & Hossner, 1995/.

Table 4. Key arsenic reactions in groundwater regimes /Edwards 1994/.

Groundwater	**Key reactions**
Aerobic	$Mn^{2+} \rightarrow Mn^{4+} \rightarrow MnO_2 \cdot HAsO_4$ $Fe^{2+} \rightarrow Fe^{3+} \rightarrow Fe(OH)_3 \cdot HAsO_4$ $HAsO_2 \rightarrow HAsO_4^{2-}$ $HPO_4^{2-} \Leftrightarrow HAsO_4^{2-}$ • Oxidation of As(III) to As(V) • Sorption-co-precipitation of As to oxides • Exchange of Phosphate for sorbed As(V)
Anaerobic with no H_2S	$HAsO_4^{2-} \rightarrow HAsO_2$ $Fe(OH)_3 \cdot H_2AsO_4 \rightarrow Fe^{2+} + HAsO_2$ $MnO_2 \cdot H_2AsO_4 \rightarrow Mn^{2+} + HAsO_2$ • Reduction of As(V) to As(III) • Reduction of Fe/Mn oxides • Release of soluble As
Anaerobic with H_2S	$HAsO_2 + HS \rightarrow As_2S_3$ or AsS $Fe^{2+} \rightarrow FeS \cdot HAsO_2$ • Precipitation of soluble As(III) as oripment or realgar, or coprecipitation with FeS

In *anoxic zones without sulphides,* As(III) is stable, and dissolved forms of iron and manganese are favoured. The arsenic mobility, or solubility, is at highest in this zone because:

- As(III) is believed to sorb less strongly onto oxides than As(V) and
- Co-precipitated-sorbed arsenic is released upon dissolution of arsenic-containing iron and manganese oxides.

In *anoxic zones with sulphides*, As(III) becomes immobilised because of the formation of orpiment, realgar, or arsenopyrite, or is coprecipitated with iron pyrite /Edwards, 1994/.

2.3. Toxicity and Arsenosis

Arsenic has acquired an unparalleled reputation as a poison, with arsenic trioxide, a tasteless and odourless inorganic arsenic compound, constituting a convenient agent for homicide. The toxicity of arsenic is dependent on its oxidation state, chemical form and solubility in the biological media. The toxicity scale of arsenic decreases in the order: arsine > inorganic As(III) > organic As(III) > inorganic As(V) > organic As(V) > arsonium compounds and elemental arsenic /Viraraghavan et al., 1996/.

Inorganic arsenic is a documented human carcinogen A relatively high incidence of skin and possibly other cancers have been observed in population ingesting water containing high concentrations of arsenic /Liang & Sharma, 1997/.

In the recent years the spot wise occurrence of arsenic in the groundwater is increasingly acknowledged as a major health problem for the respective communities, cf. Table 5

Table 5. Some of the major endemic arsenicsis reported /Chowdhury et al., 1997/

Location	Years	No of exposed	% having skin lesions
India, West Bengal	1978 - 1995	1 000 000	20
Taiwan	1961 - 1985	103 000	91
Chile, Antofagasta	1958 - 1970	130 000	16
Argentina, Monte Quemade	1938 - 1981	10 000	"many"
Mexico, Lagunera Region	1963 - 1983	200 000	21
Thailand, Ronpiboon	1987 - 1988	14 000	18

The most common signs of long-term, low level arsenic exposure from drinking water are dermal changes These include variations in skin pigments, hyperkeratoses, and ulcerations Palmoplantar keratoses are often surmounted by small, corn-like, elevated nodules up to 10 mm in diameter The blackfoot disease, an endemic peripheral vascular disorder first found in Southwest Taiwan (ca 0 01-0.9 mg/l), is also associated with use of arsenic contaminated well water for drinking /Brown et al., 1989, Cheng et al., 1994/

In a population drinking arsenic contaminated water, a great variety of specific as well as none-specific symptoms may be observed at a large biological variations and interactions /Mazumder et al., 1997/ Table 6 shows some of the effects of arsenic reported to be due to exposure through drinking water

Table 6. Toxicological effects of arsenic reported due to exposure to high arsenic concentrations in the drinking water /WHO, 1996. Wadud, 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	Coarctation of aorta, Cardiovascular disturb.	Among children
Cancer	Bladder, Kidney, Skin & Lungs, Liver & Colon	-
Mortality	-	Mainly due to cancer

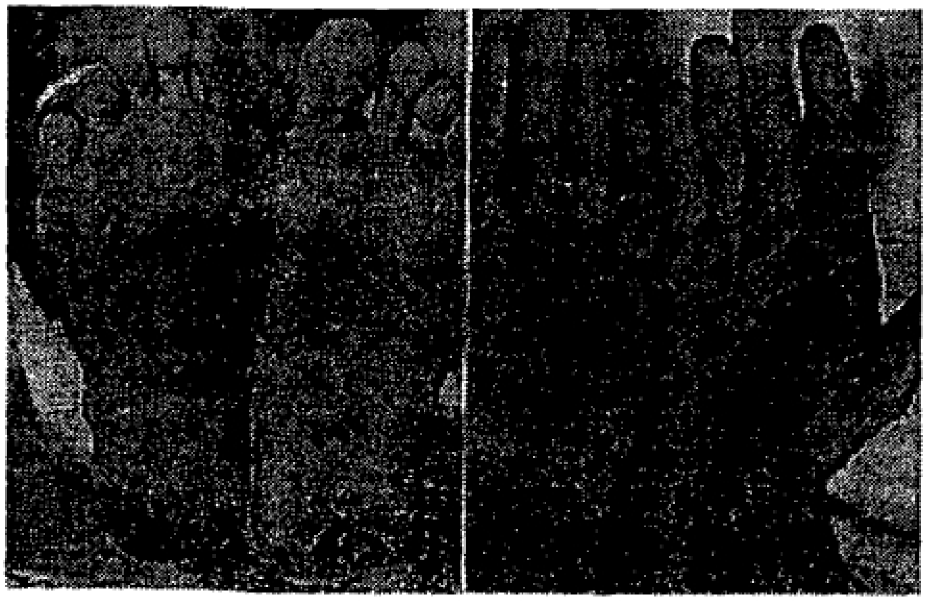

Figure 3. Typical most visible symptoms of arsenosis or "Blackfoot Disease" /Dahi, 1997b/.

2.4. Guidelines

Arsenic is a wide-spread element in the environment. Since it is known to be toxic and carcinogenic, low maximum allowable limits have been adopted for its occurrence in food and drinking water. The guideline values for arsenic in drinking water established by various countries/organisations are listed in the following table.

Table 7. Guideline values for arsenic in drinking water established by various regulatory agencies /Viraraghavan et al., 1994/.

Country/Organisation	Maximum contaminant level (MCL), mg/l
Canada	25
USA	50
France	50
Germany	40
European Economic Community (EEC)	50
India	50
China	50
Taiwan	50

Although arsenic toxicity clearly depends on its chemical form, with arsenite(III) being much more toxic than the oxidized arsenate(V) species, the guideline value is targeted only to the total arsenic.

In 1984, WHO recommended the guideline value 0.05 mg/l /WHO, 1984/. Recent epidemiological studies in Taiwan, where large population groups have been drinking the arsenic contaminated water for long time, have shown that arsenic may cause liver, lung, kidney, and bladder cancer in addition to the previously acknowledged risk of skin cancer. With a view to reduce the risk of getting skin cancer, and taking into consideration the practical detection limit in the available analyses, a provisional guideline value for total arsenic in drinking water of 0.01 mg/l is established in 1993. The estimated excess lifetime skin cancer risk associated with exposure to this concentration is 6×10^{-4} /WHO, vol. 1, 1993; WHO, vol 2, 1996/.

The drinking water standard for arsenic in the proposed Environmental Quality Standards (EQS) for Bangladesh is 0 05 mg/l /Hossain & Ali, 1997/.

2.5. Removal Methods

Various treatment methods have been studied with respect to removal of arsenic from drinking water mainly under laboratory conditions /Dahi, 1997a; Kartinen & Martin, 1995, Viraraghavan et al., 1996/ The various treatment methods include:

- Adsorption-corprecipitation using aluminum or iron salts for coagulation, lime softening or conventional iron/manganese removal.
- Sorption techniques using activated alumina, activated carbon, ion exchange resin and other media.
- Membrane processes like reverse osmosis and electrodialysis.

The advantages and disadvantages of different arsenic removal methods are summarized in Table 8.

Table 8. Overview of dearsenation methods and their advantages and disadvantages. Membrane methods are considered as non appropriate /Dahi, 1997a/.

Method	*Advantages*	*Disadvantages*
Co-precipitation:	• No monitoring of a break through is required.	• Serious short and long term problems with toxic sludge
	• Relatively low cost, simple chemicals.	• Multiple chemicals requirement
	• ,Low capital costs.	• Operation requires training and discipline
Alum coagulation	Durable powder chemicals normally available.	Efficient pre-oxidation is a must
Iron coagulation	More efficient than alum on weigh basis.	Medium removal of As(III)
Lime softening	Most common chemicals	Re-adjustment of pH is required.
Sorption techniques:	• No daily sludge problem	• Requires monitoring of break through or filter use
		• Requires periodical regeneration or medium shift
Activated alumina	Relatively well known and commercially available.	Re-adjustment of pH is required
Iron coated sand	Expected to be cheap.	Yet to be standardised.
	No regeneration is required	Toxic solid waste.
Ion exchange resin	Well defined medium and hence capacity.	High cost medium
		High tech operation & maintenance
		Regeneration creates a sludge problem
Other Sorbents	Plenty of possibilities & combinations	Not yet properly studied.
Membrane techniques:	• Well defined performance.	• High running costs.
	• High removal efficiency.	• High investment costs
	• No solid waste.	• High tech operation and maintenance
	• Low space requirement.	• Toxic wastewater.
	• Capable of removal of other contaminants, if any.	• Re-adjustment of water quality is required
Reverse osmosis		Membrane does not withstand oxidising agents.
Electrodialysis		Membrane does not withstand oxidising agents

2.5.1. Oxidation of As(III) to As(V)

As mentioned in Section 2 2, the As(III) is present as a none-ionized acid up to pH 8 (pKa=9.23), while As(V) is present as mono and di-ionized forms. This is the reason that the trivalent arsenic, As(III) or arsenite, can not be removed as easy and complete as the pentavalent, As(V) or arsenate in most removal methods In other words, if the removal capacity of a method has to be at maximum, the arsenite has to be oxidized to arsinate prior to treatment /Committee, 1988/.

The complete oxidation of As(III) to As(V) can be achieved by the use of any strong oxidant such as chlorine, ozone, UV-activated hydrogen peroxide, permanganate and manganese dioxide. Each of these oxidants has its specific advantages and disadvantages, which have to be considered when aiming at an optimized arsenite (III) removal process /Borho & Wilderer, 1996/.

The redox reactions of As(III) with manganese(IV) and manganese(III)-oxides at neutral pH can be written /Driehaus et al., 1995/:

$$H_3AsO_3 + MnO_2 \rightarrow HAsO_4^{2-} + Mn^{2+} + H_2O \qquad E^{\circ}=0.67V \qquad \text{eq. 11}$$

$$H_3AsO_3 + 2MnOOH + 2H^+ \rightarrow HAsO_4^{2-} + 2Mn^{2+} + 3H_2O \qquad E^{\circ}=0.95V \qquad \text{eq. 12}$$

Arsenious acid can also be oxidized by some oxidants like the following reactions /Dahi, 1997a/:

$$H_3AsO_3 + ½O_2 \rightarrow H_2AsO_4^- + 2H^+ \qquad \text{eq. 13}$$

$$H_3AsO_3 + HClO \rightarrow H_2AsO_4^- + 2H^+ + Cl^- \qquad \text{eq. 14}$$

$$H_3AsO_3 + 2/3MnO_4^- \rightarrow H_2AsO_4^- + 2/3MnO_2 + 1/3H^+ + 1/3H_2O \qquad \text{eq. 15}$$

/Böckelen & Niebner, 1992/ tested several oxidation agents, such as atmospheric oxygen, pure oxygen, and ozone. They found that the oxidation by air was very slow Ozonation is very rapid. It is the method of choice to ensure a total oxidation within shortest time.

Practically speaking however, chlorine compounds are the only affordable oxidation agents for use in developing countries. Among these, the bleaching powder is the agent of choice for transportation and use at household level in rural areas, cf. Table 9 /Dahi, 1991/

Table 9. Commercially available chlorine compounds.

Sodium hypochlorite	$NaClO$	Solution	Solution	10 %
Chlorinated lime*	$CaClOCl$	Solid	Solution	35 %
Calcium hypochlorite	$Ca(ClO)_2$	Solid	Solution	30-70 %
Organic Chlorides, e.g.	$NaOOCC_6H_2\cdot$ $\cdot SO_2NCl_2$	Solid	Powder/Sol.	60-90 %
Chlorine	Cl_2	Gas	Gas	100 %

* Also called "bleaching powder"

2.5.2. Coagulation

Coagulation is one of the most conventional processes used for drinking water treatment. The hydrous oxides of aluminium, iron, and magnesium formed during coagulation or softening processes are strong sorbents for many trace inorganic materials included arsenic. These hydroxides are quite amorphous and have significantly high binding capacities (moles of sites per kilogram of solid). Thus the floc formed in water treatment has a great adsorptive capacity. For example, amorphous iron oxyhydroxide has about 6 moles of sites per kg of $Fe(OH)_3(s)$, the specific surface area of the amorphous materials is as high as 600 m^2/g The binding capacity of $Al(OH)_3(s)$ is 1.6 mol/kg of $Al(OH)_3(s)$. /Committee, 1988/

2.5.2.1. Mechanisms of Coagulation

Addition of iron or aluminium coagulants to water simultaneous with proper efficient stirring, the coagulants will be first dissolved in the water. Subsequently aluminium or iron hydroxides will be coagulated as microflocs, which will be gathered into settleable macroflocs during the subsequent flocculation process ***Coagulation*** refers to chemical reactions leading to the formation of $Al(OH)_3$ or $Fe(OH)_3$ and aluminium or iron polymers from the coagulants ***Flocculation*** is the sequence of electrostatic reactions and chemical bridging binding the macromolecules together in larger flocs /Bregnhøj, 1992/. The reactions may be described as in the following equations

$$FeCl_3 \cdot 6H_2O \Rightarrow Fe^{3+} + 3Cl^- + 6H_2O \qquad \text{eq. 16}$$

$$Fe^{3+} + 3H_2O \Rightarrow Fe(OH)_3 + 3H^+ \qquad \text{eq. 17}$$

$$Al_2(SO_4)_3 \cdot 18H_2O \Rightarrow 2Al^{3+} + 3SO_4^{2-} + 18H_2O \qquad \text{eq. 18}$$

$$2Al^{3+} + 6H_2O \Rightarrow 2Al(OH)_3 + 6H^+$$ eq. 19

Arsenic is then removed through co-precipitation, adsorption and final sedimentation. ***Co-precipitation*** is defined as a none stochiometric incorporation of soluble arsenic species into a growing hydroxide phase via. inclusion, occlusion, or adsorption. ***Adsorption*** refers to formation of surface complexes between soluble arsenic and the solid oxyhydroxide surface site as indicated in the following example reactions /Edwards, 1994/:

$$\equiv Fe - OH + H_2AsO_4^- + H^+ \rightarrow Fe - H_2AsO_4 + H_2O$$ (arsenate sorption) eq. 20

$$\equiv Fe - OH + H_3AsO_3 \rightarrow \equiv Fe - H_2AsO_3 + H_2O$$ (arsenite sorption) eq. 21

in which $\equiv Fe\text{-}OH$ is an hydroxide surface site.

/Edwards, 1994/ has conducted some batch experiments for illuminating the As(V) removal mechanisms in the coagulation process. In his experiments, increasing concentration of As(V) solutions (0.03 to 30 mg/l) are treated with a fixed 90 mM dosage of Fe(III) as $FeCl_3$ and Al(III) as alum (30 mg/l $Al_2(SO_4)_3 \cdot 18H_2O$, 14.6 mg/l $FeCl_3$). By comparing of the removal in jars where the coagulants are added to arsenic contaminated water with the removal in jars where the arsenic is added to preformed hydroxide flocs, it is found that the density of sorbed As(V), measured as mols As sorbed per mol of Fe or Al, increased as a function of the residual As(V) in solution. Better removal was observed in the case of the hydroxide solids formed in situ, while the preformed oxides had much less removal capacity. It was concluded that the removal is mainly due to coprecipitation (see Figure 4)

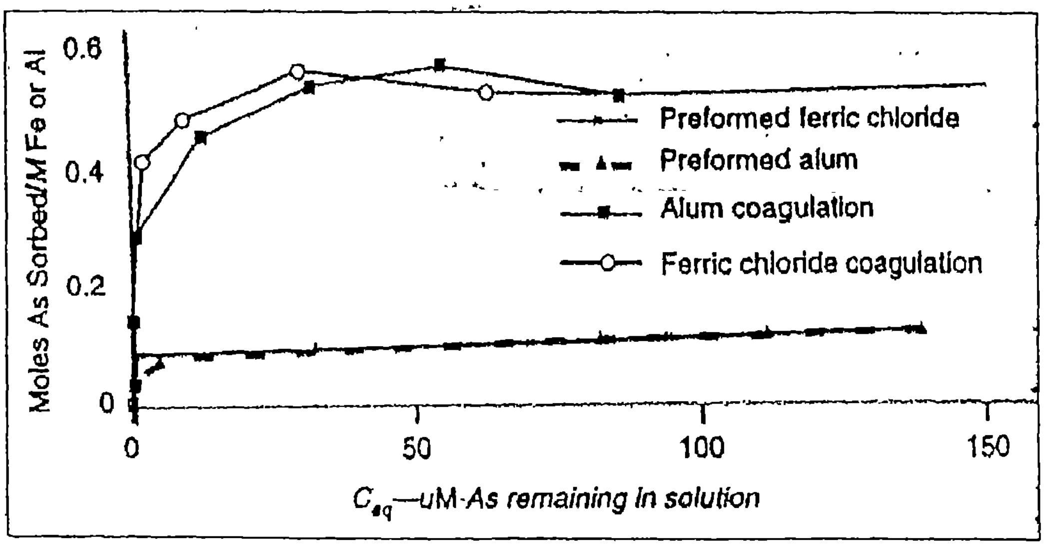

Figure 4. A comparison of arsenic removal by alum and ferric chloride and of preformed solids (adsorption) and solids formed in situ (coagulation) /Edwards, 1994/.

In a study conducted by Böckelen & Niebner /1992/, it is also found that the adsorption has no influence on the reached As level, i. e. the co-precipitation is the dominating process.

Hering et al. /1996/ conduct some bench-scale experiments in model freshwater systems to investigate the effects of various parameters on the removal of arsenic by adsorption onto preformed hydrous ferric oxide and during coagulation with $FeCl_3$. The initial arsenic concentrations are between 2 and 100 mg/l, pH from 4 to 9, and the coagulant dosage is between 0.49 and 24.3 mg/ l $FeCl_3$. They conclude that the adsorption plays an important role, not solely though

Cheng et al. /1994/ carry out study coagulation to treat As(V)-spiked water at various pH conditions in bench, pilot, and demonstration scale It is found that

1 $FeCl_3$ is much more effective than alum when compared on a weight dosage basis.

2. $FeCl_3$ coagulation is pH-independent between 5.5 and 7.0.

3. Alum coagulation is pH-dependent. The As(V) removal is deteriorated at pH > 7.

4. Increasing coagulant dosage will increase arsenic removal in both cases.

Similar conclusions are drawn in many other studies /Sorg & Logsdon, 1978; Hathaway & Rubel, 1987; Shen, 1973; Gulledge & O'connor, 1973/ Gulledge and O'conner explain that As(V) adsorbed less on both $Al(OH)_3$ and $Fe(OH)_3$ at pH 8 than at a pH of 5-7.

Cheng et al. /1994/ show that treatment using 20 mg/l of alum or alternatively 30 mg/l of ferric chloride, results in almost same relative arsenic removal, even at initial As(V) concentration varying in the range 2.2 to 128 mg/l Similarly Edwards /1994/, Hering et al /1996/ and Scott et al. /1994/ show that the percentage of arsenic removed by the use of alum and ferric chloride coagulation is independent of initial arsenic (V) concentration even over a wider range of conditions.

McNeill & Edwards /1997b/ analyze some full-scale arsenic removal data. They suggest that alum and ferric chloride have same magnitude of capacity for sorbing soluble As(V), when calculated on molar basis for stable flocs and pH below 7.6. Similar conclusion on this point is achieved in the study of Edwards /1994/. In additional Edwards /1994/ concludes that $Al(AsO_4)$ and $Fe(AsO_4)$ precipitates are not produced during the removal processes, even in situations where As(V) is present in initial concentrations as high as 20 mg/l

In the study of Edwards /1994/ it is concluded that sorptive removal of As(V) is highly dependent on pH, where higher sorption is achieved at lower pH. Furthermore the sorptive removal is to a lesser extent dependent on the coagulant dosage and the initial As(V) concentration On the contrary, As(III) removal is independent on pH and highly dependent on the coagulant dosage and the initial As(III) concentration. Similar results are presented in /Böckelen & Niebner, 1992/

The presence of other ions such as sulfate in the arsenic contaminated water seems to deteriorate the removal of As(III), and to a less extend the removal of As(V), in the ferric chloride coagulation /Hering et al, 1996/.

Extensive water works experiences /Committee, 1988/ have demonstrated that not less than 90 percent removal of As(V) can be achieved through application of alum at pH values < 7, by use of ferric chloride at pH values < 8.5, and by application of lime at pH values > 10.5. The effective removal of arsenic in the last case is presumably due to adsorption on $Mg(OH)_2(s)$

The removal process is described as a complexation of a soluble inorganic compound, X, by a solid complexation agent, S, according to the equation /Committee, 1988/:

$$X + S \xrightarrow{Ks} SX \qquad \text{eq. 22}$$

SX is the produced surface complex and Ks is the binding intensity quotient, defined as follows:

$$Ks = [SX]/[X][S] \qquad \text{eq. 23}$$

The estimated values for Ks is presented in Table 10 for different pH conditions.

Table 10. Binding quotients for the adsorption of As *on $Fe(OH)_3(s)$ and $Al(OH)_3$ (s) when these solids are formed during the coagulation process (Ks given in litres per mol) /Committee, 1988/.*

Adsorbate	log ks for $Fe(OH)_3$ (s)		Log ks for $Al(OH)_3$ (s)
	pH 7	PH 8	pH 8
As(III)	4.5	4 6	
As(V)		5 1	5.1

Using the estimated rate constant, Ks, the percentage of arsenic expected to be sorbed in a similar treatment process may be calculated from the equation:

$$\%absorbed = \frac{10^{-4} \cdot Ks}{1 + 10^{-6} \cdot D \cdot Ks} \qquad \text{eq. 24}$$

where: *D* is the dosage of the solid, mg/l
Ks, is the binding intensity quotient, l/mol

2.5.2.2. *Alum Coagulation*

Iron and aluminium are the most common coagulants in water treatment processes. Amorphous $Al(OH)_3$ is formed, as mentioned in Section 2.5.2.1, by the addition of alum to water. According to thermodynamic data for aluminium equilibria, aluminium is least soluble around pH of 6.2. As the alum dosage is increased to nearly 30 mg/l at a final pH of 7.0-8.0, the precipitation of solid aluminium hydroxide tends to occur to a greater extent, and a sweep coagulation mechanism tends to dominate. At pH < 5.0, polymeric species can predominate /Cheng et al. 1994/.

The technical product of alum may vary and is not always well defined. Basically alum is either aluminium sulphate, $Al_2(SO_4)_3.xH_2O$ or potassium aluminium sulphate, $KAl(SO_4)_2.xH_2O$ or a mix of the two compounds. Alum is often used in drinking water and waste water treatment as coagulants to remove particles /Bregnhøj, 1992/.

In the alum coagulation process aluminium sulphate is dissolved and added to the water under efficient mixing for one to few minutes Rapidly the aluminium hydroxide micro-flocs are produced and through flocculation process gathered into larger easily settling flocs. Hereafter the mixture is allowed to settle. During this flocculation process all kinds of micro-particles and negatively charged ions are removed by electrostatic attachment to the flocs.

The treated water can be decanted. Safety filtration is however required in order to ensure that no sludge particles are escaping in the treated water.

As the trivalent arsenic occurs in none ionized form, it will not be subject to significant removal. Oxidation of As(III) to As(V) is thus required as a pre-treatment. This can be achieved by addition of any chlorine product or by addition of permanganate as described in Section 2.5.1.

The alum dearsenation is thus based on pre-oxidation + conventional coagulation, flocculation, and sedimentation techniques. According to /Kartinen & Martin, 1995/ when chlorine was used and the pH reduced to about 7 or less, arsenic removal from water containing 0.3 mg/l arsenic using 30 mg/l of alum can reach about 90 %.

2.5.2.3. *Iron Coagulation*

As described in Section 2.5.2.1, freshly precipitated amorphous ferric hydroxide, $Fe(OH)_3$ (am), is formed by the addition of ferric chloride, $FeCl_3$, to water in the pH range of 6 - 10. At higher pH, i. e. > 10, the principal soluble species present is the monomeric anion $Fe(OH)^{4-}$ At lower pH levels, i. e. < 6, the dominant soluble species are cationic monomers such as Fe^{3+} and $Fe(OH)_2^+$. Fe(III) is least soluble at a pH about 8 $FeCl_3$ is a stronger acid and is less soluble than aluminium sulphate /Cheng et al, 1994/.

The iron dearsenation resembles the alum method In stead of Alum ferric sulphate $Fe_2(SO_4)_3$ or ferric chloride $FeCl_3$ are added As with alum precipitation, it is also important to oxidise the As(III) to As(V) to achieve better removal rates. According to Kartinen & Martin /1995/, when chlorine is used for initial As concentrations of 0.3 mg/l and dosage of about 30 mg ferric sulphate/l, removal efficiencies about more than 95 % can be achieved. In the iron coagulation pH is not that important as in the case of alum coagulation.

2.5.2.4. Arsenic Removal via Fe-Mn Oxidation

The geochemistry of arsenic reveals that high arsenic concentrations are often correlated to high Fe(II) and/or Mn(II). During Fe(II) and Mn(II) removal the arsenic can be removed through the coagulation process, i.e., oxidation to remove Fe(II) and Mn(II) leads to the formation of hydroxides that remove soluble arsenic by co-precipitation or adsorption reactions /Edwards, 1994/.

Removal of the soluble As(V) during oxidation of ferrous iron is quit significant, whereas the removal during oxidation of Mn(II) is less. In addition, pH is not significant in the manganese precipitation /Edwards, 1994/. A survey of full-scale treatment plants made by /McNeill & Edwards, 1995/ also demonstrated that oxidation of Fe^{2+} at a concentration level > 1.5 mg/l Fe^{+2}, results in 80 - 95 % arsenic removal. On the contrary, plants that only oxidize Mn^{+2} do not remove significant amounts of arsenic.

2.5.2.5. Lime Softening

Hard waters tend to have higher arsenic concentration. Lime softening is a well known method for removing hardness by adding fresh calcined lime, i. e. calcium oxide or CaO. When the hardness of the water is higher than 150 $mgCaCO_3/l$, the lime softening is often recommended in the drinking water treatment /McNeill and Edwards, 1997a/.

Arsenic removal can be facilitated by a variety of solids formed during softening including $CaCO_3$, $Mg(OH)_2$, $Mn(OH)_2$ and $Fe(OH)_3$. McNeill & Edwards /1997a/ have found that the arsenic removal follow a linear isotherm for $CaCO_3$, $Mg(OH)_2$, and $Fe(OH)_3$ with constant percentage arsenic removal, regardless the initial arsenic concentrations. On the other hand, for the $Mn(OH)_2$ solids, the arsenic removal is sensitive to the initial arsenic concentrations in the water.

The arsenic removal efficiencies of the lime softening process are significantly affected by the pH and the presence (or absence) of chlorine. The use of chlorination as a pre-treatment is demonstrated in many studies to improve the arsenic removal. The arsenic removal increases as pH increases up to pH = 11.

Because of the chemical similarities mentioned above between arsenic and orthophosphate, the presence of orthophosphate in the raw water is expected to interfere with the arsenic removal through competition for sorption sites.

$Mg(OH)_2$ is very efficient in sorbing arsenate. About 90 % removal is achieved in bench-scale experiments. For systems initially containing only Mn^{2+}, the arsenic removal appears to take place through the sorption onto $Mn(OH)_2$ solids, rather than through the formation of a $Mn_3(AsO_4)_2$ precipitate.

Formation of apatite, $Ca_{10}(PO_4)_6(OH)_2$, or calcium arsenate, $Ca_3(AsO_4)_2$, do not appear to take place during softening. Moreover, addition of crushed apatite does not seem to mediate any significant removal of arsenate.

Addition of a small amount of iron to waters before softening can increase the arsenate removal dramatically. Also carbonate is known to interfere with the arsenate removal in the iron based coagulation

The study made by /Sorg & Logsdon, 1978/ indicates that the removal of As(III) and As(V) via softening at pH < 10 is low. Substantially better removals occur at pH values near 10.5. That study also indicates that almost complete removal of As(V) is feasible at pH > 10.5, while As(III) removal seems to be limited to a level about 75 %.

In agreement with the above mentioned, a survey of full-scale treatment plants /McNeill & Edwards, 1995/ demonstrates that up to 90 % of the soluble arsenic(V) can be removed if the softening pH is higher than 10.5.

Dutta & Chaudhurei /1991/ carry out a lime softening laboratory study, where the total arsenic concentration in the ground water is about 0 7 mg/l, the As(III) is about 0.6 mg/l and the lime dosage up to 1.25 g/l. Up to 90 % removal is achieved at a residual pH of about 11.8.

Excess of lime would not be dissolved, but remains as a thickener and coagulant aid, which has to be removed along with the precipitate through a sedimentation/filtration process. In addition, the resulting pH is so high in the softening process, that a secondary treatment would be required in order to readjust the pH back to normal /Dahi, 1997a, Kartinen & Martin, 1995/.

2.5.2.6. Activated Alumina Systems

Activated alumina is aluminium oxide (Al_2O_3) grains prepared in a way that the grains have a high sorptive surface. The specific surface could be 200-300 m^2/g When the water passes through a packed column of activated alumina, arsenic and other components in the water are adsorbed to the surface of the grains Eventually the column becomes saturated, first at its upstream zone Later, as more water passes through, the saturated zone moves down streams and in the end the column get totally saturated, which means that the concentration of the arsenic in the effluent water increases to the same value as the influent water.

Regeneration of the saturated alumina is carried out by exposing the alumina to 4 % caustic soda, NaOH, either in batch or by flow through the column. During this process about 5-10 % alumina is lost, and the capacity of residual medium is significantly reduced, 30-40 %. After only 3-4 regenerations the media has to be replaced /Dahi, 1997a/

As in the coagulation processes, the pentavalent arsenic is removed far more efficiently than the trivalent arsenic. Hence the use of pre-chlorination improves the column capacity dramatically. It has been reported that 23000 BV of pre-chlorinated synthetically contaminated water at a level of 100 µg As/l could be treated to a break point of 50 µg/l. Without pre-chlorination of the water, only 300 BV could be treated. Similarly, 16000 BV of pre-chlorinated authentic water could be treated; compared to 700 BV for non-chlorinated water. The optimum pH is found to be 6. It is also found that deviation from this pH reduces the capacity of the activated alumina dramatically /Kartinen & Martin, 1995/.

Hathaway & Rubel /1987/ use pilot filter studies to optimize the conditions for treatment of groundwater. The best arsenic removal is achieved where 15000 bed volumes of water are treated at initial concentration of 0.09 mg As/l.

The competitive effects of other anions, such as phosphate, fluoride, chloride, sulfate and so forth are expected to reduce the adsorption capacity for As(V) /Dahi 1997a/.

2.5.2.7. Ion Exchange

Ion exchange is normally used to demineralise, to soften and de-nitrate the water. It is an adsorption process similar to activated alumina, just the medium is a better defined synthetic resin with well defined ion exchange capacity When the water containing arsenic passing through the synthetic resin, the arsenic exchanges for the chloride ions, which is loaded at the exchange sites Eventually, the resin becomes exhausted just like activated alumina and it needs to be regenerated. The principal regenerated agent is chloride, i.e a salt solution:

Arsenic exchange (R= Resin)

$$2R - Cl + HAsO_4^{2-} = R_2HAsO_4 + 2Cl^- \qquad \text{eq. 25}$$

Regeneration·

$$R_2HAsO_4 + 2Na^+ + 2Cl^- = 2R - Cl + HAsO_4^{2-} + 2Na^+ \qquad \text{eq. 26}$$

Like the other arsenic removal processes, it is important that arsenic is in the +V oxidation state in order to achieve the best removal efficiency. However, the need to oxidize the arsenic (III) could result in damaging the resin by the excess of oxidation agents.

Moreover, as sulphate is ion exchanged before arsenic, the removal capacity is highly dependent on the contents of sulphate in the raw water. One minor advantage of the ion exchange process is that the performance is less dependent on pH /Dahi, 1997a/.

2.5.2.8. *Other Sorption Media*

Several other sorption media have been reported to remove arsenic from water, e.g. activated carbon, kaolinite clay, hydrated ferric oxide, activated bauxite, titanium oxide and sand (silicium oxide) /Dahi, 1997a/.

Furthermore, iron oxide-coated sand is reported to be efficient in removing arsenic. A unit containing 6 kg of medium is demonstrated to treat about 700 l of raw water containing 1 mg As/l. It is concluded that the iron oxide-coated sand is promising for use in small systems or household level in developing countries /Joshi & Chaudhuri, 1996/.

2.5.2.9. *Membrane Techniques*

Reverse osmosis and electrodialysis are two types of membrane processes which have been demonstrated to be efficient in removing arsenic from water. For both processes, the removal rates for As(V) are better than for As(III). This is most unfortunate, as the use of pre-oxidation would be required and as the membranes are known to be sensitive to oxidation agents.

Furthermore, these methods are of no interest in developing countries, because of their nature as sophisticated technologies of high costs and requirement of skilled operation and maintenance /Dahi, 1997a/.

3. EXPERIMENTAL SETUP

3.1. Selection of Raw Water

Since artificial water in the laboratory is different in behaviour from natural water containing arsenic, laboratory results from artificial water are normally difficult to be directly used in practice. It is therefore chosen in this project to use natural water from one of the arsenic affected area, Noakhali, a district of more than 100 km south to Bangladesh's capital city Dhaka and not so far form the Bay of Bengal, see Figure 5.

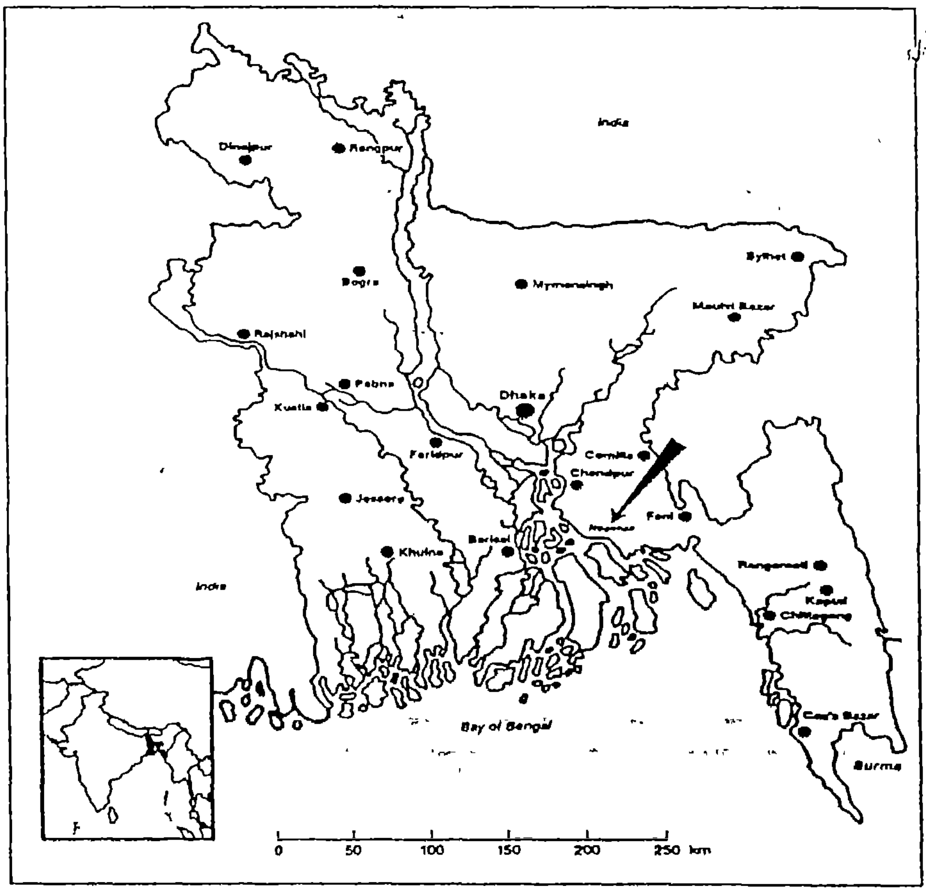

Figure 5. The map of Bangladesh.

The raw water used for all the jar test and bucket test experiments was fetched from a hand pump attached tube well in Noakhali. The Danida water supply and sanitation project has installed an IRU for this tube well, but the used water for the experiments was taken prior to the IRU, i.e. the raw groundwater was used in the experiments. The registered number of this IRU is 13.

The arsenic concentration of IRU-13 tested by MERCK arsenic test kit on site was about 0.7 mg/l, which was the highest concentration among all the tube wells tested by the same field kit. Therefor the water from IRU-13 was chosen to be used for optimizing the arsenic removal processes in this project.

By using laboratory spectrometric arsenic analysis, the arsenic concentrations of IRU-13 was found to lie between ca. 0.4 - 0.6 mg/l in the period of 08/09/97 - 27/10/97. The results are shown in Appendix 1.

Three water samples from IRU-13 fetched on 3 different days, i.e. 8 September and 20 and 27 October (see Appendices 1 and 2). The samples were preserved using HCl and were brought back to Denmark. Being about 680 mg $CaCO_3$/l in average, the total hardness of the samples was analyzed by atom absorption at IMT, DTU. The Detailed result is shown in Appendix 2.

3.2. Jar Tests

One purpose of the jar-test experiments was to determine the optimal coagulant between ferric chloride, alum and rice husk and the corresponding optimal dosage of chemicals for treating natural water from IRU-13.

Figure 6. Jar test apparatus set up.

The jar test apparatus is a six paddle stirrer which keeps a constant uniform stirring in 6 beakers at the same time. Each batch is consisted of 6 one-litre glass beakers each containing 1 litre raw groundwater contaminated by arsenic, which was fetched from IRU-13 in Noakhali, Bangladesh. Alum and ferric chloride in analytical grade were added as solution, while rice husk, a local product, was added as it is from a "tea bag".

First of all, an oxidant chemicals, sodium hyprochloride or beaching powder, was added to all jars at the same time in parallel and mixed vigorously at about 100 RPM for 5 minutes. Though the specification of arsenic species was not known due to the unavailability of analysis method by then, to ensure a better removal efficiency, a certain amount of oxidant was used for oxidizing As(III) to As(V) before the treatment processes took place.

Different dosages of chemicals were then added to all jars in parallel. The added chemicals were mixed vigorously at about 100 RPM for 1 minute and then slowly at about 25 RPM for 5 minutes. Thereafter, it was given 1 hour's settling before the water was measured for pH and sampled for the measurement of arsenic and iron concentration later on.

All chemicals added as solution were newly prepared every time right before the experiments.

3.3. Bucket Experiments

The goals of the bucket experiments were:

- to substantiate the removals observed in the jar test experiments, and
- to collect operational data at the house hold level.

These experiments were carried out using one/two 20-liters plastic buckets and a wood stick for stirring and a watch for timing the stirring.

From the jar test results, it may be seen that ferric chloride gives better arsenic removal efficiency than alum. The optimum dosage is about 90 mg/l for $FeCl_3.\ 6H_2O$ and 200 mg/l for $Al_2(SO_4)_3\cdot 18H_2O$. But these dosages are for analytical chemicals. In the bucket experiments, the technical grade chemicals should be used. The local product of ferric chloride and alum did not have any specification, which means the purity of these two chemicals were unknown. Moreover the portable balance Digi 200 used for weighing chemicals had a high uncertainty (± 1 g). So, for the sake of arsenic removal, conservative dosages of 3 g for ferric chloride and 5 g for alum were chosen respectively for treating 15 litres groundwater.

When ferric chloride was used in one bucket experiment in the village, where IRU-13 locates, the $Fe(OH)_3$ flocs were big enough but staying on the surface of the water in stead of setting down to the bottom of the bucket, no matter how much time it took. The red, thick $Fe(OH)_3$ flocs layer had a very disgusting appearance just in front of the villagers. So the coagulant was changed from ferric chloride to alum immediately, even ferric chloride showed better arsenic removal ability in the laboratory experiments.

3.3.1. One-Bucket Experiments

It was assumed that the stirring manner and duration might affect the arsenic removal efficiency. Since the method was to be used in a village by illiterate people, the procedure should be as simple as possible and at the same time as effective as possible.

The one-bucket experiments were carried out in a village just besides the IRU-13. First of all, about 2 g of bleaching powder was added to 15 litres of raw groundwater in a plastic bucket of 20 litres and mixed using a wood stick manually at about 60 RPM for 5 minutes. About 5 g of alum were then added to the oxidized water. After some time of about 60 RPM fast stir and some time of about 15 RPM slow stir (see Table 11), the water was given 1 hour for setting down, and then sampled for arsenic and/or iron analysis.

In one batch, the fast stir took 60 seconds and the slow stir took 3, 5, 7, 9, 11, 13, and 15 minutes respectively. In another batch, the fast stir took 10, 20, 40, and 80 sec, respectively, and the slow stir took 5 minutes.

The treated water was decanted and the samples were collected through a tea strainer to plastic bottle and preserved by 4 ml /l HCl.

Table 11. Data for one-bucket set up

		Fast stir (sec)	Slow stir (minutes)
Bleaching powder	2 g	60 sec	3
Alum (technical grade)	5 g	- do -	5
Volume of bucket	20 liters	- do -	7
Volume of raw water	15 liters	- do -	9
Sedimentation time	1 hour	- do -	11
Mixing with BP	5 minutes	- do -	13
Speed of fast stir	60 RPM	- do -	15
Speed of slow stir	15 RPM	10	5
		20	- do -
		40	- do -
		80	- do -

3.3.2. Two-Bucket Experiments

From the one-bucket experiments, it may be seen that the longer the slow stirring duration, the better the arsenic removal efficiency. But a longer fast stirring does not give better results. For a better quality of treated water, a two-bucket experiment was set up, see Figure 7. A simple filtration was made using sand and gravel in the second bucket.

The first bucket was used for mixing bleaching powder and alum with raw water. The second one was used for storing the treated water, which consisted a simple filter. After one hour's sedimentation, the water was decanted through a water tap fixed on the bucket and a tea strainer to the second one. From there, the water was to be filtered one more time by the simple filter before the final use for removing the micro flocs, if any, left in the withdrawn water from the first bucket

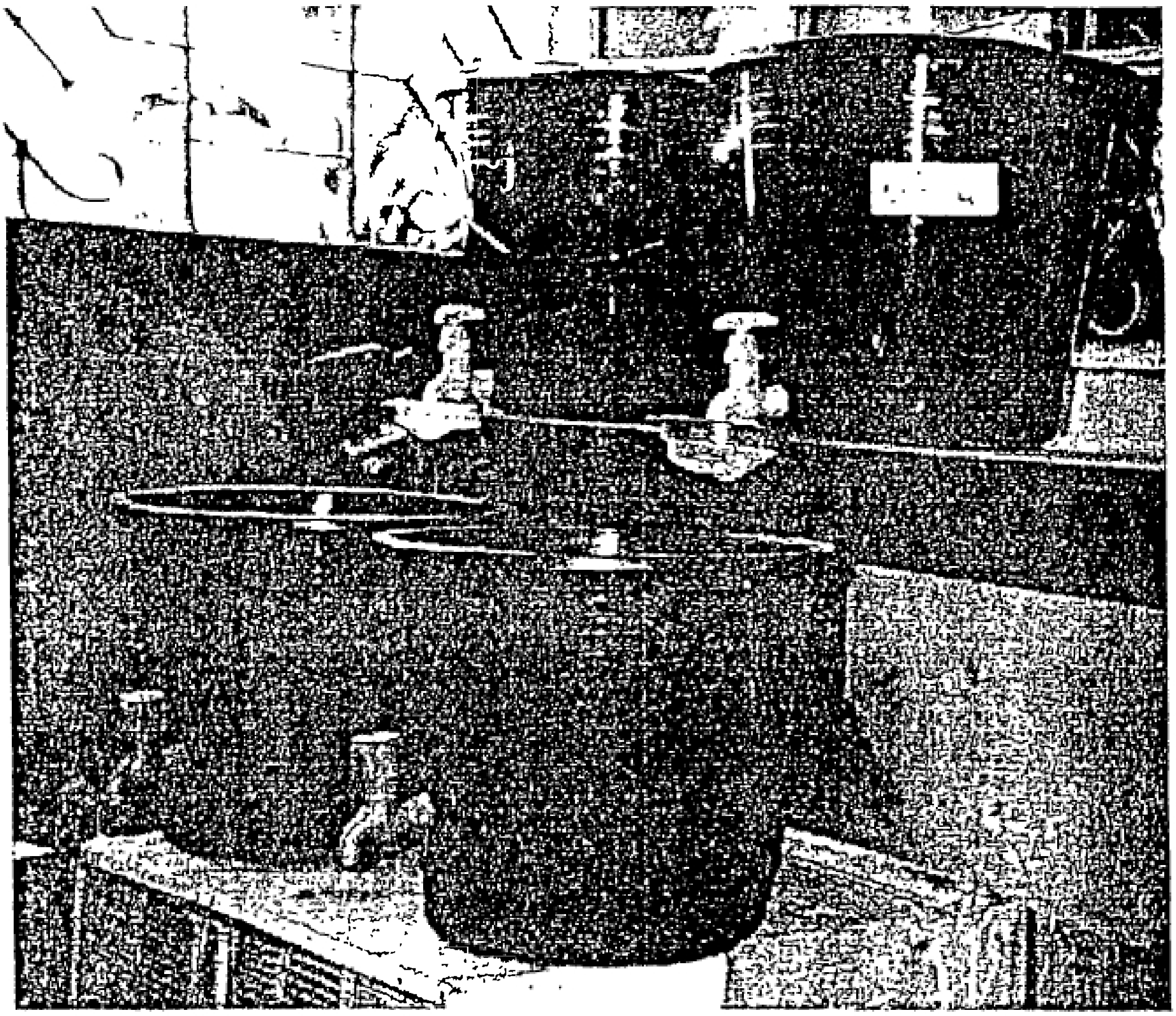

Figure 7. The two-bucket system set up.

In this two-bucket experiment, the fast stir was set for 40 sec and the slow stir was set for 10 minutes. The raw water was fetched from IRU-13 two days before the experiments. The dosage of bleaching powder and alum, sedimentation time etc. were the same as in the one-bucket experiments (see Table 11).

3.4. Arsenic Field Test Kit

For the calibration of the MERCK arsenic field test kit, water from different IRUs, individual places, and laboratory experiments, were analyzed using both the field kit and the laboratory analysis method.

The test kit consists of 100 analytical test strips, one reaction vessel, one 5 ml syringe, one plastic spoon, one bottle of reagent 1 (Zn), and one bottle of reagent 2 (HCl). (See Figure 8).

The colour scale is: 0, 0.1, 0.5, 1.0, 1.7, and 3 mg/l, from white to dark brown. The concentration is for the total arsenic. When the colour lied between two colour scales, the concentration was guessed out by eye sight.

Figure 8. MERCK arsenic test kit

The procedure of using this test kit is as follows:

- Hold the reaction zone of the test strip downwards, insert the test strip into the slit in the cap of the reaction vessel such that the cap divides the strip into two approximately equal segments.

- Place 5 ml of test solution into the reaction vessel, add 1 measuring spoon of reagent 1 (zinc powder) and shake.

- Add ten drops of reagent 2 (HCl) and close the reaction vessel immediately with the cap.

- Wait 30 minutes, shake the reaction vessel gently 2 to 3 times. Remove the test strip, immerse briefly in tap water, shake off excess liquid, and compare the reaction zone with the colour scale

3.5. Arsenic Removal in IRU and during Storage

It is said that arsenic is present in over 245 naturally occurring minerals and the principle arsenic mineral is arsenopyrite, FeAsS /Cullen & Reimer, 1989/. The oxidation of arsenopyrite may be the reason of the emerging of arsenic (see Section 2.1). Therefore, if arsenic is present, iron may also be present.

From the literature survey, it may be seen that arsenic can be removed by being sorbed on or co-precipitated with $Fe(OH)_3$. In Noakhali, it is known that the groundwater contains high iron concentration. Many IRUs have therefore been installed by DPHE-Danida Urban Water and Sanitation Project (UWASP) in that area

Because serious arsenic problems have emerged in the border area, West Bengal, India and many districts in Bangladesh, some water samples from these IRUs have recently been tested for arsenic, and the results are positive How serious the arsenic problem might be in the area and how much arsenic can be removed along with iron in the IRUs? Is it possible that these existing IRUs serve as a first line of defence to the exposure to arsenic. Since many IRUs are already in place in Noakhali, capital expenses may be minimized if arsenic can be removed using the existing iron removal units

3.5.1. Sampling from IRUs

Water was sampled by some 1-liter plastic bottles, which were washed at least 3 times using the sampling water. 1 ml/l (later the volume of acid was changed to 4 ml/l for the efficiency of preservation) of HCl was added immediately into the sample and shaked thoroughly for the purpose of preservation. The samples were taken both before and after IRUs.

3.5.2. Arsenic During Storage

The jar test experiments were run at BUET in Dhaka, and the raw water was taken from Noakhali. It was therefore not possible to fetch raw water from IRU-13 every time right before the jar test experiments Moreover, time interval between two jar test experiments can be very long, while the raw water was from the same container. If arsenic concentration remains in the water after it has been fetched for many days while there is iron in the water, how fast would the arsenic concentration change and to what extent?

For investigating this, the water was fetched from IRU-13 and then stored in the plastic container or bucket without any acid addition. The water samples were then taken from the supernatant by gently decanting to a plastic bottle everyday or every second day. 4 ml/l HCl was added immediately after sampling for preservation. The concentration for both arsenic and iron was analyzed afterwards

4. ANALYTICAL METHODOLOGY

4.1. Arsenic Analysis

4.1.1. Introduction

Arsenic concentration was measured using SDDC (silver dithyldithiocarbamate) method /Standard Methods, 1995/ with some modifications to the arsine generator and absorber assembly, see Figure 9. In the modified method, 5 ml silver diethyldithiocarbamate (SDDC) solution was put into a test tube, which is easy for washing and not easy to be broken, instead of being put into the U shape absorber in the standard method.

Moreover, 25 ml of 1 % sodium borohydride solution was used in the modified method instead of 15 ml as in the standard method, because when 15 ml sodium borohydride solution was used, the produced colour of the complexes was very weak. This may be due to the high temperature (more than 30 degree) and high humidity in Bangladesh.

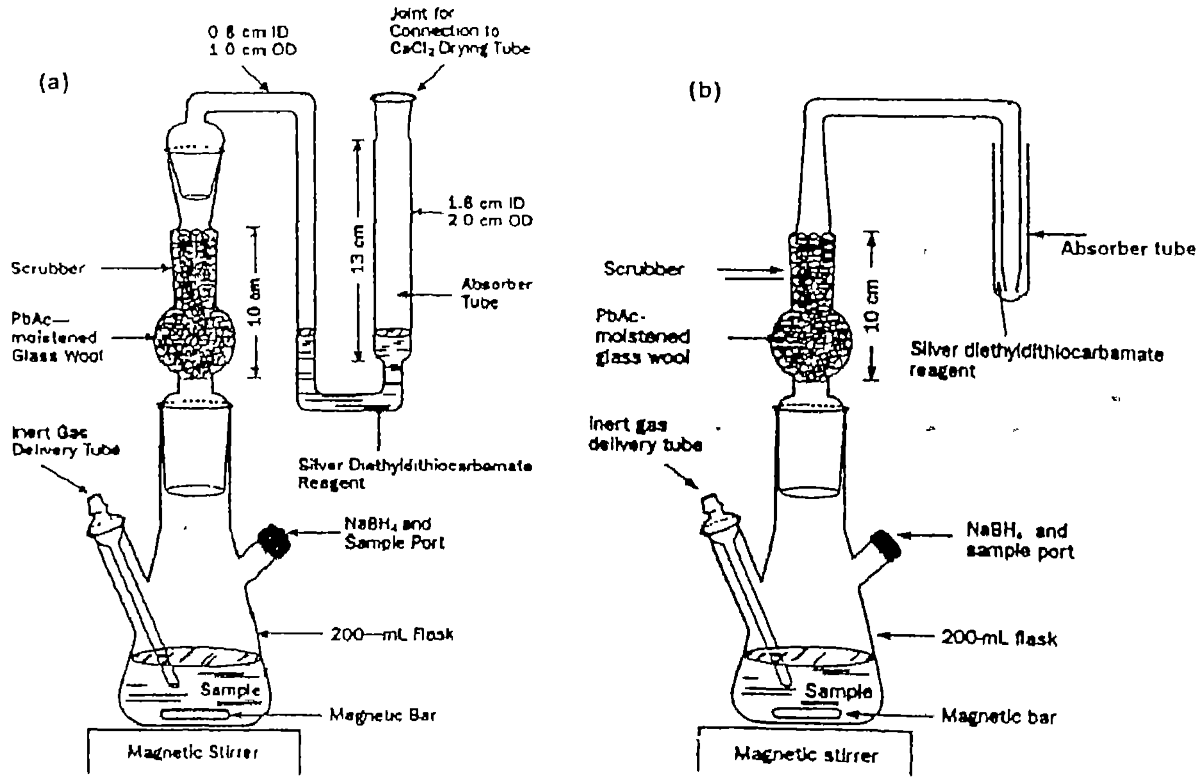

Figure 9. Single arsenic generator and absorber assembly

(a) standard method version; (b) modified version.

4.1.2. Analysis System Setup

Arsenic is a trace element. Its analysis is very complicated and very time consuming. For the need of measuring big amount of samples in a very short time, a system of five arsenic generators were arranged It can run 5 samples in parallel by using the same nitrogen cylinder and one flow meter to control the total nitrogen flow, see Figure 10 and Figure 11.

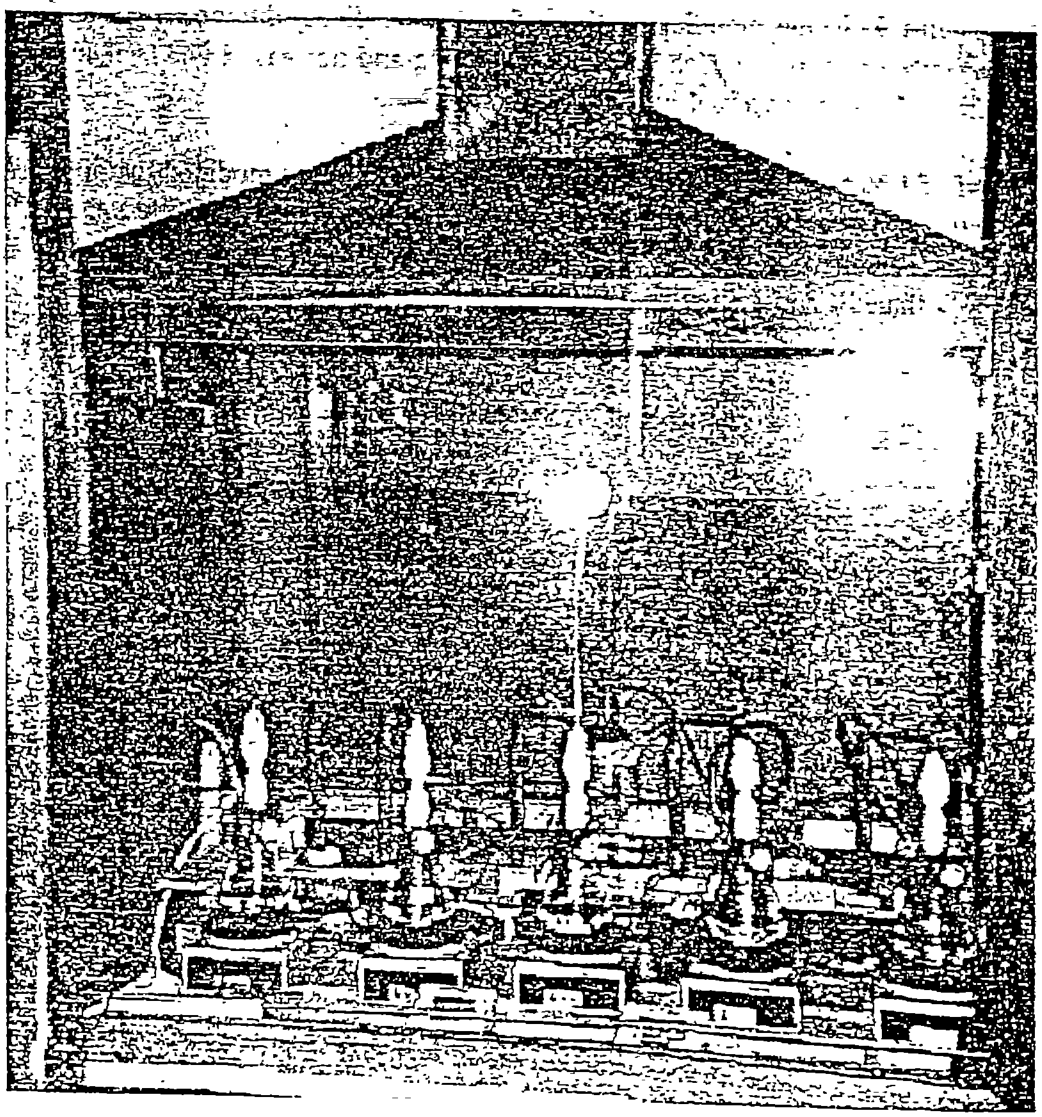

Figure 10. Arsenic generators and absorbers assembly

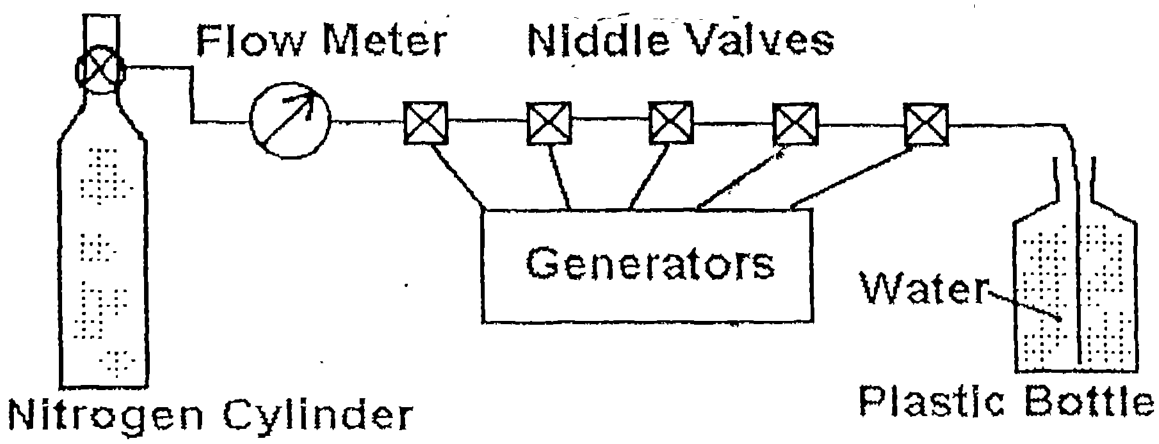

Figure 11. Sketch of the arsenic analysis system.

The flushing nitrogen gas was only 60 ml/min for each generator. There was no flow meter for any of the 5 generators to control such low flow rate. When the flow to one of the 5 generators was adjusted the other were largely affected. To solve this problem, an overflow system was arranged (the Plastic Bottle in Figure 11). Though this may waste some nitrogen gas, the flow influence of the 5 generators on each other was efficiently reduced.

All chemicals were analytical grade. The absorbence of the produced colour was measured using a DR/2010 portable datalogging spectrophotometer at 520 nm against chloroform.

4.1.3. Standard Calibration

Between 07/09/97 and 30/10/97, the standard solutions were measured about 20 times. The slope of the calibration curve was changing from time to time. The detailed results are shown in Appendix 3. The main results are summarized in Table 12, and graphically presented in Figure 12 and Figure 13.

For all these calibrations, the same analytical chemicals of the same amount have been used for every time. The only exception was that, on 07/09/97, the sodium borohydride used was purchased in Bangladesh, which was not in white powder form and was already melt and stuck together. The bottle was opened 3 days before the calibration. According to the standard method /Standard Methods, 1995/ 15 ml 1 % sodium borohydride solution was used. The resulted slope of standard curve was 1.038 (see Table 12). According to an earlier result /Liang & Shrama, 1997/, the slope of the standard curve should be higher than 1.6.

On 29/09/97, new sodium borohydride from Denmark was first opened and used. The added sodium borohydride solution was also 15 ml. The resulted slope was 1.705, which was as good as expected.

Table 12. Comparison of arsenic standard calibration by using different amount of $NaBH_4$ solution on different days.

Conc.	07/09/97	29/09/97	Conc.		8 -12/10, 15 ml $NaBH_4$		18-30/10, 25 ml $NaBH_4$	
mg/l			µg	mg/l	Average ABS	St. Dev ABS	Average ABS	St. Dev ABS
0	0.000	0.011	0	0.000	0.018	0.004	0.017	0.005
0.01	0.002	0.023	1	0.014	0.032	0.005	0.037	0.007
0.05	0.043	0.082	5	0.071	0.082	0.022	0.118	0.014
0.1	0.100	0.147	10	0.143	0.162	0.025	0.233	0.028
0.25	-	0.436	20	0.286	0.266	0.043	0.475	0.037
0.3	0.307	-	-	-	-	-	-	-
Slope	1.038	1.705	Slope	-	0.880	0.134	1.604	0.133
Intercept	-0.005	0.000	Intercept	-	0.021	0.010	0.011	0.009
Corr.	1.000	0.997	Corr.	-	0.981	0.037	0.998	0.003

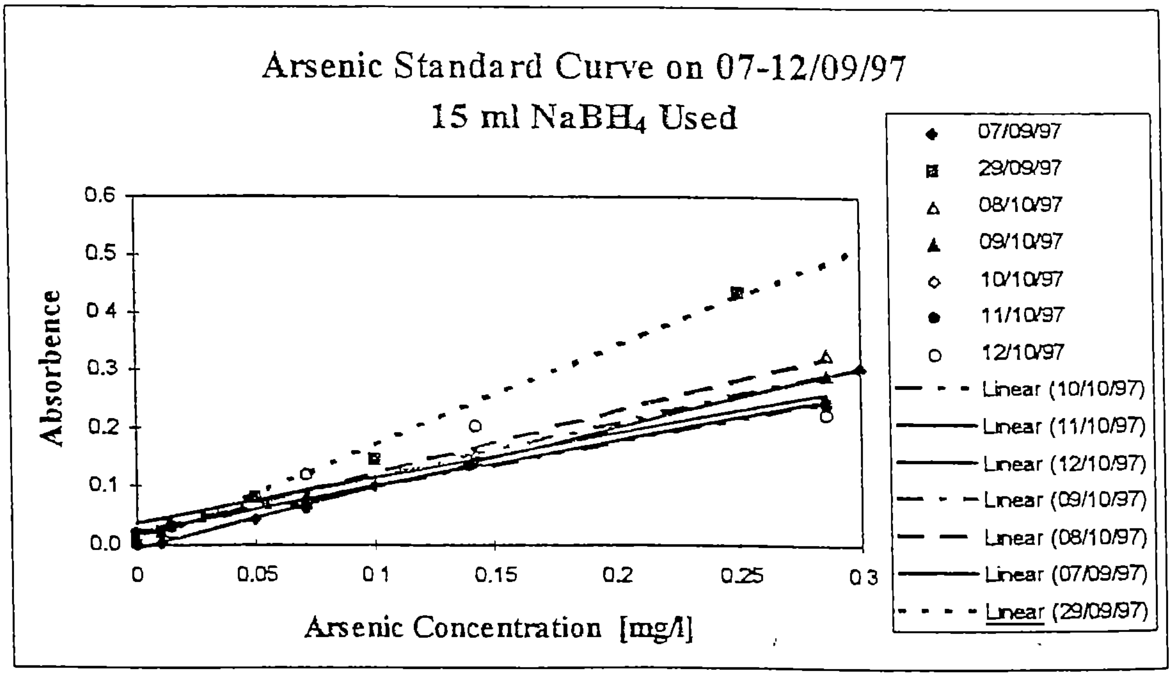

Figure 12. Arsenic standard curve on 07-12/09/97, 15 ml sodium borohydride solution used.

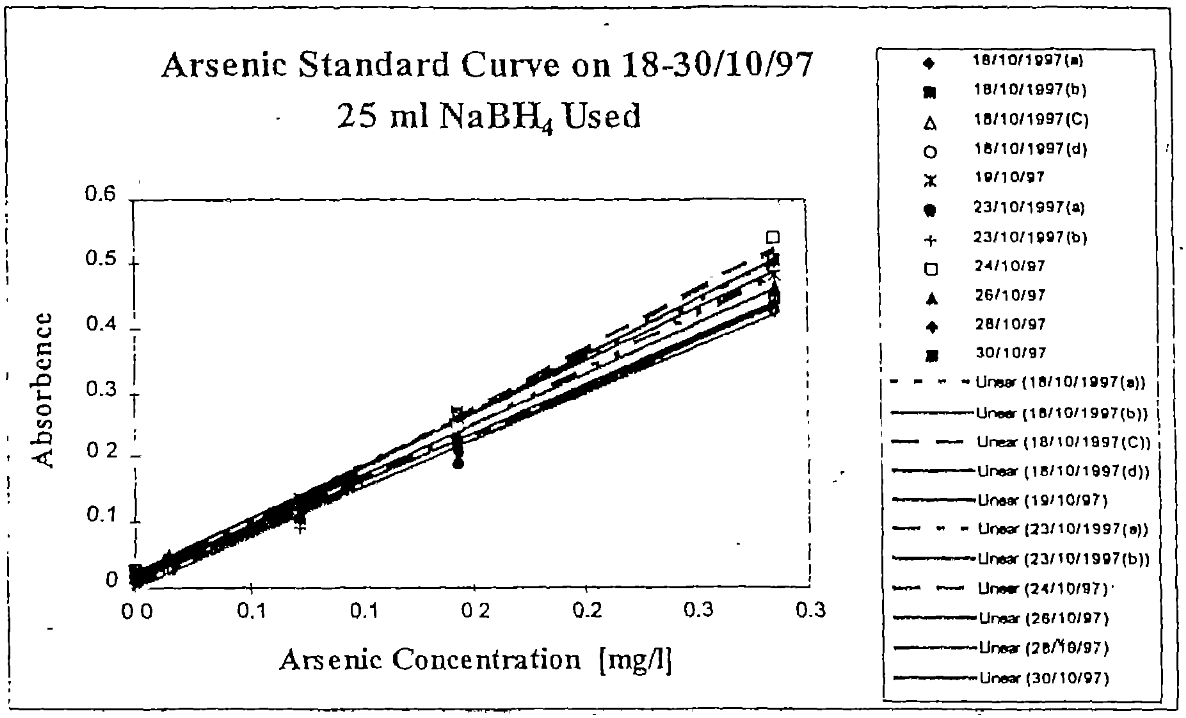

Figure 13. Arsenic standard curve on 18-30/09/97, 25 ml sodium borohydride solution used

But on 08 - 12/10/97, the same sodium borohydride as on 29/09/97 and 15 ml of the solution was used, the resulted average slope was only 0.88. It was surprisingly lower than expected.

From 18-30/10/97, the used volume of 1 % sodium borohydride solution was changed from 15 ml to 25 ml, the average slope lied at 1.604.

4.1.4. Discussions and Conclusions

From Table 12, it may be seen, that at lower arsenic concentrations, the standard deviations are almost the same between data from 08-12/09/97 and 18-30/10/97. But at higher concentrations, the standard deviations are generally higher for data from 08-12/09/97 than that from 18-10/10/97. For example, at 0.286 mg/l, the standard deviation was 0.043 for the data from 08-12/09/97 and 0.037 for the data from 18-30/10/97, respectively.

The same chemicals and analysis procedures have been used. But when different amount of the essential reductant, sodium borohydride, is used, different slopes and standard deviations are obtained. 15 ml reductant solution is apparently not enough. But when the chemicals were very fresh on 29/09/97, the 15 ml solution resulted in a high slope (1.705). This may be attributed to the tropical climate, i.e. the high temperature and humidity in Bangladesh. Moreover, when the bottle of the sodium borohydride is opened or when the chemicals are being weighted, the moisture in the air is quickly absorbed by the chemicals. Dry sodium borohydride gets wet immediately. Since sodium borohydride is a very strong reductant, its efficiency may be reduced due to reactions with water and oxygen in the air. In addition, when the chemicals is getting wetter and wetter, the actual concentration of sodium borohydride solution is getting lower and lower.

Even the slops and the standard deviations are different from time to time, but correlation coefficients are all equal to or higher than 0.99 for all tests except the one on 12/10/97 (see Appendix 3). Since the samples were measured in the same way as that for the standard solutions, the precision should be good enough even when 15 ml sodium borohydride solution was used.

4.1.5. Problems of Preservation

The water samples from IRUs collected on 08-11/09/97 were preserved by 1 ml/l HCl, which was made in India. When these samples were analyzed on 11 and 12/10/97, some precipitate was found in the bottom of some bottles. Apparently arsenic had precipitated with iron in some of the samples (see Appendix 5), i.e. for some of the raw water samples 1 ml/l HCl preservation was not enough. So the results obtained on 11 and 12/10/97 with 15 ml sodium borohydride may only be used as preliminary results. Attempting to get the real arsenic concentration, some of these samples were measured again on 26/10/97 with 25 ml sodium borohydride solution Before this analysis, the raw water samples were added 2 to 4 ml/l analytical HCl again for dissolving the precipitate. The precipitated arsenic should be released to the solution and the results are representative.

The analysis results of the IRUs both on 11-12/10/97 and 26/10/97 are shown in Appendix 5.

From 21/10/97, all of the preserved samples were added 4 ml/l analytical HCl.

4.2. Iron Analysis

The total iron concentration was analyzed by its colourimetric determination with thioglycollic acid according to /HMSO, 1972/. Thioglycollic acid instantly reduces a solution of ferric iron and reacts with ferrous iron in the presence of ammonia to give a red-purple colour, the absorbence of which was measured by using a DR/2010 portable datalogging spectrophotometer at 535 nm.

The following standard solutions are used: 0, 10, 20, 30, 50, 70, 100, 300, 500, 800 µg iron corresponding to 0, 0.2, 0,4, 0 6, 1, 1.4, 2, 6, 10, 16 mg/l.

It was assumed that there was no organic matter to be destroyed in the samples while the raw water was groundwater. The sample had a volume of 20 ml and was well mixed after each addition of chemicals (1 ml HCl, 2 ml citric acid solution, 0.1 ml thioglycollic acid and 2.5 ml ammonium hydroxide), and then distilled water was added in to the mark of 50 ml volumetric flasks.

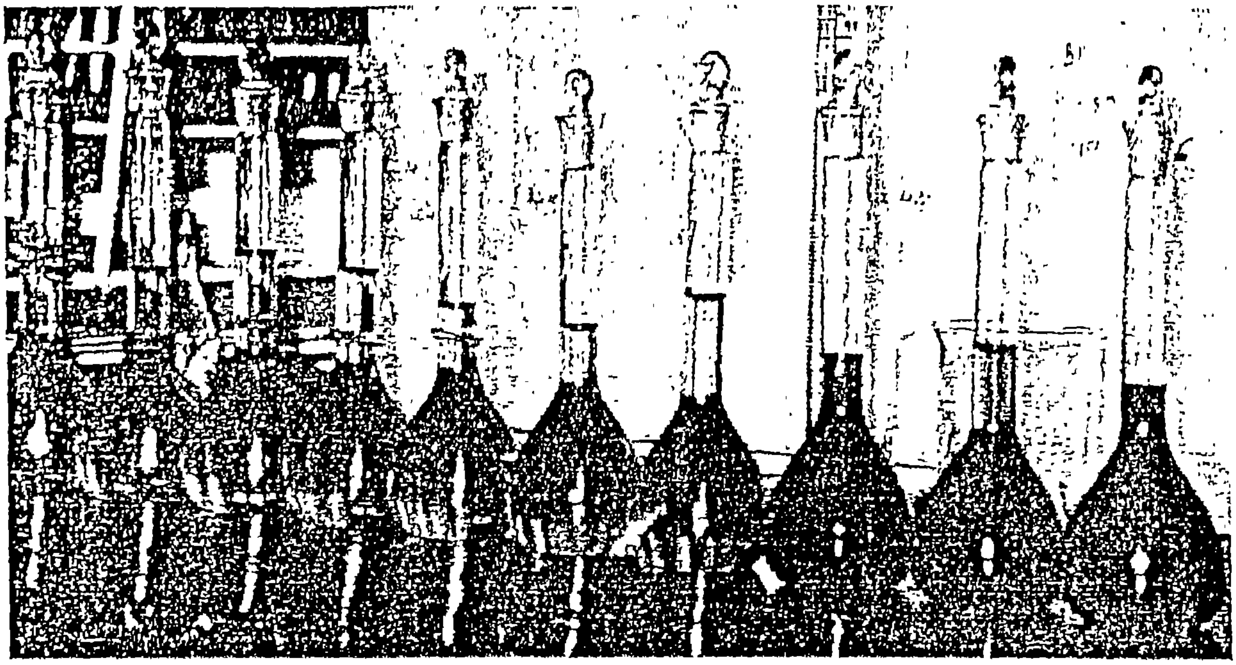

Figure 14. Colourimetric iron analysis.

The absorbence of the well mixed solution was measured using a 10 mm cell with distilled water as reference. The iron concentration of the samples was then calculated according to the calibration curve.

4.3. pH Measurements

The pH of the samples was measured with an EC10 portable pH meter, which was calibrated using pH buffer solutions 4, 7, and 9 every time before the measurement The procedure of the measurement is immersing the pH electrode in the sample and slowly stirring the solution by gently shaking the sample bottle. The pH was measured before the preservation but immediately after sampling.

5. RESULTS AND DISCUSSIONS

5.1. Arsenic Removal along with Iron in Iron Removal Plant

Water from 25 IRUs (Iron Removal Units), 4 deep tube wells, and 3 individual places were analyzed both for iron and arsenic concentrations. Because of preservation problems as described in Section 4.1.5, the arsenic analysis results from 26/10/97 are believed more reliable, which are therefore used for discussion in this section. The results are shown in Table 13, Figure 15-19. The detailed results can be found in Appendices 4 - 6.

Table 13. IRUs' Removal efficiencies on both arsenic and iron concentrations together with concentrations of As and Fe at 4 deep tube wells and 3 individual places.
** deep tube well. # individual place.*

Name	Total Fe			Total As			
	Fe_{Raw} mg/l	$Fe_{Residual}$ mg/l	Removal %	As_{Raw} mg/l	$As_{Residual}$ mg/l	Removal %	Fe_{Raw}/As_{Raw}
IRU-1	36.60	11.61	68	0.086	-	-	423
IRU-2	15.14	0.01	100	0.334	0.012	96	45
IRU-3	11.90	0.05	100	0.041	-	-	287
IRU-4	15.71	-	-	0.142	-	-	110
IRU-5	9.87	2.45	75	0.244	0.093	62	40
IRU-6	14.29	0.87	94	0.043	0.006	87	333
IRU-7	8.49	2.28	73	0.156	0.038	76	54
IRU-8	5.77	-	-	0.092	-	-	63
IRU-9	28.17	-	-	0.197	-	-	143
IRU-10	11.01	0.50	95	0.311	0.032	90	35
IRU-11	6.02	-	-	0.133	-	-	45
IRU-12	22.36	0.34	98	0.003	0	100	7938
IRU-13	6.79	2.45	64	0.478	0.216	55	14
IRU-14	11.78	4.92	58	0.188	0.145	23	63
IRU-15	10.36	0.42	96	0.071	0.010	86	146
IRU-16	11.17	2.73	76	0.605	0.311	49	18
IRU-24	12.55	0.50	96	0.118	0.102	14	106
IRU-25	12.30	0	100	0.018	0.008	56	674
IRU-26	2.98	2.04	31	0.218	0.165	24	14
IRU-30	23.42	0.00	100	0.142	0.007	95	165
IRU-34	21.03	6.06	71	0.329	0.098	70	64
IRU-35	10.28	2.28	78	0.079	0.032	60	130
IRU-36	8.05	1.84	77	0.307	0.174	43	26
IRU-39	13.28	3.18	76	0.115	0.044	62	115
IRU-40	5.04	0.13	97	0.057	0.009	85	89
*OTW-1	2.04			0.000			
*OTW-2	2.49			0.000			
*OTW-3	2.45			0.000			
*OTW-4	2.73			0.000			
#Nillershouse	0.58			0.114			
#Guesthouse	0.74			0.116			
#Femishouse	2.57			0.276			

The ratios between As(III) and As(V) in the raw water are listed in Appendix 5. The measured results of these ratios are between 0 - 4.3. It is unavailable to give a general ratio between As(III) and As(V) in Noakhali area based only on a few samples analyzed. But at most of these monitored IRUs, the ratio between As(III) and As(V) is less than 1, which means As(V) is dominating. This is consistent with the fact that the shallow water is aerobic. It should be noted that these results may only be used as preliminary results because of the preservation problem.

From Figure 15, it may be seen that the iron concentration for all the samples is higher than 1 mg/l, which is the Bangladesh guideline value for iron in drinking water. The arsenic concentration for most of the samples stays above the MCL value, 0.05 mg/l (the temporary Bangladesh standard). The results are very scattered, No clear correlation between arsenic and iron concentrations in the raw water may be observed. Even though there is a trend that if arsenic is present, iron is also present, this is not true in the opposite way.

From Table 13, it may be seen that deep tube wells contain arsenic below detectable level with low concentration of iron. At the three individual places, Nillershouse, Guesthouse and Femishouse, there are both arsenic and iron present and the arsenic concentration is higher than 0.05 mg/l.

Figure 16 shows that, at these IRUs, the better iron removal, the better arsenic removal. When iron removal is higher than 60 %, the arsenic removal is higher than 50 % except for a few cases.

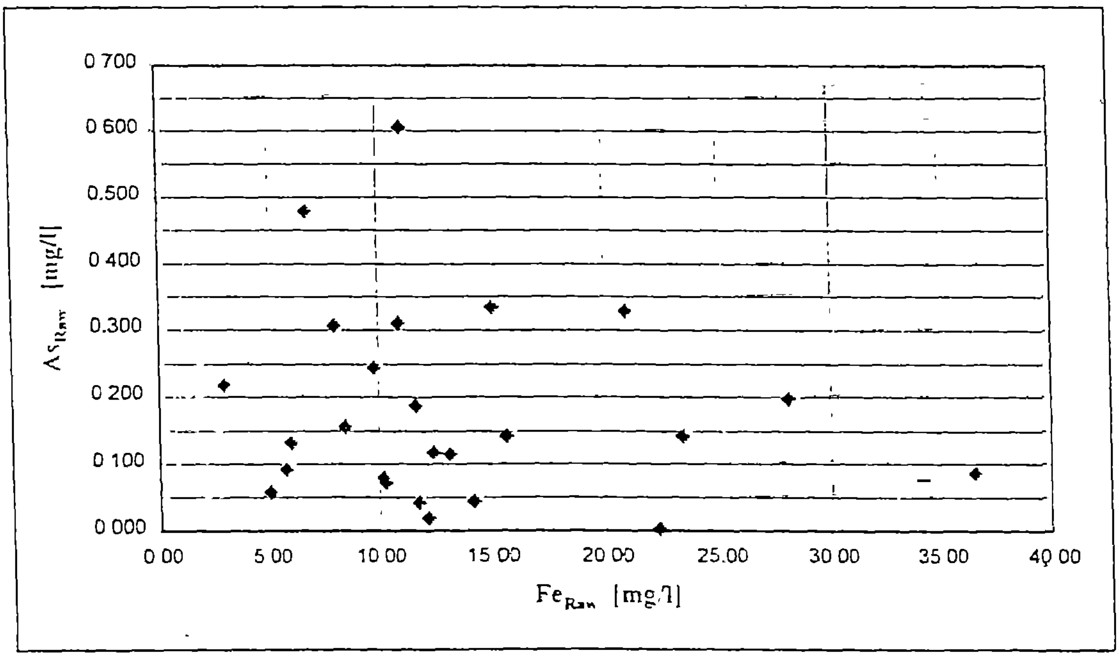

Figure 15. Arsenic concentration versus iron concentration in the raw water (before IRUs).

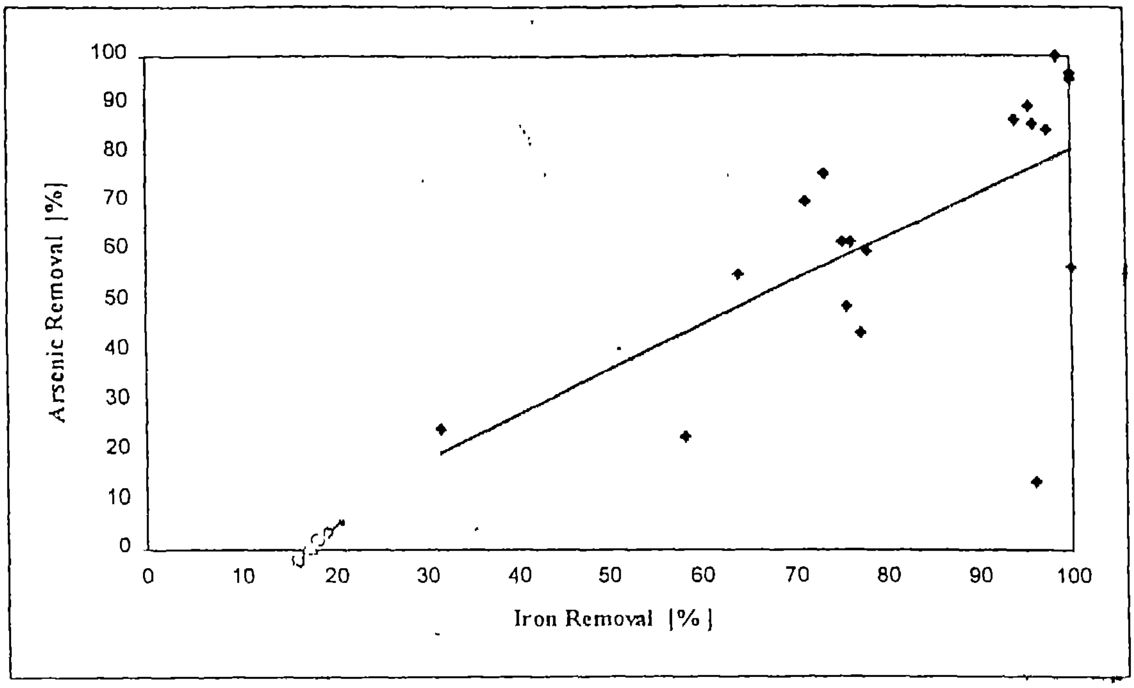

Figure 16. Arsenic removal versus iron removal at IRUs

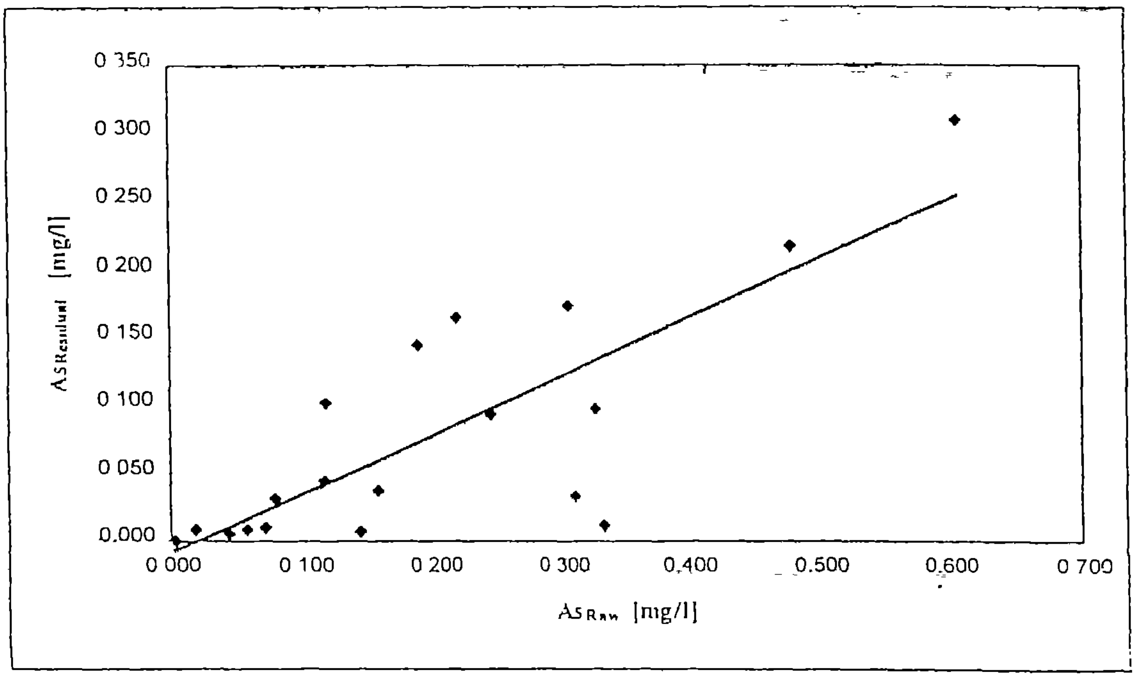

Figure 17. Residual arsenic concentration versus arsenic concentration in the raw water (before IRUs).

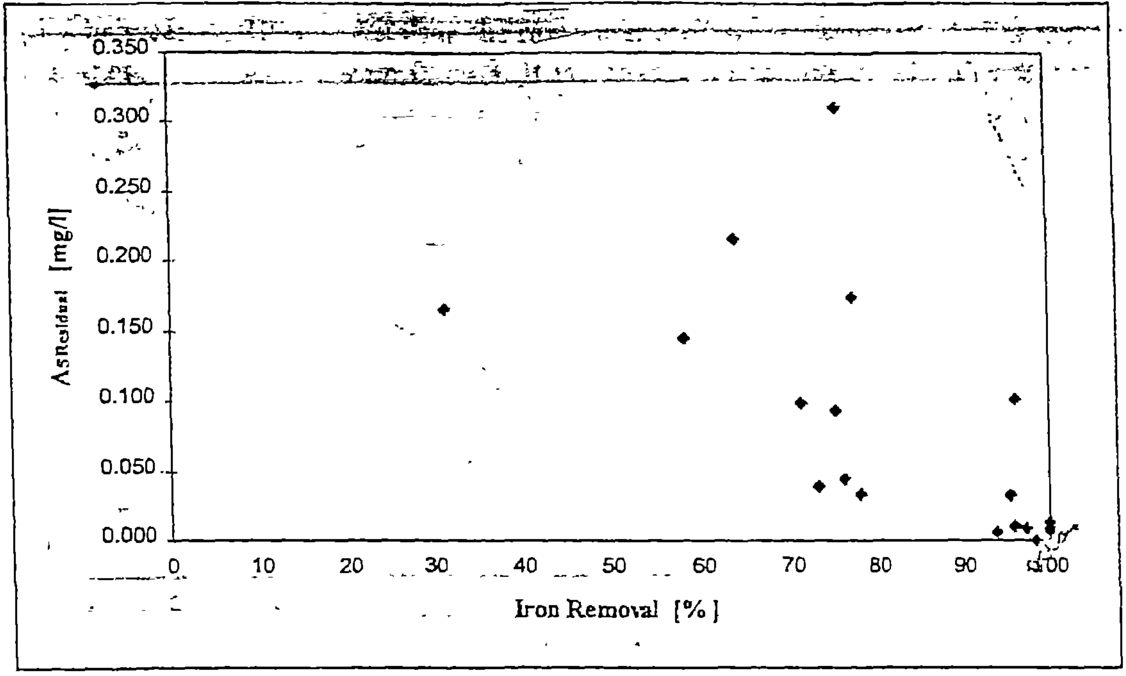

Figure 18. Residual arsenic concentration versus iron removal at the IRUs.

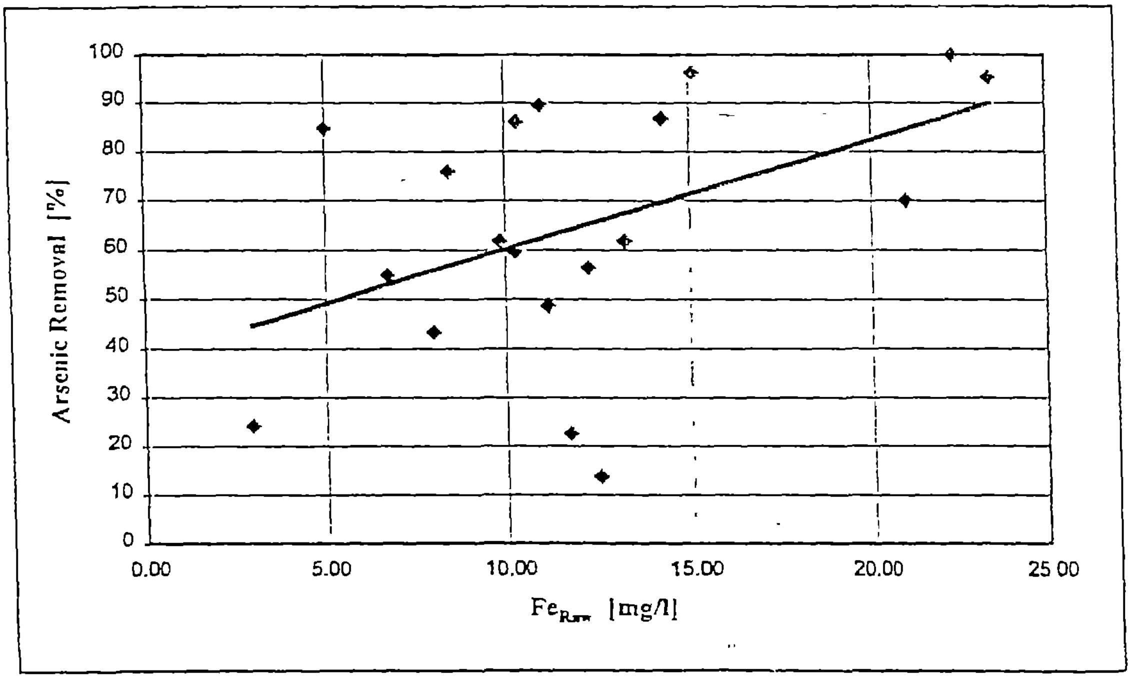

Figure 19. Arsenic removal versus iron concentrations in the raw water (before IRUs).

Figure 17 shows that the residual arsenic concentration is more or less proportional with arsenic concentration in the raw water. Many data points of the residual arsenic concentration lie below 0.05 mg/l. Even when arsenic concentration in the raw water as high as 0.3 mg/l, the residual concentration can be reduced to below 0.05 mg/l.

From Figure 18, it may be seen that when iron removal efficiency is high, very low values for the residual arsenic concentration can be obtained.

Figure 19 shows that there is a linear relation between the arsenic removal and iron concentration in the raw water. The higher the iron concentration in the raw water, the better the arsenic removal efficiency

Most of these 25 tube wells abstract shallow water, where the water is most contaminated by arsenic. These IRUs were installed for removing iron. Some of them are up-flow type, some of them are Unicef type Because of the improper design and/or the shortage of proper maintenance, these IRUs are not functioning optimally. But still about 65 % of arsenic on a average basis of these monitored IRUs can be removed along with iron.

5.2. Arsenic Removal During Storage

The detailed results are shown in Appendix 1 while the main results are listed in Table 14 and Figure 20 - 23.

From Figure 20 and Table 14, it may be seen that the arsenic and iron concentrations in the tube well of IRU-13 did not change very much in September and October, 1997. The arsenic concentration lies between 0 4 to 0 6 mg/l and the iron concentration lies around 7 mg/l.

Table 14. Arsenic removal along with iron during storage in bucket.

Fetched Time from IRU-13	Sampled Data	Standing Time (h)	Residual As (mg/l)	Residual Fe (mg/l)
08/09/97		0	0 478	7.01
09/10/97		0	0.481	-
20/10/97 (8:00)	20/10/97 (8:00)	0	0.422	6.49
	20/10/97 (13.00)	5	0.391	6.24
	21/10/97 (11:00)	27	0.389	4.69
	21/10/97 (16:30)	32.5	0.380	6.28
	22/10/97 (18:00)	58	0.384	7.65
	23/10/97 (21.00)	85	0.271	0.00
	24/10/97 (19 00)	107	0.364	0.00
	26/10/97 (19.00)	155	0.284	0.08
	28/10/97 (19:00)	203	0.365	0 00
	29/10/97 (17:30)	225.5	0.328	0.12
27/10/97 (8:30)	27/10/97 (8:30)	0	0.461	6.85
	27/10/97 (13:30)	5	0.432	4.94
	27/10/97 (17:30)	9	0.454	2.71
27/10/97 (17:30)	27/10/97 (17:30)	0	0.569	7.33

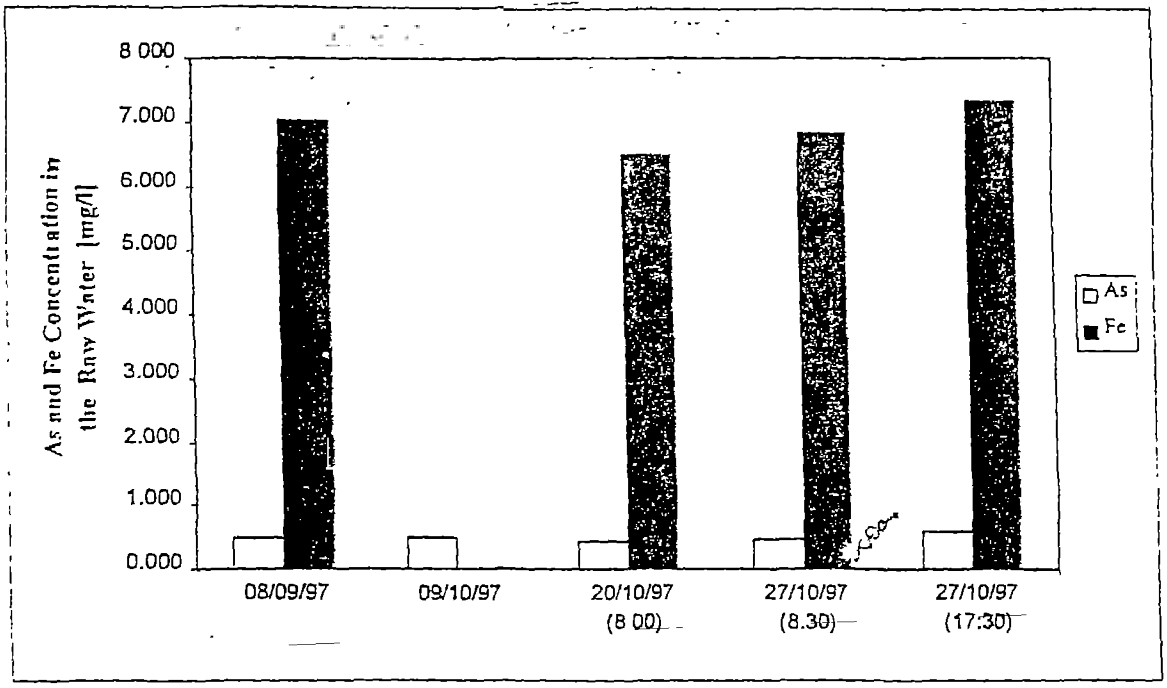

Figure 20. Variation of arsenic and iron concentrations in the raw water of IRU-13 (on 09/10/97 the iron concentration was not measured)

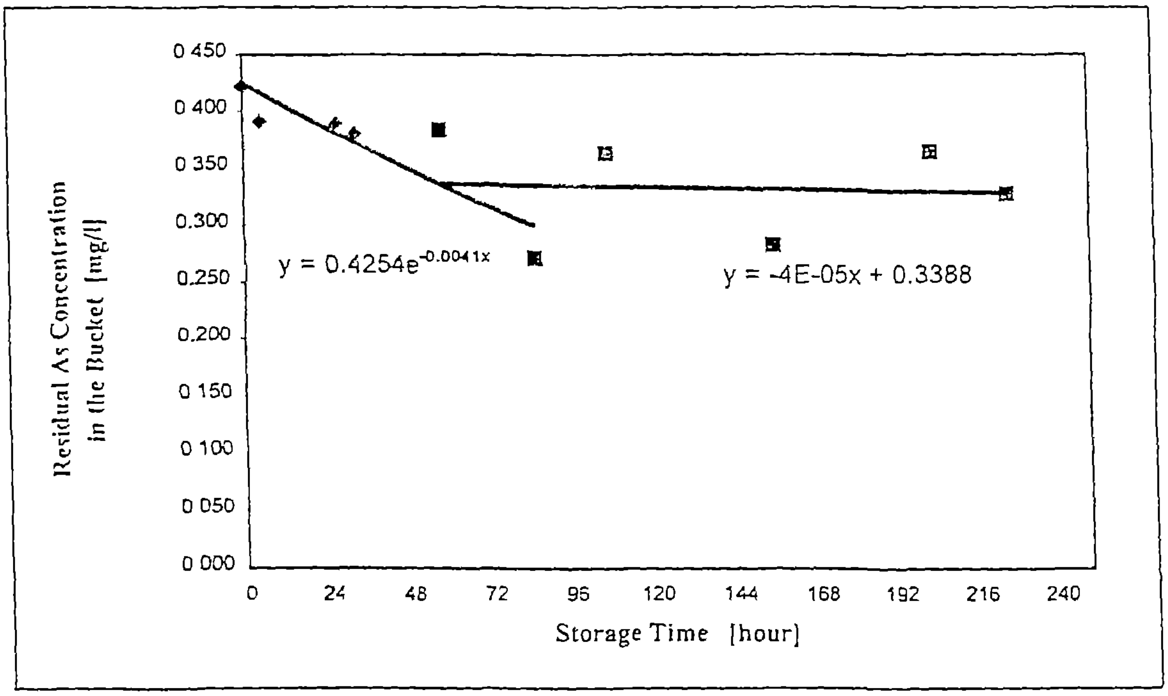

Figure 21. Residual arsenic concentration during storage (water fetched on 20/10/97).

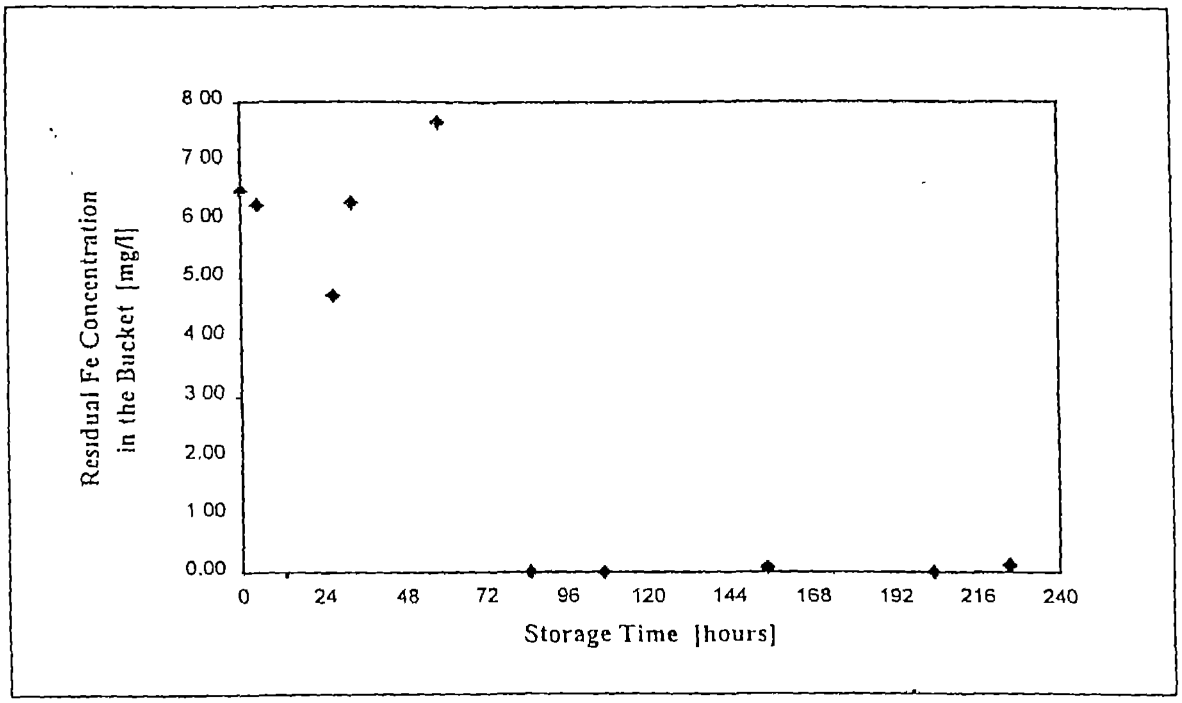

Figure 22. Residual iron concentration during storage (water fetched on 20/10/97).

Figure *21* and Figure *22* show the change of concentrations for arsenic and iron in stored buckets in the laboratory versus time. The number of data does not allow for verification of the reaction kinetics, which is not the purpose of this project either. However, if a first order reaction pattern is assumed, the arsenic removal in the initial days during storage may be described by the equation.

$$C_t = C_0 \cdot e^{-kt} \qquad \text{eq. 27}$$

where, C_t is the residual arsenic concentration at time t, mg/l
C_0 is the initial arsenic concentration, mg/l
t is the storage time, hour or day
k is the rate constant, which is estimated to be k = 0.004 h^{-1} or 0.096 d^{-1}.

The arsenic concentration only falls about 20 % in the first couple of days and thereafter the concentration remains almost constant, indicating that the arsenic removal during a normal storage of water in a bucket at house hold level is negligible.

The iron concentration also falls in the first couple of days. It becomes almost nil after about 3 days. This may explain why the arsenic concentration remains unchanged after the initial period.

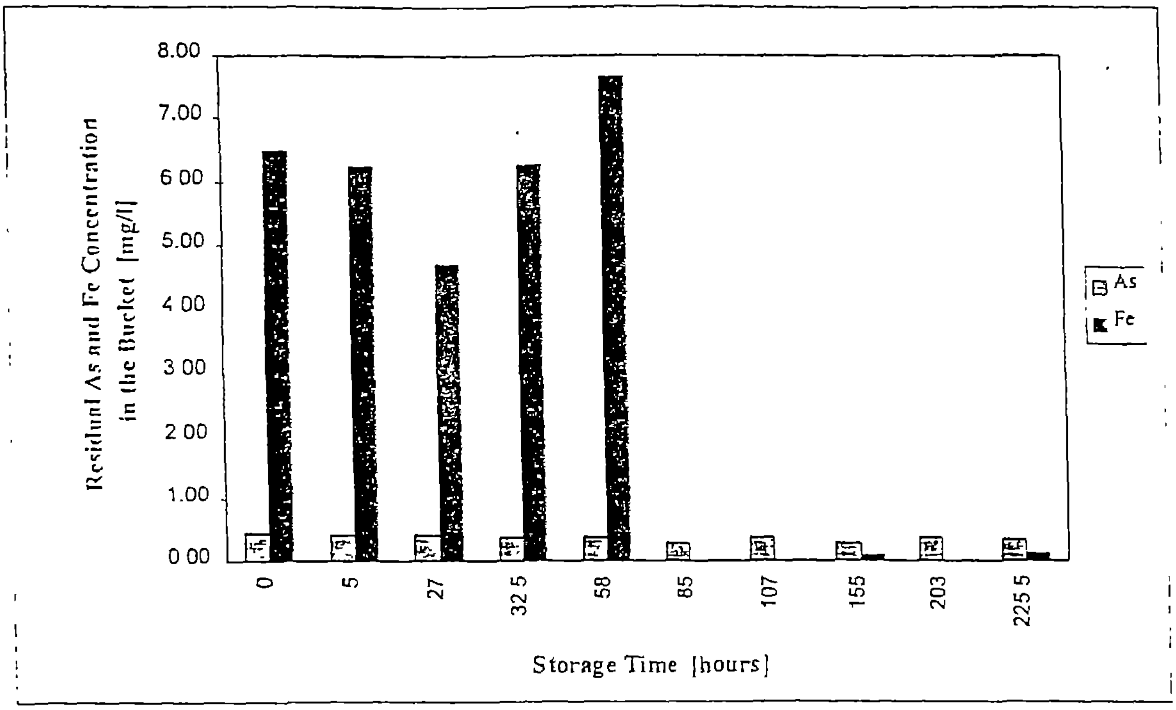

Figure 23. Comparison of residual concentration for arsenic and iron during storage (water fetched on 20/10/97).

The measured iron concentration on 26-29/10/97 may be attributed to the micro flocs coming in to water during sampling procedure, since the samples were not filtered. The rising in iron concentration on 21/10/97 (16.30) and 22/10/97 (18 00) may be due to the same reason.

5.3. Calibration of Field Test Kit

The arsenic concentration of 46 samples was measured using both MERCK test kit and the laboratory analysis method The results are listed in Table 15 The difference, X, between these two methods are calculated in column (4) Assuming X is a statistical variable which is normally distributed The mean value of this variable, μ, is an indication of the consistency between these two methods, i e, if μ is zero, there is no difference between these two methods, otherwise, it means that there is a certain difference between these two methods

According to /Conradsen, 1995/ the hypothesis is

H_0 $\mu = 0$ against H_1 $\mu \neq 0$

The test value is.

$$Z = \frac{\bar{X}}{S / \sqrt{n}}$$

Where, S^2 is the variance of X

n is the number of the realizations

Table 15. *Arsenic concentrations measured by MERCK and Spectrophotometer.*

Sample Source Column (1)	MERCK Column (2)	Spectrophotometer Column (3)	*X* (difference) Column (4) = (2) - (3)
Niller's house	0.1	0.11	-0.01
Guesthouse	0.2	0.17	0.03
Femi's house	0.3	0.28	0.02
Dulal Master Bari (Raw)	0.4	0.21	0.19
Dulal Master Bari (Treated)	0.4	0.18	0.22
Kala Miah Bahi (Raw)	0.4	0.25	0.15
Kala Miah Bahi (Treated)	0.1	0.06	0.04
Jar Test sample on 24/09	0.3	0.12	0.18
"	0.2	0.21	-0.01
"	0.2	0.15	0.05
"	0.1	0.24	-0.14
"	0.2	0.21	-0.01
"	0.2	0.12	0.08
"	0.2	0.19	0.01
"	0.1	0.08	0.02
"	0	0.06	-0.06
Jar Test Sample on 28/09	0.05	0.30	-0.25
"	0.2	0.30	-0.10
"	0.2	0.21	-0.01
"	0.2	0.22	-0.02
"	0.2	0.22	-0.02
"	0.1	0.17	-0.07
"	0.05	0.10	-0.05
"	0.05	0.09	-0.04
"	0.01	0.06	-0.05
"	0.01	0.06	-0.05
"	0	0.05	-0.05
"	0	0.04	-0.04
Jar Test Sample on 29/09	0	0.01	-0.01
"	0	0.03	-0.03
"	0	0.02	-0.02
"	0	0.02	-0.02
"	0	0.00	0.00
"	0	0.01	-0.01
"	0	0.00	0.00
IRU-1	0.25	0.09	0.16
IRU-3	0.1	0.04	0.06
IRU-9	0.3	0.20	0.10
IRU-12	0	0.00	0.00
IRU-13	0.7	0.48	0.22
IRU-14	0.4	0.19	0.21
IRU-15	0.1	0.07	0.03
OTW-1	0	0.00	0.00
OTW-2	0	0.00	0.00
OTW-3	0	0.00	0.00
OTW-4	0	0.00	0.00
Variance			0.00861
Mean			0.01552
Test Value *Z*			1.135

Inserting $S = \sqrt{0.00861}$, $\overline{X} = 0.01552$, and $n = 46$ to the above equation, it derives $Z = 1.135$.

If the significant level $\alpha = 5$ %, the critical area will be:

$$C = \{z \mid z < t(n\text{-}1)_{\alpha/2} \cup z > t(n\text{-}1)_{1\text{-}\alpha/2}\} = \{z \mid z < t(45)_{2.5\%} \cup z > t(45)_{97.5\%}\}$$
$$= \{z \mid z < -2.015 \cup z > 2.015\}$$

The calculated Z is 1.135, which lies outside of the critical area Thus the hypothesis H_0 is accepted at the 5 % significant level Though MERCK test kit does not give exactly the same value as the laboratory method, and sometimes the difference is even quite large, from the statistics point of view, it can hit the right value at 5 % significant level as the laboratory method.

From the point of view of drinking water quality control, when the arsenic concentration measured by MERCK is under the MCL value (0.05 mg/l), the samples must be re-checked by the laboratory method since the real concentration might be higher than 0.05 mg/l. Moreover it is not easy to read the colour scales at low concentrations, which in turn gives higher uncertainty.

5.4. Significance of Chemical Dosages on Arsenic Removal and pH

The jar test experiments were carried out on 14, 24, 28, and 29 September and 16, 21 October 1997. Only the jar test results carried out on 21/10/97 are discussed her. The other jar test results are shown in Appendix 7-13 according to the date when the experiments were carried out. Because the samples were not taken right before the jar tests, except for that on 21/10/97, the initial arsenic concentration is not the measured value. It is derived from the results of Sections 5.1 and 5 2, which show that the arsenic concentration changes very slightly in September and October, 1997, and the removal efficiency is very low during storage The total arsenic removal is only about 20 %, and after the initial period, the concentration for arsenic almost remains constant The added amount of bleaching powder, the dosages of coagulants, the volume of HCl for preservation, the experiments procedure and so on are also listed in the corresponding appendices

5.4.1. Ferric Chloride and Alum

The initial concentration for arsenic was 0.384 mg/l and for iron 5 48 mg/l. The added iron dosages were 0.11, 0 15, 0.18, 0.22, 0.26, 0 30, 0.33, 0 37, 0 41 mmol/l (Corresponding $FeCl_3 \cdot 6H_2O$ dosages were. 30, 40, 50, 60, 70, 80, 90, 100, 110 mg/l). The added Al dosages were. 0.24, 0.30, 0.36, 0 42, 0 48, 0 54 mmol/l (corresponding $Al_2(SO_4)_3 \cdot 18H_2O$ dosages were. 80, 100, 120, 140, 160, 180 mg/l).

The main results from jar tests on 21/10/97 are shown in Table 16 and Table 17 , and Figure 24 - 27. See Appendix 13 for more details

Table 16. The arsenic removal efficiency by adding ferric chloride. The initial arsenic concentration is 0.384 mg/l.

Dosage			Arsenic	
$FeCl_3 \cdot 6H_2O$	Fe		Residual	Removal
mg/l	mmol/l	mg/l	mg/l	%
30	0.11	6.2	0.152	60
40	0.15	8.3	0.135	65
50	0.18	10.4	0.100	74
60	0.22	12.4	0.079	79
70	0.26	14.5	0.062	84
80	0.30	16.6	0.074	81
90	0.33	18.6	0.037	90
100	0.37	20.7	0.033	91
110	0.41	22.8	0.041	89

Table 17. The arsenic removal efficiency by adding alum The initial arsenic concentration is 0.384 mg/l.

Dosage			Arsenic	
$Al_2(SO_4)_3 \cdot 18H_2O$	Al		Residual	Removal
mg/l	mmol/l	mg/l	mg/l	%
80	0.24	6.5	0.175	54
100	0.30	8.1	0.143	63
120	0.36	9.7	0.096	75
140	0.42	11.4	0.090	77
160	0.48	13.0	0.074	81
180	0.54	14.6	0.072	81

When ferric chloride was used, the arsenic concentration was reduced from 0.384 mg/l to less than 0.05 mg/l at the dosage of 90 mg/l $FeCl_3 \cdot 6H_2O$, the removal efficiency is around 90 %. When alum was used the residual arsenic concentration still lay above 0.05 mg/l even the dosage was as high as 180 mg/l $Al_2(SO_4)_3$ $18H_2O$. The removal efficiency was only obtained around 80 %. (see Table 16 and Table 17).

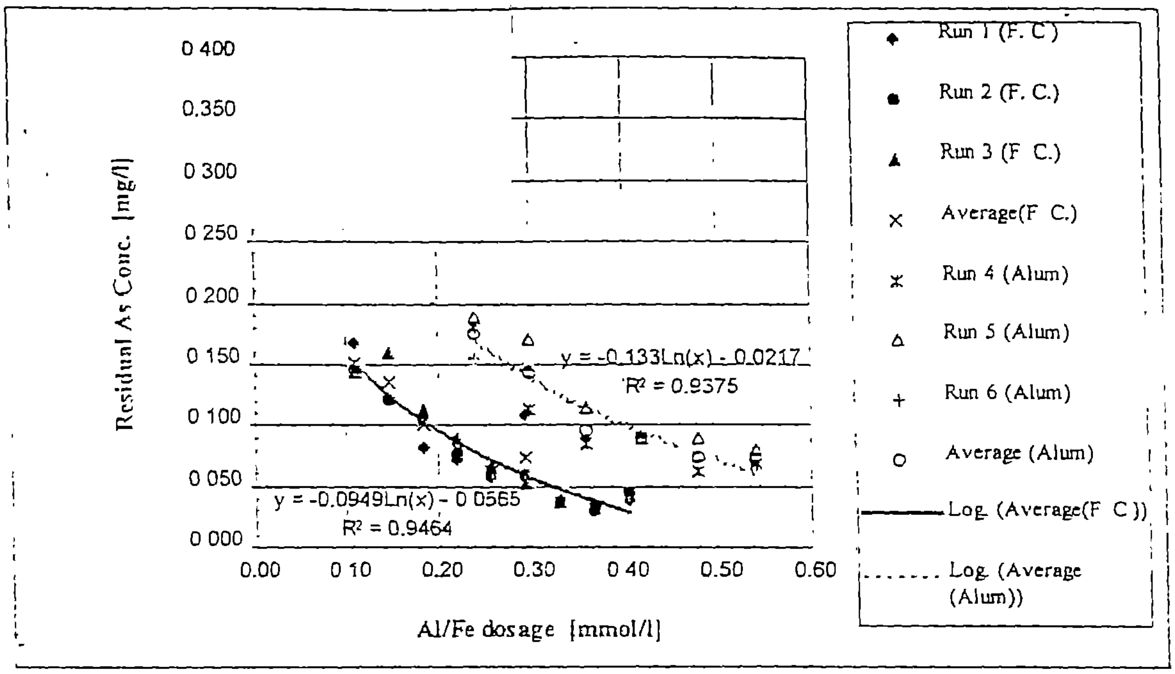

Figure 24. Influence of alum and ferric chloride dosages (molar basis) on arsenic removal.

Figure 24 shows the residual arsenic concentration versus the added dosage of chemicals measured as Al and Fe in molar basis, while Figure 25 shows the dosage curves on the weight basis of alum and ferric chloride. These two figures show clearly that both in molar and weight bases ferric chloride is more efficient than alum in removing arsenic concentration from water. The arsenic removal is increasing with the dosage of chemicals.

Using best fit curve to the measured data, the dosage curves for Al and Fe on molar basis can be expressed as the following equations for alum and ferric chloride respectively.

$$Y = -0.133Ln(X) - 0.0217 \qquad \text{eq. 28}$$

$$Y = -0.0949Ln(X) - 0.0565 \qquad \text{eq. 29}$$

where, Y is the residual arsenic concentration, mg/l

X is the Fe or Al dosage on molar basis, mmol/l

For Fe, the validity interval is 0.11 - 0.41 mmol/l, and for Al, 0.24 - 0.54 mmol/l

On the weight basis of alum and ferric chloride, the above equations change to the following equations accordingly

$$Y = -0.133Ln(X) + 0.7508 \qquad \text{eq. 30}$$

$$Y = -0.0949 Ln(X) + 0.4748 \qquad \text{eq. 31}$$

After some straightforward derivation, the above equations can further be reduced:

$$X = e^{(-7.5Y+5.6)} \qquad \text{eq. 32}$$

$$X = e^{(-10.5Y+5.0)} \qquad \text{eq. 33}$$

where, Y is the residual arsenic concentration, mg/l

X is the $FeCl_3$ $6H_2O$ or $Al_2(SO_4)_3$ $18H_2O$ dosage on weight basis, mg/l

For $FeCl_3$ $6H_2O$, the validity interval is 6.2 - 22.8 mg/l, and for Al, 6.5 - 14.6 mg/l.

Before the chemicals were added to the water, bleaching powder was first mixed with water for 5 minutes for oxidizing As(III), if any, to As(V). The existing iron in groundwater was to be precipitated as $Fe(OH)_3$, and this iron hydroxide was to absorb some arsenic in the water. Therefore, before any chemicals were added, some arsenic could already have been removed in advance by the existing iron. The remained arsenic may further be removed by the added chemicals (alum, ferric chloride, rice husk etc.) after mixing with bleaching powder.

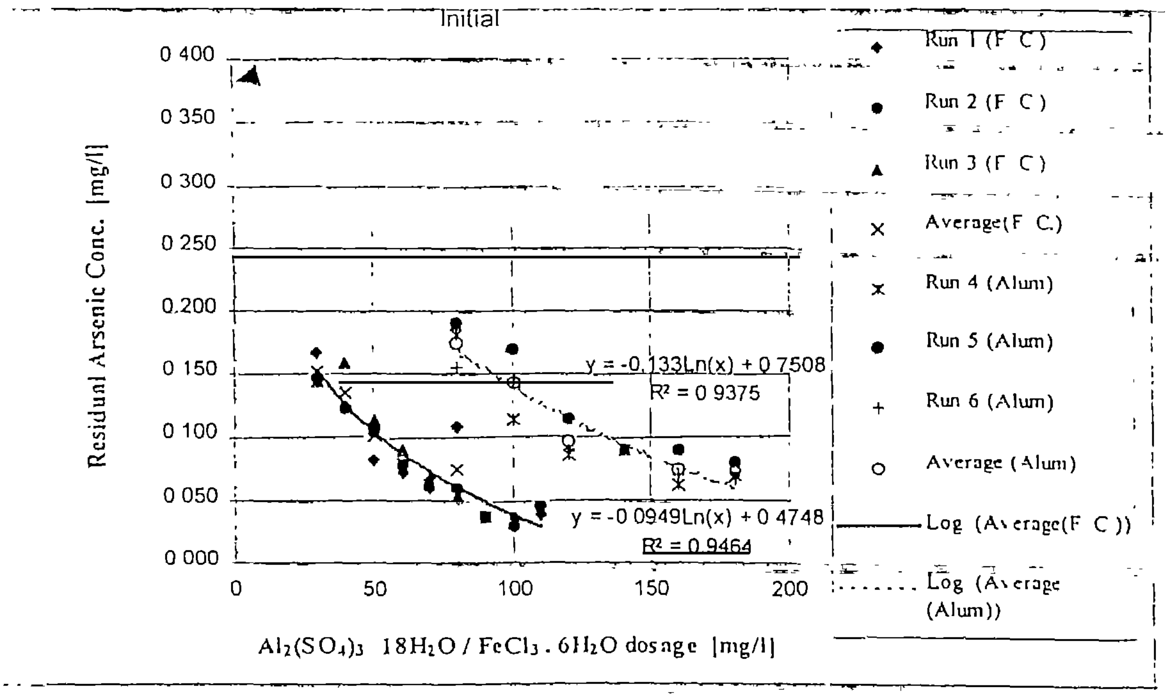

Figure 25. Significance of alum and ferric chloride dosages (weight basis) on arsenic removal.

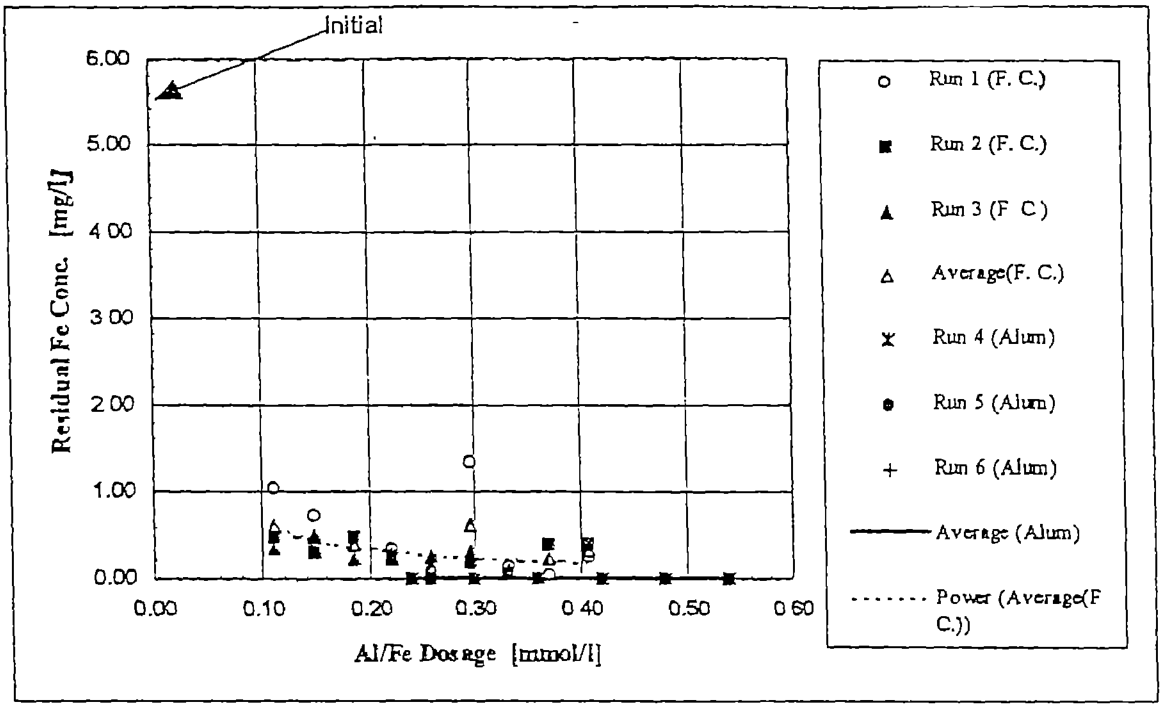

Figure 26. Significance of alum and ferric chloride dosages (molar basis) on residual iron concentrations.

Though no blind tests were included in the jar test experiments, the same water was used for jar tests on 21/10/97 and for testing arsenic removal during storage. From Table 14 in Section 5.2, it may be seen that the arsenic concentration was around 0.3 mg/l when iron concentration became zero. This concentration, 0.3 mg/l could be the residual arsenic concentration at zero alum or ferric chloride dosage.

Theoretically, the residual iron concentration should be zero if the solubility of $Fe(OH)_3$ is very small. But the measurement results were not zero when ferric chloride was used (see Figure 26), which indicates that the sedimentation may not be complete or under sampling, the micro flocs may have come into water even through coffee or tea filter. In the laboratory, the water sample may be taken through a very fine filter but no body does that in practice. So the residual iron concentration is generally not zero, even it can be zero in theory.

From Figure 26, it may be seen that almost all residual iron concentrations lie below 1 mg/l and when alum was used the residual iron concentrations were not detectable.

Ferric chloride and Alum are both acid according to eq. 16 - eq. 19, i.e. they consume the alkalinity in the water. Figure 27 shows a clear tendency of decrease in pH. There is a linear relation between the resulting pH and the dosage of the added chemicals. The decrease is, however, very small and the resulted pH is acceptable under all circumstances. This may be related to the buffer capacity of the water and to the added chlorinated lime, which may take part in the protolytic reactions when it is dissolved. There is no need to adjust the pH for the treated water, when the resulted pH is around 7.

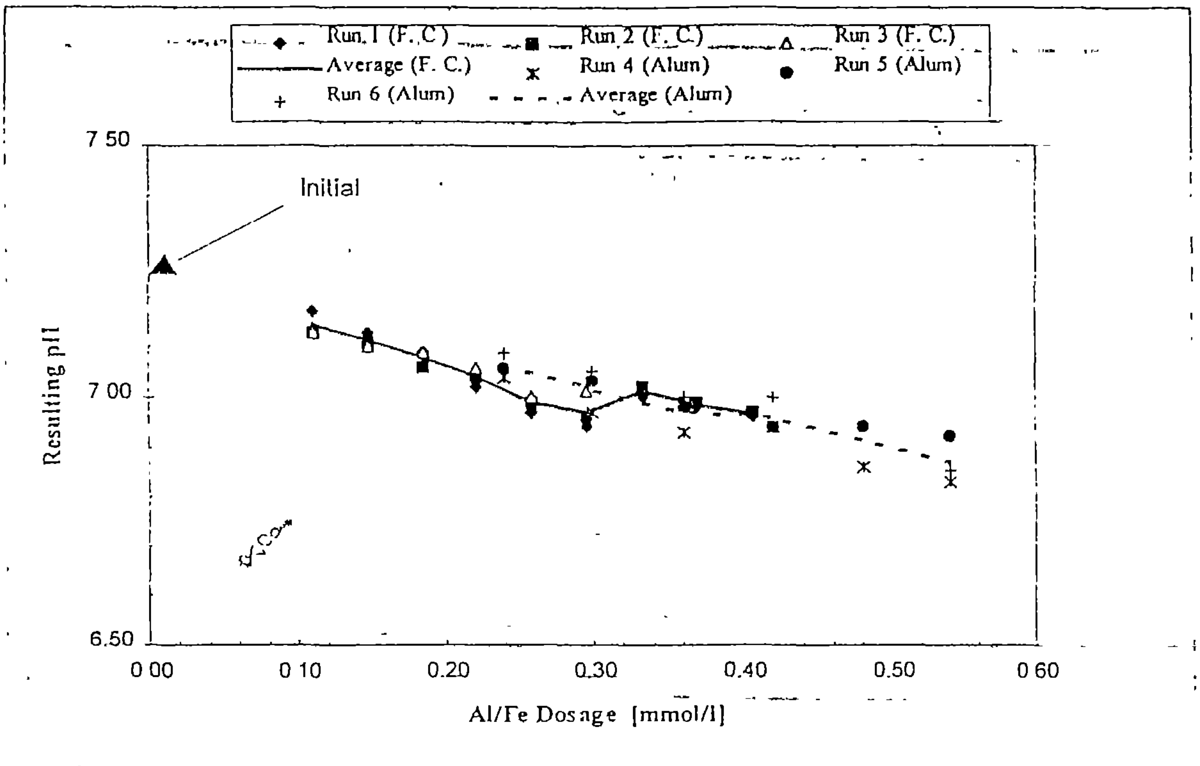

Figure 27. Significance of alum and ferric chloride dosages (molar basis) on resulting pH.

5.4.2. Rice Husk

In run 1, different rice husk dosages, from 0.6 - 3.6 g/l, were used, and in run 2, the rice husk dosages were almost identical (about 0.7 g/l) but combined with 10 mg/l alum or ferric chloride. From Table 18 and Figure 28, it may be seen that the residual arsenic concentration is below 0.05 mg/l in all cases. In run 2, when additional alum or ferric chloride was added, the residual arsenic was below detectable level.

This local product has a very good ability for arsenic removal. Unfortunately, a description of this local product has not been available. Because the rice husk has been treated by ferric chloride in advance, the contents of ferric chloride in the rice husk may be very high. Therefore it gives high arsenic removal.

When rice husk combined with alum or ferric chloride, the removal is more efficient than rice husk alone.

Though this local product has a good ability for arsenic removal, it was not chosen for further experiments because the produced flocs had a poor sedimentation ability. All the flocs lay on the water surface. Moreover, the colour of the treated water was dark green and the black rice husk ash was floating on the water. It had a very unpleasant appearance.

Table 18. Significance of rice husk dosage on arsenic removal.

Run 1	Rice Husk g/l	Dosage Additional Chemicals mg/l	Residual Total As Run 1 mg/l
	0.6	0	0.012
	1.2	0	0.028
	1.8	0	0.015
	2.4	0	0.022
	3.0	0	0.000
	3.6	0	0.006
Run 2			
	0.7	10 (alum)	0.001
	0.7	10 (alum)	0.000
	0.7	10 (alum)	0.000
	0.7	10 (ferric chloride)	0.000
	0.7	10 (ferric chloride)	0.000
	0.7	10 (ferric chloride)	0.000

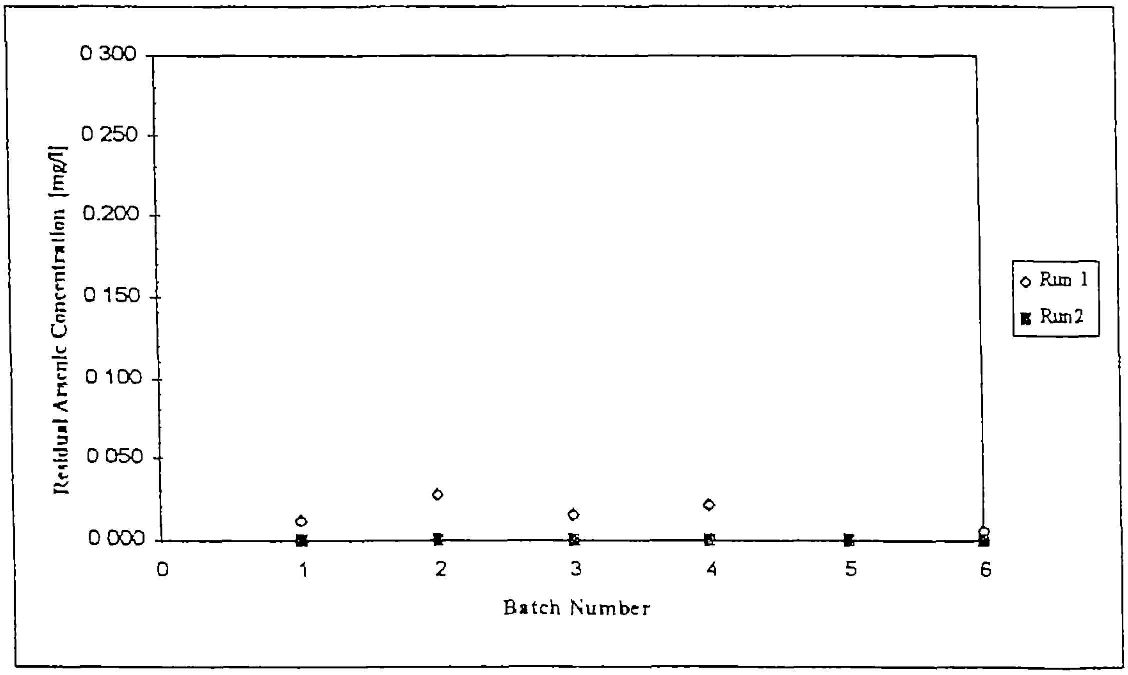

Figure 28. Significance of rice husk (weight basis) on arsenic removal (the initial arsenic concentration was higher than 0.38 mg/l).

5.5. Significance of Mixing

5.5.1. One-bucket experiments

The relation between residual arsenic or iron concentration and the duration of slow and fast stirring are shown in Figure 29-32, respectively. It may be seen that the longer duration of slow stirring the better arsenic removal. On the other hand, the longer duration of fast stirring, the worse arsenic removal. Under slow stirring the small flocs attached together to bigger flocs, which have better sedimentation abilities while fast stirring would break the bigger flocs to small ones, which consequently give poor arsenic removal.

In Figure 29, it clearly shows that, when the duration of fast stir is fixed, longer slow stir gives better arsenic removal. With 1 minute's fast stir in advance, the arsenic concentration in the treated water was under 0.05 mg/l after 10 minutes' slow stir, while the arsenic concentration is around 0.07 mg/l after 3 minutes' slow stir By keeping in mind the fact that the initial arsenic concentration is 0.556 mg/l, it may also be seen that within the first few minutes, the removing process of arsenic is very fast.

In Figure 31, it may be noticed that, at a fixed duration for slow stir, the longer fast stir gives worse arsenic removal.

Table 19. Significance of mixing in term of stirring speed and duration. Settling time is 1 hour

Run No.	Fast stir sec	Slow stir minutes	Resulting Sludge ml	Residual As mg/l	As Removal %
1	60	3	600	0.064	89
2	60	5	700	0.062	89
3	60	7	600	0.043	92
4	60	9	600	0.060	89
5	60	11	600	0.037	93
6	60	13	900	0.020	96
7	60	15	800	0.034	94
8	10	5	800	0.034	94
9	20	5	900	0.034	94
10	40	5	900	0.027	95
11	80	5	800	0.050	91

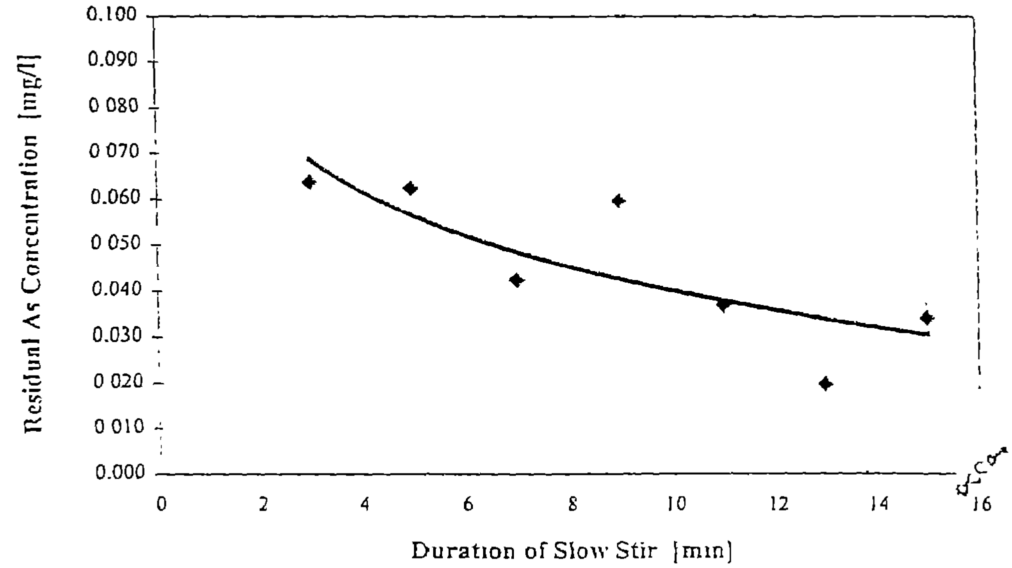

Figure 29. Residual arsenic concentration versus the slow stirring duration in the bucket experiments The initial arsenic concentration is 0.556 mg/l The fast stir is fixed at 60 sec

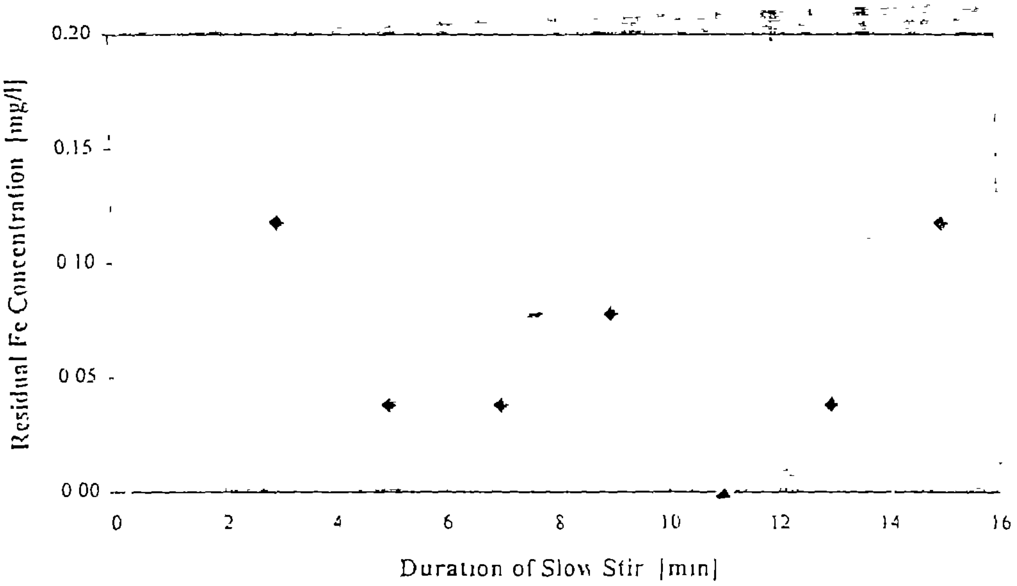

Figure 30. Residual iron concentration versus the slow stirring duration in the bucket experiments. The initial iron concentration is 7 mg/l The fast stir is fixed at 60 sec

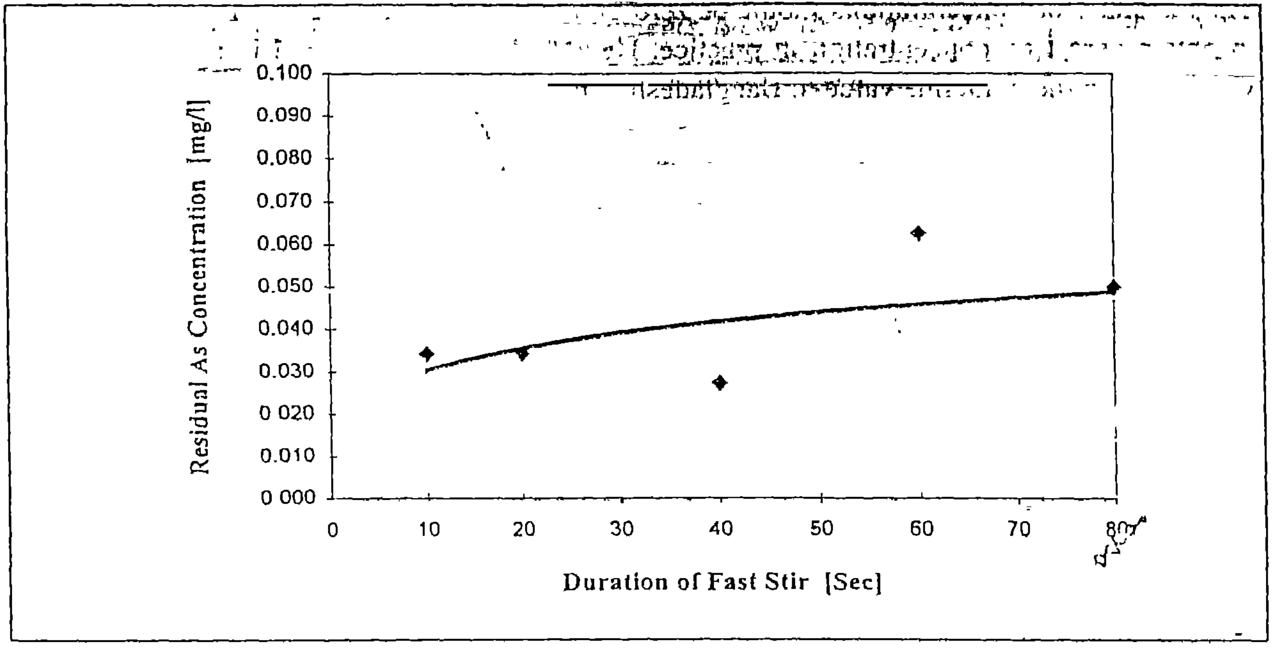

Figure 31. Residual arsenic concentration versus the fast stirring duration in the bucket experiments. The initial arsenic concentration is 0.556 mg/l. The sloe stir is fixed at 5 min.

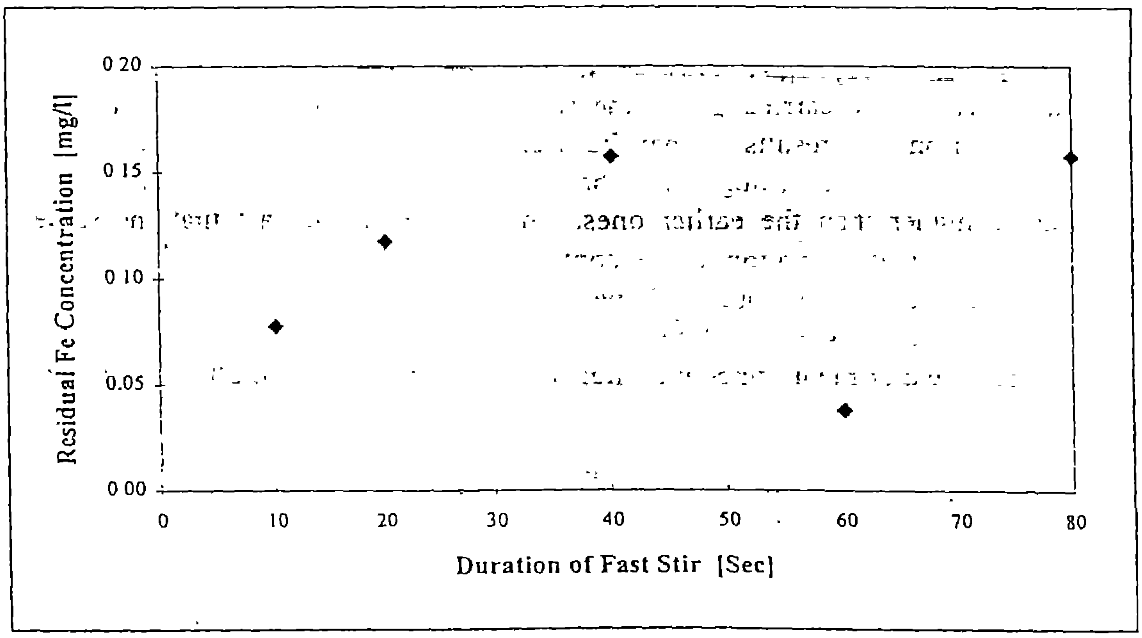

Figure 32. Residual iron concentration versus the fast stirring duration in the bucket experiments. The initial iron concentration is 7 mg/l. The slow stir is fixed at 5 min.

The residual iron concentrations should be zero as described in section 5.4.1. But it is not easy to obtain zero iron concentration in practice Nevertheless, the measured iron concentration was less than the guideline value in Bangladesh, 1 mg/l, in all experiments.

From the point of view of practical field implementation, the investigation results are very promising because they show that the arsenic removal is less sensitive to the duration of stirring than to the speed of stirring.

The recommended operation criteria may therefore given as: with fast stirring, using shorter possible duration e.g. 10 sec, and with slow stirring, using longer time duration, e.g. > 10 min.

5.5.2. Two-bucket experiments

Some batch experiments were carried out with 10 minutes' slow stir and 40 seconds' fast stir in two-bucket test experiments. Due to the shortage of time, only 2 samples after the second bucket were analyzed for arsenic and iron. The results are shown in Table 20, Figure 33 to Figure 35 and can be found in Appendix 14 for more details. The resulted pH lies between 6.5 to 7, which is not needed to be adjusted after treatment, and the concentration for arsenic and iron in the treated water lies below 0.05 and 1 mg/l, respectively.

From Table 20, it may be seen that arsenic concentration is slight lower after the second bucket than after the first one This is probably due to the uncertainty of arsenic analysis, but it may also be due to the fact that the simple filter has removed some micro flocs escaped from the first bucket.

The resulted sludge is less than 1 litre. With 15 litres raw water in total, the yield is higher than 90 %

These experiments were carried out at the same day, using the same water and the same procedure. But from the results, it may be seen that the initial concentration both for the arsenic and the iron varied through the 6 batches The concentration for arsenic and iron in batch No.6 is higher than the earlier ones. This is due to the fact that the settled clay, precipitate and so on at the bottom of the container were unavoidably disturbed when the raw water was being poured to the bucket Especially at the last batch almost all of the raw water left in the container was used After all, the residual arsenic and iron concentration is acceptable for all experiments since it all lies under 0.05 mg/l and 1 mg/l for arsenic and iron, respectively

Table 20. The results of two-bucket test experiments. Slow stir 10 minutes and fast stir 40 sec.

	Initial			Residual					
	pH	As Conc.	Fe Conc.	pH	As conc. (mg/l)		Fe Conc. (mg/l)		Sludge
Run No.		mg/l	mg/l	After 1.	After 1.	After 2.	After 1.	After 2.	ml
1	7.22	0.453	2.47	6.77	0.049	-	0.00	-	500
2	7.22	0.453	2.47	6.70	0.055	-	0.00	-	750
3	7.11	0.396	1.84	6.73	0.048	-	0.20	-	1000
4	7.04	0.409	1.24	6.62	0.035	-	0.08	-	800
5	7.13	0.365	3.91	6.74	0.046	0.041	0.00	0.04	950
6	7.15	0.508	9.36	6.64	0.045	0.035	0.04	0.00	900

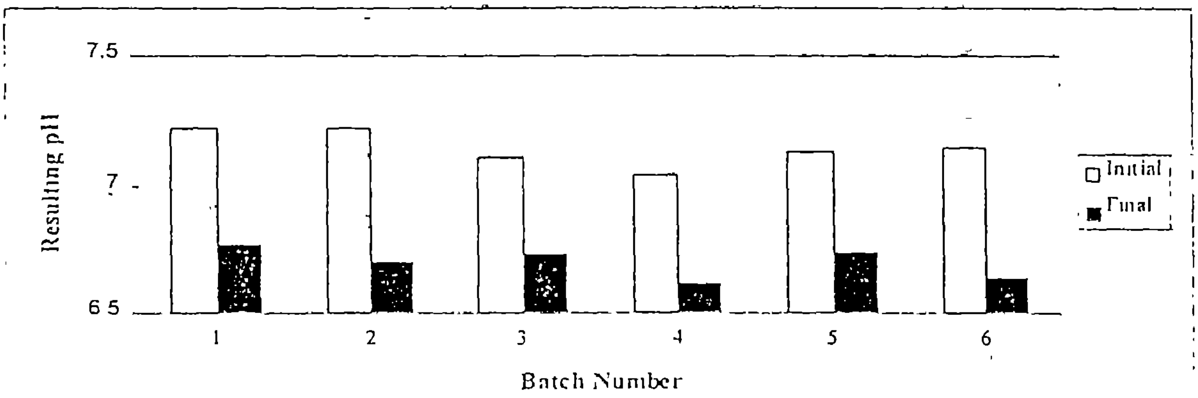

Figure 33. Resulting pH in bucket experiments. Fast stirring 40 sec and slow stirring 10 minutes.

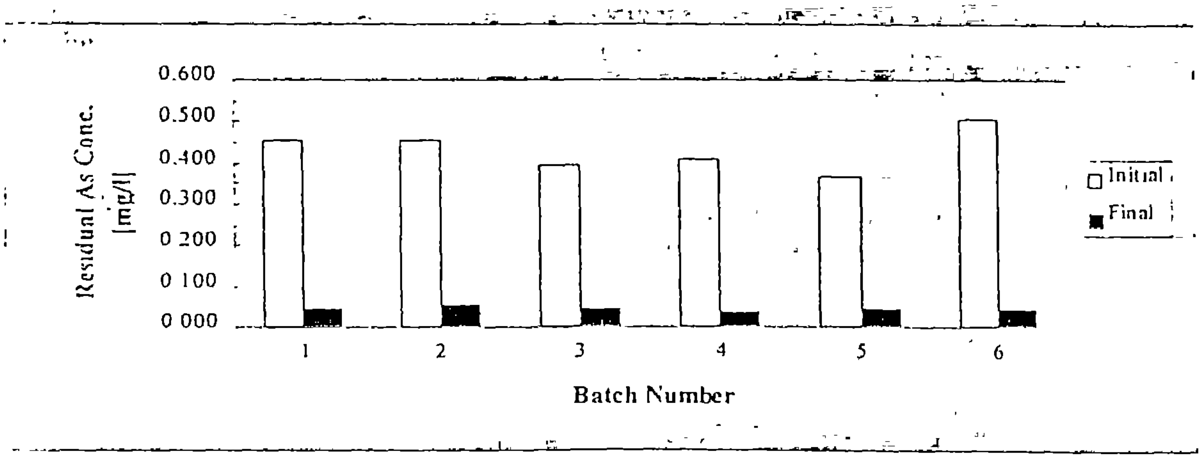

Figure 34. Residual arsenic in bucket experiments. Fast stirring 40 sec and slow stirring 10 minutes.

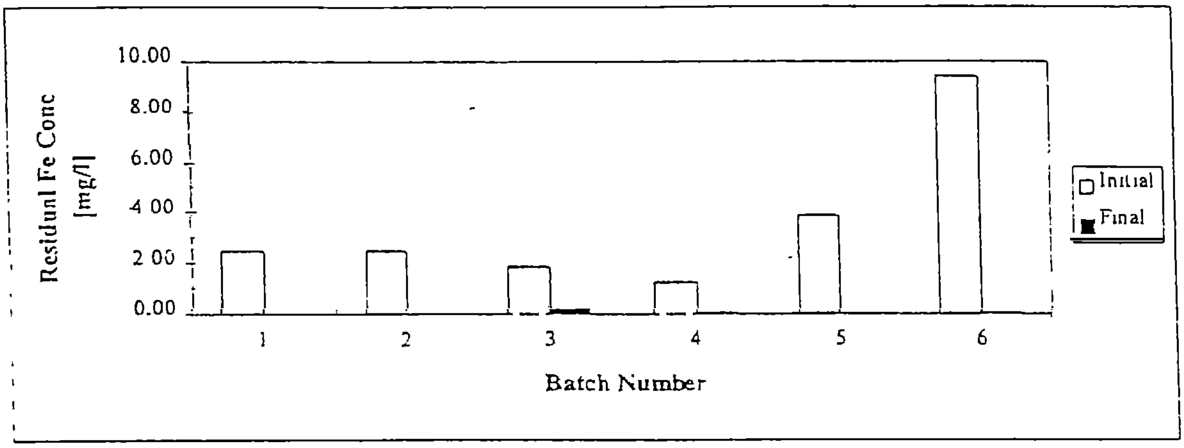

Figure 35. Residual iron in bucket experiments Fast stirring 40 sec and slow stirring 10 minutes

6. SORPTION ISOTHERMS

6.1. Introduction

As mentioned in the literature survey, arsenic removal by coagulation may be described by sorption isotherms. Normally, there are two modules which are often used to describe equilibrium concentrations in a sorption process /Dahi, 1989/. One is the Langmuir equation:

$$f^* = \hat{f} \cdot \frac{\Gamma_s \cdot S^*}{\Gamma_s \cdot S^* + 1} \qquad \text{eq. 34}$$

Where, f^* is the equilibrium concentration of sorbate on the sorbent, mg/g
S^* is the equilibrium concentration of sorbate in the water, mg/l
Γ_s is a sorption intensity constant, l/mg
$\hat{f}$ is a sorption capacity constant, mg/g

The other one is the Freundlich equation:

$$f^* = \alpha \cdot S^{*1/\beta} \qquad \text{eq. 35}$$

Where α is a sorption capacity constant, $l^{1/\beta} \cdot mg^{2/\beta} \cdot g^{-1}$
β is a sorption intensity constant -

The Freundlich equation shows that f^* has no limits except for the limits of S^* contrary to the Langmuir equation predicting a maximum f^* of $\hat{f}$.

Based on the experimental results, it's been investigated to see if there is any correlation between the concentration of arsenic on iron and the residual arsenic concentration in the aqueous phase, and between the concentration of arsenic on aluminium and the residual arsenic concentration in the aqueous phase.

The experimental results from the jar test on 21/10/97 (see Section 5.4) are used in the estimations in this chapter, even though the equilibrium may not be reached.

The initial concentration was 0.384 mg/l for arsenic and 5.48 mg/l for iron. The added iron dosages were: 6.2, 8.3, 10.4, 12.4, 14.5, 16.6, 18.6, 20.7, 22.8 mg/l (the corresponding $FeCl_3 \cdot 6H_2O$ dosages were: 30, 40, 50, 60, 70, 80, 90, 100, 110 mg/l) The added Al dosages were: 6.5, 8.1, 9.7, 11.4, 13.0, 14.6 mg/l (the corresponding $Al_2(SO_4)_3 \cdot 18H_2O$ dosages were: 80, 100, 120, 140, 160, 180 mg/l).

6.2. Testing of Langmuir and Freundlich

Figure 36 and Figure 37 show the concentration of removed arsenic in the flocculated iron, f^*, measured as mg As/g iron in the water versus the residual arsenic concentration. The flocculated iron in Figure 36 is the total iron concentration and the measured f^* is calculated as:

$$f^* = \frac{As_{initial} - As_{residual}}{Fe_{initial} + Fe_{added}} \times 1000 \qquad \text{eq. 36}$$

In Figure 37, the flocculated iron is only the added iron The measured f^* is calculated as:

$$f^* = \frac{As_{initial} - As_{residual}}{Fe_{added}} \times 1000 \qquad \text{eq. 37}$$

where, f^* is the equilibrium concentration of arsenic on iron, mg/g

$As_{initial}$ is the initial arsenic concentration, mg/l

$As_{residual}$ is the residual arsenic concentration, mg/l

$Fe_{initial}$ is the initial iron concentration, mg/l

Fe_{added} is the added iron concentration, mg/l

Figure 38 shows the concentration of removed arsenic in the flocculated aluminum, f^*, measured as mg As/g Al in the water versus the residual arsenic concentration. For the measured the calculation is performed as.

$$f^* = \frac{As_{initial} - As_{residual}}{Al_{added}} \times 1000 \qquad \text{eq. 38}$$

where Al_{added} is the added aluminium, mg/l

The estimation of the most appropriate constants for the isotherms is done using the method for nonlinear least squares fit using Microsoft Excel spread sheet The estimation can be found in Appendix 15

The constants from the Langmuir and Freundlich estimates are listed in Table 21

Table 21. Estimated constants in Langmuir and Freundlich isotherms

		$Fe_{added} + Fe_{initial}$	Fe_{added}	Al_{added}
Langmuir	$\hat{f}$	21.87	54.40	44.40
	Γ_s	40.96	10.66	15.64
Freundlich	α	31.80	94.83	61.43
	β	3.81	1.86	2.77

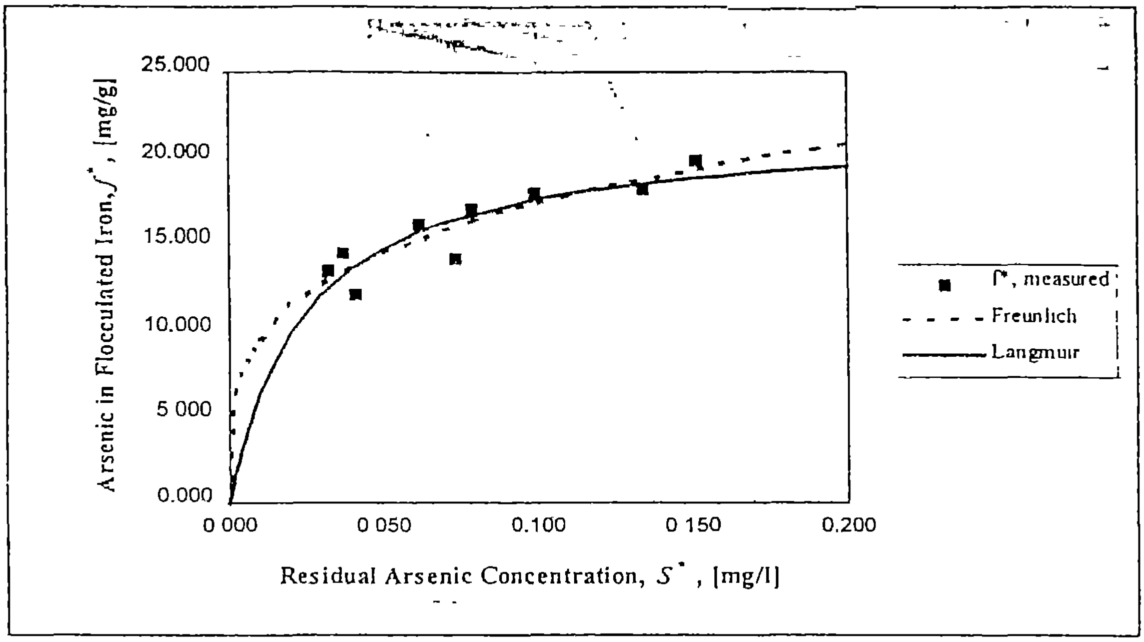

Figure 36. Langmuir and Freundlich isotherms estimates together with measured results based on the sum of added iron and already existing iron in the water.

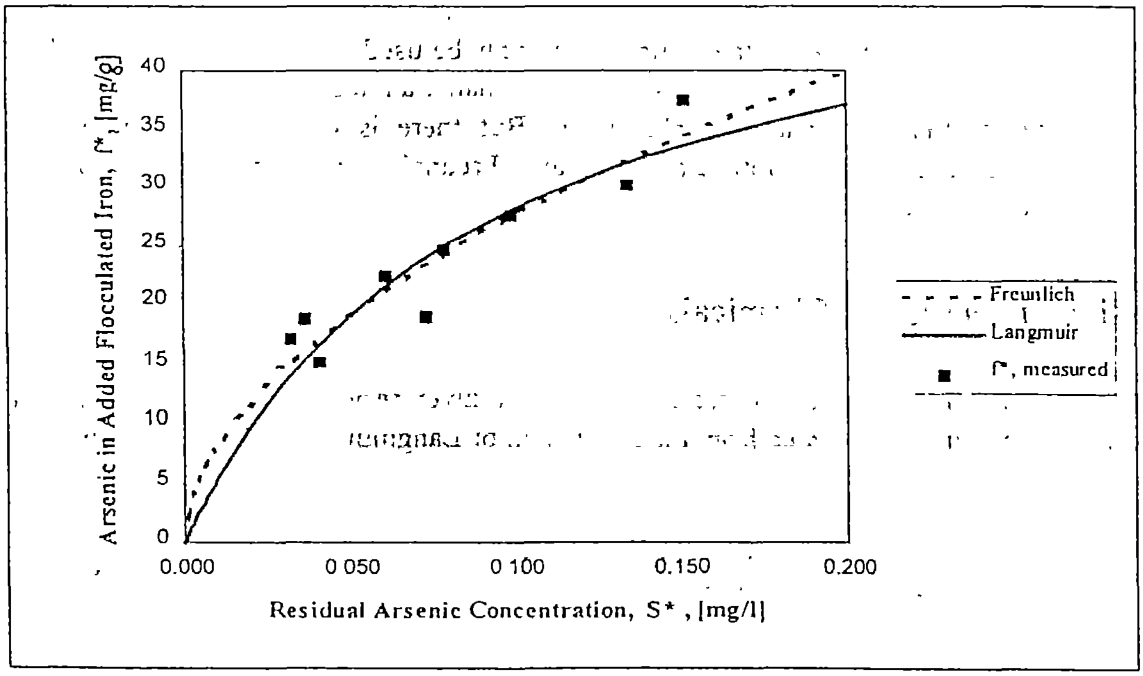

Figure 37. Langmuir and Freundlich isotherms estimates together with measured results based on the added iron to the water.

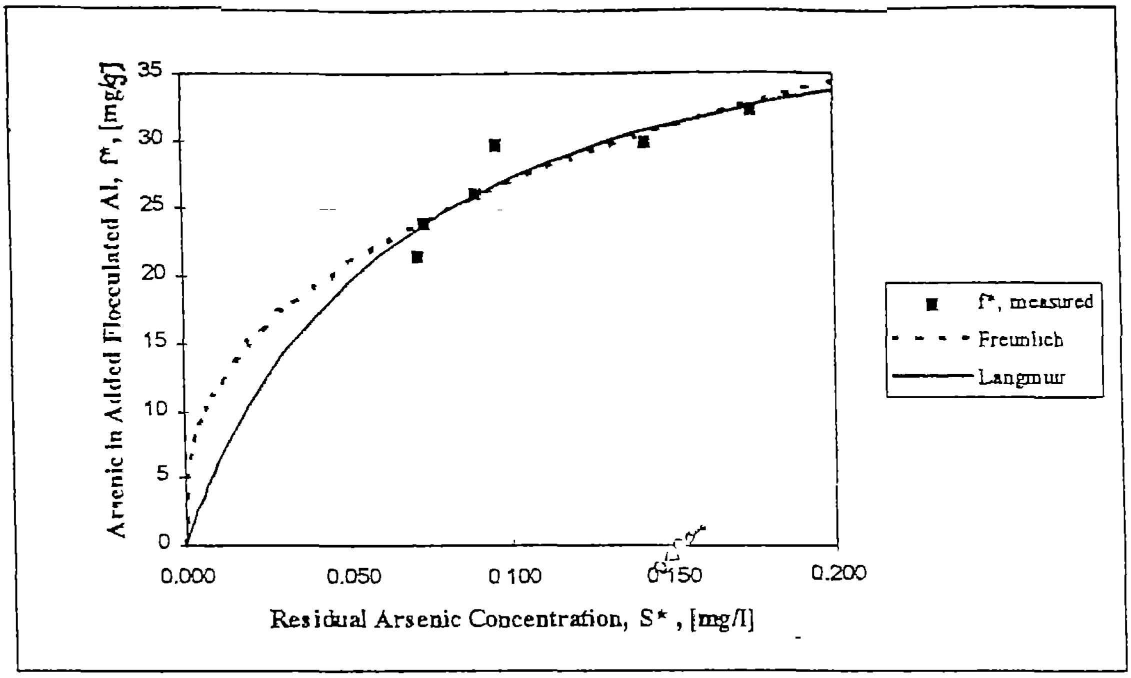

Figure 38. Langmuir and Freundlich isotherms estimates together with measured results based on the added al to the water.

6.3. Discussion

The estimated parameters are only valid in the interval where there are measured results. Beyond this interval, the estimated data or curves may only be used as preliminary results For iron, the Freunlich fits the experimental results better than Langmuir On the contrary the Langmuir fits better than Freunlich for aluminium But there is no significant difference between these two estimations. Both Langmuir and Freundlich isotherms show good a correlation with the measured results

6.4. Design on Dosage of Chemicals

The amount of aluminium or iron required for obtaining a given residual arsenic concentration in the treated water can be estimated from the Freundlich or Langmuir isotherms as follows

$$A = \frac{(As_{initial} - As_{residual}) \cdot V}{f^*} \qquad \text{eq. 39}$$

where, A is the amount of added aluminium or iron, g

V is the volume of treated water, l

f is the equilibrium concentration of arsenic on iron or aluminium estimated according to Freundlich or Langmuir isotherms, mg/g

$As_{initial}$ is the initial arsenic concentration, mg/l
$As_{residual}$ is the residual arsenic concentration, mg/l

It should be emphasised that the estimation is only valid in the interval where there are measurement results.

7. CONCLUSIONS

Parameter Correlation

No clear correlation is found between the concentration of arsenic and the concentration of iron in raw groundwater abstracted for drinking in the Noakhali area in Bangladesh. However, it is concluded that when arsenic is present, iron is likely to be present.

As analysis

Measurement of arsenic using the MERCK field test kit is concluded to hit the right value as estimated spectrophotometrically in the laboratory, at a significant level of 5 %. However, the variation may be considerable.

Storage of As Water

The arsenic concentration of raw water containing iron is found to decrease slightly, when the water is stored in a bucket. The decrease is found to be insignificant as a treatment method.

As removal in the IRU

The iron removal in the Noakhali IRUs is accompanied by removal of arsenic, on an average about 65 %. A linear correlation is derived between the arsenic removal and the iron concentration in the raw water. The better is the iron removal, the higher is the arsenic removal

As removal in the Fe and Alum Process

The arsenic removing process in the iron and alum flocculation in household buckets is very fast, taking place within the first few minutes of the experiments.

Required Mixing

Longer duration of the secondary slow stirring, results in better removal. On the contrary, prolongation of the initial fast stir results in deteriorated removal.

Required Dosage

Ferric chloride is more efficient than alum in removing arsenic from water, even on molar basis. On simple weigh basis, $FeCl_3 \cdot 6H_2O$ is about doublet as effective as $Al_2(SO_4)_3\ 18H_2O$. The use of 90 mg ferric chloride/l and 200 mg alum/l are found sufficient to reduce the arsenic concentration from about 0.4 to 0.05 mg/l.

Sorption Isotherms

For iron, the Freunlich fits the experimental results better than Langmuir On the contrary the Langmuir fits better than Freundlich for aluminium. But there is no significant difference between these two estimations. Both Langmuir and Freundlich isotherms show good a correlation with the measured results.

Sorption Modeling

The amount of ferric chloride or alum required in order to obtain a given residual arsenic can be estimated e. g. using the Freundlich isotherms as in the equation:

$$A = \frac{(As_{initial} - As_{residual}) \cdot V}{\alpha \cdot As_{residual}^{1/\beta}}$$

α and β are estimated to be 95 and 2 for ferric chloride and 61 and 3 for alum respectively, where arsenic is given in mg/l and the dosage is given in g per V litres

End pH

Lower pH is obtained in higher iron and alum dosage The resulting pH, however, lies between 6.5 to 7, indicating that no readjustment of the pH is required.

Residual Fe

The iron chloride and alum flocculation in batch are both able to remove the genuine iron contents of the ground water down to acceptable levels, below respectively 1 and 0.2 mg/l

Produced Sludge

The resulted sludge is less than 1 liter. With 15 liters raw water in total, the yield is higher than 90%.

Rice Husk Method of UNICEF

The rice husk method is able to remove arsenic from about 0 4 mg/l down to levels below 0.01 mg/l

The method however results in sludge having poor settling ability and thus quit an unpleasant appearance

Rice husk + Fe/Al

Combination of the rice husk with more alum or ferric chloride results in better sludge settlement and hence better appearance of the treated water.

The residual arsenic concentrations, which is already low in the rice husk method are even lower in the combined method, often below the detection level

8. EXPERIENCES OF FIELD WORK IN BANGLADESH

According to the plan, I was leaving for Bangladesh at the beginning of August and coming back to Denmark at the beginning of November.

I arrived in Bangladesh on 5 August 1997. The culture, religion, mentality etc. are totally different from what I had known. I first found out that transportation was very difficult and slow with no doubt. And later I also found out that transportation was very inconvenient as well remembering I am a female. In Bangladesh, a woman is not supposed to go out alone on the street in the evening time (say after 6:00 pm) So, you can not work over in the lab in the evening time. The traffic in Dhaka is not very efficient. There is very often traffic jam. No body will be surprised if you don't show up on time.

As one comes from Denmark, you may always feel "taxi" is very cheap in Bangladesh, which soon became my major transportation tool. But there are a lot of political activities in Bangladesh, which are often announced by many strikes. Nothing is so efficient as a strike in Bangladesh. Whenever there is a strike, no one is supposed to go to the street. You'd better stay home for the safety of your life, though you have plenty of work waiting for you in the laboratory

International transportation was not easy either. Some chemicals purchased in Denmark arrived in Dhaka two weeks after I did. But the sodium borohydride, the most essential chemicals was too dangerous to be transported by a flight I was told that the chemicals was to be transported to Singapore by ship and from there it could be transported to Dhaka by plane. Until one and a half month later, that chemicals was still on the way.

This project is a collaboration between DTU and DPHE-Danida Urban Water and Sanitation Project (UWASP). I was supposed to use a laboratory which was to be built by UWASP in Noakhali. They have tried very hard to make a 10 m^2 room to a laboratory, but due to many reasons the laboratory wasn't completed until 8 October 1997, which was more than two months after I arrived in Bangladesh, or by then I had less than one month left before I came back to Denmark

Before the laboratory in Noakhali could be used I started preparing the experiment at BUET by the end of August 1997. You need many different keys to open all the doors you need to get in to the laboratory, but you'll never get all the keys. Any way, I got two tables at the corner and I may use the balance, jar test apparatus and limited distilled water. Everything else should be purchased or found by myself.

If you want to buy some chemicals or equipment, you can not just do that over telephone. First of all it is not easy to get the line through to the person you want to talk with. Secondly you may get some thing you didn't order. So, you'd better go to the company by yourself. But it may take much longer time than you expected to buy even one small thing.

Bangladesh is a disaster country, flood, cyclone, storm are not anything unusual. If you want to do some field work, it's better not do that in the rain season, which is from June to August.

Bangladesh is one of the poorest countries in the world. You can buy many things there, but the quality is not as good as in Denmark. It is better to get prepared as thoroughly as possible at home.

Muslim is the national religion of the country and the society is very classified. Power, money and status are very important.

If you are a woman, you should be prepared to be treated differently.

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10. APPENDICES

Appendix 1: Concentration of Arsenic and Iron in IRU-13

This appendix shows the concentration of arsenic and iron in the tube well of IRU-13 at different time and the change of the concentration during storage in a bucket.

Note: NA means the sample was not acidified by HCl.

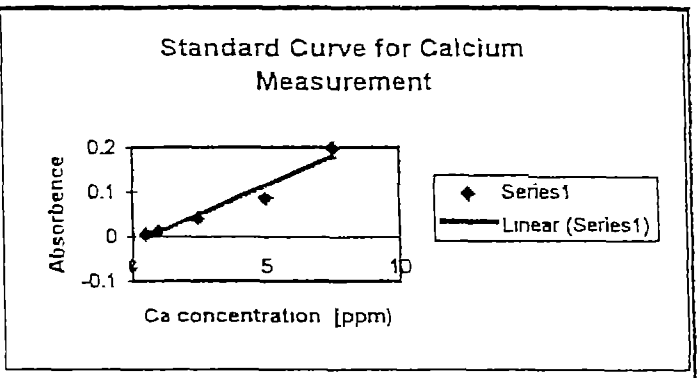
Sampled date			Arsenic		$NaBH_4$		Iron	
On site	In lab	Measured Date	Concentration (mg/l) Before IRU	After IRU	added ml	Measured Date	Concentration (mg/l) Before IRU	After IRU
08/09/97	-	-	-	-		21/09/97	6.79	2.45
"	-	12/10/97	0.390	0.194	15	-	-	-
"	-	19/10/97	0.438	-	15	-	-	-
"	-	26/10/97	0.478	0.216	25	-	-	-
"	-	-	-	-	-	25/10/97	7.01	-
06/10/97	-	19/10/97	0.316	-	25 (NA)	-	-	-
09/10/97	-	19/10/97	0.481	-	25	-	-	-
20/10/97 (8:00)	20/10/97 (8:00)	24/10/97	0.422	-	25	25/10/97	6.49	-
	20/10/97 (13:00)	"	0.391	-	25	"	6.24	-
	21/10/97 (11:00)	"	0.389	-	25	"	4.69	-
	21/10/97 (16.30)	"	0.380	-	25	"	6.28	-
	22/10/97 (18:00)	"	0.384	-	25	"	7.65	-
	23/10/97 (21:00)	"	0.271	-	25	"	0.00	-
	24/10/97 (19:00)	30/10/97	0.364	-	25	"	0.00	-
	26/10/97 (19:00)	30/10/97	0.284	-	25	30/10/97	0.08	-
	28/10/97 (19:00)	30/10/97	0.365	-	25	30/10/97	0.00	-
	29/10/97 (17:30)	30/10/97	0.328	-	25	30/10/97	0.12	-
27/10/97 (8·30)	27/10/97 (8.30)	28/10/97	0.542	-	25	30/10/97	6.85	-
	27/10/97 (8:30)	"	0.461	-	25 (NA)	30/10/97	12.23	-
	27/10/97 (13:30)	"	0.432	-	25	30/10/97	4.94	-
	27/10/97 (17.30)	"	0.454	-	25	30/10/97	2.71	-
27/10/97 (17:30)		"	0.569	0.138	25	30/10/97	7.33	1.75

Appendix 2: Hardness

Ca

Standard solutions

ppm	Abs
0.5	0.005
1	0.013
2.5	0.042
5	0.087
7.5	0.198
slope	0.026
Intercept	-0.018
Correl	0.976

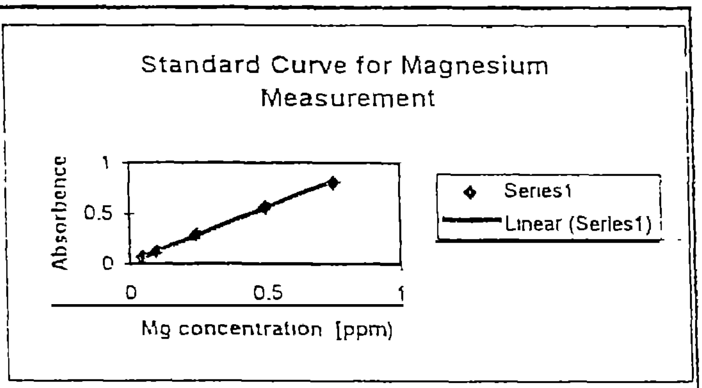


Samples	Abs	diluted conc.	Real conc		
		ppm	ppm	meq/l	mg $CaCO_3$/l
1	0.050	2.6	51.5	2.6	128.9
2	0.052	2.7	53.1	2.7	132.7
3	0.050	2.6	51.5	2.6	128.9

Mg

Standard solutions

ppm	Abs
0.05	0.067
0.1	0.118
0.25	0.287
0.5	0.561
0.75	0.804
slope	1.062
Intercept	0.017
Correl	1.000



Samples	Abs	diluted conc.	Real conc		
		ppm	ppm	meq/l	mg $CaCO_3$/l
1	0.726	0.668	133.5	11.1	556.4
2	0.71	0.653	130.5	10.9	543.9
3	0.711	0.654	130.7	10.9	544.7

Total Hardness		
	meq/l	mg $CaCO_3$/l
1	13.7	685.3
2	13.5	676.6
3	13.5	673.5
Average	14	678

Appendix 3: Arsenic Standard Curves

This appendix shows the measurement of standard curves on different day.

Conc.	07/09/97			07/09/97	29/09/97
	1st	2nd	3rd	Average	
mg/l	Abs	Abs	Abs	Abs	Abs
0	0	0	0	0.000	0.011
0.01	0.002	0.002	-	0.002	0.023
0.05	0.052	0.053	0.025	0.043	0.082
0.1	0.094	0.1	0.107	0.100	0.147
0.25	-	-	-	-	0.436
0.3	-	0.318	0.295	0.307	-
Slope	0.984	1.071	1.010	1.038	1.705
Intercept	-0.002	-0.004	-0.007	-0.005	0.000
Corr.	0.995	1.000	0.995	1.000	0.997

Conc.		08/10/97	09/10/97	10/10/97	11/10/97	12/10/97	Average	St. Dev
							08 – 12/09	08 – 12/09
µg	mg/l	Abs	Abs	Abs	Abs	Abs	Abs	Abs
0	0.000	0.021	0.021	0 014	0.020	0.013	0.018	0.004
1	0.014	-	0.037	0.030	0.034	0.025	0.032	0.005
5	0.071	0.083	0.079	0.064	0.065	0.119	0.082	0.022
10	0.143	0.157	0.157	0.141	0.149	0.204	0.162	0.025
20	0.286	0.327	0.292	0.241	0.245	0.223	0.266	0.043
Slope		1.082	0.951	0.801	0.802	0.765	0.880	0.134
Intercept		0.012	0.019	0.016	0.020	0.038	0 021	0.010
Corr.		0.998	0.999	0.997	0.995	0.914	0.981	0.037

Arsenic Standard Curves

Conc.		18/10/1997(a)	18/10/1997(b)	18/10/1997(C	18/10/1997(d)	19/10/97		19/10/97	23/10/1997(a)	23/10/1997(b)
						1st	2nd	Average	1st	2nd
µg	mg/l	Abs	Abs	Abs	Abs	Abs	Abs	Abs	Abs	Abs
0	0.000	0.023	0.019	0.019	0.016	0.023	-	0.023	0.011	0.011
1	0.014	0.038	0.043	0.039	0.041	0.049	0.035	0.042	0.035	0.029
5	0.071	0.135	0.107	0.127	0.111	0.137	-	0.137	0.114	0.09
10	0.143	0.269	0.218	0.217	0.229	0.272	-	0.272	0.19	0.211
20	0.286	0.505	0.449	0.439	0.444	0.456	0.516	0.486	0.509	0.445
Slope		1.710	1.500	1.461	1.498	1.529	1.772	1.641	1.705	1.530
Intercept		0.018	0.013	0.018	0.014	0.030	0.010	0.023	-0.004	0.000
Corr.		1.000	0.998	0.999	0.999	0.997	1.000	0.999	0.989	0.997

Conc.		24/10/97	26/10/97		26/10/97	28/10/97		28/10/97	30/10/97	Average	St. Dev
			1st	2nd	Average	1st	2nd	Average		18 – 30/10	18 – 30/10
µg	mg/l	Abs	Abs	Abs	Abs	Abs	Abs	Abs	Abs	Abs	Abs
0	0.000	0.016	0.015	-	0.015	0.011	-	0.011	0.027	0.017	0.005
1	0.014	0.035	0.049	-	0.049	0.027	-	0.027	0.026	0.037	0.007
5	0.071	0.111	0.132	-	0.132	0.118	-	0.118	0.114	0.118	0.014
10	0.143	0.247	0.229	0.241	0.235	0.208	0.202	0.205	0.269	0.233	0.028
20	0.286	0.541	0.519	0.413	0.466	0.402	0.453	0.4275	0.509	0.475	0.037
Slope		1.847	1.727	1.204	1.553	1.370	1.757	1.453	1.748	1.604	0.133
Intercept		0.000	0.011	0.069	0.020	0.012	-0.049	0.008	0.009	0.011	0.009
Corr.		0.997	0.996	1.000	1.000	1.000	1.000	0.999	0.997	0.998	0.003

Arsenic Concentration in different IRU in Noakhali

1. Samples were collected on 8-11/09/97.
2. All of the samples were preserved using HCl (1ml/l).
3. 25 ml of $NaBH_4$ solution were used.
4. Before measuring arsenic, the samples were added 2 ml HCl again

Measured on 26/10/97

Name	Precipitate		Abs		Vsample	Total As (mg/l)	
	Raw	Treated	Raw	Treated	ml	Raw	Treated
IRU-1	**	-	0 058	-	20	0.086	-
IRU-2	*	no	0.168	0.025	"	0 334	0.012
IRU-3	*	-	0.038	-	"	0 041	-
IRU-5	*	no	0.128	0.092	20/35	0.244	0.093
IRU-6	**	no	0 053	0.024	35	0 043	0 006
IRU-7	*	*	0 141	0 049	35	0.156	0 038
IRU-9	*	-	0 326	-	70	0.197	-
IRU-10	*	no	0.502	0.070	"	0.311	0.032
IRU-12	no	no	0 024	0.009	"	0.003	0.000
IRU-13	**	*	0.762	0 355	"	0.478	0.216
IRU-14	no	*	0.311	0.245	"	0.188	0.145
IRU-15	*	no	0.130	0 035	"	0.071	0.010
IRU-16	*	**	0.960	0.502	"	0.605	0.311
IRU-24	****	*	0.203	0.178	"	0 118	0.102
IRU-25	****	no	0.048	0.032	"	0.018	0.008
IRU-26	***	**	0.358	0.276	"	0.218	0.165
IRU-30	**	no	0.240	0.030	"	0.142	0.007
IRU-34	***	*	0.530	0.172	"	0.329	0.098
IRU-35	*	*	0.142	0.069	"	0.079	0.032
IRU-36	*	no	0.496	0 290	"	0.307	0.174
IRU-39	no	no	0.199	0.088	"	0.115	0.044
IRU-40	***	no	0.108	0.033	"	0 057	0.009

Standard Solution on 26/10/97				
Conc.		Abs		
µg	mg/l	1st	2nd	Average
0	0.000	0 015	-	0.015
1	0.014	0 049	-	0.049
5	0.071	0.132	-	0.132
10	0.143	0.229	0.241	0.235
20	0.286	0.519	0.413	0.466
Slope		1.727		1.553
Intercept		0 011		0.020
Corr.		0 996		1.000

Arsenic Concentration in different IRU in Noakhali

Overview of the Total Arsenic in Different IRUs Measured on Different time

Name	Total As		Measured on 11-12/10/97			Measured on 26/10/97		
	Raw	Treated		Raw	Treated		Raw	Treated
IRU-1	0.086	-	IRU-1	0.070	-	IRU-1	0.086	-
IRU-2	0.334	0.012	IRU-2	0.323	0.026	IRU-2	0.334	0.012
IRU-3	0.041	-	IRU-3	0.003	-	IRU-3	0.041	-
IRU-4	0.142	-	IRU-4	0.142	-			
IRU-5	0.244	0.093	IRU-5	0.250	0.056	IRU-5	0.244	0.093
IRU-6	0.043	0.006	IRU-6	0.097	0.022	IRU-6	0.043	0.006
IRU-7	0.156	0.038	IRU-7	0.207	0.093	IRU-7	0.156	0.038
IRU-8	0.092	-	IRU-8	0.092	-			
IRU-9	0.197	-	IRU-9	0.276	-	IRU-9	0.197	-
IRU-10	0.311	0.032	IRU-10	0.245	0.042	IRU-10	0.311	0.032
IRU-11	0.133	-	IRU-11	0.133	-			
IRU-12	0.003	0.000	IRU-12	0.000	0.002	IRU-12	0.003	0.000
IRU-13	0.478	0.216	IRU-13	0.390	0.194	IRU-13	0.478	0.216
IRU-14	0.188	0.145	IRU-14	0.141	0.200	IRU-14	0.188	0.145
IRU-15	0.071	0.010	IRU-15	0.078	0.013	IRU-15	0.071	0.010
IRU-16	0.605	0.311	IRU-16	0.279	-	IRU-16	0.605	0.311
IRU-24	0.118	0.102				IRU-24	0.118	0.102
IRU-25	0.018	0.008				IRU-25	0.018	0.008
IRU-26	0.218	0.165				IRU-26	0.218	0.165
IRU-30	0.142	0.007				IRU-30	0.142	0.007
IRU-34	0.329	0.098				IRU-34	0.329	0.098
IRU-35	0.079	0.032				IRU-35	0.079	0.032
IRU-36	0.307	0.174				IRU-36	0.307	0.174
IRU-39	0.115	0.044				IRU-39	0.115	0.044
IRU-40	0.057	0.009				IRU-40	0.057	0.009

Appendix 5: Arsenic Concentration in different IRUs in Noakhali

1. Samples were collcted on 8-11/09/97.
2. All of the samples were preserved using HCl (1ml/l).
3. 15 ml of $NaBH_4$ solution were used.

Standard Solutions			
Conc.		11/10/97	12/10/97
µg	mg/l	Abs	
0	0.000	0.020	0.013
1	0.014	0.034	0.025
5	0 071	0.065	0.119
10	0.143	0.149	0.204
20	0.286	0.245	
Slope		0.802	1.373
Intercept		0.020	0.012
Corr.		0 995	0.997

Measured on 11/10/97 and 12/10/97

Name	Date		Absorbence				Arsenic Concentration (mg/l)						Ratio
	Measured		Raw		Treated		Raw		Treated		Total As		Raw Water
	R	T	As(III)	As(V)	As(III)	As(V)	As(III)	As(V)	As(III)	As(V)	Raw	Treated	As(III)/As(V)
IRU-1	12/10/97	-	0.013	0.107	-	-	0 001	0.069	-	-	0 070	-	0.0
IRU-2	11/10/97	11/10/97	0.064	0.235	0.025	0.036	0.055	0.268	0.006	0 020	0.323	0.026	0.2
IRU-3	12/10/97	-	0.011	0.016	-	-	0.000	0.003	-	-	0 003	-	0.0
IRU-4	12/10/97	-	0.014	0.205	-	-	0.002	0.141	-	-	0.142	-	0.0
IRU-5	11/10/97	11/10/97	0.035	0.206	0.031	0.054	0.019	0.232	0.014	0.042	0.250	0.056	0.1
IRU-6	11/10/97	12/10/97	0.004	0.098	0.012	0.042	0.000	0.097	0.000	0.022	0.097	0.022	0.0
IRU-7	11/10/97	11/10/97	0.013	0.186	0.010	0.095	0.000	0.207	0 000	0.093	0 207	0 093	0.0
IRU-8	12/10/97	-	0.037	0.113	-	-	0.018	0 074	-	-	0.092	-	0.2
IRU-9	12/10/97	-	0.016	0.386	-	-	0.003	0.273	-	-	0 276	-	0.0
IRU-10	11/10/97	11/10/97	0.043	0.194	0.014	0.054	0.029	0.217	0.000	0.042	0.245	0 042	0.1
IRU-11	12/10/97	-	0.015	0.191	-	-	0.002	0.131	-	-	0.133	-	0 0
IRU-12	11/10/97	12/10/97	0.008	0.014	0.008	0.014	0.000	0.000	0.000	0.002	0.000	0.002	-
IRU-13	12/10/97	12/10/97	0.447	0.112	0.018	0.272	0.317	0.073	0.005	0 190	0.390	0.194	4.3
IRU-14	12/10/97	12/10/97	0.141	0.076	0.014	0.284	0.094	0.047	0.002	0.198	0.141	0 200	2.0
IRU-15	12/10/97	12/10/97	0.051	0 080	0.009	0.03	0.029	0.050	0.000	0.013	0.078	0.013	0.6
IRU-16	12/10/97	-	0.015	0.392	-	-	0.002	0.277	-	-	0.279	-	0.0

Appendix 4: As and Fe Concentrations in Some Individual Places

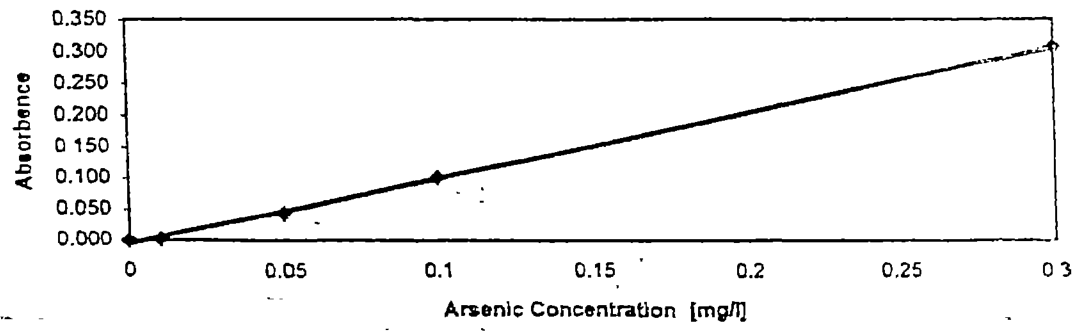
This appendix shows concentration of arsenic and iron from some individual places and 4 deep tube wells, OTW 1-4.

Note:
1) (S) denotes sampling, (M) denotes measuring
(R) denotes raw water, (T) denotes treated water.
2) Samples were preserved using HCl (1 ml /l).

	Arsenic				Iron (M. on 23/09/97)	
Sampling Point	Date (S)	Date (M)	Abs	Total As mg/l	Abs	Total Fe mg/l
Nillers house	18/08	07/09	0.113	0.114	0.021	0.58
Danida Guesthouse	19/08	07/09	0.167	0.166	0.025	0.74
Maklin Feml	19/08	07/09	0.281	0.276	0.070	2.57
Dulal Master Bari (R)	18/08	07/09	0.216	0.213	0.138	5.33
Dulal Master Bari (T)	18/08	07/09	0.186	0.184	0.076	2.81
Kala Miah Bahl (R)	18/08	07/09	0.256	0.252	0.300	11.90
Kala Miah Bahl (T)	18/08	07/09	0.056	0.059	0.008	0.05
OTW-1	18/08	10/10	0.012	0.000	0.057	2.04
OTW-2	18/08	10/10	0.014	0.000	0.068	2.49
OTW-3	18/08	10/10	0.013	0.000	0.067	2.45
OTW-4	18/08	10/10	0.016	0.000	0.074	2.73

As Standard Curve on 07/09/97			
Conc. mg/l	Abs	Slope	Inter.
0	0.000	1.038	-0.005
0.01	0.002		
0.05	0.043		
0.1	0.100		
0.3	0.307		

Arsenic Standard Curve on 07/09/97



Appendix 6: Iron Concentration in different IRUs, Noakhali

1) Samples were collected on 8-11/9/97, and measured on 21/9/97.

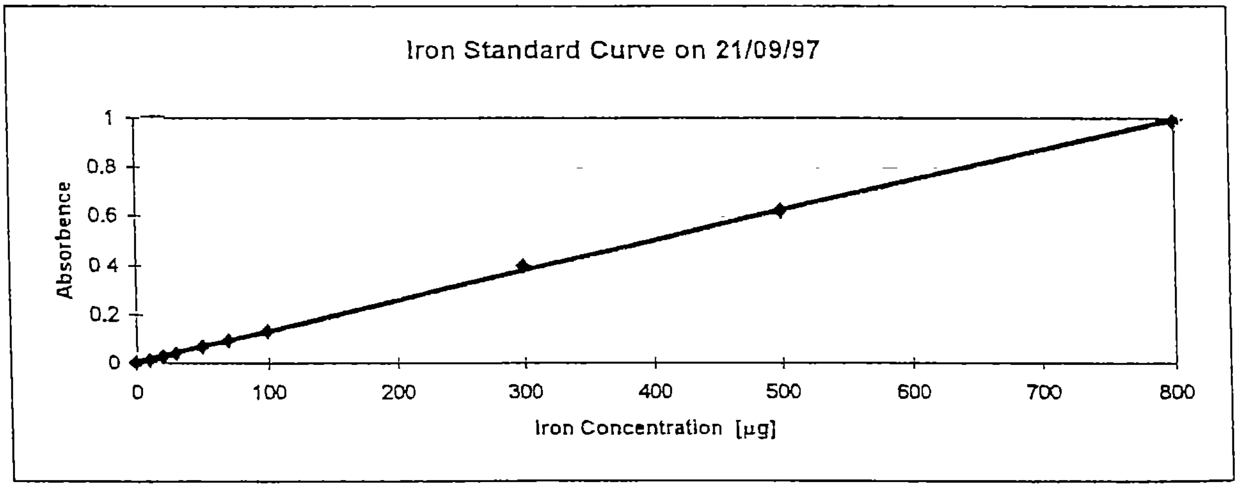
		Absorbence		Fe concentration (mg/l)	
No.	Name	Raw Water	Treated Wat	Raw Water	reated Water
1	RU - CHA - 0	0.909	0.293	36.60	11.61
2	RU - CHA - 0	0.380	0.007	15.14	0.01
3	RU - CHA - 0	0.300	0.008	11.90	0.05
4	RU - CHA - 0	0.394	-	15.71	-
5	RU - CHA - 0	0.250	0.067	9.87	2.45
6	RU - CHA - 0	0.359	0.028	14.29	0.87
7	RU - CHA - 0	0.216	0.063	8.49	2.28
8	RU - CHA - 0	0.149	-	5.77	-
9	RU - CHA - 0	0.701	-	28.17	-
10	RU - CHA - 1	0.278	0.019	11.01	0.50
11	RU - CHA - 1	0.155	-	6.02	-
12	RU - CHA - 1	0.558	0.015	22.36	0.34
13	RU - CHA - 1	0.174	0.067	6.79	2.45
14	RU - CHA - 1	0.297	0.128	11.78	4.92
15	RU - CHA - 1	0.262	0.017	10.36	0.42
16	RU - LAK - 1	0.282	0.074	11.17	2.73
17	RU - LAK - 1	-	-	-	-
18	RU - LAK - 1	0.330	-	13.12	-
19	RU - LAK - 1	0.307	-	12.18	-
20	RU - LAK - 2	0.153	-	5.94	-
21	RU - LAK - 2	0.349	-	13.89	-
22	RU - LAK - 2	-	-	-	-
23	RU - LAK - 2	-	-	-	-
24	RU - LAK - 2	0.316	0.019	12.55	0.50
25	RU - LAK - 2	0.310	0.004	12.30	0.00
26	RU - LAK - 2	0.080	0.057	2.97	2.04
27	RU - LAK - 2	0.385	0.050	15.35	1.76
28	RU - LAK - 2	-	-	-	-
29	RU - LAK - 2	0.128	-	4.92	-
30	RU - LAK - 3	0.584	0.003	23.42	0.00
31	RU - LAK - 3	-	-	-	-
32	RU - LAK - 3	0.227	-	8.94	-
33	RU - LAK - 3	0.400	-	15.96	-
34	RU - LAK - 3	0.525	0.156	21.03	6.06
35	RU - LAK - 3	0.260	0.063	10.28	2.28
36	RU - LAK - 3	0.205	0.052	8.05	1.84
37	RU - LAK - 3	0.238	-	9.38	-
38	RU - LAK - 3	0.814	-	32.75	-
39	RU - LAK - 3	0.334	0.085	13.28	3.18
40	RU - LAK - 4	0.131	0.010	5.04	0.13

Iron Concentration in different IRUs, Noakhali

This standard calibration was used for calculating the iron concnetration in different IRUs.

Iron Standard Solutions on 21/09/97.

No.	Conc.		ABS	Slope	Inter.	Corr.
	µg	mg/l				
1	0	0	0.002	0.001	0.007	0.9997
2	10	0.2	0.014			
3	20	0.4	0.027			
4	30	0.6	0.041			
5	50	1	0.068			
6	70	1.4	0.095			
7	100	2	0.133			
8	300	6	0.397			
9	500	10	0.621			
10	800	16	0.986			



Appendix 7: Arsenic Analysis of Jar Test Samples

Note:
(M) denotes measured, (S) denotes sampled

Arsenic Standard Solutions				
Conc.			Abs	
µg	mg/l	08/10/97	09/10/97	10/10/97
0	0.000	0.021	0.021	0.014
1	0.014	-	0.037	0.030
5	0.071	0.083	0.079	0.064
10	0.143	0.157	0.157	0.141
20	0.286	0.327	0.292	0.241
Slope		1.082	0.951	0.801
Intercept		0.012	0.019	0.016
Corr.		0.998	0.999	0.997

Date (S)	Date (M)	Dosage mg/l	ABS	Conc. mg/l
Run1, Alum				
28/09/97	09/10/97	10	0.301	0.296
		20	0.309	0.305
		30	0.223	0.214
		40	0.225	0.216
		50	0.227	0.218
		60	0.179	0.168

Run2, Alum				
28/09/97	08/10/97	70	0.117	0.097
		80	0.105	0.086
		90	0.075	0.058
		100	0.074	0.058
		110	0.070	0.054
		120	0.052	0.037

Run 3, Ferric Chloride				
28/09/97	09/10/97	10	0.239	0.231
		20	0.197	0.187
		30	0.079	0.063
		40	0.049	0.031
		50	0.055	0.037
		60	0.070	0.053

Arsenic Analysis of Jar Test Samples

Run 4, Ferric Chloride

28/09/97	09/10/97	70	0.038	0.020
		80	0.029	0.010
		90	0.026	0.007
		100	0.021	0.002
		110	0.019	0.000
		120	0.019	0.000

Run 1, Rice Husk

29/09/97	09/10/97	0.6	0.031	0.012
		1.2	0.046	0.028
		1.8	0.034	0.015
		2.4	0.040	0.022
		3.0	0.018	0.000
		3.6	0.025	0.006

Run 2, Rice Husk

29/09/97	09/10/97	0.7	0.020	0.001
		0.7	0.018	0.000
		0.7	0.019	0.000
		0.7	0.018	0.000
		0.7	0.017	0.000
		0.7	0.013	0.000

Run 1, Alum

14/09/97	09/10/97	5	0.350	0.348
		10	0.411	0.412
		20	0.038	0.020
		30	0.030	0.011
		40	0.022	0.003
		50	0.011	0

Run 2, Alum

14/09/97	10/10/97	5	0.399	0.479
		10	0.390	0.468
		20	0.242	0.283
		30	0.246	0.288
		40	0.231	0.269
		50	0.204	0.235

Arsenic Analysis of Jar Test Samples

Run 3, Alum				
14/09/97	10/10/97	5	0.152	0.341
		10	0.165	0.373
		20	0.094	0.196
		30	0.092	0.191
		40	0.060	0.111
		50	0.189	0.217

Run 1, Alum				
24/09/97	09/10/97	10	0.135	0.122
		20	0.219	0.210
		30	0.164	0.152
		40	0.245	0.237
		50	0.219	0.210
24/09	10/10	60	0.112	0.120

Run 2, Ferric Chloride				
24/09/97	10/10/97	10	0.169	0.192
		20	0.081	0.082
		30	0.066	0.063
		40	0.032	0.020
		50	0.040	0.030
		60	0.064	0.060

Run 3, Alum				
24/09/97	10/10/97	10	0.310	0.368
		20	0.272	0.320
		30	0.149	0.167
		40	0.138	0.153
		50	0.182	0.208
		60	0.143	0.159

Appendix 8: Results of Jar Test on 14/09/97 (Alum added)

1) 1 liter sample in each beaker.
2) 2 min mixing with NaClO at 100 RPM
3) 3 min mixing with Alum at 100 RPM
4) Then 5 min slowly stir at 25 RPM.
5) Samples are not preserved.
6) There was ca. 14-18 ml sludge.
7) $Al_2(SO_4)_3 \cdot 16H_2O$. (molecular weight is 630 g)
8) Raw water was fetched on 9/9/97, the arsenic concentration is about 0.478 mg/l.
9) NaClO solution contains 5.25% chlorine.

Date:14/09/07 *5 mg/l of NaClO added (5 ml of 1 mg/ml NaClO solution)*

1. run (sampled after 18 hours)

Beaker No.	Dosage Alum mg/l	Dosage Al mmol/l	pH Initial	pH Final	Set. time h	Residual Total As mg/l	Floc	As removal Efficiency %
1	5	0.02	7.29	7.46	-	0.348	small	-
2	10	0.03	"	7.46	-	0.412	small	-
3	20	0.06	"	7.44	-	0.020	small	-
4	30	0.10	"	7.34	2	0.011	large	-
5	40	0.13	"	7.34	2	0.003	large	-
6	50	0.16	"	7.32	1	0.000	large	-

Date:14/09/07 *50 mg/l of NaClO added (1 ml of 5.25% NaClO solution)*

2. run (sampled after 17 hours)

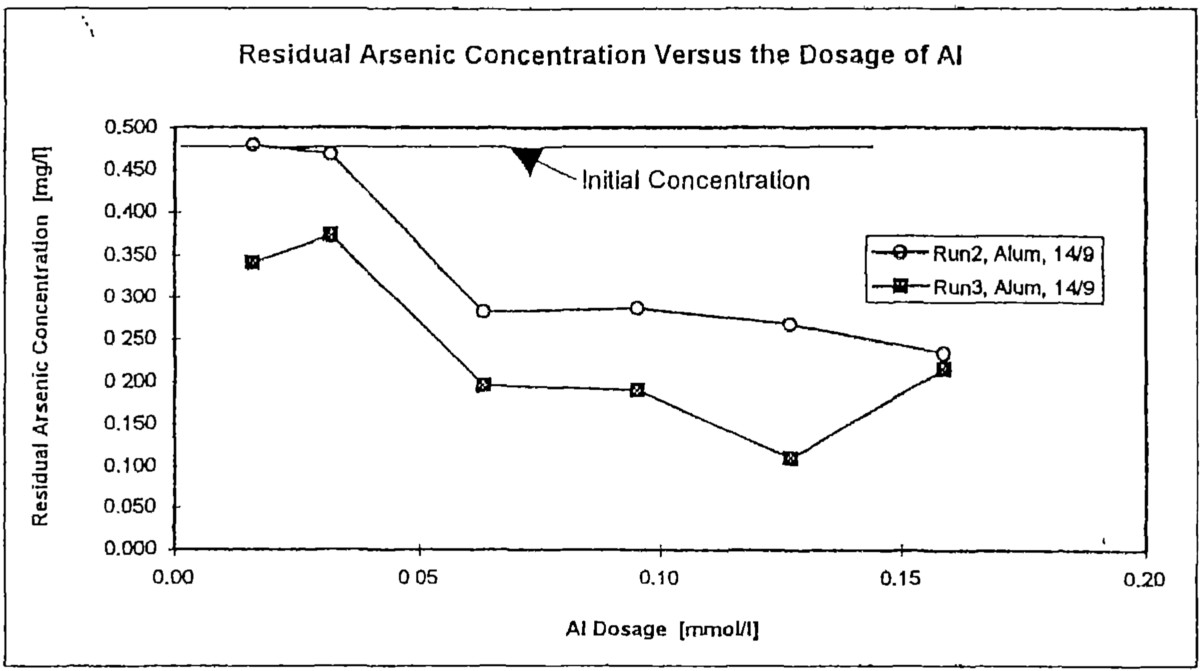
Beaker No.	Dosage Alum mg/l	Dosage Al mmol/l	pH Initial	pH Final	Set. time h	Residual Total As mg/l	Floc	As removal Efficiency %
1	5	0.02	7.29	7 42	-	0 479	small	0
2	10	0.03	"	7.34	-	0.468	small	2
3	20	0.06	"	7.34	-	0.283	small	41
4	30	0.10	"	7.30	2	0.288	large	40
5	40	0.13	"	7.28	2	0.269	large	44
6	50	0.16	"	7.23	1	0.235	large	51

Date:15/09/07

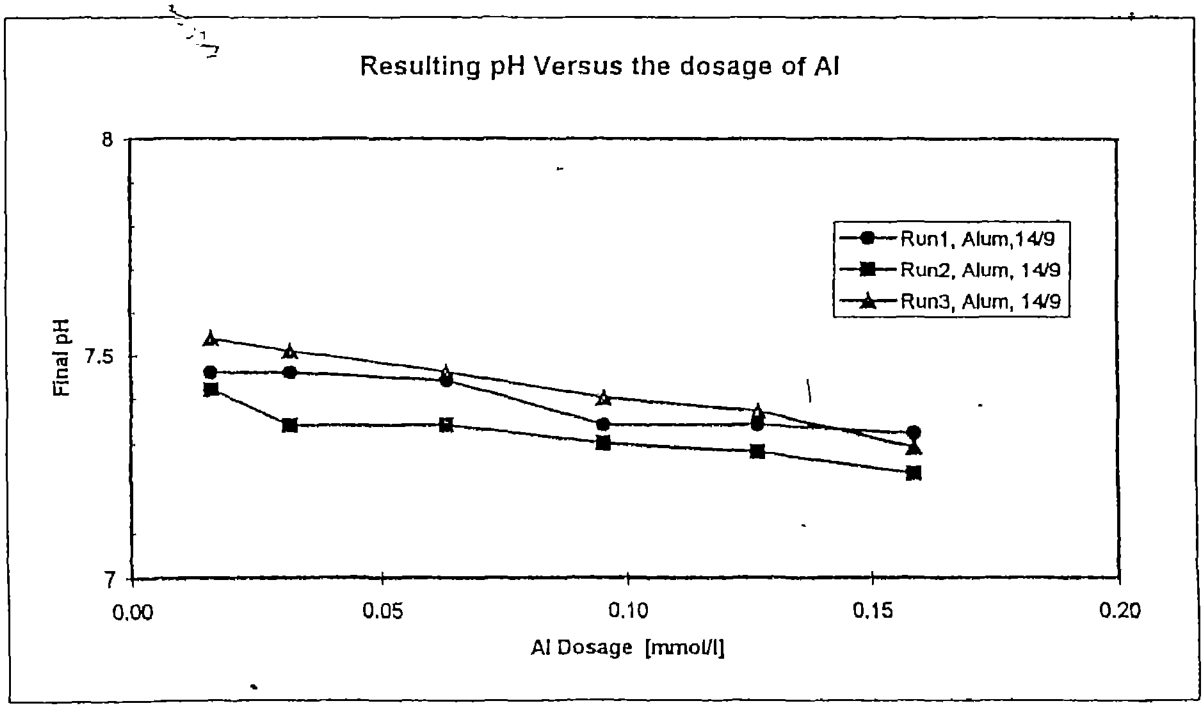
3. run

50 mg/l of NaClO added (1 ml of 5.25% NaClO solution)

Beaker No.	Dosage Alum mg/l	Dosage Al mmol/l	pH Initial	pH Final	Set. time h	Residual Total As mg/l	Floc	As removal Efficiency %
1	5	0.02	7.29	7.54	-	0.341	small	29
2	10	0.03	"	7.51	-	0.373	small	22
3	20	0.06	"	7.46	-	0.196	small	59
4	30	0.10	"	7.40	2	0.191	large	60
5	40	0.13	"	7.37	2	0.111	large	77
6	50	0.16	"	7.29	1	0.217	large	55



Residual Arsenic Concentration Versus the Dosage of Al



Resulting pH Versus the dosage of Al

Appendix 9: Results of Jar Test on 24/09/97

1) 1 liter sample in each beaker.
2) 2 min mixing with bleaching powder at 100 RPM
3) 3 min mixing with added chemicals at 100 RPM.
4) Then 5 min slowly stir at 25 RPM.
5) Sedimentation time is 1 hour, the yield is about 980 ml.
6) There is ca. 10% of chlorine in the bleaching powder.
7) Samples are preserved.
8) $Al_2(SO_4)_3\ 16H_2O$; $FeCl_3\ 6H_2O$
9) Raw water was fetched on 9/9/97.
10) The initial arsenic concentration is 0.478 x 80% = 0.38 mg/l.

Date:24/09/97 *Chlorine dosage is 100 mg (1 g of BP was added in solid form).*

1. run (Alum added)

Beaker	Dosage			pH		Residual	As removal
	Alum	Al				Total As	Efficiency
No.	mg/l	mmol/l	mg/l	Initial	Residual	mg/l	%
1	10	0.03	0.86	7.29	7.98	0.122	68
2	20	0.06	1.71	"	7.93	0.210	45
3	30	0.10	2.57	"	8.05	0.152	60
4	40	0.13	3.43	"	7.99	0.237	38
5	50	0.16	4.29	"	8.08	0.210	45
6	60	0.19	5.14	"	7.75	0.120	69

Date:24/09/97 *Chlorine dosage is 0.5 mg (5 ml of 1 g/l Bleaching Powder added)*

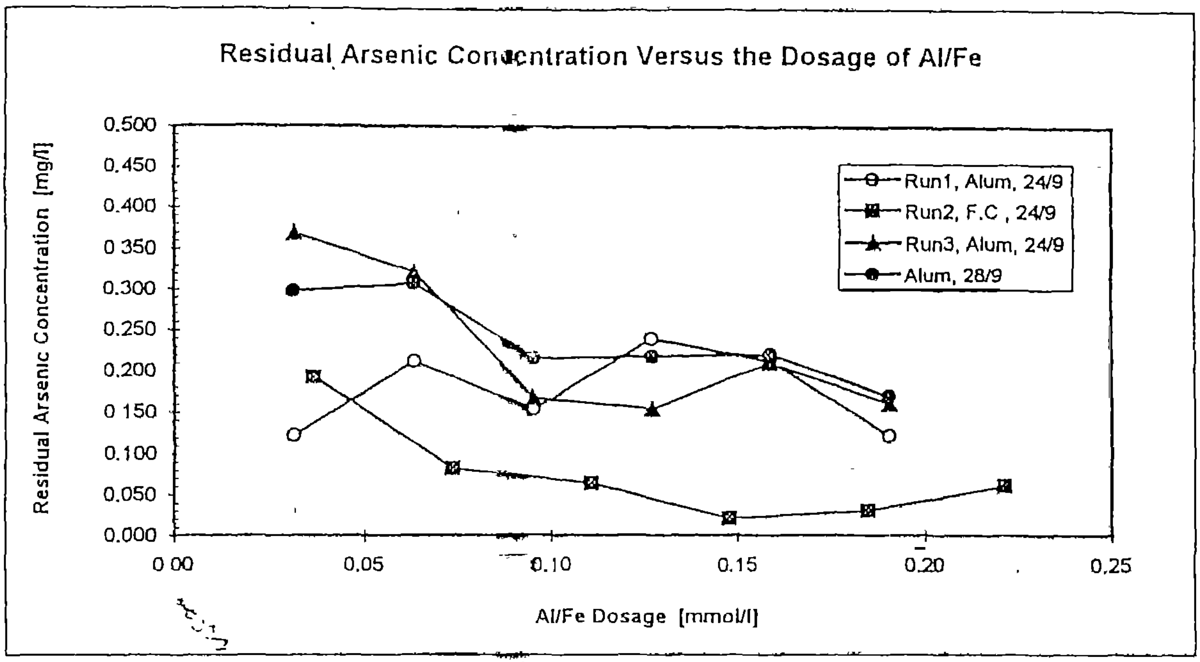
2. run (Ferric Chloride added)

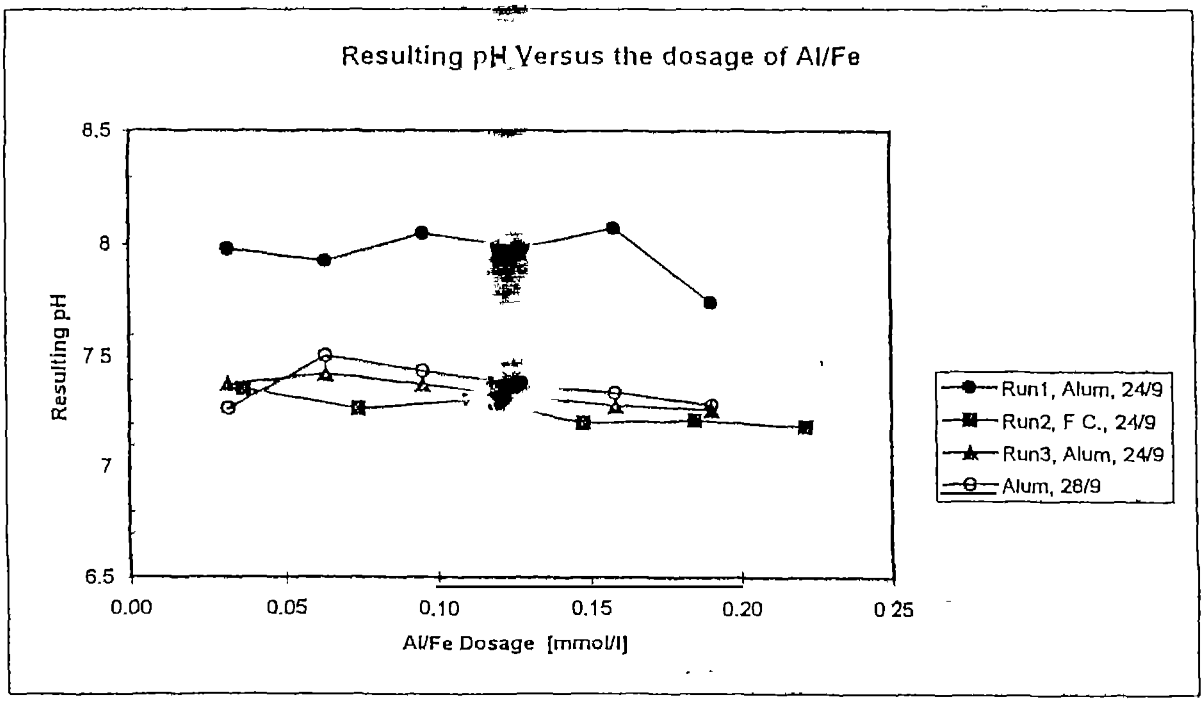
Beaker	Dosage			pH		Residual	As removal
	F. C.	Fe				Total As	Efficiency
No.	mg/l	mmol/l	mg/l	Initial	Residual	mg/l	%
1	10	0.04	2.07	7.29	7.36	0.192	50
2	20	0.07	4.14	"	7.27	0.082	79
3	30	0.11	6.21	"	7.31	0.063	84
4	40	0.15	8.28	"	7.21	0.020	95
5	50	0.18	10.35	"	7.22	0.030	92
6	60	0.22	12.42	"	7.19	0.060	84

Date:24/09/07 *Chlorine dosage is 0.5 mg (5 ml of 1 g/l Bleaching Powder added)*

3. run (Alum added)

Beaker	Dosage			pH		Residual	As removal
	Alum	Al				Total As	Efficiency
No.	mg/l	mmol/l	mg/l	Initial	Residual	mg/l	%
1	10	0.03	0.86	7.29	7.38	0.368	4
2	20	0.06	1.71	"	7.43	0.320	16
3	30	0.10	2.57	"	7.38	0.167	56
4	40	0.13	3.43	"	7.33	0.153	60
5	50	0.16	4.29	"	7.29	0.208	46
6	60	0.19	5.14	"	7.27	0.159	58


Residual Arsenic Concentration Versus the Dosage of Al/Fe
Residual Arsenic Concentration [mg/l]
0.500
0.450
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
0.00
0.05
0.10
0.15
0.20
0.25
Al/Fe Dosage [mmol/l]
Run1, Alum, 24/9
Run2, F.C , 24/9
Run3, Alum, 24/9
Alum, 28/9


Resulting pH Versus the dosage of Al/Fe
Resulting pH
8.5
8
7.5
7
6.5
0.00
0.05
0.10
0.15
0.20
0.25
Al/Fe Dosage [mmol/l]
Run1, Alum, 24/9
Run2, F C., 24/9
Run3, Alum, 24/9
Alum, 28/9

Appendix 10: Results of Jar Test Run on 28/09/97

1) 1 liter sample in each beaker.
2) 5 min mixing with Bleaching Powder at 100 RPM
3) 1 min mixing with added chemicals at 100 RPM
4) Then 5 min slowly stir at 25 RPM.
5) There is ca. 10% of Chlorine in the bleaching powder.
6) Samples are preserved.
7) $Al_2(SO_4)_3\ 16H_2O$; $FeCl_3\ 6H_2O$
7) The initial As is about 0.478x80% =0.38 mg/l
8) Run 2-4 used raw water was acidified in advance.
9) The yield is about 980 ml.

Date:28/09/97 — Chlorine dosage is 0.5 mg/l

1. run (Alum added)

Beaker	Dosage			pH		Set. time		As Removal
No.	Alum	Al		Initial	Residual		Residual	Efficiency (%)
	mg/l	mmol/l	mg/l			h		%
1	10	0.03	0.86	7.29	7.27	1.5	0.296	22
2	20	0.06	1.71	"	7.51	1.5	0.305	20
3	30	0.10	2.57	"	7.44	1.5	0.214	44
4	40	0.13	3.43	"	7.38	1.5	0.216	43
5	50	0.16	4.29	"	7.35	1.5	0.218	43
6	60	0.19	5.14	"	7.29	1.5	0.168	56

Date:28/09/97 Chlorine dosage is 0.5 mg/l

2. run (Alum added)

Beaker	Dosage			pH		Set. time		As Removal
No.	Alum	Al		Initial	Residual		Residual	Efficiency (%)
	mg/l	mmol/l	mg/l			h		%
1	70	0.22	6.00	6.77	6.70	1	0.097	74
2	80	0.25	6.86	"	6.65	1	0.086	77
3	90	0.29	7.71	"	6.64	1	0.058	85
4	100	0.32	8.57	"	6.62	1	0.058	85
5	110	0.35	9.43	"	6.61	1	0.054	86
6	120	0.38	10.29	"	6.60	1	0.037	90

Date:28/09/97 *Chlorine dosage is 0.5 mg/l*

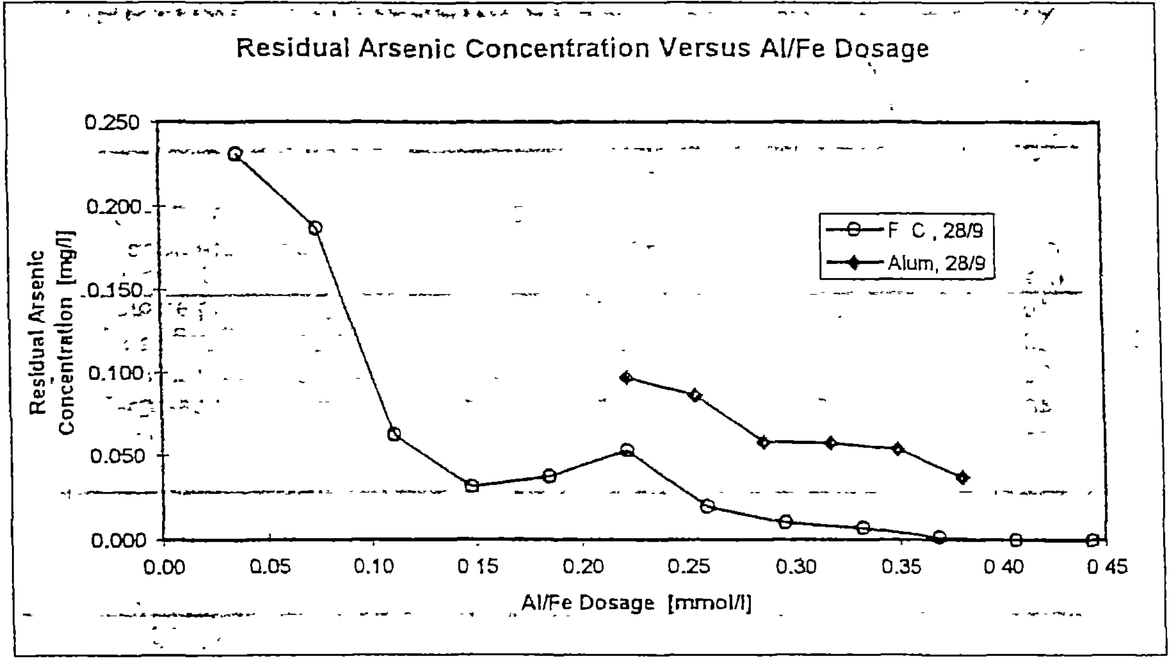
3. run (Ferric Chloride added)

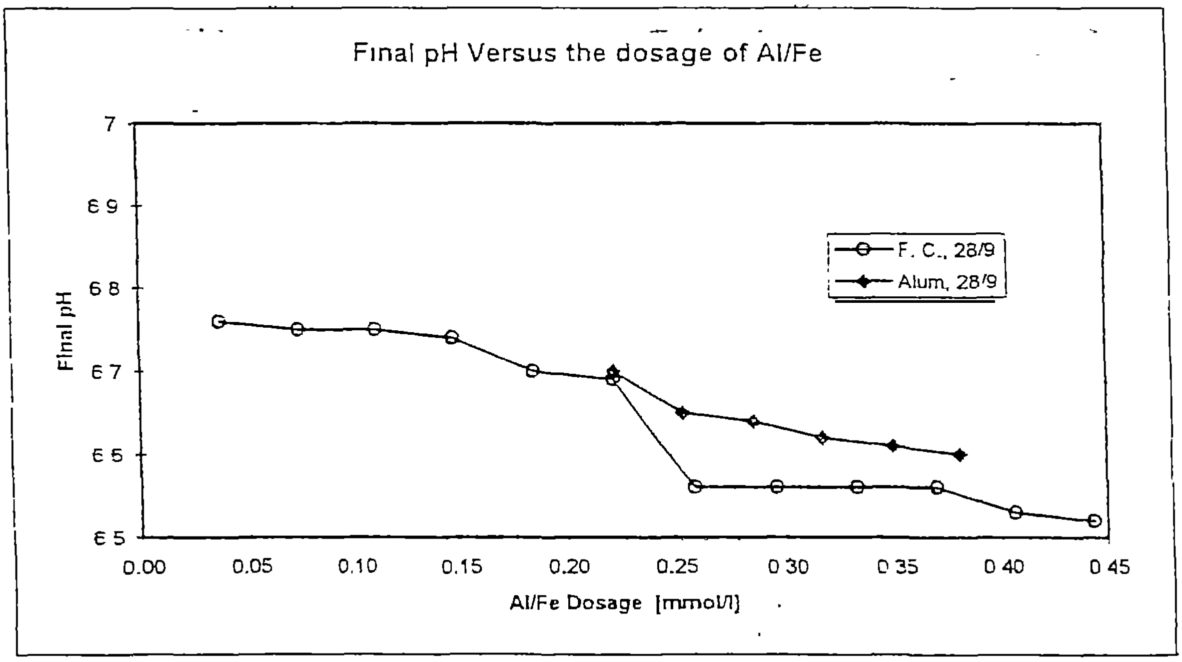
Beaker	Dosage			pH		Set. time		As Removal
No.	F. C	Fe		Initial	Residual		Residual	Efficiency (%)
	mg/l	mmol/l	mg/l			h		%
1	10	0.04	2.07	6.77	6.76	1	0.231	39
2	20	0.07	4.14	"	6.75	1	0.187	51
3	30	0.11	6.21	"	6.75	1	0.063	84
4	40	0.15	8.28	"	6.74	1	0.031	92
5	50	0.18	10.35	"	6.70	1	0.037	90
6	60	0.22	12.42	"	6.69	1	0.053	86

Date:28/09/97 *Chlorine dosage is 0.5 mg/l*

4. run (Ferric Chloride added)

Beaker	Dosage			pH		Set. time		As Removal
No.	Alum	Al		Initial	Residual		Residual	Efficiency (%)
	mg/l	mmol/l	mg/l			h		%
1	70	0.26	14.49	6.77	6.56	10	0.020	95
2	80	0.30	16.56	"	6.56	10	0.010	97
3	90	0.33	18.63	"	6.56	10	0.007	98
4	100	0.37	20.70	"	6.56	10	0.002	100
5	110	0.41	22.77	"	6.53	10	0.000	100
6	120	0.44	24.84	"	6.52	10	0.000	100


Residual Arsenic Concentration Versus Al/Fe Dosage
Residual Arsenic Concentration [mg/l]
0.250
0.200
0.150
0.100
0.050
0.000
0.00
0.05
0.10
0 15
0.20
0.25
0.30
0.35
0 40
0 45
Al/Fe Dosage [mmol/l]
F C , 28/9
Alum, 28/9


Final pH Versus the dosage of Al/Fe
Final pH
7
6 9
6 8
6 7
6 5
6 5
0.00
0.05
0.10
0.15
0.20
0.25
0 30
0 35
0 40
0 45
Al/Fe Dosage [mmol/l]
F. C., 28/9
Alum, 28/9

Appendix 11: Results of Jar Test Run on 29/09/97

1) 1 liter sample in each beaker.
2) 5 min mixing with BP at 100 RPM
3) 1 min mixing with Alum at 100 RPM
4) Then 5 min slowly stir at 25 RPM.
5) There is ca. 10% of Chlorine in the Bleaching Powder
6) Samples are preserved.
7) In the tea bag, BP is ca 0 8265 g and RH is ca 7 2859 g.
8) $Al_2(SO_4)_3$ $16H_2O$; $FeCl_3$ $6H_2O$
9) The initial arsenic concentration was about 0.478 x 80% = 0.38 mg/l.
10) The sludge was unstable and stayed on the top of the water
11) The first run was sampled through a tea strainer after 3 hours, and the second run was sampled through cafe filter after 24 hours. There is black ask flowing in the water

Date:29/09/97 *Belching Powder ca 0.7 g from the tea bag*

1. run (Rice Husk added)

Beaker No.	R. H. Dosage g/l	pH Initial	As Residual mg/l	As Removal Efficiency %	Dose/UNICEF dose
1	0.6	6.77	0.012	97	1
2	1.2	"	0.028	93	2
3	1 8	"	0.015	96	3
4	2.4	"	0 022	94	4
5	3.0	"	0.000	100	5
6	3.6	"	0.006	98	6

Belching Powder ca 0.7 g form the tea bag

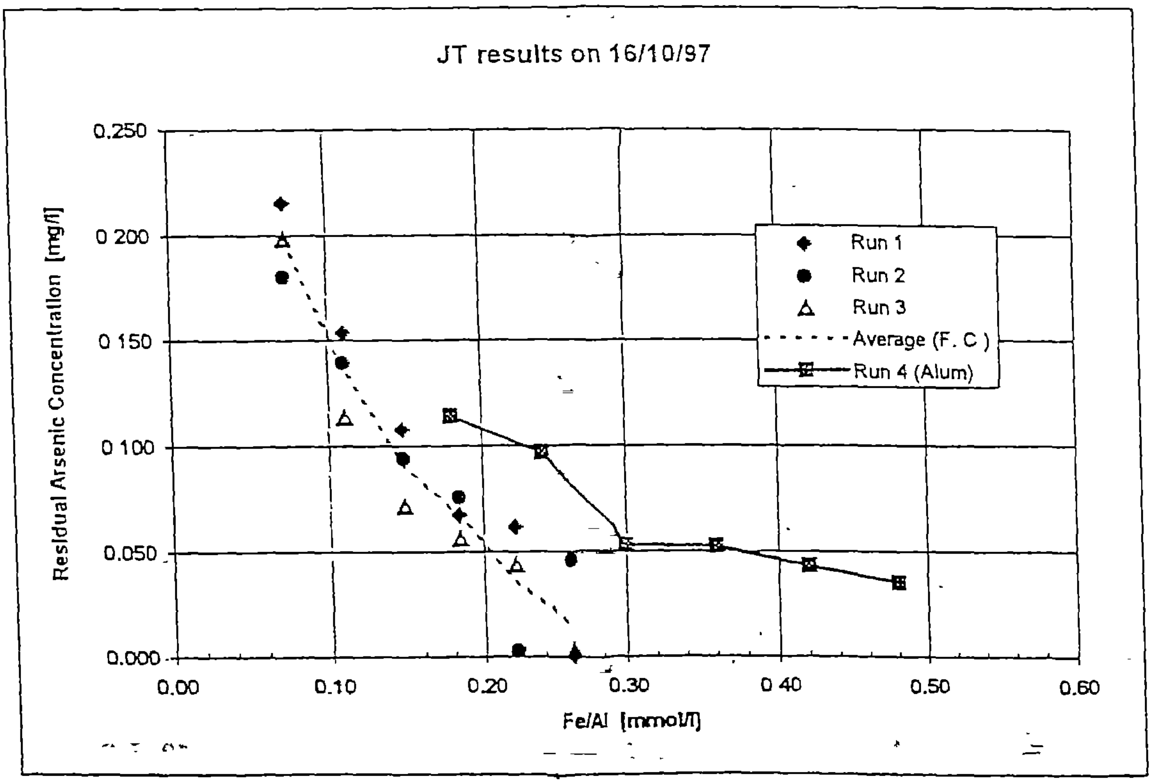
2. run (Rice Husk added)

Beaker	R. H.	pH		As Removal	Addition
No.	Dosage	Initial	Residual	Efficiency	Chemicals
	g/l			%	mg/l
1	0 7	6.77	0.001	100	10 Alum
2	0.7	"	0 000	100	10 Alum
3	0.7	"	0.000	100	10 Alum
4	0.7	"	0.000	100	10 F C.
5	0.7	"	0.000	100	10 F. C.
6	0.7	"	0.000	100	10 F. C.

Appendix 12: Results of Jar Tests on 16/10/97

	$FeCl_3 . 6H_2O$		$Al_2(SO_4)_3 .18\ H_2O$	
No.	Dosage mg/l	Treated water	Dosage mg/l	Treated water
1	20	not very clear	60	
2	30	clear	80	
3	40	clear	100	after 1 h there were still micro flocs.
4	50	clear	120	
5	60	very clear	140	
6	70	very clear	160	

1. At higher dosage of $FeCl_3 .6\ H_2O$ the flocs are very big and they set down very quickly (in 10 minutes). The flocs are yellow brown.
2. All samples are filtered by tea filter.
3. Settling time is 1 hour.
4. The initial arsenic concentration is about 0.478 x 80% = 0.38 mg/l
5. All of the samples were preserved by HCl (1 ml/l).
6. 25 ml of $NaBH_4$ were used for the arsenic analysis.
7) Bleaching powder was added (0.5 mg/l chlorine).



Results of Jar Tests on 16/10/97

1. *Ferric Chloride ($FeCl_3 . 6H_2O$) added*

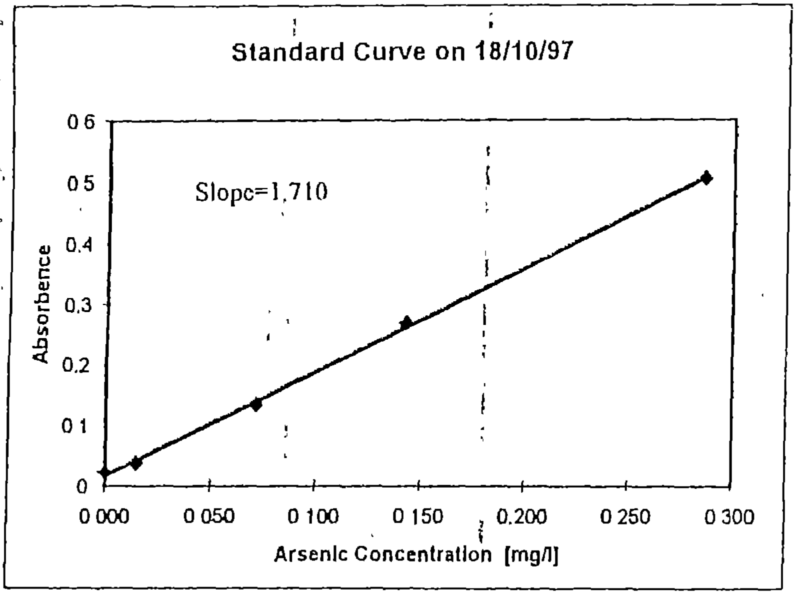
No.	Date(M)	Dosage		Abs				Arsenic Concentration (mg/l)				St. Dev
		F. C. (mg/l)	Fe (mmol/l)	Run 1	Run 2	Run 3	Average	Run 1	Run 2	Run 3	Average (F. C.)	
1	18/10/97	20	0.07	0.387	0.327	0.357	0.357	0.216	0.181	0.198	0.198	0.018
2	18/10/97	30	0.11	0.281	0.257	0.212	0.250	0.154	0.140	0.113	0.136	0.020
3	18/10/97	40	0.15	0.202	0.179	0.14	0.174	0.108	0.094	0.071	0.091	0.018
4	18/10/97	50	0.18	0.133	0.147	0.114	0.131	0.067	0.075	0.056	0.066	0.010
5	18/10/97	60	0.22	0.123	0.023	0.093	0.080	0.061	0.003	0.044	0.036	0.030
6	19/10/97	70	0.26	0.022	0.098	0.028	0.049	0.000	0.046	0.003	0.016	0.026

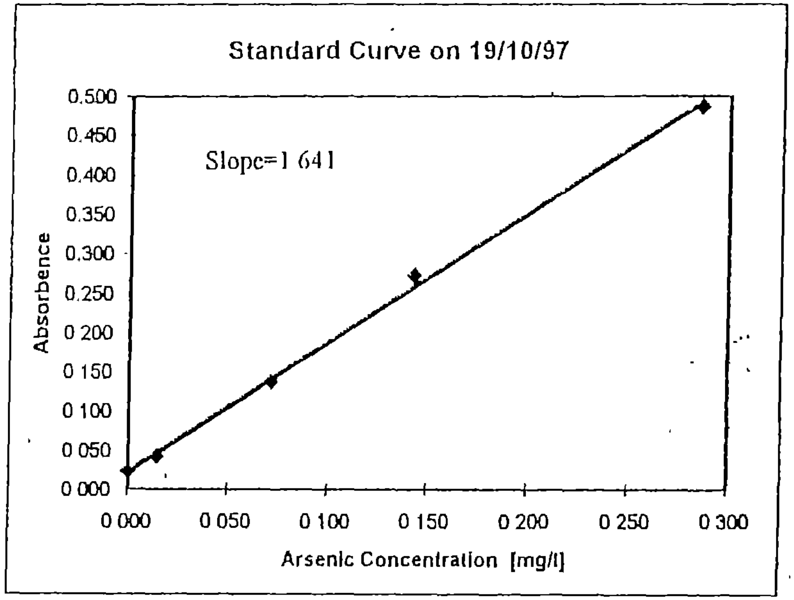
2. *Alum ($Al_2(SO_4)_3 . 18H_2O$) added*

No.	Date(M)	Dosage		Abs	As conc. (mg/l)
		Alum (mg/l)	Al (mmol/l)	Run 4	Run 4 (Alum)
1	19/10/97	60	0.18	0.210	0.114
2	19/10/97	80	0.24	0.182	0.097
3	19/10/97	100	0.30	0.110	0.053
4	19/10/97	120	0.36	0.109	0.052
5	19/10/97	140	0.42	0.094	0.043
6	19/10/97	160	0.48	0.081	0.035

Arsenic Standard on 18/10/97		
Conc.		Abs
µg	mg/l	
0	0.000	0.023
1	0.014	0.038
5	0.071	0.135
10	0.143	0.269
20	0.286	0.505
Slope		1.710
Intercept		0.018
Corr.		0.9996

Arsenic Standard on 19/10/97				
Conc.		Abs		
µg	mg/l	1st	2nd	Average
0	0.000	0.023		0.023
1	0.014	0.049	0.035	0.042
5	0.071	0.137		0.137
10	0.143	0.272		0.272
20	0.286	0.456	0.516	0.486
Slope				1.641
Intercept				0.023
Corr.				0.9991


Standard Curve on 18/10/97


Standard Curve on 19/10/97

Appendix 13: Results of Jar Tests on 21/10/97 (As)

1. The samples were collected on 21/10/97 through a coffee filter after 1 hour sedimentation and measured on 23-24/10/97.
2. 5 min mixing with BP (0 5 mg/l chlorine), 1 min fast stir and 5 min slow stir.
3. All samples were preserved by HCl (4 ml/l).
4. 25 ml of $NaBH_4$ were used for the analysis of Arsenic.
5. The raw water was fetched on 20/10/97 and the initial As concentration was 0 384 mg/l

Arsenic Analysis

1. Ferric Chloride ($FeCl_3 . 6H_2O$) added

No.	Dosage		Measured	Abs				Residual Arsenic Concentration (mg/l)				St. Dev
	F. C. (mg/l)	Fe (mmol/l)	Date	Run 1	Run 2	Run 3	Average	Run 1 (F C)	Run 2 (F. C.)	Run 3 (F. C.)	Average(F. C.)	
1	30	0.11	23/10/97	0 268	0 233	0 231	0 244	0 167	0 145	0 144	0.152	0 01
2	40	0.15	23/10/97	0 197	0 195	0 256	0 216	0 123	0 122	0 159	0 135	0.02
3	50	0 18	23/10/97	0.13	0 168	0 181	0 160	0 082	0 105	0 113	0 100	0 02
4	60	0 22	23/10/97	0 114	0 122	0 143	0 126	0 072	0 077	0 090	0 079	0 01
5	70	0.26	23/10/97	0 092	0.096	0.105	0 098	0 058	0 061	0 066	0.062	0.00
6	80	0.30	24/10/97	0.185	0.105	0.096	0.129	0 109	0.059	0.053	0.074	0.03
7	90	0.33	24/10/97	0 071	0.069		0.070	0 038	0 036		0.037	0.00
8	100	0 37	24/10/97	0.068	0 058		0.063	0.036	0 030		0 033	0 00
9	110	0.41	24/10/97	0.072	0 082		0 077	0 038	0 045		0 041	0.00

2. Alum ($Al_2(SO_4)_3 . 18H_2O$) added

No.	Dosage		Measured	Abs				Residual Arsenic Concentration (mg/l)				St. Dev
	Alum (mg/l)	Al (mmol/l)	Date	Run 4	Run 5	Run 6	Average	Run 4 (Alum)	Run 5 (Alum)	Run 6 (Alum)	Average (Alum)	
1	80	0 240	24/10/97	0 301	0 316	0 258	0 292	0.181	0 190	0.154	0 175	0.02
2	100	0 300	24/10/97	0 193	0 284	0.243	0.240	0 114	0 170	0 145	0.143	0.03
3	120	0.360	24/10/97	0.146	0.195	0.155	0 165	0 084	0 115	0 090	0 096	0.02
4	140	0.420	24/10/97	0 155	0.154	0.154	0.154	0.090	0.089	0 089	0 090	0.00
5	160	0.480	24/10/97	0.11	0.155	0.123	0.129	0.062	0.090	0 070	0 074	0 01
6	180	0.541	24/10/97	0.121	0.139	0.118	0.126	0.069	0 080	0.067	0.072	0.01

3. Arsenic Concentration in the raw water

NB. The raw water was fetched on 20/10/97 and then sampled from container or bucket in the laboratory.

Name	Sampled Date	Sampled Time	Measured Date	Abs	Conc. mg/l		NB.
IRU-1	20/10/97	08:00	24/10/97	0.204	0.422		20 ml sample
"	"	13:00	24/10/97	0 190	0.391		"
"	21/10/97	11:00	24/10/97	0.189	0.389	Before JT	"
"	21/10/97	16:30	24/10/97	0.185	0.380	After JT	"
"	22/10/97	18:00	24/10/97	0.187	0.384		"
"	23/10/97	21.00	24/10/97	0 135	0 271		"

Ferric Chloride, $FeCl_3 . 6H_2O$, Added

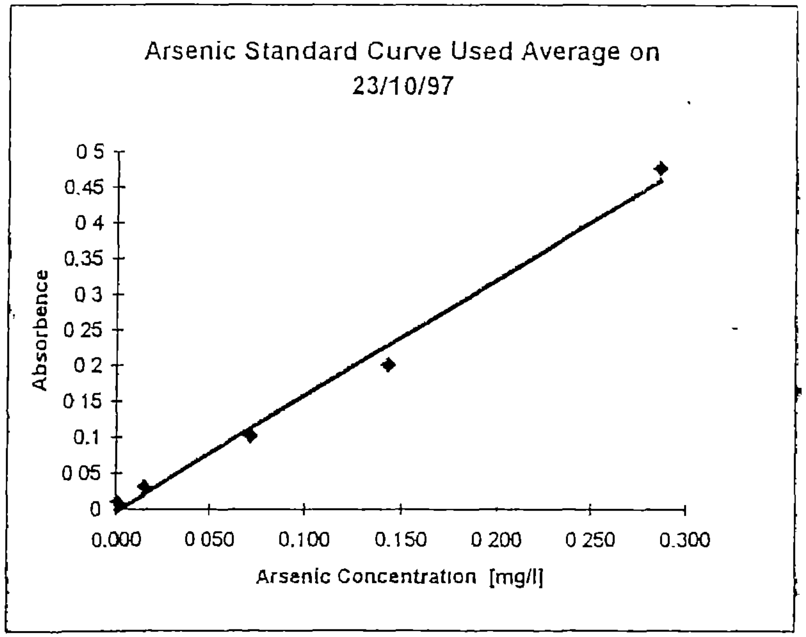
Dosage F. C. mg/l	Dosage Fe mmol/l	Arsenic Initial mg/l	Arsenic Residual mg/l	Arsenic Removal %
30	0.111	0.384	0 152	60
40	0.148	0.384	0.135	65
50	0.185	0.384	0 100	74
60	0.222	0.384	0.079	79
70	0.259	0.384	0.062	84
80	0.296	0.384	0.074	81
90	0.333	0.384	0 037	90
100	0.370	0.384	0.033	91
110	0.407	0 384	0 041	89

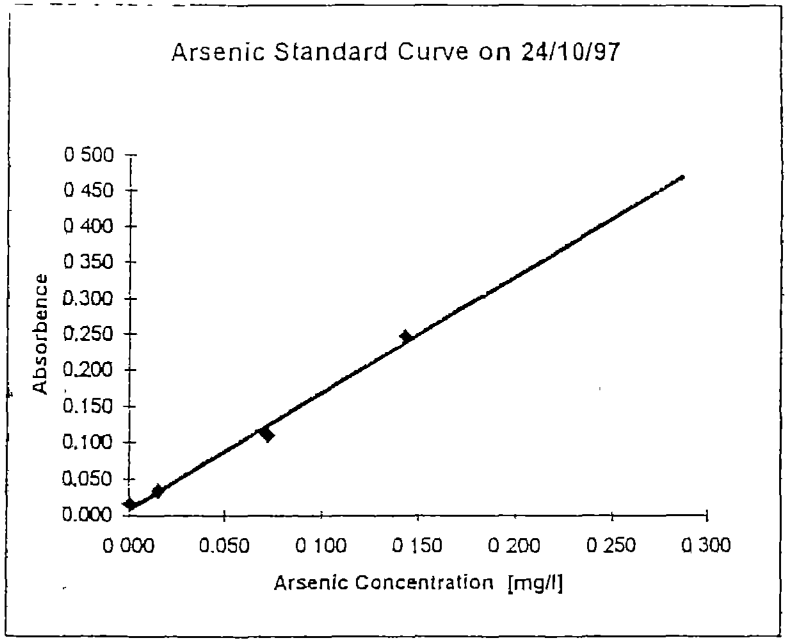
Alum, $Al_2(SO_4)_3 . 18H_2O$, Added

Dosage (mg/l) Alum mg/l	Dosage (mg/l) Al mmol/l	Arsenic Initial mg/l	Arsenic Residual mg/l	Arsenic Removal %
80	0.240	0.384	0.175	54
100	0.300	0.384	0.143	63
120	0.360	0.384	0.096	75
140	0.420	0.384	0 090	77
160	0.480	0.384	0.074	81
180	0.541	0 384	0.072	81

Arsenic Standard Curve

Concentration		Abs			
		23/10/97			24/10/97
µg	mg/l	1st	2nd	Average	
0	0.000	0.011	0.011	0.011	0.016
1	0.014	0.035	0.029	0.032	0.035
5	0.071	0.114	0.09	0.102	0.111
10	0.143	0.19	0.211	0.2005	0.247
20	0.286	0.509	0.445	0.477	
Slope		1.705	1.530	1.618	1.608
Intercept		-0.004	0.000	-0.002	0.010
Corr.		0.989	0.997	0.995	0.996





Results of Jar Tests on 21/10/97 (Fe)

1. The samples were collected on 21/10/97 through cafe filter after 1 hour sedimentation and measured on 25/10/97
2. 5 min mixing with BP, 1 min fast stir and 5 min slow stir.
3. All samples were preserved by HCl (4 ml/l).
4. 25 ml of $NaBH_4$ were used for the analysis of Arsenic.
5. The raw water was fetched on 20/10/97 and the initial iron concentraiton is 5.5 mg/l

Iron Analysis

1. Ferric Chloride ($FeCl_3 . 6H_2O$) added

NO.	Dosage		Measured	Abs				Residual Iron Concentration (mg/l)				
	F. C. (mg/l)	Fe (mmol/l)	Date	Run 1	Run 2	Run 3	Average	Run 1 (F. C.)	Run 2 (F. C.)	Run 3 (F. C.)	Average(F. C.)	St. Dev
1	30	0.11	25/10/97	0.050	0.037	0.034	0.040	1.033	0.474	0.345	0.617	0.37
2	40	0.15	25/10/97	0.043	0.033	0.037	0.038	0.732	0.302	0.474	0.502	0.22
3	50	0.18	25/10/97	0.037	0.037	0.031	0.035	0.474	0.474	0.216	0.388	0.15
4	60	0.22	25/10/97	0.034	0.032	0.031	0.032	0.345	0.259	0.216	0.273	0.07
5	70	0.26	25/10/97	0.028	0.026	0.032	0.029	0.087	0.001	0.259	0.116	0.13
6	80	0.30	25/10/97	0.057	0.03	0.033	0.040	1.334	0.173	0.302	0.603	0.64
7	90	0.33	25/10/97	0.029	0.027	-	0.028	0.130	0.044	-	0.087	0.06
8	100	0.37	25/10/97	0.027	0.035	-	0.031	0.044	0.388	-	0.216	0.24
9	110	0.41	25/10/97	0.032	0.035	-	0.034	0.259	0.388	-	0.323	0.09

2. Alum ($Al_2(SO_4)_3 . 18H_2O$) added

No.	Dosage		Measured	Abs				Residual Iron Concentration (mg/l)				
	Alum (mg/l)	Al (mmol/l)	Date	Run 4	Run 5	Run 6	Average	Run 4 (Alum)	Run 5 (Alum)	Run 6 (Alum)	Average (Alum)	St. Dev
1	80	0.24	25/10/97	0.014	0.013	0.014	0.014	0	0	0	0	0
2	100	0.30	25/10/97	0.013	0.011	0.018	0.014	0	0	0	0	0
3	120	0.36	25/10/97	0.011	0.011	0.018	0.013	0	0	0	0	0
4	140	0.42	25/10/97	0.013	0.012	0.010	0.012	0	0	0	0	0
5	160	0.48	25/10/97	0.008	0.013	0.009	0.010	0	0	0	0	0
6	180	0.54	25/10/97	0.011	0.010	0.007	0.009	0	0	0	0	0

3. Iron Concentration in the raw water

NB. The raw water was fetched on 20/10/97 and then sampled from container or bucket in the laboratory

		Sampled		Measured	Abs	Conc.	NB.
Name	Date	Time	Date		mg/l		
IRU-13	20/10/97	08 00	25/10/97	0.18	6 49		20 ml sample
''	-	13:00	25/10/97	0 17	6 24		''
''	21/10/97	11 00	25/10/97	0.14	4 69	Before JT	''
''	21/10/97	16.30	25/10/97	0.17	6 28	After JT	''
''	22/10/97	18.00	25/10/97	0.20	7,65		''
	23/10/97	21 00	25/10/97	0 02	0.00		
	24/10/97	19·00	25/10/97	0 02	0.00		

Ferric Chloride, $FeCl_3 . 6H_2O$, Added

Dosage			Iron	
F. C. mg/l	Fe mmol/l	Initial mg/l	Residual mg/l	Removal %
30	0.11	5 48	0 62	89
40	0.15	5.48	0.50	91
50	0.18	5.48	0.39	93
60	0.22	5.48	0.27	95
70	0.26	5.48	0.12	98
80	0.30	5.48	0.60	89
90	0.33	5 48	0.09	98
100	0 37	5.48	0.22	96
110	0 41	5 48	0.32	94

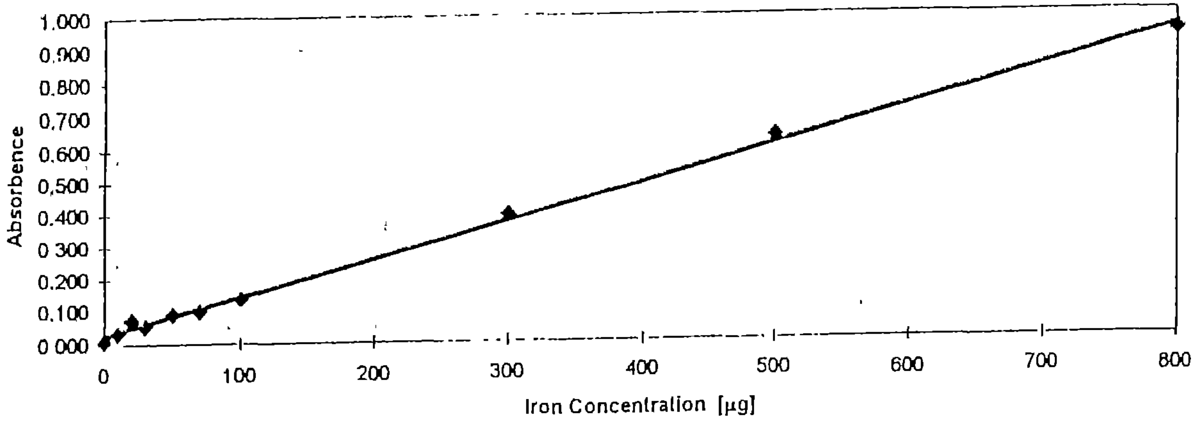
Alum, $Al_2(SO_4)_3 . 18H_2O$, Added

Dosage (mg/l)			Iron	
Alum mg/l	Al mmol/l	Initial mg/l	Residual mg/l	Removal %
80	0 24	5.48	0 00	100
100	0.30	5.48	0.00	100
120	0.36	5.48	0.00	100
140	0.42	5.48	0.00	100
160	0 48	5.48	0.00	100
180	0 54	5.48	0.00	100

Iron Standard on 25/09/97.

No.	Conc. µg	Conc. mg/l	Abs	Slope	Inter.	Corr.
1	0	0	0.010	0.001	0.026	0.999
2	10	0.2	0.033			
3	20	0.4	0.072			
4	30	0.6	0.052			
5	50	1	0.088			
6	70	1.4	0.097			
7	100	2	0.134			
8	300	6	0.395			
9	500	10	0.627			
10	800	16	0.938			

Iron Standard Curved on 25/10/97



Results of Jar Tests on 21/10/97 (pH)

pH Measurement

The Initial pH is 7.23.

1. Ferric Chloride ($FeCl_3 . 6H_2O$) added

No.	Dosage		Residual pH				St. Dev
	F. C. (mg/l)	Fe (mmol/l)	Run 1	Run 2	Run 3	Average	
1	30	0.11	7.17	7.13	7.13	7.14	0.02
2	40	0.15	7.13	7.11	7.10	7.11	0.02
3	50	0.18	7.09	7.06	7.09	7.08	0.02
4	60	0.22	7.02	7.04	7.06	7.04	0.02
5	70	0.26	6.97	6.99	7.00	6.99	0.02
6	80	0.30	6.94	6.96	7.01	6.97	0.04
7	90	0.33	7.00	7.02	-	7.01	0.01
8	100	0.37	6.98	6.99	-	6.99	0.01
9	110	0.41	6.96	6.97	-	6.97	0.01

2. Alum ($Al_2(SO_4)_3 . 18H_2O$) added

No.	Dosage		Residual pH				St. Dev
	Alum (mg/l)	Al (mmol/l)	Run 4	Run 5	Run 6	Average	
1	80	0.24	7.04	7.06	7.09	7.06	0.03
2	100	0.30	6.97	7.03	7.05	7.02	0.04
3	120	0.36	6.93	6.98	7.00	6.97	0.04
4	140	0.42	6.94	6.94	7.00	6.96	0.03
5	160	0.48	6.86	6.94	6.94	6.91	0.05
6	180	0.54	6.83	6.92	6.85	6.87	0.05

Appendix 14: Results of Bucket Experiments on 27/10/97 (As)

1. The added chemical was Alum, technical grade
2. The dosage of Alum was ca. 5 g/15 l.
3. The dosage of Bleaching Powder was ca 2 g/15l water.
4. The Bleaching Powder was mixed with water for 5 min at ca. 60 RPM.
5. Fast stir was ca. 60 RPM, and slow stir was ca. 15 RPM.
6. Sedimentation time was 1 hour.
7. The samples were taken and preserved by HCl (4 ml/l) on 27/10/97.
8. Arsenic was measured on 28/10/97 and Iron on 30/10/97.
9. 25 ml of $NaBH_4$ were used for the analysis of Arsenic.
10. Initial arsenic concentration of Bucket Tests was 0.556 mg/l.

1. Arsenic Analysis

No.	Fast stir sec	Slow stir min	Sludge ml	Abs	Residual As mg/l	As Removal %
1	60	3	600	0.101	0.064	89
2	60	5	700	0.099	0.062	89
3	60	7	600	0.070	0.043	92
4	60	9	600	0.095	0.060	89
5	60	11	600	0.062	0.037	93
6	60	13	900	0.037	0.020	96
7	60	15	800	0.058	0.034	94
8	10	5	800	0.058	0.034	94
9	20	5	900	0.058	0.034	94
10	40	5	900	0.048	0.027	95
11	80	5	800	0.081	0.050	91

Arsenic Standard Solutions on 28/10/97

µg	mg/l	ABS 1st	ABS 2nd	ABS Average
0	0.000	0.011	-	0.011
1	0.014	0.027	-	0.027
5	0.071	0.118	-	0.118
10	0.143	0.208	0.202	0.205
20	0.286	0.402	0.453	0.428
Slope				**1.453**
Intercept				**0.008**
Corr.				**0.999**

Results of Bucket Experiments on 29/10/97

1. The added chemical was Alum, technical grade
2. The dosage of Alum was ca. 5 g/15 l.
3. The dosage of Bleaching Powder was ca 2 g/15l water.
4. The Bleaching Powder was mixed with water for 5 min at ca. 60 RPM.
5. Fast stir was ca. 60 RPM, and slow stir was ca. 15 RPM
6. Sedimentation time was 1 hour.
7. The samples were taken and ~~preserved by HCl~~ (4 ml/l) on 29/10/97.
8. 25 ml of NaBH4 were used for the analysis of Arsenic.
9. The system consists of two buckets, the first one was used for mixing chemicals and the second one was for treated water, which had a simple gravel filter at the bottom.
10. The raw water was fetched on 27/10/97.

No.	pH		Arsenic						Iron						Sludge
	Initial	Residual	Initial		After Bucket				Initial		After Bucket				
			Abs	Conc.	1	2	1	2	Abs	Conc.	1	2	1	2	
				mg/l	Abs		mg/l			mg/l	Abs		mg/l		ml
1	7.22	6.77	0.405	0.453	0.094	-	0.049	-	0.065	2.473	0.001	-	0	-	500
2	7.22	6.70	-	-	0.105	-	0.055	-	-	-	0.003	-	0	-	750
3	7.11	6.73	0.355	0.396	0.093	-	0.048	-	0.049	1.836	0.008	-	0.203	-	1000
4	7.04	6.62	0.367	0.409	0.071	-	0.035	-	0.034	1.238	0.005	-	0.083	-	800
5	7.13	6.74	0.328	0.365	0.089	0.081	0.046	0.041	0.101	3.907	0	0.004	0	0.044	950
6	7.15	6.64	0.453	0.508	0.088	0.071	0.045	0.035	0.238	9.364	0.004	0.002	0.044	-0.036	900

Arsenic Standard Solutions on 30/10/97		
µg	mg/l	Abs
0	0.000	0.027
1	0.014	0.026
5	0.071	0.114
10	0.143	0.269
20	0.286	0.509
Slope		1.748
Intercept		0.009
Corr.		0.9973

Iron Standard Solutions				
Conc.		Abs		
µg	mg/l	1st	2nd	Average
0	0	-0.004		-0.004
10	0.2	0.01		0.01
20	0.4	0.023		0.023
30	0.6	0.038	0.04	0.039
50	1	0.065	0.067	0.066
70	1.4	0.092	0.094	0.093
100	2	0.131	0.137	0.134
300	6	0.381	0.395	0.388
500	10	0.646	0.648	0.647
800	16	0.993		0.993
Slope		0.001	0.001	0.001
Intercept		0.002	0.004	0.003
Corr.		0.9997	0.9999	0.9997

Results of Bucket Experiments on 27/10/97 (Fe)

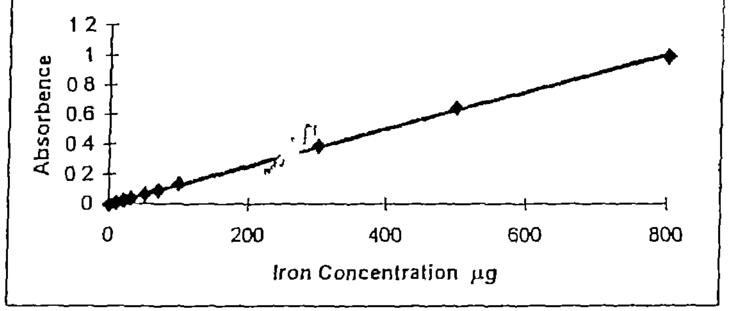
1. The added chemical was Alum, technical grade
2. The dosage of Alum was ca. 5 g/15 l.
3. The dosage of Bleaching Powder was ca 2 g/15l water.
4. The Bleaching Powder was mixed with water for 5 min at ca. 60 RPM.
5. *Fast stir was ca. 60 RPM, and slow stir was ca. 15 RPM.*
6. *Sedimentation time was 1 hour*
7. *The samples were taken and preserved by HCl (4 ml/l) on 27/10/97*
8. Arsenic was measured on 28/10/97 and Iron was on 30/10/97.
9. 25 ml of $NaBH_4$ were used for the analysis of Arsenic.
10. Initial Iron Concentration of Bucket Tests was 7.09 mg/l

Standard Solutions on 30/10/97				
Conc.		Abs		
µg	mg/l	1st	2nd	Average
0	0	-0.004	-	-0.004
10	0.2	0.01	-	0.01
20	0.4	0.023	-	0.023
30	0.6	0.038	0.04	0.039
50	1	0.065	0.067	0.067
70	1.4	0.092	0.094	0.093
100	2	0.131	0.137	0.134
300	6	0.381	0.395	0.388
500	10	0.646	0.648	0.647
800	16	0.993	-	0.993
Slope		0.001	0.001	0.001
Intercept		0.002	0.004	0.003
Corr.		1.000	1.000	1.000

2. Iron Analysis

No.	Fast stir sec	Slow stir min	Settling time (h)	Abs	Conc. mg/l	Removal %
1	60	3	1	0.006	0.12	98
2	60	5	1	0.004	0.04	99
3	60	7	1	0.004	0.04	99
4	60	9	1	0.005	0.08	99
5	60	11	1	0.003	0.00	100
6	60	13	1	0.004	0.04	99
7	60	15	1	0.006	0.12	98
8	10	5	1	0.005	0.08	99
9	20	5	1	0.006	0.12	98
10	40	5	1	0.007	0.16	98
11	80	5	1	0.007	0.16	98

Standard Curve on 30/10/97



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Appendix 15: Estimation of Sorption Isotherms

The two models Langmuir and Freundlich descring equilibrium concentrations are tested based on the results of the jar test experiments on 21/10/97. The two equations of Langmuir and Freundlich can be found in Section 6.
The estimation of the appropriate constants is done using the methods for nonlinear least squares fit and using the Solve function of Mircrosoft Excel program.

1. Estimation according to the sum of added and initial Fe

Dosage		Initial	As		f*	Freunlich		Langmuir	
$FeCl_3$ $6H_2O$ mg/l	Fe mg/l	Fe mg/l	Initial mg/l	Residual (S*) mg/l	Measured mgAs/g Fe	f* Estimated	diff^2	f* Estimated	diff^2
30	6.2	5.5	0.384	0.152	19.88	19.39	0.24	18.85	1.07
40	8.3	5.5	0.384	0.135	18.15	18.78	0.40	18.52	0.14
50	10.4	5.5	0.384	0.100	17.98	17.36	0.38	17.58	0.16
60	12.4	5.5	0.384	0.079	17.05	16.34	0.50	16.72	0.11
70	14.5	5.5	0.384	0.062	16.17	15.29	0.77	15.66	0.26
80	16.6	5.5	0.384	0.074	14.10	16.02	3.68	16.42	5.38
90	18.6	5.5	0.384	0.037	14.41	13.38	1.05	13.19	1.48
100	20.7	5.5	0.384	0.033	13.43	12.95	0.23	12.53	0.82
110	22.8	5.5	0.384	0.041	12.14	13.78	2.68	13.76	2.64
						sum	9.94	sum	12.04
				alfa	31.80			gamma	40.96
				beta	3.81			f, hat	21.87

3. Estimation according to added Fe

Dosage		Initial	As		f*	Freunlich		Langmuir	
FeCl$_3$ 6H$_2$O	Fe	Fe	Initial	Residual (S*)	Measured	f*	diff^2	f*	diff^2
mg/l	mg/l	mg/l	mg/l	mg/l	mgAs/g Fe	Estimated		Estimated	
30	6.2	5.5	0.384	0.152	37.43	34.41	9.12	33.64	14.40
40	8.3	5.5	0.384	0.135	30.17	32.25	4.33	32.07	3.61
50	10.4	5.5	0.384	0.100	27.50	27.45	0.00	28.05	0.31
60	12.4	5.5	0.384	0.079	24.57	24.24	0.11	24.91	0.12
70	14.5	5.5	0.384	0.062	22.29	21.16	1.28	21.55	0.54
80	16.6	5.5	0.384	0.074	18.77	23.29	20.40	23.91	26.40
90	18.6	5.5	0.384	0.037	18.65	16.11	6.44	15.41	10.46
100	20.7	5.5	0.384	0.033	16.99	15.06	3.72	14.07	8.53
110	22.8	5.5	0.384	0.041	15.06	17.10	4.14	16.67	2.57
						sum	49.54	sum	66.93
				alfa	94.83			gamma	10.66
				beta	1.86			f, hat	54.40

2. Estimation according to added Al

Dosage		As		f*	Freunlich		Langmuir	
Al$_2$(SO4)$_3$ 18H$_2$O	Al	Initial	Residual As	Measured	f*	diff^2	f*	diff^2
mg/l	mg/l	mg/l	mg/l	mgAs/g Al	Estimated		Estimated	
80	6.5	0.384	0.175	32.30	32.75	0.20	32.52	0.05
100	8.1	0.384	0.143	29.81	30.44	0.40	30.67	0.75
120	9.7	0.384	0.096	29.61	26.41	10.24	26.69	8.51
140	11.4	0.384	0.090	25.98	25.72	0.07	25.90	0.01
160	13.0	0.384	0.074	23.94	24.01	0.01	23.82	0.01
180	14.6	0.384	0.072	21.42	23.76	5.50	23.51	4.36
					sum	16.42	sum	13.69
			alfa	61.43			gamma	15.64
			beta	2.77			f, hat	44.40