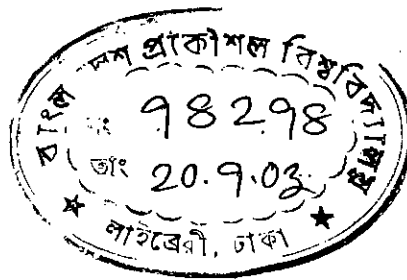


DEVELOPMENT OF A COMMUNITY BASED ARSENIC-IRON REMOVAL UNIT

BY
KHONDOKER MAHBUB HASSAN



A thesis submitted to the Department of Civil Engineering of
Bangladesh University of Engineering and Technology, Dhaka, in partial fulfillment
of the requirements for the degree
of
MASTER OF SCIENCE IN CIVIL ENGINEERING

26th JULY, 2003

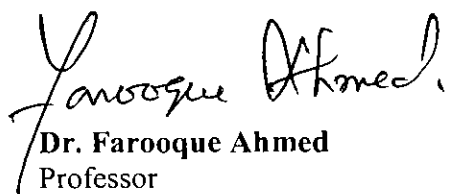


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A thesis approved as to style and content for the degree of M.Sc, Engg. (Civil):



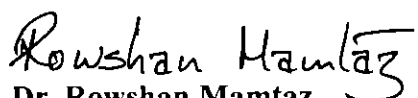
Dr. Farooque Ahmed
Professor
Environmental Engg. Division
Dept. of Civil Engineering, BUET
Dhaka-1000

**Chairman
(Supervisor)**



Dr. Sk. Sekender Ali
Professor and Head
Dept. of Civil Engineering, BUET
Dhaka-1000

Member



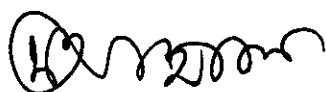
Dr. Rowshan Mamtaz
Associate Professor
Dept. of Civil Engineering, BUET
Dhaka-1000

Member



Dr. M. Ashraf Ali
Associate Professor
Dept. of Civil Engineering, BUET
Dhaka-1000

Member



Professor Engr. M.A. Hannan
Rector
Engineering Staff College Bangladesh (ESCB)
Ramna, Dhaka.

**Member
(External)**

26th July, 2003

DECLARATION

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

26th July, 2003

Khondoker Mahbub Hassan

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ABSTRACT

Widespread arsenic contamination and presence of high concentration of iron in groundwater are major water quality problem in Bangladesh, where water supply is heavily dependent on groundwater. Although a few household arsenic removal units have been developed and tested in the field, little attempt has been made in the development of a community type arsenic-iron removal unit.

The present study focused on development of a community based arsenic-iron removal unit (AIRU) adopting the technique of adsorption and co-precipitation of arsenic onto the flocs of ferric hydroxide, making use of the naturally occurring iron of groundwater. In order to simulate the field conditions in Bangladesh, in addition to laboratory model tests, five treatment units were constructed and their performance was monitored in different water quality conditions of the country. The AIRU, which is attached to a tubewell, has mainly two chambers, down-flow flocculator and up-flow roughing filter. The flocculation and roughing filtration processes in the AIRU were accomplished through the use of coarse media gravel beds.

The operation and maintenance of the developed AIRU are simpler and more user friendly in comparison to the previously developed community based water treatment units. The reduction of flow of treated water for the AIRU was not significant in comparison to the tubewell water flow (initially 82% and after six weeks of operation 63%). The clogging and maintenance requirement of the AIRU was not frequent and the cleaning procedures were simple. Cleaning was performed without removing the coarse media gravel beds from the AIRU and the chance of external bacterial contamination was almost negligible.

The AIRU was constructed by local mason using locally available materials. Raw water with arsenic concentration up to 200ppb and the iron-arsenic concentration ratio ≥ 30 (by weight) was treated with the AIRU satisfying Bangladesh Standards (50ppb As) without using any chemicals. For arsenic concentration above 200ppb and iron-arsenic concentration ratio < 30 , intermittent dosing of an oxidizing agent (bleaching powder) was required. Use of sorptive media (Read-F), in addition to AIRU, eliminated the use of oxidizing agent and this would increase the active life of Read-F media significantly.

Iron removal efficiency up to 90% was achieved through the AIRU for the face velocity less than $0.5 \text{ m}^3/\text{m}^2\text{-hr}$ and the removal efficiency was a function of raw water iron concentration and it increased with the passage of time. Number of beneficiaries and water consumption was increased by about 10 folds after the installation of the AIRU.

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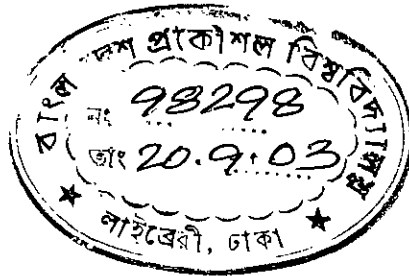
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Chapter 1

INTRODUCTION

1.1 GENERAL

In recent years there has been widespread coverage in the media about the problems of arsenic in Bangladesh's drinking water. This has been an unforeseen consequence of a large-scale programme to replace contaminated surface water sources by 'safe' ground water. Over a period of about 20-25 years about four million wells have been installed to utilize the groundwater from deeper aquifer layers, typically less than 200m deep (UNICEF, 1999), never suspecting the presence of arsenic in the aquifers carrying the groundwater. The alluvial aquifer that underlies the Ganges-Brahmaputra river basin contains arsenic in mineral form and has been widely tapped for obtaining drinking and irrigation water.

In Bangladesh, ground water which is free from pathogenic microorganism and available in adequate quantity in shallow aquifers has become popular and cost effective source of water for the scattered rural population of the country. Extraction of the ground water from shallow tubewells have been found to be the best option for rural water supply and Bangladesh has achieved a remarkable success by providing 97% of the rural population with tubewell water. However, at this success in water supply, it is unfortunate that the presence of arsenic in addition to iron in drinking water has emerged as a serious threat to public health challenge.

An estimate indicates that more than 35 million people in the country are potentially at risk from drinking contaminated water (Smith et al., 2000). This indeed brings the problem to a catastrophic scale that has not been experienced by humankind before. The Bangladesh government, with support from international agencies and local and international NGO groups, have initiated a number of programmes to determine the extent of the problem. Considering the unprecedented scale of this disaster, it has been a major challenge to come up with a cohesive strategy to tackle the problem.

In a study developed by British Geological Survey (2000) on arsenic concentration in tubewell water, provides a picture of the arsenic contamination in Bangladesh.

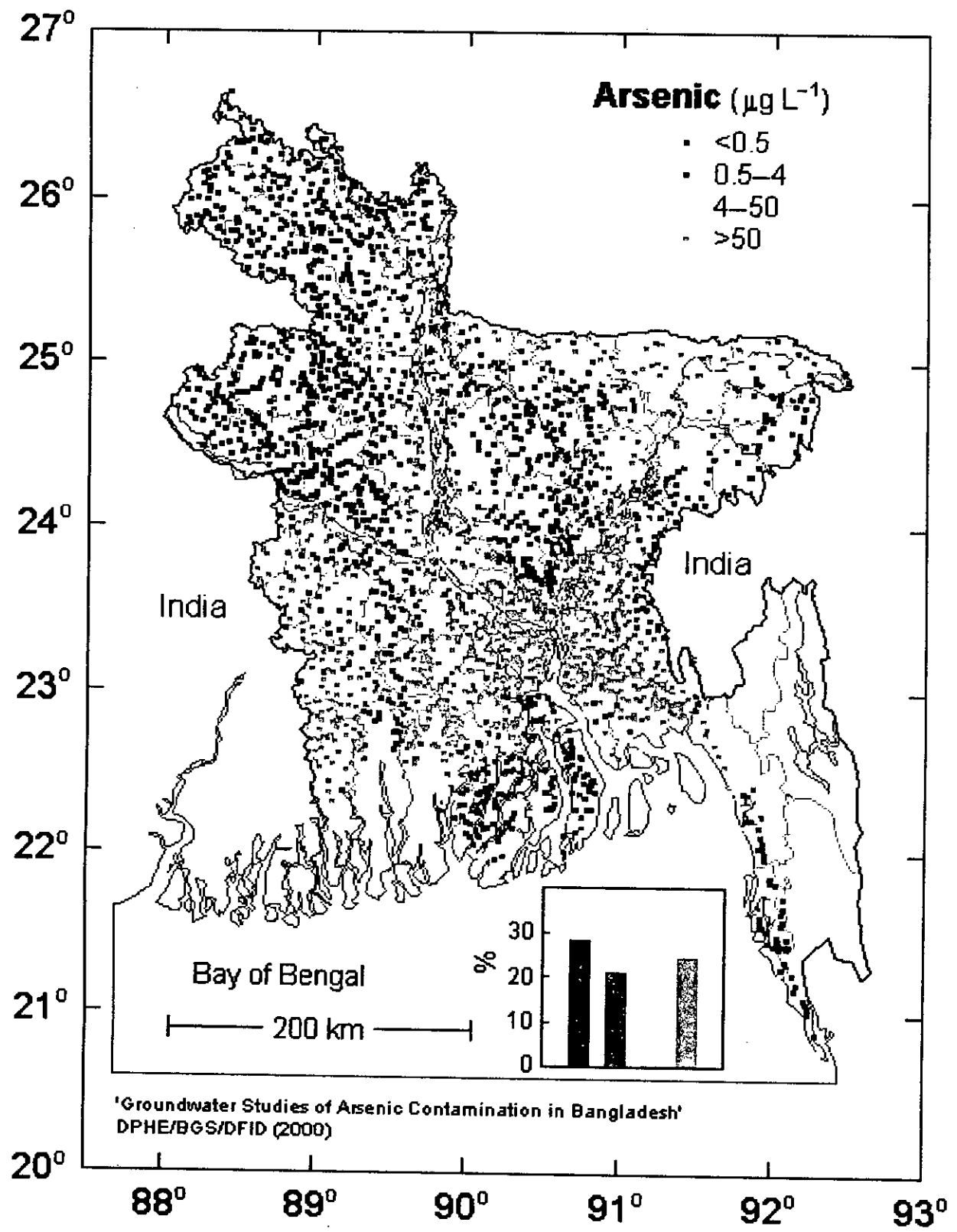


Figure 1.1: Arsenic Contamination in Bangladesh (DPHE / BGS / DFID, 2000)

It shows that tubewells in large parts of Sylhet and Dhaka divisions, most of Chittagong division except the Hill Tracts area, significant parts of Rajshahi division and most parts of Khulna and Barisal divisions except the coastal areas are contaminated with arsenic. Highly affected districts include Sylhet, Sunamgonj, Comilla, B-Baria, Narayngonj, Chandpur, Laksmipur, Feni, Noakhali, Sariatpur, Munshiganj, Bagerhat, Satkhira, Jessore, Jhenaidah, Chuadanga, Nawabganj, Manikganj, Faridpur and Gopalganj. Presence of arsenic in the coastal areas is low because most of the groundwater in this saline area is extracted from arsenic-free deep aquifer.

Bangladesh is a tropical country with a total surface area of about 144,000 km² and an estimated population of 129 million as of July 2000 (UN, 2000). Of the surface area available, about 70% is arable and about 10-15% comprises forests and woodlands. World Bank estimates put the contribution of agricultural sector to national GDP at about 25%, while a vast majority (~76%) of the population lives in rural settings (World Bank, 2000). Incidentally this rural population is the one most impacted by the arsenic contamination, largely because of lack of access to safe drinking water. Even in the cities only about half the population has access to safe water (UN, 2000).

Table 1.1: Arsenic Contamination Scenario in Bangladesh (DPHE / DFID, 1998)

| Division | No. of Districts | No. of affected Districts | No. of Thanas | No. of affected Thanas | % of affected Thanas of the Divisions | % of affected Thanas against the Country |
|-------------|------------------|---------------------------|---------------|------------------------|---------------------------------------|--|
| Dhaka | 17 | 16 | 134 | 61 | 45 | 12 |
| Chittagong | 11 | 7 | 93 | 21 | 22 | 4 |
| Rajshahi | 16 | 16 | 127 | 35 | 27 | 7 |
| Khulna | 20 | 10 | 63 | 42 | 66 | 9 |
| Barisal | 6 | 6 | 38 | 18 | 47 | 4 |
| Sylhet | 4 | 4 | 35 | 34 | 97 | 7 |
| 6 Divisions | 64 | 59 | 490 | 211 | - | 43 |

Note: Table represents affected thanas, where As concentrations in ground water is > 0.05 mg/L

The number of patients showing symptoms of arsenic toxicity are increasing as results from recent studies are becoming available. In a recent study by the National Institute of Preventive and Social Medicine (NIPSOM), above 6000 cases were identified in 162 villages in the 37 districts, mostly in the rural areas. Among the identified patients, 53% were male, 47% female and the most affected age group were found to be 20-40 years. It is believed that systematic study covering all the arsenic affected districts would reveal many more arsenic affected patients in Bangladesh.

The national steering committee on arsenic has informed that about 8500 arsenic patients have so far been detected across the country. It has been suggested in the popular media that this may be the largest mass poisoning in the history (New York Times, November 10, 1998). It is beyond the accident at Bhopal, India in 1984 and Chernobyl, Ukraine in 1986.

On the other hand groundwater collected through hand pump tube wells in Bangladesh carries a high concentration of iron and in many locations the concentration is much higher than the acceptable limit. This is probably because of the fact that alluvial deposits containing trace of iron compounds underlie most of the places of Bangladesh and shallow hand pump tube wells are drilled in such deposits to collect water. Although, iron does not cause any direct health problem, due to aesthetic reasons, rural people generally refuse to use tube well water in iron problem areas and they become more inclined to use the unprotected surface water sources. In a survey conducted by UNICEF and the World Health Organization (WHO) in Bangladesh in 1976, it was found that the attack rate of diarrhoeal diseases in the iron prone areas is 53% higher than that in the other areas (Ahmed, F. 1981). Iron problem is acute in ground water in the districts of Manikgonj, Gopalganj, Norshingdi, Narayangonj, Comilla, Rajshahi, Sirajgong, Bagerhat, Sylhet, Sonamgonj, Noakhali, Khulna, Jessore and Kurigram. The World Health Organization (WHO) suggested a guideline value of 0.3 mg/L of iron for drinking water. This limit can hardly be maintained in rural water supply in Bangladesh. For this reason, the Department of Environment (DOE, 1991), Bangladesh, recommended a desirable limit of 1 mg/L of iron in drinking water. But in the case of hand pump tube wells in rural areas, the maximum tolerable limit was set at 5 mg/L in the absence of a better source.

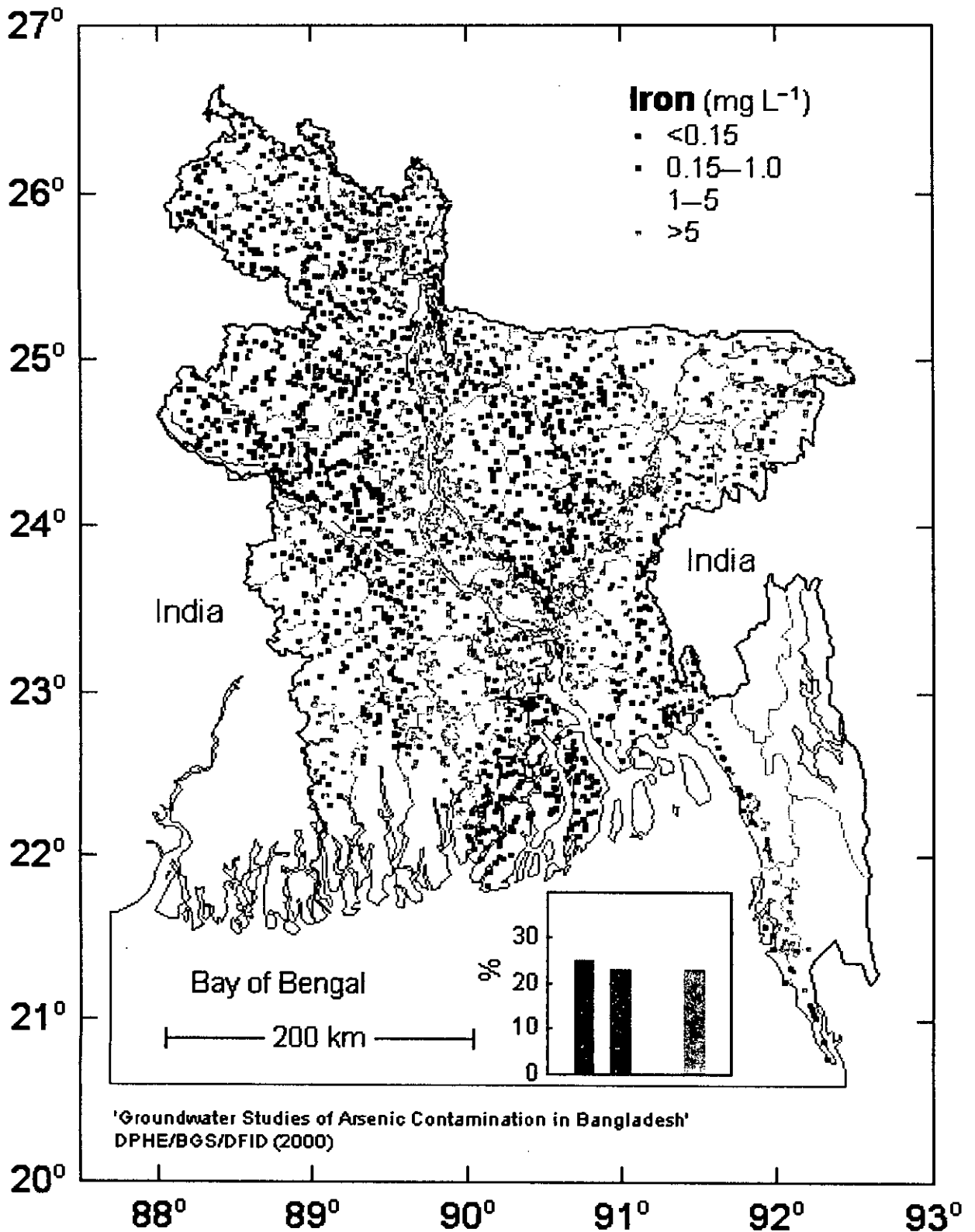


Figure 1.2: Iron Contamination in Bangladesh (DPHE / BGS / DFID, 2000)

This local standard is being followed in rural water supply in Bangladesh. Based on the distribution of iron bearing aquifers, allowable limits in Bangladesh and people's acceptability, the country may be divided into three iron problem areas (Ali, 1990).

Area Type-I: Iron Problem Free Zones:

Iron content of hand pump tube well water in this zone is less than 1 mg/L. Rural people accept it as excellent water and installation of Iron Removal Plant (IRP) is not required.

Area Type-II: Moderate Iron Problem Zones:

Iron content of hand pump tube well water in this zone is between 1 to 5 mg/L. People consider this water as good, medium or bad depending on the concentration of iron. Installation of IRP in this zone is optional.

Area Type-III: Acute Iron Problem Zones:

Iron content of hand pump tube well water is higher than 5 mg/L. In some places iron content has been found as high as 25 mg/L. Installation of IRP is absolutely essential to increase tube well water consumption.

1.2 RATIONALE OF THE STUDY

Arsenic toxicity has no known effective medicine for treatment, but drinking of arsenic free water can help the arsenic affected people to get rid of the symptoms of arsenic toxicity. There is an urgent need to ensure supply of arsenic free drinking water to the millions of arsenic affected people in Bangladesh. The options that are commonly suggested as possible alternatives to arsenic affected groundwater include: (1) Arsenic free deep tube well water, (2) Surface water, (3) Rainwater harvesting, and (4) Treatment of groundwater for arsenic removal. While arsenic-free deep aquifers have been identified in some places, this option appears to be too expensive for large-scale use in rural areas. The principal problem with surface water is bacteriological contamination. In addition availability of surface water is not uniform throughout the year. Rainwater harvesting can be a probable alternative. But seasonal variation in rainfall pattern, proper storage of rainwater and public acceptances are some of the issues that need to be adequately addressed. Groundwater treated for arsenic

removal is another very promising option to provide arsenic-free water to the rural population. Since people are already accustomed to using groundwater and millions of tube wells are already there in the rural areas, this option can make use this available infrastructure. It should be noted that only water used for drinking and cooking purposes need to be treated; so volume of water that need to be treated would not be very high.

Various technologies have been used for removing arsenic from groundwater. The most commonly used technologies include co-precipitation with alum or iron; adsorptive filtration (e.g., using activated alumina, Read-F etc.); ion exchange; microbial process and membrane processes such as reverse osmosis. Ion exchange and membrane techniques appear to be too expensive for large-scale use in Bangladesh. Apart from cost, both ion exchange and membrane techniques would require higher levels of technical expertise on the part of the user for operation and maintenance. Presence of high concentrations of iron in the groundwater, which precipitates as ferric hydroxide solids after extraction, would definitely interfere with the efficiency of membranes. Microbial processes are still at a development stage.

Arsenic removal by coagulation, adsorption and co-precipitation to be the most promising techniques for use in Bangladesh. Recent experiences with adsorptive filtration devices designed for arsenic removal suggest that high iron concentration in groundwater of Bangladesh, which clogs the filter media, is a particular concern for such systems. Freshly precipitated amorphous ferric hydroxide, $\text{Fe}(\text{OH})_3$ is formed by oxidation of natural iron extracted with ground water through simple aeration. Arsenic is primarily removed by adsorption onto the surface of $\text{Fe}(\text{OH})_3$ and subsequent co-precipitation. The level of treatment achievable with higher initial arsenic concentration is also important since the World Health Organization (WHO) has already reduced its recommended limit for arsenic in drinking water from 0.05 mg/L to 0.01 mg/L and the limit is currently under review in a number of other countries. Such a revision of arsenic standard may also be forthcoming in Bangladesh.

In Bangladesh, arsenic removal by adsorption and co-precipitation onto the flocs of ferric hydroxide could be a very effective technique, particularly in view of the presence of elevated levels of iron in many regions of the country. Arsenic has often been found to be associated with high iron concentrations. Naturally occurring iron, which forms ferric hydroxide flocs upon extraction, therefore, can play an important role in removing arsenic from groundwater.

A study by Ahmed, et al. (1989) about the ground water quality of shallow aquifers reveal that iron content of groundwater in most of the places of Bangladesh is greater than 1.0 mg/L and in many locations the iron content of groundwater is more than 5 mg/L. The study also shows that groundwater of about 65% of the area of Bangladesh has average iron content more than 2 mg/L. In an another study by Hossain and Huda (1997) it has been pointed out that 19.5% areas of Bangladesh contain iron more than 5 mg/L.

Arsenic and iron concentrations were determined for 100 groundwater samples from four districts in the northeastern region of the country in a study (Hossain and Ali, 1997). Concentration of iron and arsenic of these samples are summarized in Table: 1.2 on the following page. All 27 groundwater samples with iron concentration below 0.5 mg/L were found to have arsenic concentration below 0.05 mg/L, satisfying the drinking water standard for Bangladesh, and 24 out of these 27 samples (i.e., about 89 percent) satisfied the WHO arsenic standard of 0.01 mg/L. Of the 10 samples with iron concentration between 0.5 and 1.0 mg/L, 9 satisfied the Bangladesh standard for arsenic and only one exceeded the 0.05 mg/L limit. The drinking water standard for iron in Bangladesh is 1 mg/L. Thus out of the 37 groundwater samples satisfying the drinking water standard for iron, 36 also satisfied the Bangladesh standard for arsenic and only one exceeded the limit. There were 35 samples with iron concentration between 1.0 and 5.0 mg/L. Out of these, 18 samples (i.e., about 51 percent) exceeded the 0.05 mg/L limit of arsenic, and only 8 samples (i.e., about 23 percent) satisfied the WHO standard of 0.01 mg/L. Of the 28 samples with iron concentration above 5.0 mg/L, none satisfied the WHO limit of 0.01 mg/L; only 7 samples had arsenic concentration below 0.05 mg/L and 21 samples (i.e., 75 percent) exceeded the 0.05 mg/L limit of arsenic.

Table 1.2: Number of Tube wells with Various Levels of As and Fe (Hossain and Ali, 1997)

| As Conc. (mg/L) ↓ | Iron Concentration (mg/L) | | | | No. of samples |
|----------------------|---------------------------|--------------|--------------|-------|----------------|
| | ≤ 0.50 | > 0.5 to 1.0 | > 1.0 to 5.0 | > 5.0 | |
| As ≤ 0.01 | 24 | 7 | 8 | 0 | 39 |
| 0.05 ≤ As > 0.01 | 3 | 2 | 9 | 7 | 21 |
| 0.10 ≤ As > 0.05 | 0 | 1 | 8 | 11 | 20 |
| As > 0.10 | 0 | 0 | 10 | 10 | 20 |
| No. of Samples | 27 | 10 | 35 | 28 | |

Thus, this study suggests that high arsenic concentrations are, in general, accompanied by high iron concentration and there is a strong positive correlation between the concentrations of iron and arsenic in groundwater of Bangladesh.

Although few households type arsenic removal units have been developed and tested in the field, little attempt has been made in the development of a community based combined arsenic-iron removal unit. Therefore, there is a serious need of developing a small-scale community type iron and arsenic removal unit. It was understood from the previous studies that removal of iron and arsenic was not the main problem in the water treatment units; the main concern was regular maintenance through community participation. So, some unit should be developed which is simple in operation and maintenance and which can avoid any bacteriological contamination. Community participation in design, operation and maintenance should be the major part for sustainable development of the treatment unit.

From Laboratory based extensive model studies it has been found that up-flow gravel bed flocculator cum roughing filter is very efficient for the removal of both arsenic and iron (over 85%) without using granular sand filter (Ahmed, 1998). Moreover, it has been observed that cleaning and maintenance of the bed can be done simply through periodically flushing/drainage without much trouble. Thus, a research project on "Development of a

Community Based Arsenic-Iron Removal Unit (AIRU)" has been taken to find out a probable solution in this regard. Success of this project might significantly contribute towards finding out a sustainable solution of water supply problems for arsenic and iron affected areas of Bangladesh.

1.3 OBJECTIVES OF THE PRESENT RESEARCH

Following were the major objectives of the study:

- To develop a small-scale community type combined arsenic and iron removal unit (AIRU) adopting co-precipitation and adsorption of arsenic on to natural iron content in groundwater and using locally available materials.
- To conduct both laboratory and field tests of the AIRU to study the arsenic and iron removal performances in different water quality conditions.
- To assess the operation and maintenance problems of the AIRU at the field level and to find out probable solutions through design modification and community participation.

1.4 SCOPE OF THE STUDY

Detail laboratory analysis and model tests were carried out to determine the optimum gravel sizes and depths of gravel beds of the flocculator and roughing filter of the AIRU for effective removal of arsenic and iron, optimum face velocity, iron-arsenic ratio for effective removal of arsenic through co-precipitation with iron, arsenic adsorption limit of the AIRU.

On the other hand this study evaluates the removal efficiency of arsenic and iron from groundwater through the AIRU at the field level following the techniques of adsorption and co-precipitation of arsenic with natural iron content in 5 (five) different water quality conditions of the country. Community participation was the major concern for specially operation and maintenance aspects. The operation and maintenance problems of the AIRU at the field level were assessed through long term monitoring and also by field questionnaire survey regarding the user opinion. It was tried to find out probable solutions of the problems encountered through design modifications and community participation.

1.5 ORGANIZATION OF THE THESIS

Apart from this chapter, the remainder of the thesis has been divided into five chapters:

Chapter 2 presents literature review concerning occurrence of arsenic and iron, global arsenic problems, sources of arsenic, uses of arsenic, effect of arsenic on health and behavior of arsenic in the environment. This chapter emphasizes the chemistry of arsenic and iron. The technologies and unit processes of arsenic and iron removal are also discussed in this chapter.

Chapter 3 briefly reviews the methodologies of this research work concerning the associated unit processes with the treatment unit and the detail design of the AIRU for laboratory model test and field construction. The laboratory experimental set up and determination of variable parameters, construction and monitoring of the AIRU under different water quality conditions at the field level are also focused in this chapter.

Chapter 4 represents the detail laboratory analysis and test results that had been carried out through AIRU-Model to determine the optimum face velocity, iron-arsenic ratio for effective removal of arsenic through co-precipitation with iron, gravel sizes for down flow flocculator and for up flow pre-filter, depth of gravel beds, arsenic adsorption limit of the AIRU gravel beds etc.

Chapter 5 represents the performance study of the AIRU at the field level in respect of arsenic and iron removal efficiency, flow pattern, effects on the number of users and water consumption for different water quality conditions of the country. Performance of Read-F adsorbent column attachment with the existing AIRU is also focused in this chapter. Community participation in determining the operation and maintenance problems with the AIRU and subsequent modifications are also discussed in this chapter.

Finally, in Chapter 6 major conclusions of the study has been cited. It was attempted to determine and to set important design parameters for different water quality conditions. Recommendations for future study are also provided here.

Chapter 2

LITERATURE REVIEW

2.1 ARSENIC IN GROUND WATER

2.1.1 INTRODUCTION

Arsenic, probably the oldest known human poison, has six characteristics (Azcue & Nriagu, 1994):

- It is a virulent poison on acute ingestion, 76 mg arsenic (III) is considered to be lethal to adults.
- It is extremely toxic on long-term exposure to very low concentrations. The WHO acceptable skin cancer risk is calculated to be 0.17 μg arsenic/L. of water (WHO, 1996).
- It is not visible in water and food. Even heavy contaminated water may be clear and colourless.
- It has no taste. Even heavy contaminated water may have a pleasant taste.
- It has no smell, even at deadly concentrations.
- It is difficult to analyze, even when occurring in water in concentrations double as high as the WHO guideline.

It is probably because of these characteristics, arsenic has been used to settle down jealousy and powder conspiracy in the past. Arsenic has been called the secret poison. It is said that Napoleon Bonaparte was one among several historical dignitaries who is suspected to have been given the secret poison. Another peculiar issue of arsenic is that it is used as medicine and food additive, where it is still playing some role. Today arsenic is known as one of the several toxic industrial and geo-chemical pollutants. Numerous recent investigations have demonstrated that arsenic constitutes a serious health risk not wise in many countries. Although arsenic contents in the food may play an important role, the air borne and the water borne arsenic intoxication are now quite well documented.

2.1.2 HISTORICAL REVIEW

Arsenic is derived from the Greek word for orpiment (Forbes, 1964). In the fourth century B.C., Aristotle named arsenic sulfide as sandarach (Nriagu, 1994). The name is probably connected with the root sand or sard, meaning red. Ancient Indian cultures valued arsenic compounds during the age of Buddha. The magnitude of names for white arsenic in Sanskrit (Sankh and Sabala Kshara), Hindi (Sanbul-Khar, Sammal khar, Sankhyaia sanbul, and Sankyhia), and Bengali (Sanka or Senko) suggest general familiarity and extensive use of this compound presumably in some nefarious ways (Bagachi, 1969).

The discovery of elemental arsenic is generally credited to the German Dominican scholar and alchemist Albertus Magnus (1193-1280) (Nriagu, 1994). His description of a substance (De Rebus Metallicis) in arsenic compounds is supposedly the first reference to the metallic form of arsenic (Nriagu, 1994). According to Berthelot (1893), metallic arsenic was first mentioned in the third or fourth century by Zosimus, who referred to it as a second mercury that burns up to the "soul of the color" or white oxide. Geber (Jabir ibn Haiyan), an Arabian alchemist of the eighth century, apparently produced arsenic from its sulfides, but his product was not recognized a metal (Parr, 1958). In 1641, Schorder, in his pharmacopoeia, divulged a procedure for obtaining elemental arsenic through the reduction of arsenious oxide with charcoal (Aitchinson, 1960). Meyer postulated that arsenic was first prepared by western alchemists in the thirteenth century. Later, in 1675, Leery obtained a regales, a metallic arsenic, by heating arsine's oxide with soap and potash (Aitchinson, 1960). Brand, in 1733, carried out the first accurate experiments on the chemical nature of arsenic and showed that white arsenic was the clax or oxide of the element (Hunter, 1978).

2.1.3 OCCURRENCE OF ARSENIC

Arsenic is found in everywhere in the environment. It is found in atmosphere, biosphere, hydrosphere, pedosphere and geosphere and transferred from one to another by natural processes or human activities such as mining, agriculture, industrial processes etc. Arsenic is mainly found in the form of its mineral compounds and widely distributed in air, water, soils and in rocks and earth crust. The relative proportion of arsenic in rock, soil, water, biota and atmosphere with respect to soil is shown in the following table and it may be seen that rocks

and minerals are the main reservoirs of arsenic, which is mobilized in the other media of the environment by natural weathering processes, biological activity, volcanic eruption and anthropogenic activities.

Table 2.1: Ratios of Arsenic Concentrations in Natural Reservoir with respect to Soil
(Mackenzie et al., 1979)

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

Arsenic is associated with igneous and sedimentary rocks, particularly with sulfidic ores. Natural phenomena such as weathering, biological activity and volcanic activity, together with anthropogenic inputs are responsible for the emission of arsenic into the atmosphere, from where it is redistributed on the earth's surface by rain and dry fallout. Arsenic is also mobilized by dissolution in water, with aquatic and soil sediment concentrations being controlled by a variety of input and removal mechanisms (Cullen and Reimer, 1989). There is general agreement that most anthropogenic atmospheric input is due to smelting operations and fossil fuel combustion, but still unresolved is the extent to which man's activities contribute to the overall arsenic cycle (Edlestein, 1985). The above figure shows a comprehensive cyclic transfer of arsenic (Bhumbla and Keefer, 1994). In nature arsenic goes through the reactions of oxidation-reduction, precipitation-dissolution, adsorption-desorption and organic and biochemical methylation. All of these reactions control the mobilization and bio-accumulation of arsenic in the environment (Bhumbla and Keefer, 1994).

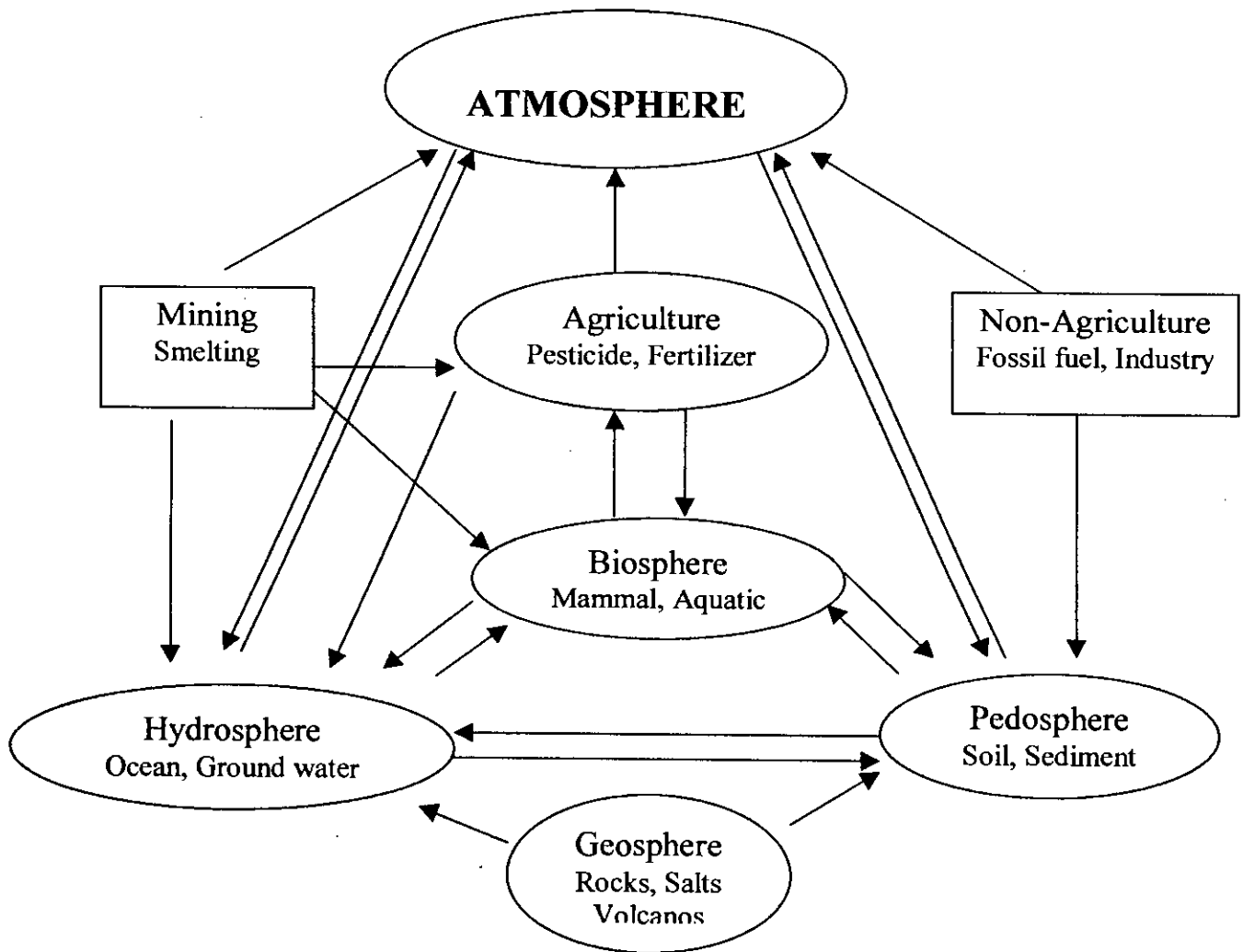


Figure 2.1: The Environmental Cycle of Arsenic (Bhumbla & Keefer, 1994)

2.1.4 GLOBAL ARSENIC PROBLEM

The arsenic pollution of groundwater has become a major global disaster. Exploitation of groundwater from arsenic contaminated aquifers has resulted in mobilizing the arsenic and led to mass poisoning in the region, which is defined by the generic term arsenicosis (Rahman et al., 2001). Presence of arsenic from natural sources in the groundwater is not unusual and has been documented in many parts of the world. The state of arsenic contamination of drinking water and its consequences in selected countries have been described shortly in this section. It has been summarized from (Ahmed, 2002), (Chowdhury, 1997), (Smith, 1997), (AAN, 1997), (Smedly and Kinniburgh, 2002) and (Giger et al., 2001).

Argentina:

- The first notification of water borne arsenicosis were reported as early as the beginning of this century.
- The term “Bell Ville Disease” was used to describe arsenic caused skin manifestations.
- Area affected: 1 million km².
- Population exposed: about 2 million.
- Levels of arsenic in the range of <1-5300 µg/L. Arsenic is mainly in the form of As(V).
- The source of contamination was found to be natural due to the soil composition polluting the shallow well waters. Also high arsenic content in some river waters.
- Oxidizing, neutral to high pH, high alkalinity groundwater condition, Holocene and volcanic ash type aquifers.

Chile:

- Arsenic is not reported to be a problem in 12 of the 13 provinces of Chile.
- The arsenic exposure is thus contained one province, Region II, extending over an area of 1,25,000 km² and inhabited by 4,00,000 people.
- The region is very arid with limited water resources, even very deep wells are not reliable sources of water for the towns of the region.
- Antofagasta, the largest city of the region is inhabited by 2/3 of the regions population.
- Its water supply utilizes three rivers. The water originates from the Andes, brought on aqueducts from upstream sites.
- In 1957 and for 12 years to come the drinking water contained arsenic 800 – 1300 µg/L.
- In 1962 the first cases of arsenicosis were reported.
- In 1970 a treatment plant was completed reducing the arsenic contents to 40 µg/L.
- It is estimated that 7% of the deaths from 1989-1993 were caused by previous exposure to arsenic.

Hungary:

- Arsenic contamination has been identifies in groundwater in alluvial sediment in the southern part of the Great Hungarian Plain.

- About 110,000 km² area consists of quaternary sediment are arsenic affected.
- Population exposed to arsenic contamination is 29,000.
- Arsenic concentration in the range <2 – 176 µg/L.

Inner Mongolia, P.R. China:

- The first case of arsenic poisoning was discovered in 1990.
- Many of the arsenic affected areas are located in the arid region (rainfall 200-300mm/yr)
- 90% of the well tested had arsenic at level higher than 50 µg/L.
- The highest concentration detected in the well water was 2400 µg/L.
- The arsenic contamination is combined with too high concentrations of fluoride.
- 35% of the 612 checked inhabitants were found arsenic lesions in a survey.
- More serious effects were detected including high cancer mortality.
- Arsenicosis seemed to cause much suffering and to affect the inhabitants of the region.

Mexico:

- The Lagunera region of northern Mexico have been reported to have arsenic problems.
- The area affected is 32,000 km².
- A population of 1,27,000 inhabitants have been drinking water containing 100-500 µg/L arsenic. Arsenic is mainly As(V).
- Volcanic sediment type aquifer having oxidizing, neutral to high pH groundwater condition.

Nepal:

- Arsenic contaminated tubewell have been identified in 20 Terai districts.
- Estimated population exposed to arsenic exceeding 50 µg/L is 5,50,000 (2.4% of the total population).
- Estimated population exposed to arsenic exceeding 10 µg/L is 3.19 million (13.6%).

Taiwan:

- The arsenic problem in Taiwan was reported since 1968, now best known and most studied case of arsenic contamination.
- It is Taiwan that gave arsenicosis the name "Black Foot Diseases".
- Survey of over 83,000 wells showed that 19% of the tube wells had arsenic over 50 µg/L.
- 1,00,000 inhabitants were exposed to well water containing arsenic 10-1820 µg/L, on an average about 500 µg/L for over 40 years.
- Studies in Taiwan provided data to develop dose-response relationships for skin, bladder and lung cancers.
- The contaminated aquifer is sediment type with shale.
- Black Foot Disease is shown to indicate an increased risk for bladder and lung cancer.

Thailand:

- In 1996 arsenic is reported to occur in some shallow as well as deep tubewells in southern Thailand.
- Area affected is 100 km².
- The concentrations found are between 1 and 500 µg/L.
- Oxidation of arsenopyrite from former tin mining. Aquifer type includes dredged quaternary alluvium and mine tailings.

USA:

- USA is probably the only (mildly) arsenic affected country which has carried out a nation wide survey of arsenic occurrence in drinking water.
- About 3,47,000 people had received public supplied water containing arsenic more than 50 µg/L.
- About 2.5 million people had received public supplied water containing arsenic more than 10 µg/L.
- Small water supplies serving 1,000 to 10,000 persons contaminated with arsenic exceeding 50 µg/L, 10 µg/L and 5 µg/L are estimated to be 1%, 7.5% and 13% respectively.

- Arsenic contaminated area in USA include about 2,00,000 km² in Arizona (arsenic up to 1300 µg/L), 5000 km² in California (arsenic in the range of 1-2600 µg/L) and 1300 km² in Nevada (arsenic up to 2600 µg/L).
- Studies from 1972 to 1982 showed correlation with specific skin alterations and neurological abnormalities.

Vietnam:

- Arsenic contamination of tubewells water have been found in the large deltas of the Mekong and Red rivers.
- In most affected districts, groundwater with average arsenic concentration of 430 µg/L and maximum arsenic concentration of 3000 µg/L is directly used as drinking water.
- Alarming levels of arsenic in the range of 2000 to 3000 µg/L in groundwater were found on both sides of the Red river.
- Arsenic concentration in water supply in Hanoi city is within the range of 25-91 µg/L after treatment and 7-82 µg/L at the tap water.
- Arsenic contamination is due to noxic condition of the aquifer.

West Bengal , India:

- The arsenic pollution is of geological origin and widespread in Holocene alluvium/deltaic sediment.
- The arsenic is mainly found in the groundwater pumped from intermediate depth. As a common rule, neither shallow nor deep aquifer show above permissible limit arsenic contents.
- High arsenic groundwater is characterized by high iron, calcium, magnesium and bicarbonate and by low chloride, sulfate and fluoride.
- About 3115 habitations, 15 non-municipal areas and 9 municipalities in 8 districts are found affected.
- The affected area is 23,000 km².
- About 5.31 million people are exposed to high arsenic content in drinking water.
- Estimated 3,00,000 people are suffering from various stages of arsenicosis.

Arsenic Problem in Bangladesh (Ahmed, 2002):

- Arsenic contaminated tubewell was first detected in 1993 at Chapai Nawabgonj district.
- An estimated 29 million people are exposed to arsenic from tubewell water exceeding 50 $\mu\text{g/L}$, 49 million people to more than 10 $\mu\text{g/L}$.
- Arsenic content in tubewell water ranges between $<0.5 - 2500 \mu\text{g/L}$.
- Tubewell water in 211 Thanas out of 490 has been found to be contaminated with arsenic exceeding 50 $\mu\text{g/L}$.
- Complete screening of total population in 61 Thanas has identified about 13,000 cases of skin lesion.
- Probably the genotoxic effects of arsenic in Bangladesh will show up later as experienced in other parts of the world.

2.1.5 USES OF ARSENIC

Until the nineteenth century, arsenic (As_2O_3) was the preferred poison of most homicidal practitioners, to the point where laws were passed against possession of it. Despite this, Flower's solution (1% potassium arsenate, discovered in 1786) became the most widely used medication for a variety of illness for 150 years. Donovan's solution (arsenic iodide) and deValagin's solution (arsenic trichloride) were also recommended to treat rheumatism, arthritis, asthma, malaria, trypanosome infections, tuberculosis and diabetes (Leonard, 1991). Several poisoning cases have been reported from the historical use of arsenical pigments for coloring artificial flowers, toys, wallpaper and wrapping papers (Nriagu, 1994). A vast literature exists regarding the hypothesis that arsenic poisoning was the cause of Napoleon's death due to its presence in green pigments of the wallpaper (Jones, 1982; Richardson, 1974). White arsenic sublimes on heating and it has been claimed that candles with poisoned wicks were used to poison Leopold I of Austria in 1970 (Nriagu, 1994). In fact, death lamps in which oil and wax impregnated with arsenic and other substances are burned have been used to poison victims slowly (Gimlette and Desmond, 1981). From the 1860s until the introduction of DDT and other organic pesticides in the 1940s, inorganic compounds of arsenic remained the dominant insecticides available to farmers and fruit growers (Nriagu

and Azcue, 1990). The major use of arsenic, about 75% of the total consumption, still is in the agricultural field in the form of monosodium methylarsonate (MSMA), di-sodium methylarsonate (DSMA), dimethyl arsenic acid (Cacodylic acid) and arsenic acid (Nriagu and Azcue, 1994). Arsenic acid is used in the formation of wood preservative salts and sodium arsenate solutions are used for debarking trees, in cattle and sheep dips and in aquatic weed control. Minor addition of arsenic (0.02-0.5%) to copper and copper alloys raise the recrystallization temperature and improve corrosion resistance (Carapella, 1978). Main modern uses of arsenic are shown in the following table:

Table 2.2: Principal Modern Uses of Arsenic Compounds

| Sector | Uses |
|-------------|--|
| Agriculture | Pesticides, Insecticides, Defoliants, Wood preservatives, Debarking trees, Soil steriliant. |
| Livestock | Feed additives, Disease prevention (Swine dysentery, Heartworm infection), Cattle and sheep dips, Algaecides. |
| Medicine | Antisyphylitic, Drugs, Treatment of trypanosomiasis, Amebiasis, Sleeping sickness. |
| Electronics | Solar cells, Optoelectronic devices, Semiconductor applications, Light-emitting diodes (digital watches). |
| Industry | Glassware, Electro photography, Catalysts, Pyrotechnics, Antifouling paints, Dyes and soaps, Ceramics, Pharmaceutical substance. |
| Metallurgy | Alloys (automotive body solder and radiators), Battery plates (hardening). |

2.1.6 SOURCES OF ARSENIC

Natural Sources:

Arsenic bearing minerals are the primary natural sources of arsenic. There are more than 245 such minerals, mostly ores containing sulfide, along with copper, nickel, lead, cobalt and other metals as well as some oxides. The following table provides a list of some important arsenic bearing minerals:

Table 2.3: Naturally Occurring Minerals Containing Arsenic (NRCC, 1978)

| Mineral | Formula | Mineral | Formula |
|-------------------|---|------------------|--|
| Arsenite | As | Pearcite | Ag ₁₆ As ₂ S ₁₂ |
| Antimony arsenide | AsSb | Proustite | Ag ₂ AsS ₃ |
| Realger | AsS | Energite | Cu ₃ AsS ₄ |
| Orpiment | As ₂ S ₃ | Rathite | Pb ₃ As ₅ S ₁₀ |
| Arsenopyrite | FeAsS | Arsenolite | As ₂ O ₃ |
| Nicolite | NiAsS | Mutite | Pb ₅ (PO ₄ ,AsO ₄) ₃ Cl |
| Gersdorffite | CoAsS | Adamite | Zn ₂ AsO ₄ (OH) |
| Cobaltite | CoAsS | Erythrite | Co ₃ AsO ₄ .8H ₂ O |
| Smaltite | (Co,Ni)As _x | Annabergite | N ₁₃ (AsO ₄) ₂ .8H ₂ O |
| Skutteridite | (Co,Ni)As _x | Scorodite | (Fe,Al)AsO ₄ .2H ₂ O |
| Loellingite | FeAs ₂ | Pharmacosiderite | Fe ₃ (AsO ₄) ₂ OH ₃ |
| Tennantite | Cu ₁₂ As ₄ S ₁₃ | Olivenite | Cu ₂ (AsO ₄)OH |
| Jordanite | (Pb,Ti) ₁₃ As ₇ S ₂₃ | Beaudanite | PbFe ₃ (AsO ₄)SO ₄ |

The most important ores of arsenic are Arsenopyrite or Mispickel (FeAsS), Realgar (As₄S₄), Orpiment (As₂S₃), Loellingite (FeAs₂), Nicolite (NiAs), Cobalt-glance (CoAsS), Nickel-glance (NiAsS), Smaltite (CoAs₂) and Arsenolite (As₂O₃). Among these, Arsenopyrite is probably the most common mineral. Weathering of rock converts arsenic rich metal sulfides to arsenic trioxide, which eventually finds its way into surface water, ground water and sediments. Arsenic is often found to be associated with iron oxyhydroxides in sediments because of its affinity for iron oxyhydroxides. The oxidized forms of arsenic may be converted back to sulfides by anaerobic processes occurring on land and in sediments. Volatile forms of arsenic, e.g., arsine (AsH₃) and trimethyl arsine [(CH₃)₃As] enter the atmosphere from land and water and are returned by rain and atmospheric fallout. Arsenic occurs in uncontaminated soil at an average concentration of about 5 to 6 mg/kg, but this varies among geographic regions.

Anthropogenic Sources:

Recent estimates have placed the ratio of natural to anthropogenic inputs of arsenic at 60:40. The global production rates of arsenic compounds determined in recent surveys are shown in the following table:

Table 2.4: Production Rates of the Main Arsenical Compounds (Alloway, 1990)

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

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

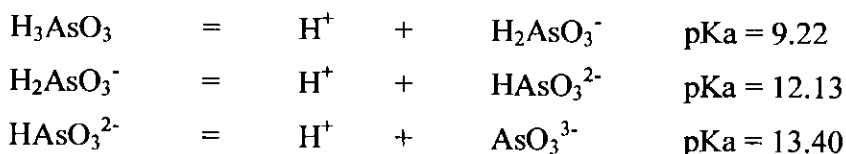
2.1.7 CHEMISTRY OF ARSENIC

a) Acid-Base Chemistry:

Apart from elementary arsenic with oxidation state of 0, arsenic is stable in the oxidation states of +5, +3 and -3, but generally found in water only in the trivalent and pentavalent states. The oxidation state is closely related to the arsenic immobilization and hence the release of arsenic from its geological formations into the water bodies and biosphere. Both the oxidation state and the release are determined by the soil and water pH, the redox potential, the in excess occurrence of sulfide, the occurrence of other ions as well as solids of especially iron and manganese (Dahi, 1997). The oxides of both As(III) and As(V) are

soluble in water. The dissolution implies direct reaction with the water, hydration, where the oxides behave like non-metals and exhibit acidic character. As(III) forms arsenious acid and As(V) forms the arsenic acid. The two acids dissociate to form respectively arsenite and arsenate ions as shown in the following reactions with their equilibrium constants (Cherry et al., 1979):

Dissociation of Arsenious Acid:



Dissociation of Arsenic Acid:

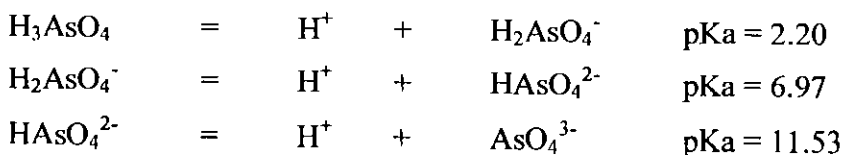


Table 2.5: Arsenic Species and their Environmental Importance (Kartinen & Martin, 1995)

| Sl. | Compounds | Example | Env. Significance / Dominant pH region |
|-----|--|--|---|
| 1 | Trivalent Arsenic Oxidation State: +3 | As (III) | Dominant under Anaerobic Condition 10 Times more Toxic than As (V) |
| | (Arsenite, Inorganic) | H ₃ AsO ₃ H ₂ AsO ₃ ⁻ HAsO ₃ ²⁻ AsO ₃ ³⁻ | pH = 0-9 pH = 10-12 pH = 13 pH = 14 |
| 2 | Pentavalent Arsenic Oxidation State: +5 | As (V) | Dominant under Aerobic Condition 10 Times less Toxic than As (III) |
| | (Arsenate, Inorganic) | H ₃ AsO ₄ H ₂ AsO ₄ ⁻ HAsO ₄ ²⁻ AsO ₄ ³⁻ | pH = 0-2 pH = 3-6 pH = 7-11 pH = 12-14 |

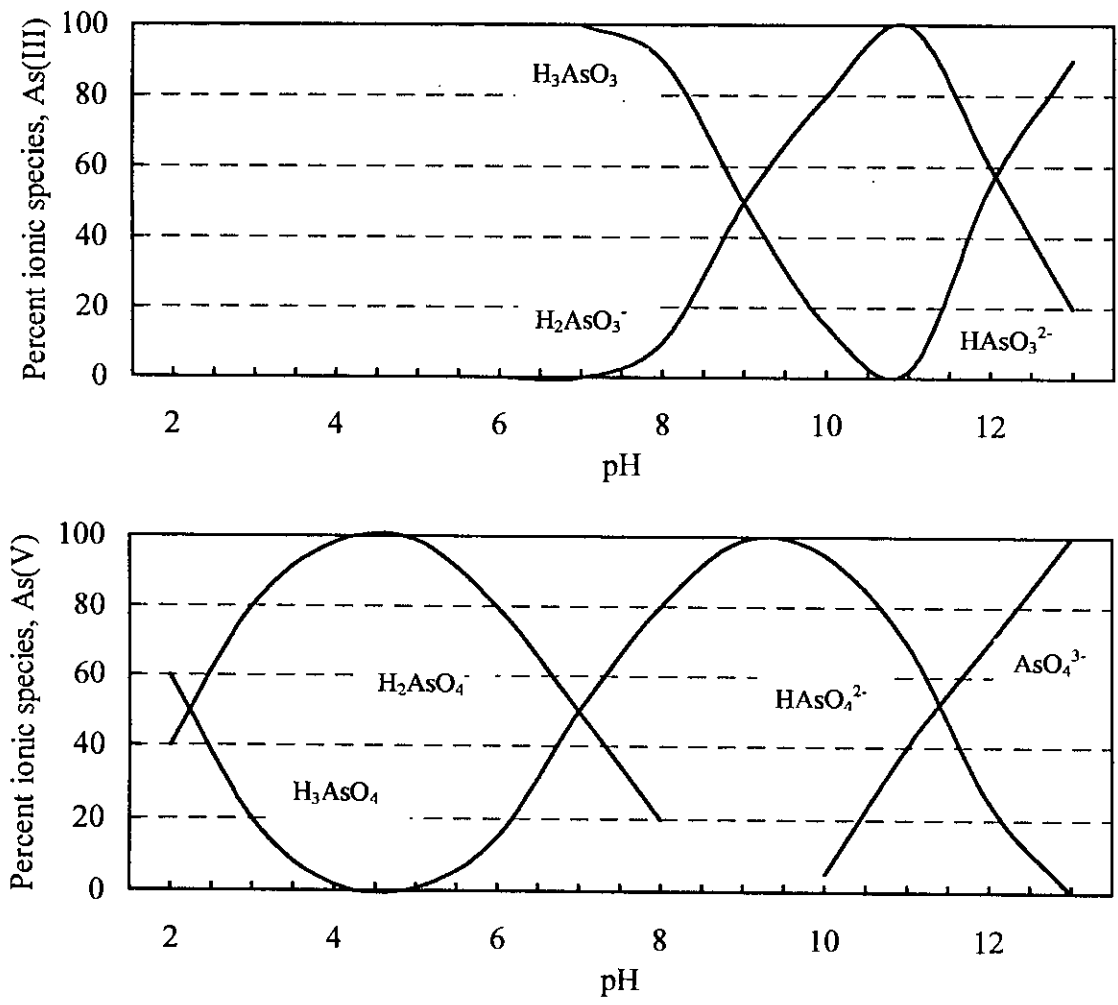


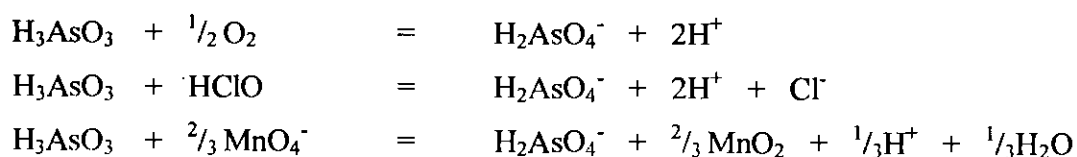
Figure 2.2: Predominance Diagram of As(III) and As(V) as a Function of pH
(Gupta and Chen, 1978; Montgomery, 1985)

Within the range of natural waters (particularly groundwater), where pH is usually between 6 and 9, the trivalent inorganic arsenic is found as non-dissociated arseneous acid (H_3AsO_3); While the pentavalent arsenic is primarily found as the ionized forms ($H_2AsO_4^-$, $HAsO_4^{2-}$). As most treatment process are more capable to remove ions, the trivalent arsenic is more difficult to remove from the water than the pentavalent (Kartinen and Martin, 1995).

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

Chlorine is widely used for oxidation purpose, but may lead to chlorinated by-products, namely trihalomethenes (THMs), from reactions with natural organic matter. Ozone, widely

used in surface water treatment for oxidation and disinfection, is quite effective but is not feasible for a specific application with As(III) oxidation. Permanganate oxidizes As(III), ferrous and manganese ions specially and quickly. Chlorine and permanganate are able to oxidize arsenic (III) to (V) within a very short time, e.g., half an hour or even few minutes (Dahi, 1997).

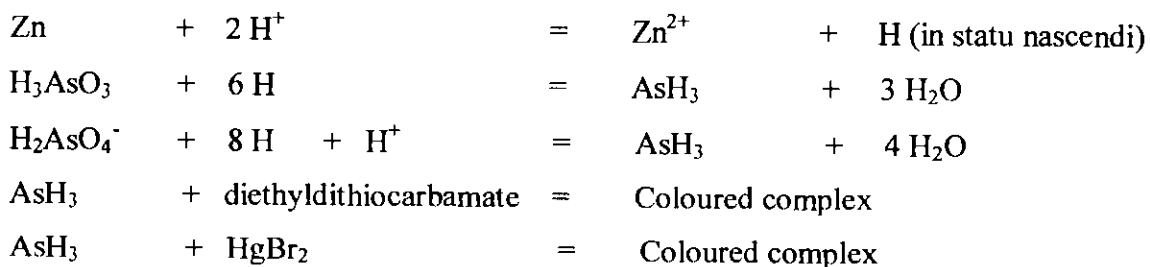


Air oxidation of arsenic is very slow and can take weeks for oxidation (Pierce and Moore, 1982) but chemicals like chlorine and permanganate can widely oxidize arsenite to arsenate under wide range of conditions.

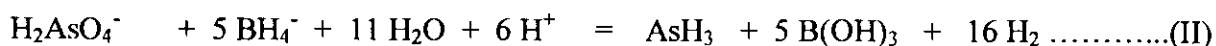
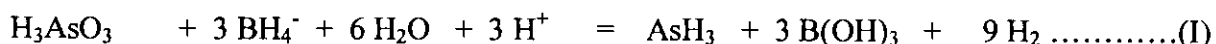
Analysis Reactions of Arsenic:

Determination of arsenic by the "hydride generation" methods involve reduction of arsenic, present in water either as As(III) or As(V), into arsenic hydride or arsine (AsH_3). Arsine is insoluble in water making it easy to purge arsenic from the water phase. It is quantitatively captured by organic solvents (e.g., silver diethyldithiocarbamate, mercuric bromide), forming coloured complexes. These two properties of arsenic make it unique in the arsenic analytical chemistry and enables its detection in small quantities by the so-called Marsh's test.

In acidic solutions, arsine generation can be carried out by metallic Zinc according to the following reactions:



Alternatively, as suggested in the latest Standard Methods (AWWA, 2000), the arsine development can be carried out using sodium borohydride, according to the following reactions:



Reaction (I) can be preformed at pH=6, whereas reaction (II) demands strong acidification. This very important detail allows for quantitative differentiation between arsenate and arsenite. It should be noted that the methylated arsenic compounds do not take part in this arsenic generation. They therefore escape the standard analytical procedures based on arsenic generation. Sulfide may interfere in coloration of the reagents. It is therefore scrubbed off by gas flow through lead acetate.

Adsorption – Desorption Theory :

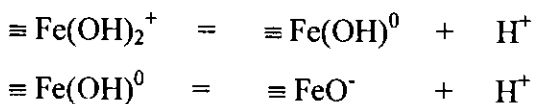
Adsorption – desorption reactions are very important in determining the mobility of arsenic in nature as well as its removal in many treatment systems. Attachment of arsenic to an iron oxide surface is an example of an adsorption reaction. The reverse of this reaction, arsenic becoming detached from such a surface is an example of desorption. Both arsenate and arsenite adsorb to surfaces of a wide range of solids including iron, aluminium and manganese oxides (e.g., iron oxyhydroxides), and clay minerals.

Unlike many heavy metals (eg, lead, zinc, cadmium) which exist in water primarily as cations, arsenic exists primarily as oxyanions (e.g., HAsO_4^{2-} , H_2AsO_4^-) and adsorb on hydrous oxide surfaces as anions. Besides arsenic, a number of other ions present in natural water (e.g., phosphate, silicate, sulfate) also have strong affinity for solid surfaces and presence of high concentrations of these ions can reduce removal efficiency of arsenic in adsorption-based treatment system.

Adsorption – desorption of arsenic onto iron oxide surface are important controlling reactions in the subsurface because iron oxides are widespread in the hydro-geologic environment as

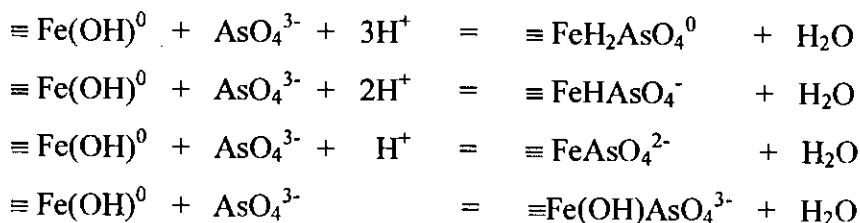
coating on other solids and because arsenate adsorbs strongly to iron oxide surfaces in acidic and near – neutral pH conditions. Desorption of arsenite is favored at higher (i.e., alkaline) pH values. The pH dependence of arsenate adsorption-desorption appears to be related to the change in net charge on iron-oxide surface with pH. The net charge on iron oxide surface changes from positive to negative as pH increases above the “zero-point-of-charge” (pH at which net surface charge is zero). The “zero-point-of-charge” is about 7.7 for goethite (crystalline iron oxide) and about 8.0 for ferrihydrite (amorphous iron oxide). Thus as pH increases above about 8, the net negative surface charge on iron oxides can repel the negatively charged ions such as arsenate. Compared to arsenate, arsenite is less strongly adsorbed by iron oxides.

According to the two-layer model (Dzombak and Morel, 1990), surface ionization reactions resulting in development of surface charge on iron oxide surfaces can be described by:



The adsorption-desorption reactions of arsenate and arsenite on hydrous ferric oxide modeled using the generalized two-layer model are shown by the following reactions.

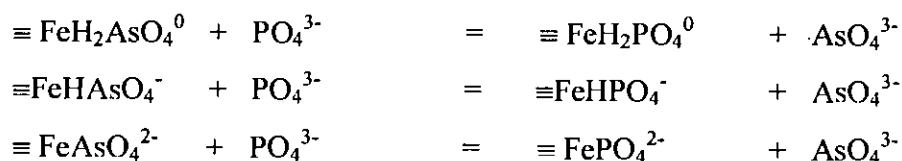
Arsenate Adsorption:



Arsenite Adsorption:

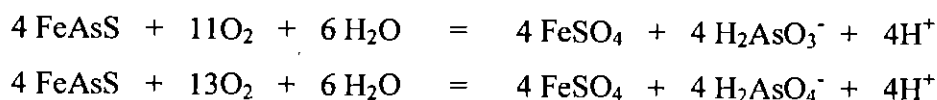


Possible desorption of arsenate in the presence of phosphate ions are shown by the following reactions:



Precipitation and dissolution:

Precipitation – dissolution reaction are important mechanisms controlling mobility of arsenic in the subsurface. As an example, because arsenic often coprecipitates with iron oxide, iron oxide may act as an arsenic source (case of dissolution) or a sink (case of precipitation) for ground water (USGS, 1999). In Bangladesh, reductive dissolution of iron oxyhydroxides and consequent release of adsorbed arsenic could be an important mechanism of arsenic mobilization in the subsurface. Oxidative dissolution reactions (Bhumbla and Keefer, 1994) of arsenopyrite (FeAsS) is shown as follows:



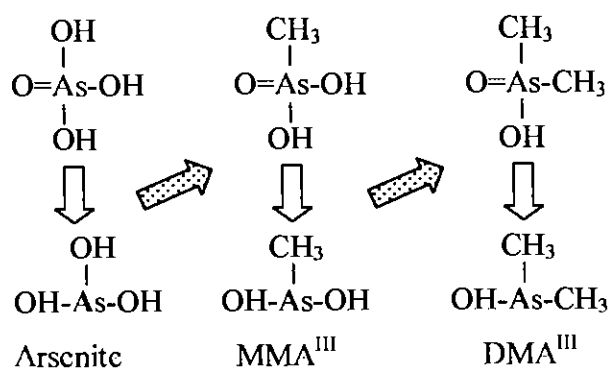
Methylation Reactions:

Arsenic taken by mammals is subject to either direct excretion, direct accumulation in some parts of the body (e.g., nails, hair and skin tissue), or to bio-transformation of arsenic contaminated soils. Humans are exposed to arsenic mostly in the forms of arsenate/arsenite and organic arsenosugars/arsenobetaines and marine products. The inorganic forms are more toxic than organic forms. Methylation seems to be the most important pathway of bio-transformation of inorganic arsenic. The inorganic forms are metabolized by consecutive reduction and methylation reactions in humans and mammals to dimethylated arsenic (DMA), which is excreted into urine (Suzuki, 2002). The toxicity of arsenite is highly dependent on animal species, which in turn depends on the differences in the metabolism shown in the following figure. The methylation process leading to DMA was believed to be the detoxification pathway, but recent studies document it as toxification pathway (Suzuki, 2002). Research works are being carried out to better understand these processes.

Arsenate

MMA^V

DMA^V



MMA^V: mono-methyl arsonic acid

MMA^{III}: mono-methyl arsonous acid

DMA^V: di-methyl arsinic acid

DMA^{III}: di-methyl arsenous acid

← reduction

← methylation

Fig. 2.4: Reduction and Methylation Reactions in the Metabolism of Arsenic (Suzuki, 2002)

2.1.8 TECHNOLOGIES USED FOR ARSENIC REMOVAL IN BANGLADESH

General:

In the context of prevalence of high concentrations of arsenic in tubewell water, wide ranges of technologies have been tried for the removal of arsenic from drinking water. The most common technologies utilized the conventional processes of oxidation, co-precipitation and adsorption onto coagulated flocs, adsorption onto sorptive media, ion exchange and membrane techniques for arsenic removal. The conventional technologies have been scaled down to meet the requirements of households and communities and suit the rural environment. Some technologies utilized indigenous materials for arsenic removal. This article presents a short review of the processes and removal units used for arsenic removal in Bangladesh.

2.1.8 (I) Unit Processes of Arsenic Removal

(a) Oxidation, Co-Precipitation and Adsorption:

Arsenic is present in groundwater in As(III) and As(V) forms in different proportions. Most treatment methods are effective in removing arsenic in pentavalent form and hence include

an oxidation step as pretreatment to convert arsenite to arsenate. Atmospheric oxygen, hypochloride and permanganate are commonly used for oxidation in developing countries. Water treatment with coagulants such as alum, $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$, ferric chloride, FeCl_3 and ferric sulfate $\text{Fe}_2(\text{SO}_4)_3 \cdot 7\text{H}_2\text{O}$ are effective in removing arsenic from water. Ferric salts have been found to be more effective in removing arsenic than alum on a weight basis and effective over a wider range of pH. In both cases pentavalent arsenic can be more effectively removed than trivalent arsenic.

Arsenic adsorbed on aluminum hydroxide flocs as Al-As and on ferric hydroxide flocs as Fe-As complexes are removed by sedimentation. Filtration may be required to ensure complete removal of all flocs.

This process is effective in removing arsenic but associates with high operation costs of chemicals as well as frequent maintenance due to clogging of filter bed.

(b) Passive Sedimentation:

Passive sedimentation received considerable attention because of rural people's habit of drinking stored water from pitchers. Oxidation of water during collection and subsequent storage in houses may cause a reduction in arsenic concentration in stored water (Bashi Pani). Experiments conducted in Bangladesh showed zero to high reduction in arsenic content by passive sedimentation. Arsenic reduction by plain sedimentation appears to be dependent on water quality particularly the presence of precipitating iron in water. Ahmed et al., (2000) showed that more than 50% reduction in arsenic content is possible by sedimentation of tubewell water containing 380-480 mg/L of alkalinity as CaCO_3 and 8-12 mg/L of iron but cannot be relied to reduce arsenic to desired level. Most studies showed a reduction of 0 to 25% of the initial concentration of arsenic in groundwater. In rapid assessment of technologies, passive sedimentation failed to reduce arsenic to the desired level of 50 $\mu\text{g/L}$ in any well (BAMWSP, DFID, Water Aid, 2001).

(c) In-situ Oxidation:

In-situ oxidation of arsenic and iron in the aquifer has been tried under DPHE-Danida Arsenic Mitigation Pilot Project. The aerated tubewell water is stored in a tank and released back into the aquifers through the tubewell by opening a valve in a pipe connecting the water tank to the tubewell pipe under the pump head. The dissolved oxygen in water oxidizes arsenite to less mobile arsenate and also the ferrous iron in the aquifer to ferric iron, resulting a reduction in arsenic content in tubewell water. Experimental results show that arsenic in the tubewell water following in-situ oxidation is reduced to about half due to underground precipitation and adsorption on ferric iron (Ahmed, 2001).

(d) Solar Oxidation:

SORAS is a simple method of solar oxidation of arsenic in transparent bottles to reduce arsenic content of drinking water (Wegelin et al., 2000). Ultraviolet radiation can catalyze the process of oxidation of arsenite in presence of other oxidants like oxygen (Young, 1996). Experiments in Bangladesh show that the process on average can reduce arsenic content of water to about one-third (Ahmed, 2001).

(e) Naturally Occurring Iron:

The use of naturally occurring iron precipitates in ground water in Bangladesh is a promising method of removing arsenic by adsorption. The iron precipitates $[\text{Fe}(\text{OH})_3]$ formed by oxidation of dissolved iron $[\text{Fe}(\text{OH})_2]$ present in groundwater, have the affinity for the adsorption of arsenic. Only aeration and sedimentation of tubewell water rich in dissolved iron has been found to remove arsenic. The iron removal plants (IRP) in Bangladesh constructed on the principles of aeration, sedimentation and filtration have been found to remove arsenic without any added chemicals. The conventional community type IRP, depending on the above operating principles, more or less work as arsenic removal plants (ARP) as well. Results show that most IRPs can lower arsenic content of tubewell water to half to one-fifth of the original concentrations (Ahmed, 2001). Increasing the contact time between arsenic species and iron flocs can increase the efficiency of these community types Fe-As removal plants. Community participation in operation and maintenance in the local level is absolutely essential for effective use of these plants.

Some medium scale Fe-As removal plants of capacities 2000-3000 m³/d have been constructed for water supplies in district towns based on the same principle. The treatment processes in these plants include aeration, sedimentation and rapid sand filtration with provision for addition of chemical, if required. These plants are working well except that treated water requirement for washing the filter beds is very high. Operations of small and medium size IRP-cum-ARPs in Bangladesh suggest that arsenic removal by co-precipitation and adsorption on natural iron flocs has good potential.

(f) Sorptive Filtration Media:

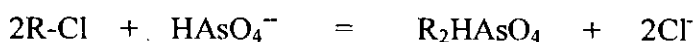
Several sorptive media have been reported to remove arsenic from water. These are activated alumina, activated carbon, iron and manganese coated sand, kaolinite clay, hydrated ferric oxide, activated bauxite, titanium oxide, silicium oxide and many natural and synthetic media. The efficiency of sorptive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

Activated alumina (Al₂O₃) having good sorptive surface is an effective medium for arsenic removal. When water passes through a packed column of activated alumina, the impurities including arsenic present in water are absorbed on the surfaces of activated alumina grains. Eventually the column becomes saturated, first at its upstream zone and later the saturated zone moves downstream towards the bottom end and finally the column get totally saturated. Regeneration of saturated alumina is carried out by exposing the medium to 4% caustic soda (NaOH), either in batch or by flow through the column resulting in a high arsenic contaminated caustic waste water. The residual caustic soda is then washed out and the medium is neutralized with a 2% solution of sulfuric acid rinse. During the process about 5-10% alumina is lost and the capacity of the regenerated medium is reduced by 30-40% (Ahmed, 2001). The activated alumina needs replacement after 3-4 regeneration. Like coagulation process, pre-chlorination improves the column capacity dramatically.

(g) Ion Exchange:

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

Arsenic exchange



Regeneration



Where, R stands for ion exchange resin.

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

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

(h) Membrane Techniques:

Membrane techniques like reverse osmosis, nanofiltration and electrodialysis are capable of removing all kinds of dissolved solids including arsenic from water (Ahmed, 2001). In this process water is allowed to pass through special filter media which physically retain the impurities present in water. The water, for treatment by membrane techniques, shall be free from suspended solids and the arsenic in water shall be in pentavalent form. Most membranes, however, cannot withstand oxidizing agent.

2.1.8 (II) Arsenic Removal Units

(a) Bucket Treatment Unit:

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

The DPHE-Danida Project in Bangladesh distributed several thousands BTU units in rural areas. These units are based on chemical dosages of 200 mg/L aluminum sulfate and 2 mg/L of potassium permanganate supplied in crushed powder form. The units were reported to have very good performance in arsenic removal in both field and laboratory conditions (Sarkar et al., 2000). Extensive study of DPHE-Danida BTU under BAMWSP, DFID, Water Aid (2001) rapid assessment program showed mixed results. In many cases, the units under rural operating conditions fails to remove arsenic to the desired level of 0.05 mg/L in Bangladesh (Ahmed, 2001). Poor mixing and variable water quality particularly pH, phosphate, nitrate, sulfate and chloride of groundwater in different locations of Bangladesh appeared to be the cause of poor performance in rapid assessment.

Bangladesh University of Engineering and Technology (BUET) modified the BTU and obtained better results by using 100 mg/L of ferric chloride and 1.4 mg/L of potassium permanganate in modified BTU units. The arsenic contents of treated water were mostly below 20 ppb and never exceeded 37 ppb while arsenic concentrations of tubewell water varied between 375 to 640 ppb (Ahmed, 2001). The BTU is a promising technology for arsenic removal at household level at low cost. It can be built by locally available materials and is effective in removing arsenic if operated properly.

(b) Stevens Institute Technology:

This technology also uses two buckets, one to mix chemicals (reported to be iron sulfate and calcium hypochloride) supplied in packets and the other to separate floc by the processes of sedimentation and filtration. The second bucket has a second inner bucket with slits on the sides to help sedimentation and keeping the filter sand bed in place. The chemicals form visible large flocs on mixing by stirring with stick. Rapid assessment showed that the technology was effective in reducing arsenic levels to less than 0.05 mg/L in case of 80 to 95% of the samples tested (BAMWSP, DFID, Water Aid, 2001). The sand bed used for filtration is quickly clogged by flocs and requires washing at least twice a week.

(c) BCSIR Filter Unit:

Bangladesh Council of Scientific and Industrial Research (BCSIR) has developed an arsenic removal system, which uses the process of coagulation, co-precipitation with an iron based chemical followed by sand filtration. The unit did not take part in a comprehensive evaluation process (Ahmed, 2001).

(d) Fill and Draw Units:

It is a community type treatment unit designed and installed under DPHE-Danida Arsenic Mitigation Pilot Project. It is 600 L capacity (effective) tank with slightly tapered bottom for collection and withdraw of settled sludge. The tank is fitted with a manually operated mixer with flat-blade impellers. The tank is filled with arsenic contaminated water and required quantity of oxidant and coagulants are added to the water. The water is then mixed for 30 seconds by rotating the mixing device at the rate of 60 rpm and left overnight for

sedimentation. The water takes some times to become completely still which helps flocculation. The floc formation is caused by the hydraulic gradient of the rotating water in the tank. The settled water is then drawn through a pipe fitted at a level, few inches above the bottom of the tank and passed through a sand bed and finally collected through a tap for drinking purpose. The mixing and flocculation processes in this unit are better controlled to effectively higher removal of arsenic (Ahmed, 2001). The experimental units installed by DPHE-Danida Project are serving the clusters of families and educational institutions.

(e) Arsenic Removal Unit Attached to Tubewell:

The principles of arsenic removal by alum coagulation, sedimentation and filtration have been employed in a compact unit for water treatment in the village level in West Bengal, India. The arsenic removal plant attached to hand tubewell has been found effective in removing 90% arsenic from tubewell water having initial arsenic concentration of 300 $\mu\text{g/L}$ (Ahmed, 2001). The treatment process involves addition of sodium hypochloride (Cl_2), and aluminum alum in diluted form, mixing, flocculation, sedimentation and up flow filtration in a compact unit. This process was found effective in removing arsenic but associated with high operation costs of chemicals as well as frequent maintenance due to clogging of filter bed.

(f) Chemical Packages:

In Bangladesh different types of chemical packages have been distributed in the forms of tea bags, small packets and powder of tablet form for the removal of arsenic from drinking water. The principals involved in arsenic removal by these chemicals involve oxidation, sorption and co-precipitation. Application methodology and efficiency of any of these chemicals have not been fully optimized by long experimentation. Quality assurance and dosage control in rural condition are extremely difficult. The residuals of added chemicals in water after treatment can do equal harm. The use of unknown chemicals and patented process without adequate information should be totally discouraged (Ahmed, 2001).

(g) Activated Alumina Based Units:

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

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

(h) Granular Ferric Hydroxide:

M/S Pal Trockner (P) Ltd., India and Sidko Ltd., Bangladesh installed several Granular Ferric Hydroxide based arsenic removal units in India and Bangladesh. The Granular Ferric Hydroxide (Adsorb As®) is arsenic selective adsorbent developed by Technical University, Berlin, Germany. The unit requires iron removal as pretreatment to avoid clogging to filter bed. The proponents of the unit claim to have very high arsenic removal capacity and produces non-toxic spent granular ferric hydroxide (Ahmed, 2001).

(i) Read-F Arsenic Removal Unit:

Read-F is an adsorbent produced and promoted by Shin Nihon Salt Co. Ltd., Japan for arsenic removal in Bangladesh. Read-F displays high selectivity for arsenic ions under a broad range of conditions and effectively adsorbs both arsenite and arsenate without the need for pretreatment. The Read-F is Ethylene-vinyl alcohol copolymer (EVOH)-borne

hydrous cerium oxide in which hydrous cerium oxide ($\text{CeO}_2 \cdot n\text{H}_2\text{O}$), is the adsorbent. The material contains no organic solvent or other volatile substance and is not classified as hazardous material. Laboratory test at BUET and field testing of the materials at 4 sites under the supervision of BAMWSP showed that the adsorbent is highly efficient in removing arsenic from groundwater (SNSCL, 2000).

(j) Iron Coated Sand:

BUET has constructed and tested iron coated sand based small-scale unit for the removal of arsenic from ground water. Iron coated sand has been prepared following a procedure similar to that adopted by Joshi and Choudhury (1996). The iron content of the iron coated sand was found to be 25 mg/g of sand. For raw water having both As(III) and As(V) of concentration $300\mu\text{g/L}$ when filtered through iron coated sand, it was found that 350 bed volume (BV) could be treated satisfying the Bangladesh drinking water standard of 50 ppb (Ali, 2001). The saturated medium is regenerated by passing 0.2N sodium hydroxide followed by washing with distilled water. No significant change in bed volume (BV) in arsenic removal was found after 5 regeneration cycles. It was interesting to note that iron coated sand is equally effective in removing both As(III) and As(V). Iron coated brick dust has also been developed in Bangladesh for arsenic removal from drinking water.

(k) Indigenous Filters:

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

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

The Sono 3-Kolshi Filter uses zero valent iron fillings and coarse sand in the top Kolshi, wood coke and fine sand in the middle Kolshi while the bottom Kolshi is the collector of the filtered water (Khan et al., 2000). This unit has been found to be very effective in removing arsenic but the media was found contaminated with the growth of microorganism (BAMWSP, DFID and Water Aid, 2000). The one-time use unit becomes quickly clogged, if groundwater contains excessive iron.

The Garnet homemade filter contains relatively inert materials like brick chips and sand as filtering media. No chemical is added to the system. Air oxidation and adsorption on iron-rich brick chips and flocs of naturally present iron in groundwater could be the reason for arsenic removal from groundwater. The unit produced inadequate quantity of water and did not show reliable results in different areas of Bangladesh and under different operating conditions (Ahmed, 2001). The Chari filter also uses brick chips and inert aggregates in different Charis as filter media. The effectiveness of this media in arsenic removal is not known (Ahmed, 2001).

The Shafi and Adarsha filters use clay material as filter media in the form of candle. The Shafi filter was reported to have good arsenic removal capacity but suffered from clogging of filter media (Ahmed, 2001). The Adarsha filter participated in the rapid assessment program but failed to meet the technical criterion of reducing arsenic to acceptable level (BAMWSP, DFID and Water Aid, 2000). Bijoypur clay and treated cellulose were found to absorb arsenic from water (Khair, 2000).

(1) Cartridge Filters:

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

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

The Chiyoda Arsenic Removal Unit could treat 800 BV meeting the WHO guideline value of 10 µg/L and 1300 BV meeting the Bangladesh Standard of 50 µg/L when the feed water arsenic concentration was 300 µg/L (Ahmed, 2001). The Coolmart Water Purifier could treat only 20 L of water with a effluent arsenic content of 25 µg/L (Ahmed et al., 2000). The initial and operation costs of these units are high and beyond the reach of the rural people.

(m) MRT-1000 and Reid System Ltd.:

Jago Corporation Limited promoted a household reverse osmosis water dispenser MRT-1000 manufactured by B & T Science Co. Limited, Taiwan. This system was tested at BUET and showed a As(III) removal efficiency more than 80% (Ahmed, 2001). A wider spectrum reverse osmosis system named Reid System Limited was also promoted in Bangladesh. Experimental results showed that the system could effectively reduce arsenic content along with other impurities in water (Ahmed, 2001). The capital and operational costs of the reverse osmosis system would be relatively high.

(n) Low-pressure Nanofiltration and Reverse Osmosis:

Oh et al. (2000) applied reverse osmosis and nanofiltration membrane processes for the treatment of arsenic contaminated water applying low pressure by bicycle pump. A nanofiltration membrane process coupled with a bicycle pump could be operated under condition of low recovery and low-pressure range from 0.2 to 0.7 Mpa. Arsenite was found to have lower rejection than arsenate in ionized forms and water containing higher arsenite requires pre-oxidation for reduction of total arsenic acceptable level. In tubewell water in Bangladesh the average ratio of arsenite to total arsenic was found to be 0.25 (Ahmed, 2001). However, the reverse osmosis process coupled with a bicycle pump system operating at 4 Mpa can be used for arsenic removal because of its high arsenite rejection. The study concluded that low-pressure nanofiltration with pre-oxidation or reverse osmosis with a bicycle pump device could be used for the treatment of arsenic contaminated groundwater in rural areas (Oh et al., 2000).

2.1.9 COMPARATIVE MERITS AND DEMERITS OF ARSENIC REMOVAL TECHNOLOGIES

The following Table summarizes the relative advantages and disadvantages of different arsenic removal technologies.

Table 2.6: A Comparison of the Main Arsenic Removal Technologies (Ahmed, 2001)

| Technologies | Advantages | Disadvantages |
|--|--|--|
| <u>Oxidation-precipitation</u> <ul style="list-style-type: none"> • Air Oxidation • Chemical Oxidation | <ul style="list-style-type: none"> • Simple and Low cost • Simple and Rapid process | <ul style="list-style-type: none"> • Less Removal Efficiency • Toxic Residual |
| <u>Coagulation-Coprecipitation</u> <ul style="list-style-type: none"> • Alum Coagulation • Iron Coagulation | <ul style="list-style-type: none"> • Easily Available Chemical • Effective Over Wider pH Range | <ul style="list-style-type: none"> • Produces Toxic Sludge • Relatively Costly Chemicals |
| <u>Sorptive Techniques</u> <ul style="list-style-type: none"> • Activated Alumina • Iron Coated Sand • Ion Exchange Resin | <ul style="list-style-type: none"> • Commercially Available • Plenty of Possibilities • High Removal Efficiency | <ul style="list-style-type: none"> • Produces Toxic Waste • High Technical O & M • Relatively High Cost |
| <u>Membrane Techniques</u> <ul style="list-style-type: none"> • Reverse Osmosis • Electrodialysis | <ul style="list-style-type: none"> • No Toxic Waste Produces • Capable of Removing Other Contaminants | <ul style="list-style-type: none"> • High Technical O & M • Toxic Waste Water Produces |
| <ul style="list-style-type: none"> • Microbial Processes | <ul style="list-style-type: none"> • Should be Less Costly | <ul style="list-style-type: none"> • Not Yet Fully Established |

2.1.10 HEALTH IMPLICATIONS OF ARSENIC IN DRINKING WATER

Acute arsenic exposures (high concentrations ingested over a short time period) can cause a variety of adverse effects (Frederick et al., 1994). The severity of the effect depends primarily on the level of exposure. Acute high dosage oral exposure to arsenic typically leads to gastrointestinal irritation accompanied by difficulty in swallowing, thirst, abnormally low blood pressure and convulsions. Death may occur from cardiovascular collapse.

The respiratory tract, nervous system and skin may be considered as the critical targets of prolonged arsenic exposures. Arsenic level in tissues and excreta are of limited importance on diagnosing chronic arsenic poisoning. The lethal dosage (LD_{50}) to humans is estimated at 1-4 mg As/kg body weight for an adult (Vallee et al., 1960, Winship, 1984). Short-term exposure to dosages of 500 μ g As/kg/d can cause serious blood pressure, nervous system disorder, gastro-intestinal irritation and other ill effects and also may led to short death. Short-term intake of dosages from 30-300 μ g As/kg/d do not cause serious effects in most people, but some may experience relatively mild effects (USEPA, 1993). Prolonged arsenic toxication results are shown in the following table:

Table 2.7: Arsenic Poisoning from Drinking Water

| Sl | Main organ | Effects | Reference |
|----|--------------------|---|--------------------|
| 1 | Nervous system | Ataxia, Paralysis, peripheral neuropathy | Valle et al., 1960 |
| 2 | Respiratory system | Nasal septum perforation, bronchitis, cancer | Luh et al., 1973 |
| 3 | Skin | Melanosis, dermatitis, hyperkeratosis, cancer | Yeh,S., 1973 |
| 4 | Heart | Heart and occlusive arterial disease | Hindmarsh, 1977 |
| 5 | Liver | Liver cirrhoses and cancer | Zadivar, 1977 |

Chronic exposure to low concentrations of arsenic are of primary interest when the health significance of arsenic in drinking water is evaluated (Frederick et al., 1994). The most common signs of long-term, low level arsenic exposure from drinking water are dermal changes, these include variations in skin pigments, hyperkeratosis and ulceration (Tseng et al., 1968). Vascular effects are also associated with chronic arsenic exposure (Tseng, 1977; Borgono et al., 1977). A small area on the southwest coast of Taiwan where Black-foot disease, a peripheral vascular disease is endemic has been studied extensively (Tseng et al., 1968). Studies of Canada (Hindmarsh et al., 1977) and the United States (Southwick et al., 1983) report neurological effects after exposure from drinking water containing arsenic. Enlargement of the liver was observed in populations in India that were exposed to arsenic in drinking water (Abernathy and Ohanian, 1993).

On the basis of current evidence, it appears that ingested inorganic arsenic increases the risk of cancers of the liver, kidney, bladder and possibly other internal sites (Bates et al., 1992). Inhaled arsenic has been shown to be associated with increased lung cancer risks in smelter worker populations in the United States, Sweden and Japan. In a study by Devilliers and Beker (1969), the incidence of leukemia was threefold greater in people exposed to arsenic than in the general Canadian population.

2.1.11 DRINKING WATER STANDARDS FOR ARSENIC

The Tolerable Daily Intake (TDI), is an estimate of the amount of substance per kg of body weight that can be ingested daily over a life time without appreciable health risk. For a proven human carcinogen chemical like arsenic it is accepted that the threshold value of TDI does not exist (Dahi, 1997). This is because, theoretically there will always be a probability of harmful effect, i.e., risk at any level of exposure.

Estimated risks are normally based on 60 kg person, drinking 2 L of water per day, for a life time of 70 years. The WHO guideline value for substances in drinking water is the concentration corresponding to an upper bound estimate of an excess lifetime cancer risk of 10^{-5} . In other words it is the concentration expected to give one additional cancer case per 100,000 people ingesting the water for 70 years.

On this basis the arsenic concentration for acceptable skin cancer risk is calculated to be $0.17\mu\text{g/L}$. For practical limitation in available analysis methods, only a provisional guideline value of $10\mu\text{g/L}$ is established (Dahi, 1998). Thus the estimated excess lifetime skin cancer risk associated with exposure to $10\mu\text{g/L}$ drinking water concentration for a lifetime of 70 years is: $P = (10\mu\text{g/L} \cdot 10^{-5}) / 0.17\mu\text{g/L} = 6 \cdot 10^{-4}$; i.e., 6 additional skin cancer cases per 10,000 exposed.

For comparison the national standards adopted are $10\mu\text{g/L}$ in the European Union, $25\mu\text{g/L}$ in Canada and $50\mu\text{g/L}$ in Bangladesh Standard.

2.2 IRON IN GROUND WATER

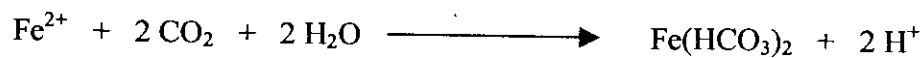
2.2.1 INTRODUCTION

The presence of iron in ground water is now considered to be a major problem throughout the world and produce numerous adverse effects. These problems are severe in the context of Bangladesh as groundwater is a vital source for the safe drinking water supply. In some places of Bangladesh the concentration of iron in ground water is at a much higher level than the limit acceptable to the rural people. People of those areas generally refuse to use tube well water and inclined to use pond and river waters.

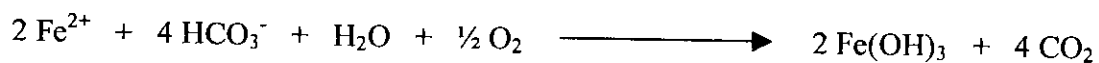
2.2.2 OCCURRENCE OF IRON

The element iron is an abundant and widespread constituent of rocks and soils. Dissolved iron is found in ground water from wells located in shale, sandstone and alluvial deposits. In igneous rocks the principal minerals containing iron as an essential component include the pyroxenes, amphiboles, magnetite and the nesosilicates such as olivine. The composition of olivine ranges from Mg_2SiO_4 to Fe_2SiO_4 (forsterite to fayalite) with ferrous iron substituting freely for magnesium. Most commonly, the iron in igneous rocks is in the ferrous form but may be mixed with ferric iron as in magnetite Fe_3O_4 (Hem, 1970). Common mineral deposits of iron include ferric oxide and hydroxides such as hematite Fe_2O_3 and ferric hydroxide $Fe(OH)_3$. Sedimentary forms of iron include sulfides such as pyrite and marcasite; two minerals with identical chemical composition FeS_2 but different crystalline structures. Carbonates such as siderite $FeCO_3$ and mixed oxides such as magnetite Fe_3O_4 . The ferrous oxides and sulfides are the usual sources of dissolved iron in ground water. Weathering of iron silicates can produce dissolved iron in near surface water. However, this is a relatively slow process.

Ferrous iron Fe^{2+} is chemically reduced, soluble form that exist in a reducing environment (in absence of dissolved oxygen and low pH). Many ground waters are low in dissolved oxygen and are supersaturated with CO_2 owing to weathering of carbonate rocks or to increased CO_2 concentration in the soil gas. The lower pH value of ground water due to the presence of CO_2 and mineral acids and absence of dissolved oxygen creates favorable conditions to hold iron in high concentration in ground water as ferrous bicarbonate (Bell, 1965).



Upon exposure to the atmosphere dissolution of CO_2 from supersaturated ground water occurs, leading to an increase in pH value. At the same time aeration of the ground water occurs and increases the dissolved oxygen concentration. As a result rate of oxidation of soluble ferrous iron to insoluble ferric iron increases, which precipitates from solution as hydrous ferric oxides.



The oxidation of iron in natural system is more complex than indicated by the above equation. Iron can also enter in water through solution or infusion of organic bodies such as wood, leaves and so forth. Iron is an essential element in both plant and animal metabolism. Iron, therefore is to be expected in organic wastes and in plant debris in soil and the activities in the biosphere may have a strong influence on the occurrence of iron in water (Hem, 1970). Iron may present as soluble ferrous bicarbonate in alkaline well or spring waters; as soluble ferrous sulfate in acid drainage waters or waters containing sulfur; as soluble organic carbon-iron compound in colored swamp waters; as suspended insoluble ferric hydroxide formed from iron bearing well waters, which are subsequently exposed to air and as a product of pipe corrosion producing red water (Ali, 1990).

2.2.3 CHEMISTRY OF IRON IN WATER

Iron Fe^{2+} is a chemically reduced soluble form that may exist in a reducing environment. Upon exposure to the atmosphere dissolution of CO_2 and H_2S from supersaturated ground water occurs leading to an increase in pH value. At the same time aeration of the ground water occurs and increases the dissolved oxygen concentration. Thus aeration and dissolution of CO_2 increases the rate of oxidation of soluble ferrous iron to insoluble ferric iron. But the oxidized and precipitated iron particles are so small in size that it is very difficult to separate them through sedimentation. Coagulation and flocculation are the process by which these small particles are allowed to grow or flocculate to sizes that settle at satisfactory velocities.

Solubility of Iron:

In the pH range encountered in natural waters, soluble ferrous iron consists primarily of Fe^{2+} and FeOH^+ . While greatly limited in solubility at neutral pH, the aqueous ferric ions consists predominantly of $\text{Fe}(\text{OH})_2^+$ and $\text{Fe}(\text{OH})_4^-$ (O'Connor, 1971). In alkaline water which is devoid of sulfide, phosphate and organic hydroxide; ferrous carbonate, ferric hydroxide or mixture of them exist depending on the concentration of oxidizing agents and pH. According to Ghosh, et al., (1966) in alkaline natural water, the solubility of ferrous iron is limited by the solubility of ferrous carbonate in the pH range of 6-9, above which the solubility equilibrium of ferrous hydroxide becomes limiting again. Theoretically iron that precipitates from a supersaturated solution of this type would be either ferrous carbonate or ferrous hydroxide depending on the pH. Under practical conditions, however, the precipitation of basic carbonates [e.g. $\text{Fe}(\text{OH})_2 \cdot \text{FeCO}_3$] with somewhat different solubility characteristics is probable, especially in the pH range of 8 to 11.

On aeration or by the addition of oxidizing agents, iron is oxidized from the ferrous to ferric form. Once oxidized, the solubility of iron is severely limited over a wide range of pH values from 4 to 13 by the solubility of ferric hydroxide. The following figure shows plot of the solubility of Fe(III) in water having a concentration of total carbonic species 10^{-3} M (Stumm, 1964). To take advantage of this solubility restriction, the basic step in the removal of iron is oxidation of ferrous iron to ferric iron. Ferric ions generally have a stronger tendency to form complexes than ferrous ions. Complex formation of ferric ions with o-phosphate silicate and many organic bases is stable and very difficult to precipitate.

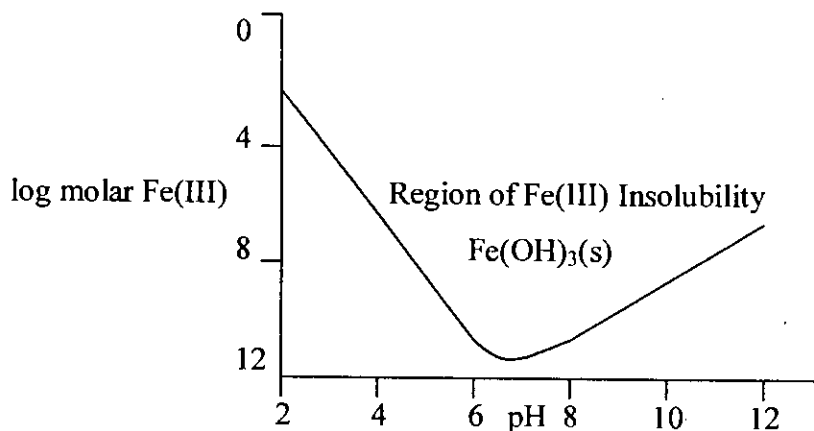
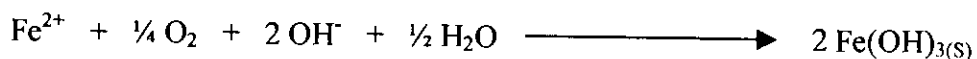


Figure 2.5: Solubility of Fe(III) at 25°C (Fair, Geyer and Okun, 1958)

The Kinetics of Iron Oxidation:

In the presence of dissolved oxygen, soluble ferrous iron Fe^{2+} oxidizes to ferric oxides or hydroxides. The stoichiometric relationship being (O'Connor, 1971) as follows:



Which indicates that 1 mg/L of oxygen will oxidize 7 mg/L of ferrous iron. So the oxygen demand and correspondingly the oxygen gas transfer requirements are very small. It is believed that the oxidation of ferrous iron proceeds stepwise through various ferrous-ferric species.

Effect of Fe^{2+} and Partial Pressure of O_2 :

Ghosh et al., (1966) stated that the rate of ferrous iron oxidation is of the first order with respect to ferrous iron concentration (Fe^{2+}) and the partial pressure of oxygen ($p\text{O}_2$).

Thus the rate law constant

$$-d/dt (\text{Fe}^{2+}) = k_1 (\text{Fe}^{2+}) p\text{O}_2$$

It was also observed in the above study that the rate of iron oxidation remains unaffected by dissolved oxygen if the concentration exceeds 5 mg/L.

Effect of pH Value:

Usually ground water contains a high concentration of CO_2 . The aeration not only results in the oxidation of ferrous iron but also serves to remove CO_2 resulting in an increase in pH. Oxidation of ferrous iron increases rapidly at pH of 7.0 or above and is very slow below 6.0. Reaction rates are strongly pH dependent. Stumm and Lee (1961) indicated that an increase of one pH unit, causes 100 fold increase in the rate of reaction i.e. there is a second order relationship between the rate of reaction and the hydroxyl ion concentration.

Therefore,

$$-d/dt (\text{Fe}^{2+}) = K (\text{Fe}^{2+}) p\text{O}_2 [\text{OH}^-]^2$$

Where, $d/dt (\text{Fe}^{2+})$ = Rate of Fe(II) oxidation, mol/L/min

Fe^{2+} = Ferrous ion concentration, mol/L

$p\text{O}_2$ = Partial pressure of oxygen, atmosphere

OH^- = Hydroxyl ion concentration, mol/L

K = Reaction rate constant = $8.0 + (2.5) \times 10^{13} \text{ L}^2/\text{min}/\text{atmos}/\text{mol}^2$ at 20.5°C

It has been observed that the half time for Fe^{2+} oxidation at pH 7.02 is approximately 4 minutes and at pH 7.24 it is around 2 minutes, implying complete (>99%) oxidation of Fe^{2+} in a relatively short time in well aerated water at pH values greater than 7.2 and alkalinity above 450 mg/L as CaCO_3 (Stumm and Lee, 1961).

Effect of Alkalinity:

Stumm and Lee reported that the reaction rates obtained in solutions of lower alkalinity tend to be of smaller magnitude and more scattered than those obtained in solutions of higher alkalinity.

Robinson and Dixon (1968) mentioned that in order to obtain complete oxidation of the ferrous iron, the bicarbonate alkalinity of the water should be in excess of 100 mg/L as CaCO_3 . Generally, if the concentration of alkalinity reaches 130 mg/L as CaCO_3 all of the ferrous iron will be oxidized almost immediately and any further addition of chemicals would appear to be unnecessary. Low alkaline water needs some oxidizing agent (KMnO_4) without raising pH and alkalinity or some chemical additive (Na_2CO_3) to raise both pH and alkalinity.

Effect of Temperature:

The reaction rate is dependent on temperature. For a given pH value, the rate increases about 10 fold for a 15°C increase in temperature, which is mainly caused by the change in $[\text{OH}^-]$ concentration due to temperature dependence of the ionization constant of water (Stumm et al., 1961).

Effect of Ionic Strength:

Sung and Forbes (1984) showed that the rate constant K is also a function of ionic strength and the presence of complex forming anions. They observed a linear variation (decrease) of the rate constant up to an ionic strength of 0.25 M in their study. At values greater than this, increasing ionic strength actually increases the rate constant.

Effect of Chloride and Sulfate:

Sung and Morgan (1980) observed that chloride and sulfate ions have a significant retarding influence on the rate constant in the pH range from 6.5 to 7.2. Later Sung and Forbes (1984) mentioned that for typical fresh water iron removal, chloro-complexes of iron could probably be ignored because of the effect of ionic strength and chloro-complexes may not be as important as the effects of temperature and pH.

Effect of Organic Matter:

Ferrous iron is capable of forming complexes with organic matter which is resistant to oxidation even in the presence of dissolved oxygen. The relative strength of such complexes have stability constants of approximately 10^4 (Theis and Singer, 1974).

Catalytic Effect:

For a given pH value and oxygen concentration, the addition of as little as 0.02 mg/L of Cu^{2+} reduces the oxygenation time by a factor of 5 (Stumm and Lee, 1961).

Sung and Morgan (1980) studied the effect of ferric hydroxide on the oxygenation of ferrous iron and stated that auto catalysis is noticeable only for pH around 7 and above. Cox, (1969) has described the use of contact bed oxidation in iron removal. The purpose of contact bed according to him is to facilitate oxidation of iron or manganese through the catalytic action of previously precipitated oxides of these minerals on the gravel or ore.

2.2.4 UNIT PROCESSES OF IRON REMOVAL

The methods used to remove inorganic iron is entirely different to those used for organic iron. Inorganic iron refers to the clear and sparkling well water that turn turbid on exposure

to air. Organic iron is coloured with humic acids. For selection of iron removal method, type of iron present should be detected first.

Aeration:

This is the process of bringing water into intimate contact with air with the objectives of (a) addition of O₂ (b) removal of CO₂ (c) removal of various organic compounds responsible for taste and odour. This is a physical phenomenon in which gas molecules are exchanged between a liquid and a gas at a gas-liquid interface.

In water treatment plant for iron removal, aeration is done with the aims of removal of CO₂ from water which in turn will result in an increase in pH value and in the mean time addition of O₂ to water to oxidize dissolved ferrous iron to insoluble ferric iron.

The solubility or addition of a gas depends on:

- Its partial pressure in the atmosphere in contact with water
- The water temperature
- The concentration of impurities.

The rate of precipitation or removal of a gas is controlled by:

- The degree of super-saturation
- The water temperature
- The interfacial area between a gas and water

The common gas transfer equation is represented as (Fair et. al., 1958)

$$C_t = C_0 + (C_s - C_0)\{1 - \exp[-k_g t]\}$$

Where,

C_t and C₀ = Concentration at time t = t and t = 0 respectively

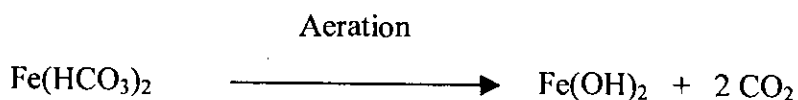
C_s = the saturation concentration at a given temperature.

k_g = gas transfer co-efficient. Becker (1924) reports the following value in cm/hr for the adsorption of oxygen in the temperature range 3.5 to 35°C, k_g = 32.3 x 1.018^(T-20). The value can be both higher and lower in different circumstances.

The above equation indicates that oxygen transfer can be optimized, no matter what its direction by controlling the following four major parameters:

- I. Generating the largest practicable area 'A' of interface between a given water volume and air.
- II. Preventing the build up of thick interfacial films or by breaking them down to keep the transfer co-efficient 'k_g' high.
- III. Inducing as long a time of exposure 't' as possible.
- IV. Ventilating the aerator and its components to maximize oxygen transfer.

In iron removal process, aeration is required to precipitate the ferrous bicarbonate to ferric hydroxide in accordance with the following equations:



Further aeration:



In order that the reaction will go to completion and precipitate the ferric hydroxide, it is necessary that the pH be approximately 7 or higher. If possible the pH should be raised to 7.5 to 8.0 but even then the reaction may take 15 minutes retention before it is complete and in some cases as much as 1 hour retention has been necessary (Walker, 1978). The length of retention time depends on the degree of aeration and the dissolved oxygen content of the aerated water. Aeration can be optimized by increasing contact time and interfacial area.

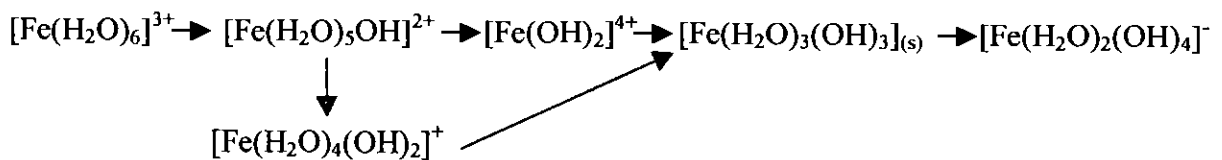
Coagulation:

In many water treatment facilities, a chemical coagulation process is used to enhance the removal of colloidal and dissolved substances from water.

When ferrous iron solution is oxygenated the precipitate is roughly concentrated in the sub-micron size range. Agglomeration of particles into groups increases the effective size and therefore the settling velocities. Hydrolysis of metal ions and aqueous chemistry of these ions are essential to an understanding of their role in coagulation.

Iron undergoes a series of hydrolytic reactions prior to precipitation of $\text{Fe}(\text{OH})_{3(s)}$. Iron salts dissociate to yield trivalent Fe^{3+} ions, which hydrate to form the aquometal ion, $\text{Fe}(\text{H}_2\text{O})_6^{3+}$. The aquometal ion can then react and form several hydrolysis species including mononuclear species and polynuclear species.

Stumm and O'Melia (1968) and others have given the stepwise conversion of the tripositive iron ion to negative iron ion as pH increases as follows:



The charge on hydrolysis products and the precipitation of metal hydroxides are both mainly controlled by pH. Sullivan and Singley (1968) have estimated the quantity of mononuclear iron species (monomers) at different pH. The dominant species upto pH 4.0 is Fe^{3+} , from 4.0 to 6.0 it is $\text{Fe}(\text{OH})_3$ and above pH 6.0 it is $\text{Fe}(\text{OH})_6^{2-}$.

Gravel Bed Flocculator:

Usually the source of power for flocculation devices are gravitational, pneumatic or mechanical. But neither mechanical mixing nor baffle mixing are feasible and practicable in many small community water supply systems. A simple solution to the flocculation process is the one involving coarse media bed in which water is allowed to flow through a packed bed of coarse media. The sinuous flow of water through the interstices of coarse media will provide repeated contacts among the small suspended particles to form compact settleable flocs. A portion of the agglomerated flocs will settle on the surface and within the interstices of coarse media. Which will further help in adsorbing finer particles as they come into

contact with the settled flocs. Moreover, in an up flow system as the flow of water emerges from the coarse media, due to sudden drop of velocity, agglomerated flocs will settle on the top of coarse media bed forming a layer of sludge which is also effective in the removal of finer particles. This type of flocculator occupies small area and no external source of power is required. Moreover the whole bed of coarse media is effective for flocculation purposes. This type of flocculator is now in use of many small community water supply systems in Thailand, India, Bangladesh and Latin American countries.

Sedimentation:

Sedimentation is the removal of particulate matter, chemical floc and precipitate from suspension through gravity settling (Hammer, 1977). The sedimentation process in water treatment provides for the settling and removal of heavier and larger suspended particles from water. Most commonly, it is used for removal of flocculated particles prior to filtration. The removal efficiency in the sedimentation basin determines the subsequent loading on the filters and accordingly, has a marked influence on their capacity, the length of filter runs and the quality of the filtered water.

The factors that affect the sedimentation process are density, size and velocity of settling particles, drag co-efficient, acceleration due to gravity, detention period and effective depth of the settling basin etc. Sedimentation can be accelerated by increasing particle size or decreasing the distance a particle must fall prior to removal. The first is achieved by coagulation and flocculation prior to sedimentation. The second can be achieved by making the basin shallower or by providing tube settlers.

Filtration:

Filtration is a unit process widely used in water treatment for the removal of particulate materials. In this process, water passes through a filter medium and particulate materials either accumulate on the surface of the medium or are collected through its depth. Filters have been found effective for removing particulate of all size ranges provided that proper design parameters are used.

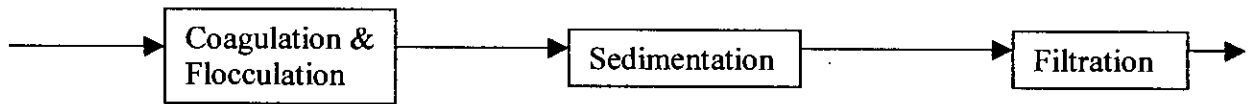


Figure 2.6: Application of Filters in Conventional Water Treatment

The principal mechanisms that are believed to contribute to the removal of materials in filter are (a) impaction (b) interception (c) sedimentation (d) adhesion (e) biological growth etc.

The efficiency of filtration is dependent on various design variables. A decrease in porosity of the granular media will increase the particulate removal efficiency. In addition, increasing the filter depth or decreasing the filter media size will improve particle capture. Two general types of filters are commonly used in water treatment: the slow sand filter and the rapid sand filter.

Slow Sand Filtration:

It consists of a layer of ungraded fine sand through which water is filtered at a low rate. The traditional rate of filtration used for normal operation is 0.1 m/hr, although it is possible to produce safe water at rates as high as 0.4 m/hr. The sand bed thickness varies between 1.0 and 1.4m. Filter sand should have an effective size between 0.15 and 0.35mm and uniformity co-efficient between 1.5 and 3.0. Slow sand filters are more practical in the treatment of water with turbidity below 50 NTU, although higher turbidities can be tolerated for a few days. The best purification occurs when the turbidity is below 10 NTU. The filter is cleaned by periodically scraping a thin layer of dirty sand from the surface when it becomes too clogged with impurities at intervals of several weeks to months. The low rate of filtration allows the formation of an active layer of microorganisms, called the schmutzdecke on the top of the sand bed which provide biological treatment. This layer is particularly effective in the removal of microorganisms from water (Schulz and Okun, 1984).

Rapid Sand Filter:

It consists of a layer of graded sand or in some instances a layer of coarser filter media (e.g., anthracite) placed on top of a layer of sand, through which water is filtered. The rate of

filtration used for normal operation is much higher than slow sand filter. Normal filtration rate is 4 m/hr., although it can be as high as 21 m/hr. Effective size of filter sand is 0.55 mm and higher and uniformity coefficient 1.5 and lower. The filter is cleaned by back washing with water. Because of the higher filtration rates, the space requirement for a rapid sand filtration plant is 20% of that required for slow sand filters (Schulz and Okun, 1984).

Roughing Filtration:

It allows deep penetration of suspended materials into a filter bed and they have a large silt storage capacity. Roughing filtration uses much larger media than either slow or rapid filtration and the media size is greater than 2.0 mm. The rate of filtration, can be as low as those used for slow sand filters or higher than those used for rapid sand filters, depending upon the type of filter, the nature of turbidity and the desired degree of turbidity removal. Roughing filters are limited, however, to average raw water turbidities of 20 to 150 NTU. The solid materials retained by the filters are removed by flushing or if necessary, by excavating the filter media, washing it and replacing it. There are basically two types of roughing filters, which are differentiated by their direction of flow and are

- Vertical flow roughing filters
- Horizontal flow roughing filters

International Reference Center for Community Water Supply and Sanitation (1983) has described the advantages of course grained 'roughing filter' which has large pores that are not liable to clog rapidly. The large pores also allow cleaning at low backwash rate, since no expansion of the filter bed is needed. In up flow type roughing filters grain sizes of 15 mm to 7 mm arranged in different layers and a flow rate of 0.5 to 1.0 m/hr have been recommended. Equina (1979) has made a study on the pretreatment of water containing iron and manganese using a horizontal-flow filter with crushed stone as the filter media. The regression analysis was made to determine the factor(s) affecting the filter performance. The length of the filter run was found to be the most important factor for the removal of iron from groundwater. At the filtration rate of 0.4 cu.m./sq.m/hr and average iron concentration of 1.24 mg/L could be removed around 47%.

2.2.5 EXISTING IRON REMOVAL TECHNOLOGIES

To remove soluble iron it is generally accepted that an oxidation process followed by a suspended solids removal process is most effective. Usually oxidation of soluble iron is accomplished by simple aeration or chlorination/potassium permanganate application. Coagulation – flocculation with sedimentation and filtration are employed as solid removal processes.

Ahmed (1987) developed a low-cost iron removal plant based on four major units, e.g. aeration channel, sedimentation and two brick chips adsorption chambers. Several plants were constructed and it was found to be effective in removing iron from No. 6 tube well with yielding capacity of 9 to 13 L/min. The plants have been found to be very effective in removing soluble iron from tubewell water in excess of 90 percent.

Ahmed (1987) conducted some studies on horizontal flow roughing filter for the removal of iron from water. It was observed that in a roughing filter of 0.4 m long with 4 to 10 mm filter grain size and a filtration rate of 0.4 m/hr, an average of over 92% iron removal could be achieved during a total run of 100 hours. It was also observed that the most important factor that affects the performance of a roughing filter is the increasing depth of penetration of iron sludge with time.

In 1986-87 UNICEF developed an improved iron removal plant consists of three units e.g. perforated ferrocement channel, sedimentation chamber and brick chip filter. The plant was found to be effective in iron removal and the filter run was also satisfactory. A study by WHO, UNICEF and DPHE (1990) on these iron removal plants showed that iron removal was satisfactory. The iron concentration was reduced to around 1.5 ppm from 15 ppm with average cleaning period of 12 days (with minimum of 5 days). With the same interval of cleaning it has been observed that the higher the concentration in raw water the higher the concentration in treated water but it was not exceeded 2.5 ppm.

For the elimination of iron from hand pump tubewell water, Aowal (1981) proposed to introduce a spray aeration, a settling tank and a plain sand filter, all housed in a single

chamber. Although an effective removal was achieved the length of run between cleaning was very short, less than 24 hours. The top layer of fine sand was needed to be removed, washed and dried for the next use, which is not easy.

Kibret (1986) has shown that dry filter is one of the alternatives that can be applied for iron removal and the process uses the self-purification capacities of iron bacteria. Investigation made on the pilot plants showed that iron removal process by dry filtration depends on the hydraulic load, filter depth, size of filter material, the development of the microorganisms and iron concentration in the raw water. Dry filter does not only remove iron but it also removes manganese, ammonia, and carbon dioxide and provides sufficient oxygen supply to the treated water. The results obtained from the test plants were not bellowing the standard limits except from the full-scale production plant. However, complete removal of iron by dry filter is feasible provided the best possible favorable combinations of the factors on which iron removal depends are found.

In 1985-86 over hundred iron removal units, which were originally designed by BUET under a research programme, were built at Sirajgonj and Comilla. These units are reported to fail due to following reasons (UNICEF report 1988):

- Lack of community participation in all activities of the project.
- Faulty construction of the unit.
- Lack of continued support and technical advice from DPHE/UNICEF.
- Difficulty in cleaning the filter due to short filter runs.
- Complicated design of the unit.

In 1988, DPHE with the help of UNICEF, Dhaka Bangladesh, designed and constructed iron removal plant for hand pump tubewells in different parts of Bangladesh. Those plants were also failed due to faulty design of sedimentation chamber, where flocs were gradually settled and mixed with treated water.

Wong (1984) has shown that processes in which oxidation is followed by removal of suspended solids can effectively remove soluble iron and manganese from water. He has developed three common processes for removing iron and manganese, e.g. (i) aeration-filtration (ii) chlorination-filtration and (iii) potassium permanganate-manganese greensand filtration.

Other processes such as ion exchange, chlorine dioxide filtration, stabilization with polyphosphates etc. have also been applied but with less frequency, owing to cost and operational considerations. Removal processes are selected on the basis of iron concentration and other conditions.

More specially, the methods used in the removal of iron are:

- I)
 - a) Aeration – Sedimentation – Filtration
 - b) Chlorination – Sedimentation – Filtration
 - c) Potassium permanganate – Manganese greensand filtration
- II) Flocculation – Sedimentation
- III) Manganese zeolite process
- IV) Stabilization method

D(a) Aeration – Sedimentation – Filtration Method:

This method was studied and developed by Wong (1984) and typically includes an aerator, retention tank and filters. Oxygen from the atmosphere reacts with iron in raw water to produce relatively insoluble salts of ferric oxide. This method is generally recommended for water with high concentration of iron above 5 mg/L. The rate of reaction depends on pH. It is more rapid at higher pH values. Retention time of several hours may be necessary after aeration depending on raw water characteristics. Sometimes sedimentation tanks with sludge collection and removal facilities are used instead of a simple retention tank if iron concentration is high. Pressure filters preferably with dual media of anthracite and sand are used to remove iron. The major disadvantage of this method is that the initial cost is too high.

I)(b) Chlorination – Sedimentation – Filtration Method:

The process consists of a chemical feed system, a small retention tank and filter. The process needs a pH adjustment system through feeding caustic soda and lime. The process generally recommended for removal of low iron concentration less than 2 mg/L.

Either gaseous chlorine or hypochlorite can be used as the oxidizing agent. The filters used in this process are similar to those used in aeration – filtration process (Wong, 1984).

I)(c) Potassium permanganate – Manganese greensand filtration Method:

The method is recommended for removal of low to moderate concentration up to 5 mg/L of iron. Equipment for this process is similar to that for chlorination – filtration process but differs in the primary oxidizing agent and the filter media. A 1-4% solution of KMnO_4 is continuously feed into the raw water line prior to filtration to reduce the amount of soluble iron going to the filter. Manganese treated greensand has the ability to oxidize and to filter. However, its oxidation capacity is limited and the bed must be regenerated with potassium permanganate after back wash. The process has an advantage in that the greensand can act as a buffer. If the feed of KMnO_4 does not oxidize all the soluble iron, the greensand will oxidize and filter it.

Major disadvantages of this process are high operational costs associated with chemical requirements and filter bed deterioration if the pH falls below 7.1. In some cases, chlorine is used in conjunction with KMnO_4 to reduce chemical costs (Wong, 1984).

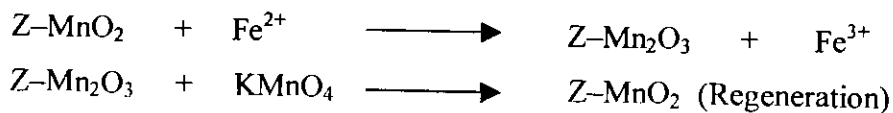
II) Flocculation and Sedimentation Method:

Sung and Forbes (1984) pointed out that oxidation of soluble iron is not the entire picture in iron removal processes. When ferrous iron solution is oxygenated, there study showed that the precipitate is roughly concentrated in the sub-micron size range. To enhance the settling character they proposed to promote coagulation/flocculation before settling.

Owens (1963) has suggested to use calcium hydroxide as the coagulant. Upon addition of lime iron hydroxide precipitates out in the suspended sludge blanket in a solid contact unit. This is very effective in the removal of colloidal particles.

III) Manganese zeolite process:

Manganese zeolite is made by coating natural greensand (glaucanite) zeolite with oxides. Manganese dioxide removes soluble iron until it becomes degenerated. The filter is regenerated using potassium permanganate (KMnO_4).



Manganese zeolite filters are generally pressure type. Disadvantages of the regenerative batch process are the possibility of soluble manganese leakage when the bed is nearly degenerated and the waste of excess KMnO_4 needed to regenerate the greensand (Clark, 1977).

IV) Stabilization Method:

The alternative to iron removal is stabilization or dispersion. According to Clark et. al. (1977) sodium hexametaphosphates at dosages of 5 mg/(mg of Fe plus Mn) have been used for this purpose. While this treatment will stabilize iron in suspension, it reportedly is not suitable where iron concentration of 1 mg/L is exceeded. Moreover, when the water is heated, the polyphosphate will revert to orthophosphate and loose its dispersing properties. The application of polyphosphate must take place prior to aeration or chlorination because the polyphosphate do not effectively stabilize precipitated ferric hydroxide. Polyphosphate dosages are limited to less than 10 mg/L because the availability of phosphorus may stimulate bacterial growths in distribution systems.

Chapter 3

METHODOLOGY

A brief description of the methodology that was followed in conducting the study is given below:

3.1 SELECTION OF UNIT PROCESSES FOR THE AIRU

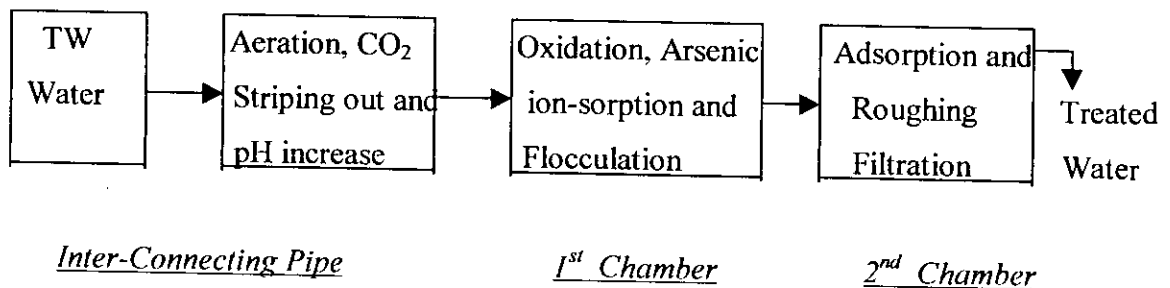


Figure 3.1: Flow Diagram of the Unit Processes of the AIRU

The AIRU is consists of major two chambers, down-flow and up-flow chambers.

- ***Inter-Connecting pipe:***

The AIRU is connected to the spout of tube well with a short piece of 75 mm PVC / flexible pipe. Water entering the first chamber is distributed uniformly over the whole bed of coarse media through a porous thin ferro-cement plate placed on the top, resulting strip out of CO₂ and increase of pH value for the oxidation of soluble iron.

- ***1st Chamber (Down-flow Gravel Bed Flocculator):***

Oxidation and subsequent precipitation of iron oxyhydroxides on the top and within the interstices of coarse media (gravel bed) adsorbs arsenic oxyanions. Sinusoidal flow across the coarse media enhance collisions for the flocculation of precipitated particles.

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- **2nd Chamber (Up-flow Gravel Bed Roughing Filter):**

Sedimentation:

Comparatively larger flocculated precipitates settle at the bottom of the 2nd chamber. The average detention time is around 25 minutes.

Roughing Filtration:

Final removal of precipitated particles both through sorption on to iron oxy hydroxides and mechanical straining take place during up-flow through the comparatively finer media (gravel bed) in the 2nd chamber.

3.2 DESIGN OF THE AIRU

(A) Laboratory AIRU-Model Design:

Flocculator:

From Hazen's equation, the following experimental relationships were obtained (Ahmed, 1995).

$$\text{Mean Velocity Gradient, } G = 8.38 \times (Q/a) \times (S/d) \text{ -----(I)}$$

$$\text{Camp Number, } G.t_d = 3.354 \times (S/d) \times L \text{ -----(II)}$$

Where, Q = Flow of Water; a = X-Sectional Area of the Flocculator Bed; S = Shape Factor = (6/ψ); ψ = 0.89 ~ 0.92 for Gravel; d = Avg. dia of Gravel.

Some experimentally best fit data for using the above two equations were obtained (Ahmed, 1995). Where, G = 10-20 Sec⁻¹; Face Velocity (Q/a) = 0.1~0.3 cm/sec.; S = 6.5; d = Avg. dia of Gravel (cm); G.t_d = 2000.

Case-I:

$$\text{From equation (I): } 10 = 8.38 \times 0.2 \times (6.5/d) \Rightarrow d = 1.0 \text{ cm} = 10 \text{ mm.}$$

$$\text{From equation (II): } 2000 = 3.354 \times (6.5/1.0) \times L \Rightarrow L = 91.74 \text{ cm} = 3 \text{ ft.}$$

$$\text{Now, Face Velocity} = 0.2 \text{ cm/sec.} = 7.2 \text{ m/hr. Pipe Diameter} = 3'' \Rightarrow a = 4.5 \times 10^{-3} \text{ m}^2$$

$$a = (Q/\text{Face Velocity}) \Rightarrow 4.5 \times 10^{-3} \text{ m}^2 = (Q/7.2 \text{ m/hr}) \Rightarrow Q = 0.03 \text{ m}^3/\text{hr} = 500 \text{ ml/min.}$$

Case-II:

From equation (I): $15 = 8.38 \times 0.2 \times (6.5/d) \Rightarrow d = 0.75 \text{ cm} = 7.5 \text{ mm}$.

From equation (II): $2000 = 3.354 \times (6.5/0.75) \times L \Rightarrow L = 70 \text{ cm} = 2'-4''$

Case-III:

From equation (I): $20 = 8.38 \times 0.2 \times (6.5/d) \Rightarrow d = 0.55 \text{ cm} = 5.5 \text{ mm}$.

From equation (II): $2000 = 3.354 \times (6.5/0.55) \times L \Rightarrow L = 50 \text{ cm} = 1'-8''$

Roughing Filter:

The optimum face velocity for removal of iron and arsenic through up-flow Roughing Filter is $0.016 \text{ cm/sec} = 0.576 \text{ m/hr}$; The most efficient gravel size is 0.75 cm dia and the depth of bed = $38.5 \text{ cm} = 15.2 \text{ inch}$ (Ahmed, 1998).

Now, $a = (Q/\text{Face Velocity}) = (0.03 \text{ m}^3/\text{hr.})/(0.576 \text{ m/hr.}) = 0.05 \text{ m}^2 \Rightarrow \text{Bucket Dia} = 10''$

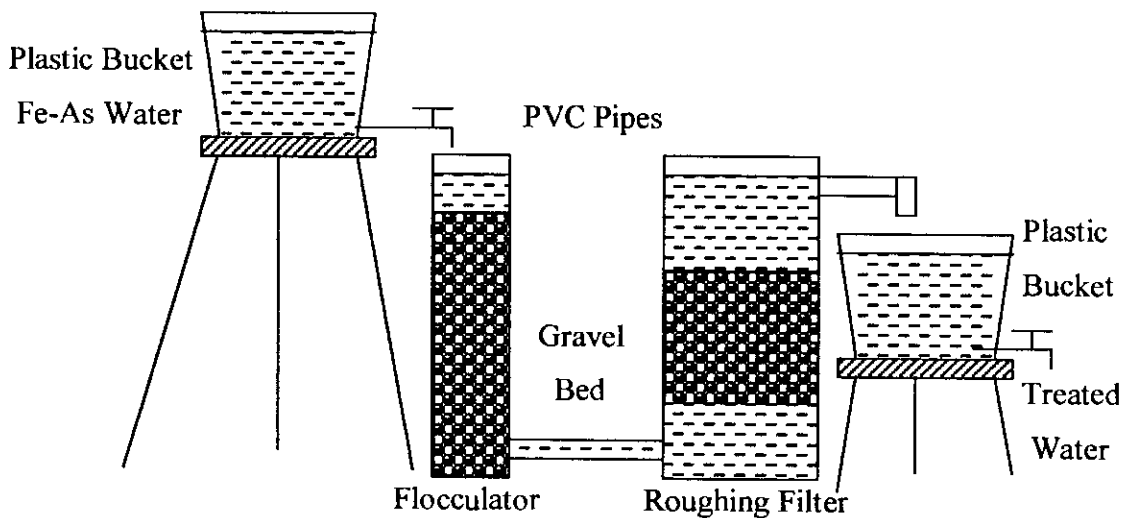


Figure 3.2: Schematic Diagram of Laboratory AIRU-Model Test Unit

(B) Recommended Design of the AIRU for Field Construction:

Aeration:

PVC 3 in diameter pipe was used for aeration purpose and for stripping out the CO₂.

Flocculator:

Mean Velocity Gradient, $G = 8.38 \times (Q/a) \times (S/d)$ -----(I)

Camp Number, $G.t_d = 3.354 \times (S/d) \times L$ -----(II)

Value of Q for hand pump tube well was obtained = 15 lit./min. = 0.9 m³/hr (Ahmed, 1985).

From equation (I): $10 = 8.38 \times 0.2 \times (6.5/d) \Rightarrow d = 1.0 \text{ cm} = 10 \text{ mm.}$

From equation (II): $2000 = 3.354 \times (6.5/1.0) \times L \Rightarrow L = 91.74 \text{ cm} = 3 \text{ ft.}$

Now, Face Velocity = 0.2 cm/sec. = 7.2 m/hr.

$a = (Q/\text{Face Velocity}) = (0.9 \text{ m}^3/\text{hr.})/(7.2 \text{ m/hr.}) = 0.125 \text{ m}^2 = 1.345 \text{ sq.ft.}$

Thus, $a = (1'-4'' \times 1')$

Design of Sedimentation Chamber:

Considering Detention Time, $t = 25 \text{ min.} = 0.4 \text{ hr.}$

Volume of Sed. Chamber = Flow x Detention Time. Thus, $V = 0.9 \text{ m}^3/\text{hr.} \times 0.4 \text{ hr.} = 0.36 \text{ m}^3.$

Now, $A = 12.3 \text{ sq.ft.} = 1.14 \text{ m}^2.$ Now, Depth $h = V/A = 0.36 \text{ m}^3/1.14 \text{ m}^2 = 0.3 \text{ m} \Rightarrow h = 1 \text{ ft.}$

Roughing Filter:

The optimum face velocity for removal of iron and arsenic is 0.016 cm/sec = 0.576 m/hr; The most efficient gravel size is 0.75 cm dia and the depth of bed = 38.5 cm = 15.2 in \approx 16 inch (Ahmed, 1998).

Now, $a = (Q/\text{Face Velocity}) = (0.9 \text{ m}^3/\text{hr.})/(0.79 \text{ m/hr}) = 1.139 \text{ m}^2 = 12.25 \text{ sq.ft.}$

$\Rightarrow a = 3'-6'' \times 3'-6''$

Note: Face Velocity 0.79 m/hr. in stead of 0.576 m/hr was used considering 70% operating time efficiency.

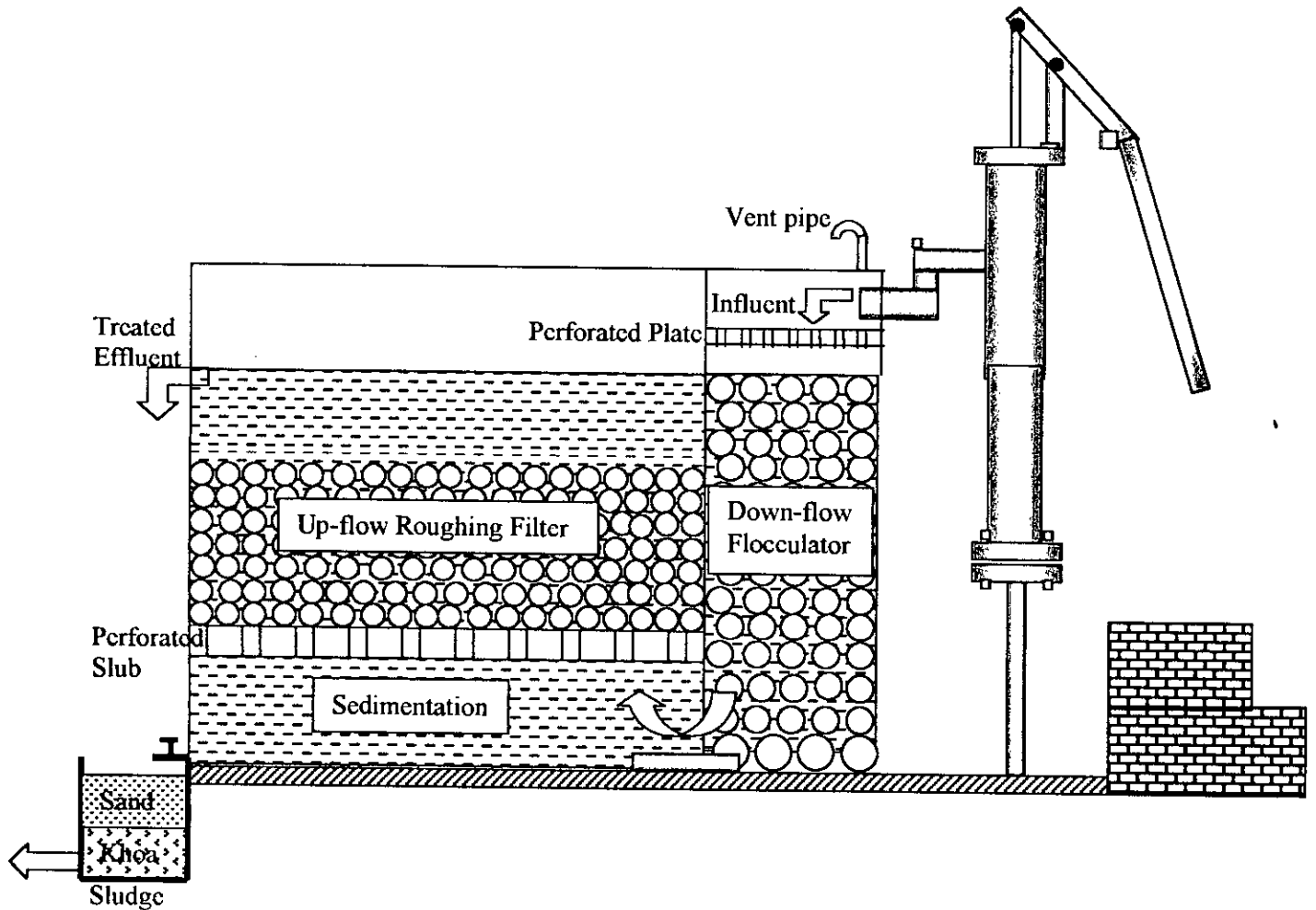


Figure 3.3: Schematic Diagram of the AIRU for Field Construction

3.3 LABORATORY MODEL STUDY OF THE AIRU

Experimental set up for AIRU-model at laboratory was done through the use of PVC pipes and plastic buckets which were placed in series containing gravel bed media of different depths and sizes of aggregates following the design criteria.

Detail laboratory analysis and tests were carried out through AIRU-Model to determine the following parameters:

- Optimum face velocity for the AIRU.
- Raw water iron-arsenic ratio for effective removal of arsenic.

- Gravel sizes for down flow flocculator and for up flow pre-filter.
- Depth of gravel beds.
- Arsenic adsorption limit of the AIRU gravel beds.

3.4 SELECTION OF FIELD SITES FOR THE CONSTRUCTION OF AIRU(S)

Five sites were selected on the basis of different water quality conditions for the construction of AIRU(s) at the field level. These areas were Site-1: Sonargaon at Narayangong district, Site-2: Jhekorgacha at Jessore district, Site-3: Chougacha at Jessore district, Site-4: Avoy nagor at Jessore district and Site-5: Jhekorgacha at Jessore district.

Since community participation in construction, operation and maintenance is the major part for sustainable development of the project, the Department of Public Health Engineering (DPHE) which is the main organization responsible for community and rural water supply of the country, were contacted and requested to extend their co-operation for this research work. The field sites were first identified by direct co-operation of the DPHE staffs. Final selection of the field sites were made by long discussion and motivation of the local people. The consequences of iron and arsenic problems in drinking water were addressed and the intervention measures were discussed among them along with humble request for their participation in all aspects of the project. They became very much interested after realizing that they have the vital role in the project. Active participation of the local people was ensured in all aspects (layout, construction, operation and maintenance) of the project works. Field sites have been selected considering water quality (mainly high arsenic and iron concentrations) of tube wells and peoples' interest in participation for the construction and maintenance works. The 1st and 2nd sites were chosen considering moderate arsenic content and the 3rd, 4th and 5th sites were chosen considering high arsenic problems. The iron concentration of all the sites were high. The targets of selecting sites for AIRU(s) were to remove arsenic with iron by co-precipitation and adsorption.

The AIRU(s) at different locations were constructed in different time.

Table 3.1: Raw Water Quality of Different Selected Tubewells

| Sl. | Tube well Sites | pH | Alkalinity as CaCO ₃ (ppm) | Iron, Fe (ppm) | Arsenic, As (ppb) | Date of Construction of AIRU(s) |
|-----|----------------------|-----|---------------------------------------|----------------|-------------------|---------------------------------|
| 1 | AIRU-1 (Sonargaon) | 7.0 | 410 | 3.0 | 106 | 9 th February, 2002 |
| 2 | AIRU-2 (Jhikorgacha) | 7.1 | 406 | 5.0 | 160 | 25 th March, 2002 |
| 3 | AIRU-3 (Chougacha) | 7.1 | 414 | 5.0 | 430 | 14 th April, 2002 |
| 4 | AIRU-4 (Avoy Nagar) | 6.9 | 330 | 4.0 | 480 | 16 th April, 2002 |
| 5 | AIRU-5 (Jhikorgacha) | 7.0 | 390 | 7.0 | 310 | 1 st June, 2002 |

3.5 SAMPLING, MONITORING AND ANALYTICAL METHODS OF TESTING

The water samples were collected and acidified at the field to avoid any interference due to precipitation of iron and preserved for the laboratory tests.

Close field observations of arsenic and iron removal efficiency of the AIRU(s) had been made through the analysis of test data. Length of filter runs between successive cleanings were also observed. Water samples were tested in the field and collected for laboratory tests following a routine. Rate of flow from the unit was measured through a known volume of bucket and counting time over the period. Moreover, pre and post-construction water consumption survey was carried out and peoples' opinion regarding the quality of treated water and difficulties in operation and maintenance of the AIRU were collected through questionnaire survey.

The water samples collected during the experimental investigation were analyzed mainly for arsenic and iron concentration in the treated water. The testing of water samples were performed both in the field through the use of field kits (Merck's-German, HACH-USA) and in the Environmental Engineering Laboratory, BUET following standard methods and by using Atomic Adsorption Spectrophotometer.

Chapter 4

LABORATORY ANALYSIS AND TEST RESULTS

4.1 INTRODUCTION

Detail laboratory analysis and tests were carried out through AIRU-Model to determine some important parameters. Since arsenic adsorption mechanism is dependent on contact time, thus optimum face velocity through the AIRU gravel bed flocculator and roughing filter was determined. The AIRU was based on arsenic removal by co-precipitation and adsorption on to iron oxy hydroxides, so the range of raw water iron-arsenic ratio for effective removal of arsenic was also determined. Again, the removal efficiency of arsenic and iron through the AIRU was highly dependent on the size of gravel and the depth of gravel bed due to variable surface area for adsorption. Arsenic adsorption limit of the AIRU gravel bed was determined for getting idea about the applicability of the unit under different water quality conditions.

4.2 OPTIMUM SIZES AND DEPTHS OF GRAVEL BEDS FOR THE AIRU

For variable gravel sizes and depths of three different AIRU-Models, the removal efficiency of arsenic and iron was observed. Both the arsenic and iron removal efficiency was found higher in case of the 1st unit having flocculator gravel size, $d=10\text{mm}$ and depth of bed, $L=92\text{cm}$ in comparison to other two units having smaller depth of beds 70cm and 50cm with smaller gravel sizes of 7.5mm and 5.5mm respectively. Although the gravel size 7.5mm and depth of bed 38.5cm for roughing filter was fixed in all three units, due to less depth of gravel bed in the flocculator and resulting less contact time of iron and arsenic with the gravel media led to inadequate removal efficiency.

Gradually increased removal efficiency of both iron and arsenic for all the three units were noticed due to cumulative deposition of iron oxy hydroxide precipitates in the interstices of the gravel bed media which corresponds to increased adsorption sites for arsenic removal. The gravel size, $d=10\text{mm}$ and depth of gravel bed, $L=92\text{cm}$ were found optimum for the design of flocculator of the AIRU. The above findings are represented graphically as shown in figure 4.1 and 4.2 on the following page:

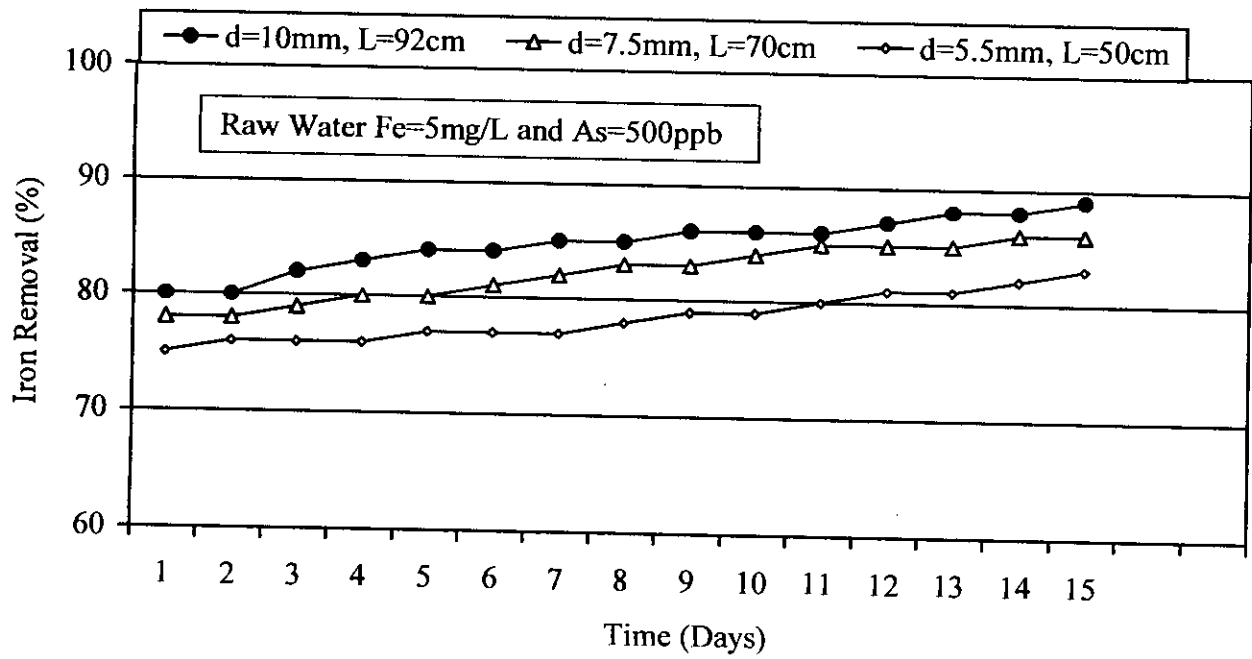


Fig.4.1 Variation of Iron Removal (%) with Time
(Different AIRU-Models at Laboratory)

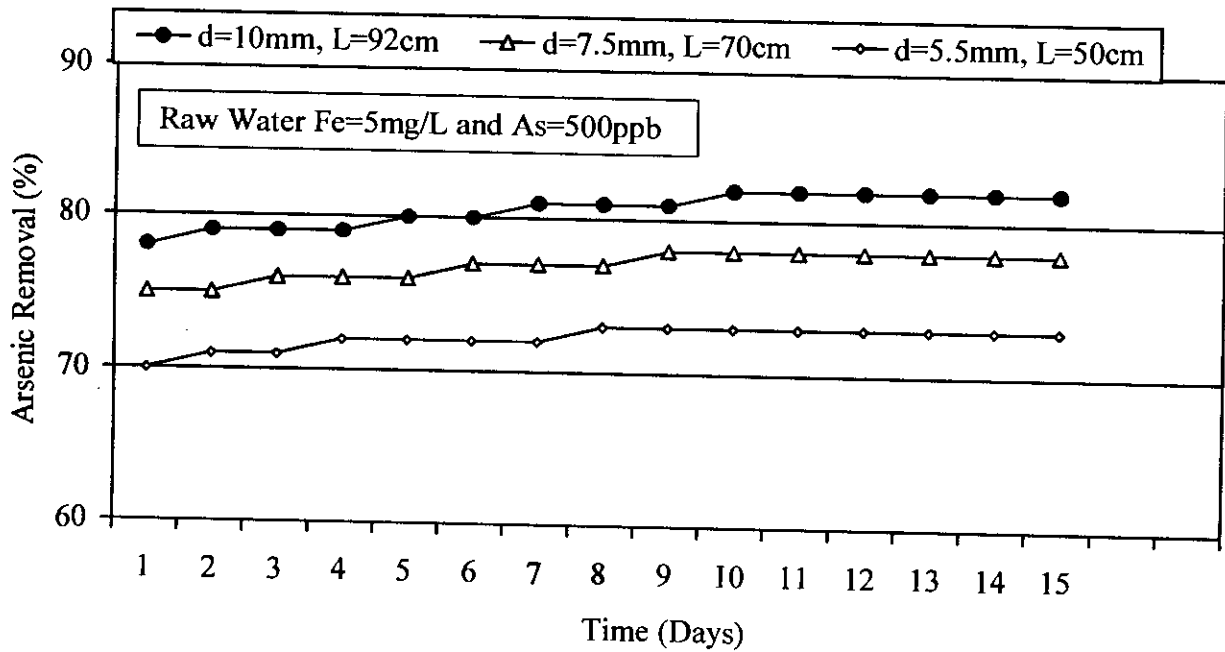


Fig.4.2 Variation of Arsenic Removal (%) with Time
(Different AIRU-Models at Laboratory)

4.3 OPTIMUM FACE VELOCITY FOR THE AIRU

The iron removal efficiency was found the highest at the least face velocity and for higher raw water iron concentration. The efficiency decreases slightly with the increasing face velocity from 0.1m/hr to 0.5m/hr. But advancing forward beyond the face velocity greater than 0.5m/hr, a sharp decrease in the removal performance was observed. It was due to shearing and sloughing of the previously deposited iron hydroxide precipitates in the interstices of the gravel bed media and also due to less contact time to settle down the iron hydroxide precipitates in the mini sedimentation basin within the interstices of the gravel bed. Although the highest removal efficiency corresponds to the least face velocity but it requires very big structural dimensions and associated with high expenditure. Thus, 0.5m/hr face velocity was considered to be the optimum for design purpose of the AIRU. The above conditions are shown in figure 4.3 as follows:

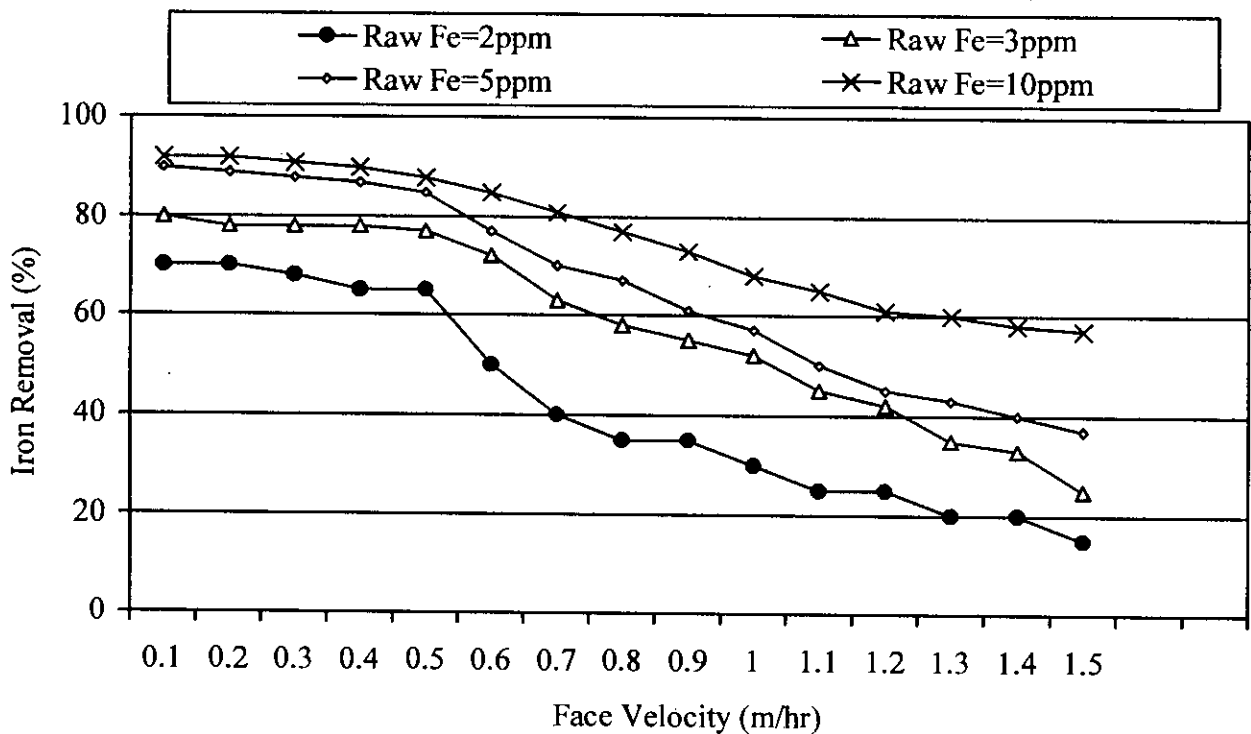


Fig.4.3 Variation of Iron Removal (%) with Face Velocity (AIRU-Model at Laboratory)

4.4 EFFECT OF Fe/As RATIO ON REMOVAL EFFICIENCY

Case-I: Arsenic(V)

The arsenic removal efficiency was found increasing with the gradual increase of raw water iron-arsenic ratio. The sharp fall of arsenic concentration in the treated water at the initial stage of the curves shown in figure 4.4 on the following page was due to gradual increase of iron concentration in the raw water and consequent increase of iron oxy hydroxide adsorption sites for the arsenic removal.

The curves became flatter showing more or less uniform removal efficiency after the raw water iron-arsenic ratio of 10 to 30 depending on the initial arsenic concentrations. For raw water arsenic concentration of 100ppb, the curve became flat at iron-arsenic ratio 30 which indicates the raw water iron concentration of 3mg/L; Whereas, for raw water arsenic concentration of 500ppb the curve got flatter at iron-arsenic ratio 10 which indicates the raw water iron concentration of 5mg/L.

When the raw water iron concentrations increased more ($Fe > 5\text{mg/L}$) the arsenic removal efficiency increased slightly, which indicates the presence of adequate adsorption site for arsenic removal but limited contact time due to fixed face velocity (0.5m/hr). For raw water As(V) concentration up to 200ppb and at (Fe/As) of 30, treated water As falls down to 35ppb.

Case-II: Arsenic(III)

The trend of arsenic removal performance here is analogous to the previous presentation but comparatively lower efficiency had been noticed. It was due to less affinity of As(III) adsorption by iron hydroxides in the normal pH range (6.5-8.5). For raw water As(III) concentration of 200ppb and at (Fe/As) of 30, treated water arsenic falls down to 75ppb as shown in figure 4.5; whereas for As(V) it was found 35ppb.

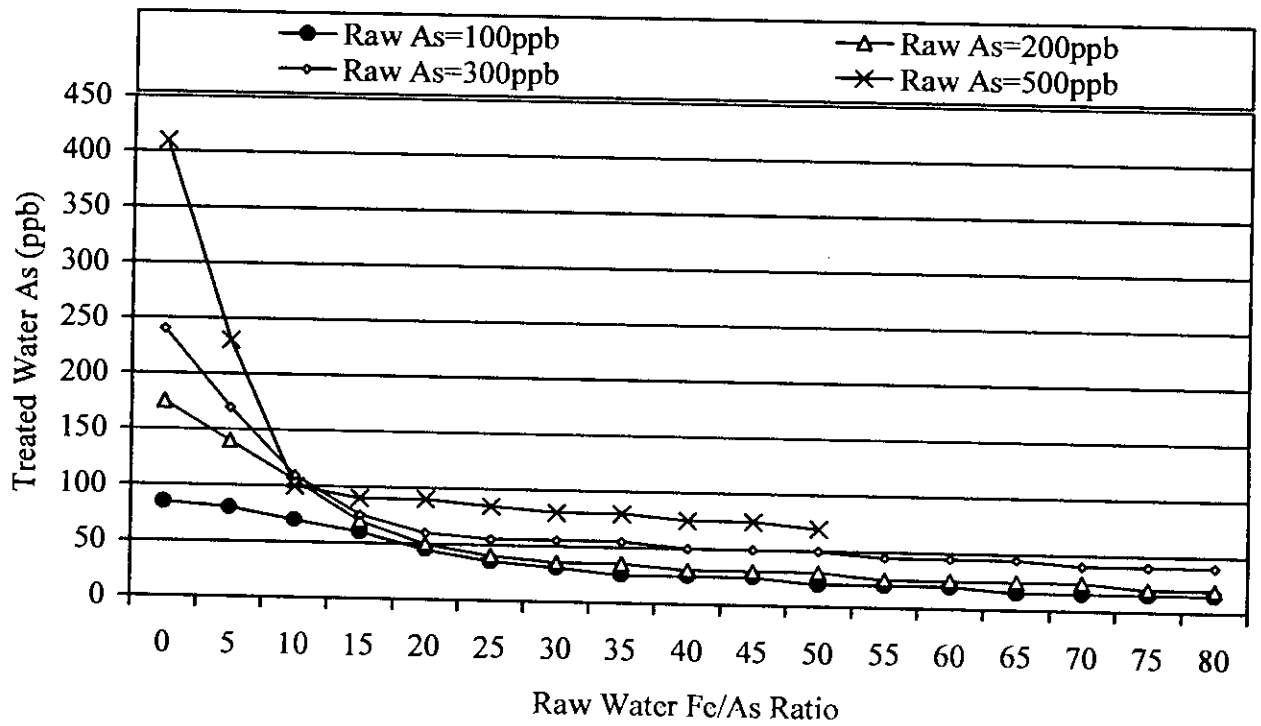


Fig.4.4 Variation of Arsenic(V) in Treated Water with Raw Water Iron/Arsenic Ratio (by wt.)

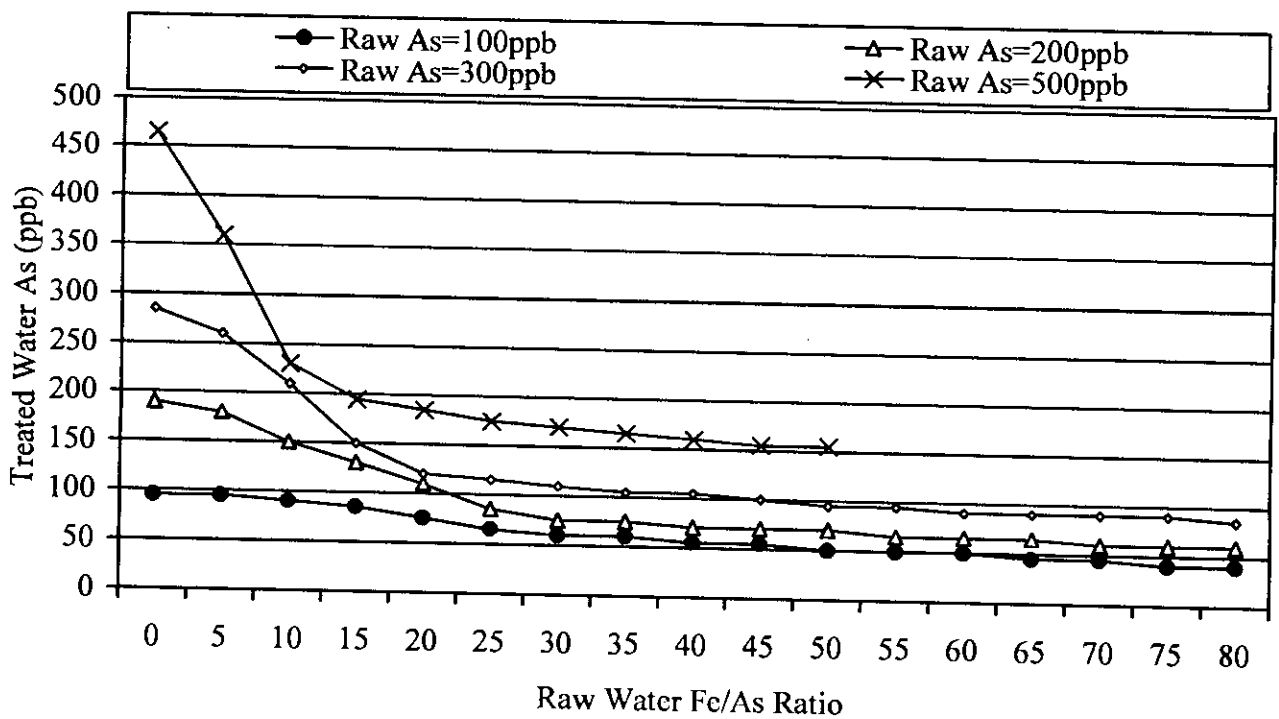


Fig.4.5 Variation of Arsenic(III) in Treated Water with Raw Water Iron/Arsenic Ratio (by wt.)

4.5 ARSENIC ADSORPTION LIMIT OF THE AIRU GRAVEL BEDS

As the face velocity increases, the adsorption of arsenic on to iron hydroxide precipitates decreases due to less contact time. In case of the designed AIRU and for raw water iron concentration of 5mg/L and arsenic concentration of 500ppb, the variation of treated water arsenic concentration with face velocity was observed and presented in the following Fig. 4.6. The face velocity for acceptable arsenic concentration of 50ppb (Bangladesh Standard) was found 0.4 m/hr for As(V) and 0.1 m/hr for As(III). The increased face velocity for As(V) in comparison to As(III) was due to higher adsorption affinity of As(V) on to iron hydroxide in the normal pH range (6.5-8.5). At the face velocity of 0.2 m/hr the treated arsenic concentrations were found As(V)=30ppb and As(III)=70ppb. Thus, for design purpose where the raw water arsenic concentration is within 500ppb and iron concentration is at least 5mg/L, design face velocity of 0.2 m/hr can be optimum to offset the same proportional effects of As(V) & As(III) and to maintain the ultimate product quality within the acceptable limit ($30 \times 0.5 + 70 \times 0.5 = 50$ ppb) without using any chemicals.

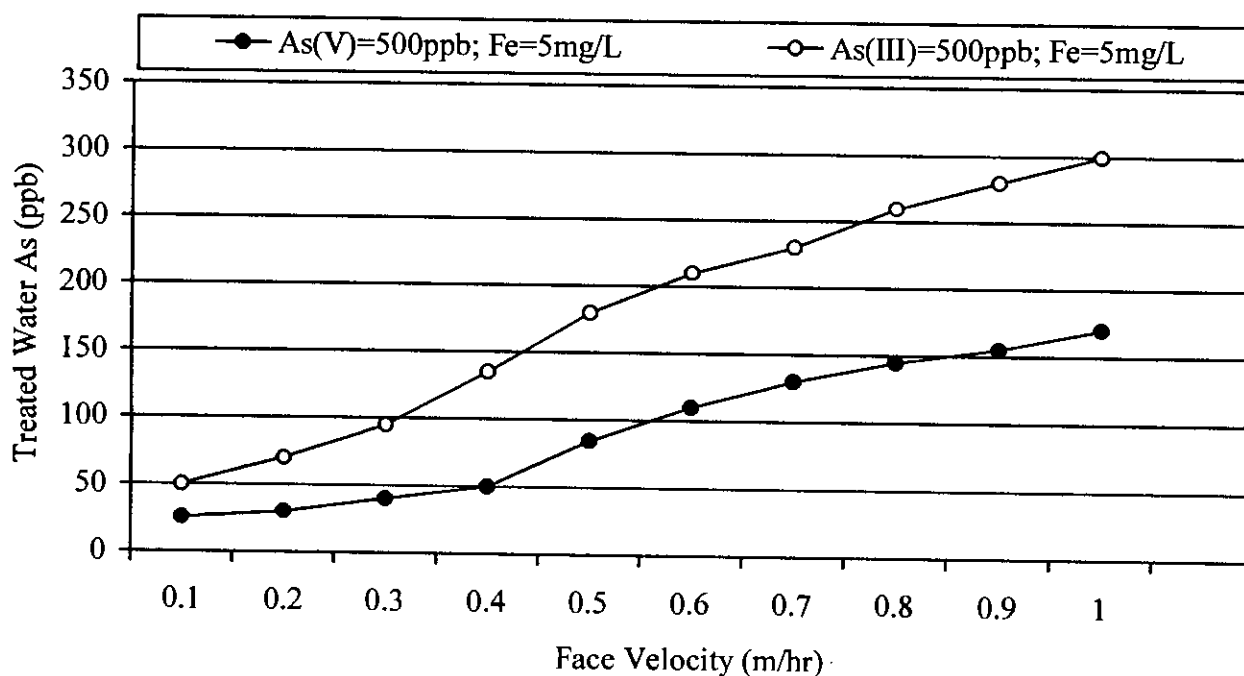


Fig.4.6 Variation of Arsenic Concentrations in Treated Water with Face Velocity (AIRU-Model at Laboratory)

Chapter 5

FIELD PERFORMANCE OF THE AIRU

5.1 VARIATION OF ARSENIC CONCENTRATIONS WITH BED VOLUME

AIRU-1 (Sonargaon):

Appreciable arsenic removal efficiency was noticed from the very beginning of the commissioning of the AIRU. The concentration of arsenic in the treated water was found less than 30ppb indicating a removal efficiency over 70%. Effluent arsenic concentration decreased with the passage of time due to gradually deposition of iron flocs on gravel surfaces. The precipitated iron particles along with other metal oxy-hydroxides provided increased adsorption surfaces. However, due to clogging of the interstices of coarse media the flow also reduced significantly (around 50%) with time when the bed was cleaned before the break through curve reached to the maximum contaminant level (MCL). Fig.5.1 shows first three cycles of filter run which indicates that the length of filter runs between cleaning were not uniform and reduced in successive cycles. However, the initial arsenic concentration was found slightly less in successive cycles due to the presence of previously deposited iron precipitates which was not cleaned completely. Approximately 240, 200, and 160BV were achieved respectively in the first three cycles which are satisfactory considering the economic advantages of using gravel in comparison to other adsorption media.

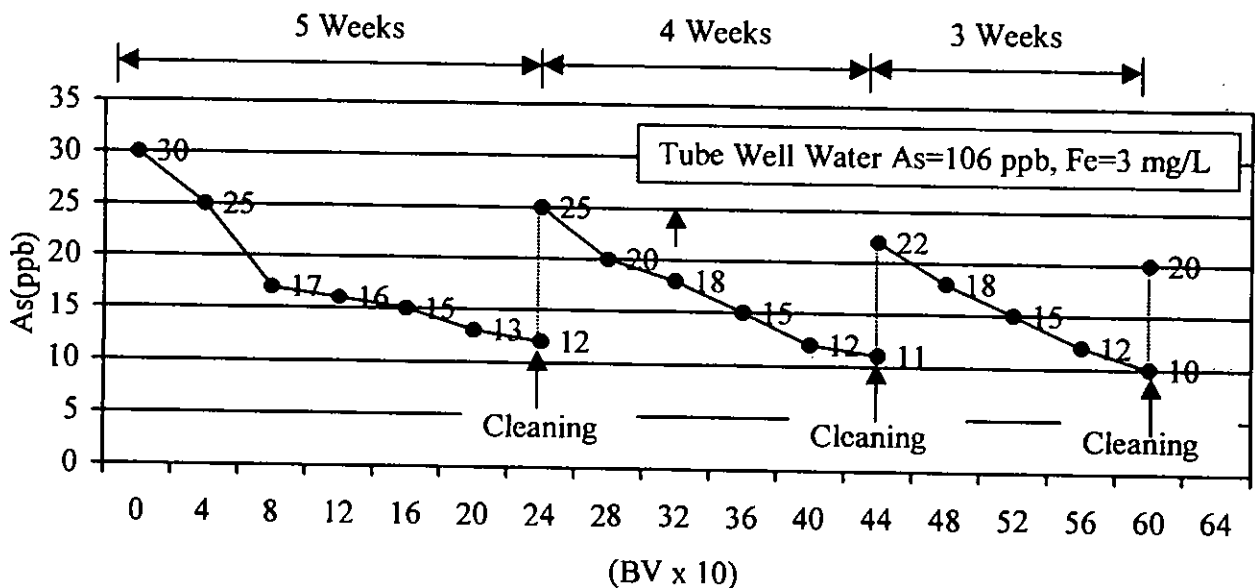


Fig.5.1 Variation of Arsenic in Treated Water with Bed Volume (AIRU-1)

AIRU-2 (Jikargacha):

Although the influent arsenic concentration was comparatively higher in the second unit the removal performance was found better in comparison to the first unit. The arsenic concentration in the treated water was found less than 32 ppb indicating over 80% removal efficiency. This was because the raw water iron concentration was also higher resulting more deposition of iron precipitates on coarse media. Moreover, due to the increase of adsorption surfaces through reduction of number of chambers from three to two, the length of run between cleaning was also longer (around 5 weeks) and around 320 BV was achieved before the flow reduced to less than 50% of its influent flow. Fig.5.2 shows the first two cycles of filter run.

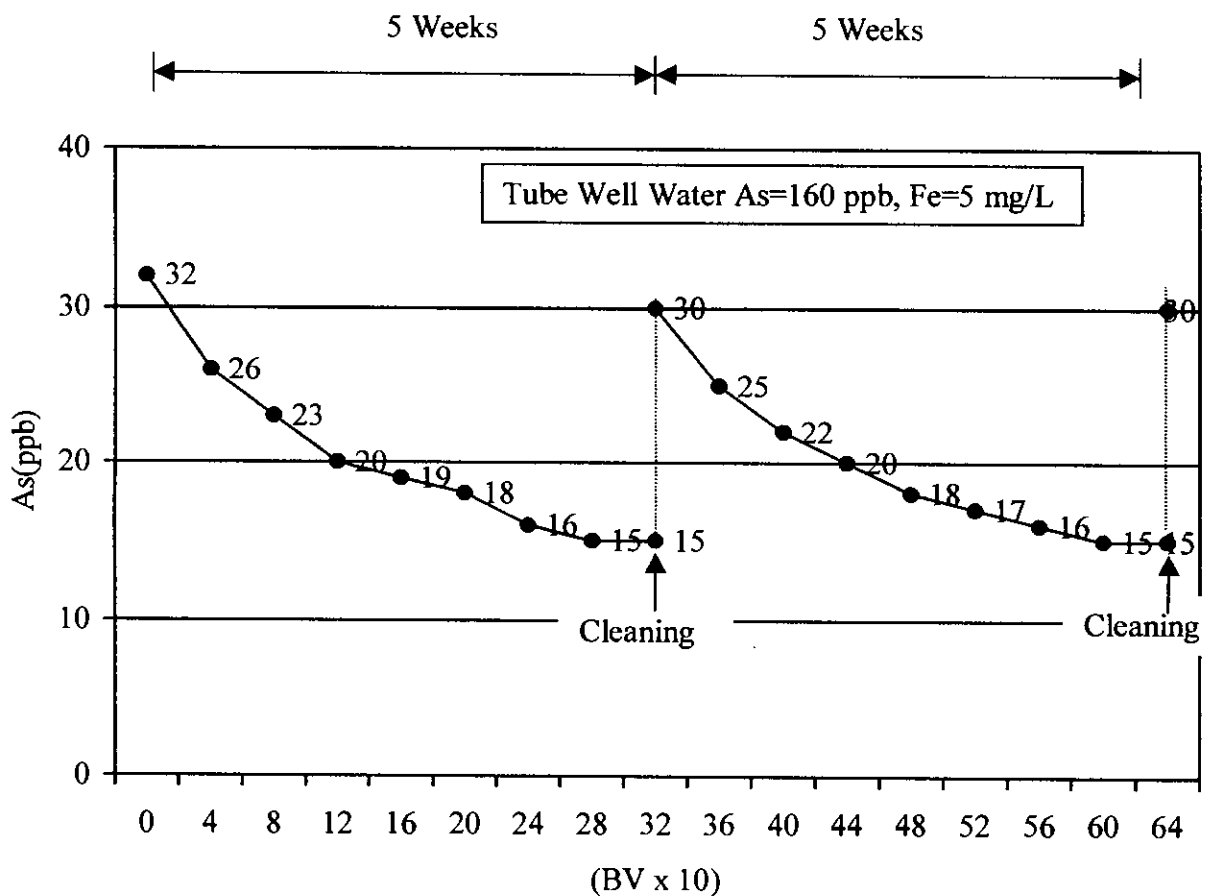


Fig.5.2 Variation of Arsenic in Treated Water with Bed Volume (AIRU-2)

AIRU-3 (Chougacha):

The influent arsenic concentration in the third unit was 430 ppb which is reasonably higher in comparison to first and second units. Intermittent dosage of bleaching powder oxidized As(III) to As(V) and aided the adequate adsorption of arsenic on iron oxy hydroxides. The step up pattern of arsenic concentration from 30 ppb to 75 ppb was observed in the range of (250 ~ 400) BV due to gradually avoiding the intermittent bleaching powder dosage in this time interval. As a result break through curve reached to the maximum contaminant level (MCL) before the effluent flow reduced significantly to 50% of the influent flow of water. The unit was operated for further period of time to determine the maximum effluent arsenic concentration and the corresponding bed volume at the point when the effluent flow reduced to 50% of its influent flow was found around 400 BV. Maximum 75 ppb effluent arsenic concentration was detected at that condition, however, after cleaning and subsequent addition of bleaching powder the arsenic concentration reduced to 45 ppb. The result indicates that for tube wells with acute arsenic problem (approximately over 200 ppb) intermittent dosage of some oxidizing agent is required to maintain the effluent arsenic concentration within the permissible limit.

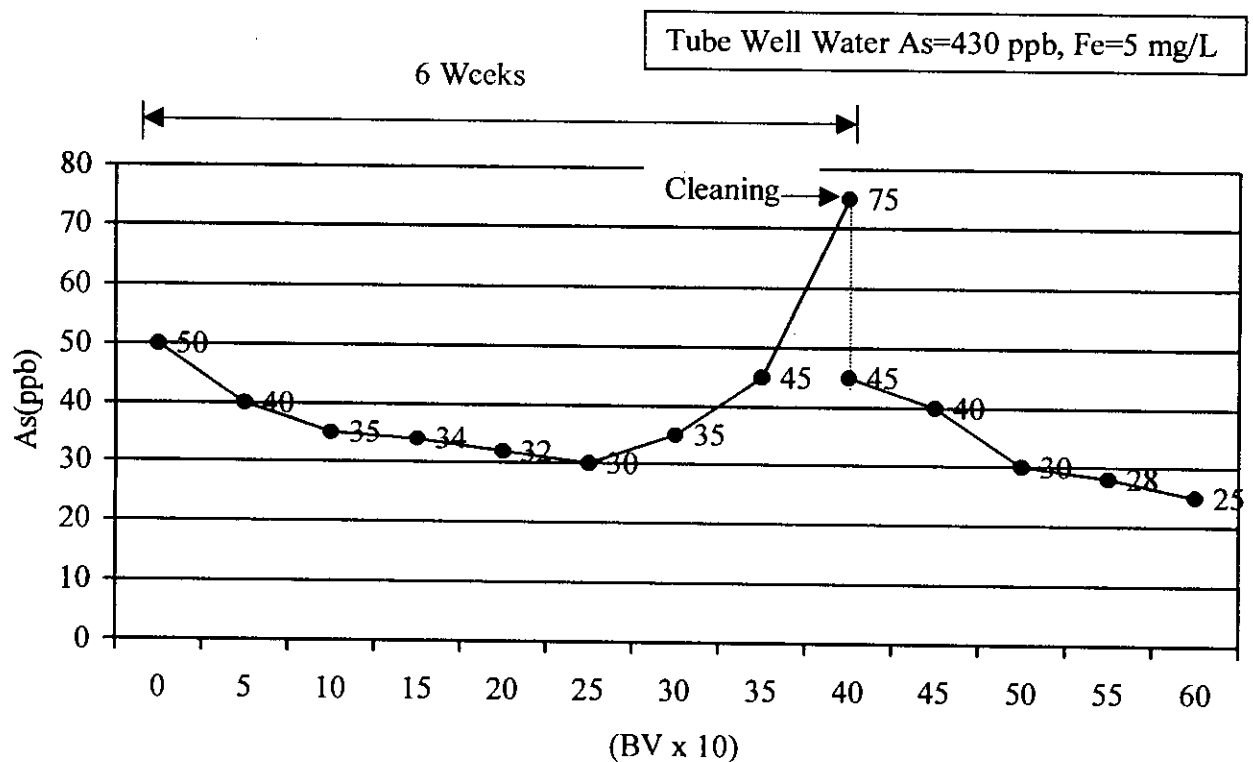


Fig.5.3 Variation of Arsenic in Treated Water with Bed Volume (AIRU-3)

AIRU-4 (Avoy nagar):

Similar to the third unit influent arsenic concentration of the fourth unit was also reasonably high. As a consequence the break through curve reached to the maximum contaminant level (MCL) at bed volume around 350 due to gradually avoiding the intermittent dosage of bleaching powder before the effluent flow reduced significantly to 50% of the influent flow. However, at the beginning of the operation the initial arsenic concentration was higher than the MCL of 50 ppb and reduced below the allowable limit after some time of operation. This was due to incomplete oxidation of As(III) to As(V), which eventually responsible for less adsorption of As on Fe oxy hydroxides. But when the bed was cleaned and oxidant dosage was followed after break through the initial arsenic concentration was found 50 ppb. This was due to the presence of previously deposited iron precipitates which was not removed completely during cleaning.

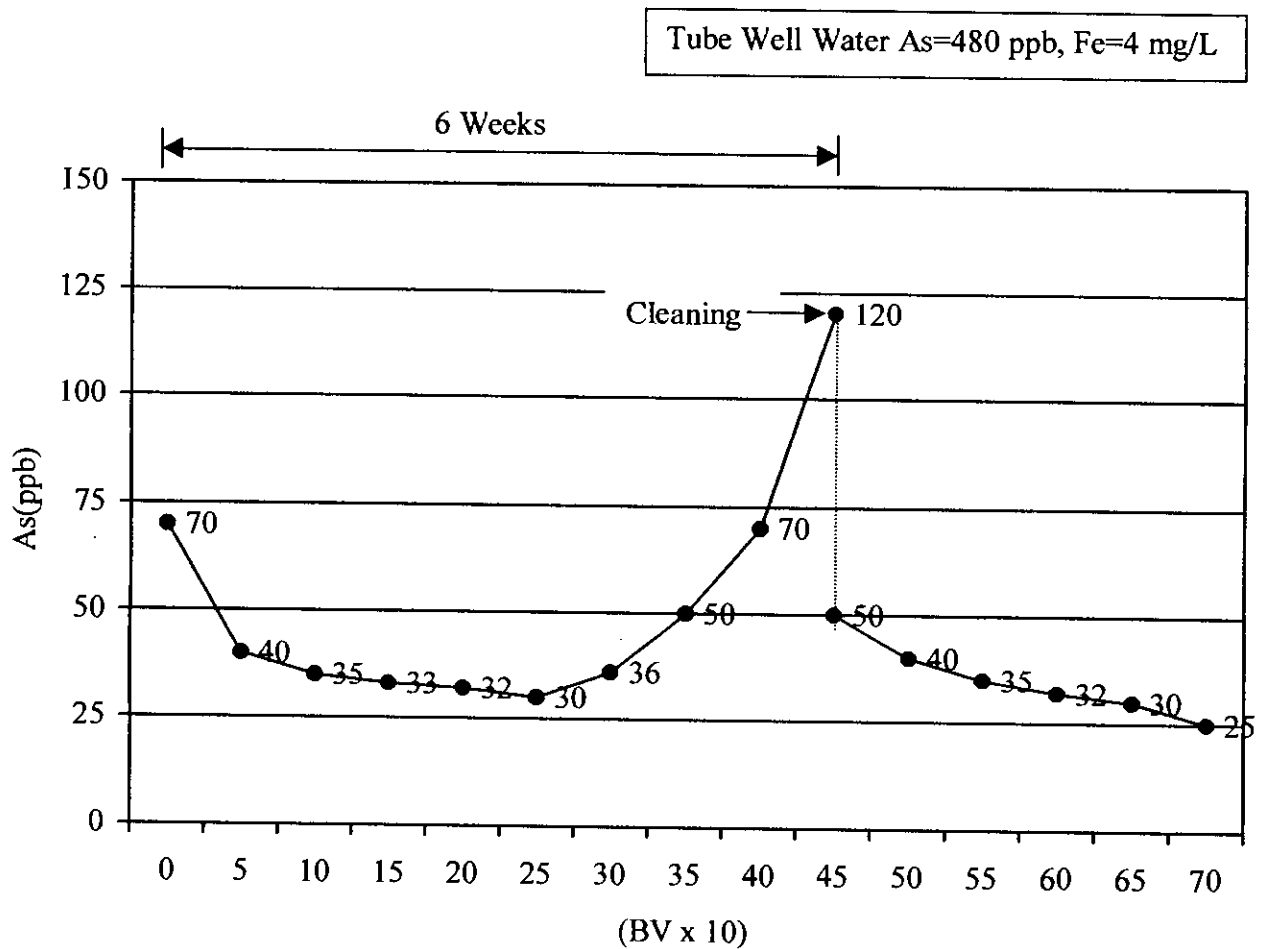


Fig.5.4 Variation of Arsenic in Treated Water with Bed Volume (AIRU-4)

AIRU-5 (Jikargacha):

Although the influent arsenic concentration was high but due to using intermittent bleaching powder dosage, break through curve never reached to the maximum contaminant level (MCL) before the effluent flow reduced significantly to 50% of the influent flow of water. The arsenic concentration in the treated water in most of the time of filter run was found less than 40 ppb indicating over 85% removal efficiency. The effluent flow of water became constricted to 50% of the influent flow at comparatively less bed volume (around 320 BV). This was because the raw water iron concentration was also higher resulting more deposition of iron precipitates on coarse media. Moreover, due to the increase of face velocity through coarse media roughing filter (approximately 1.5 m/hr) the arsenic concentration in the treated water was found fluctuating because of carrying over micro-flocs of iron hydroxides on which arsenic might adsorbed. Fig.5.5 shows the first two cycles of filter run.

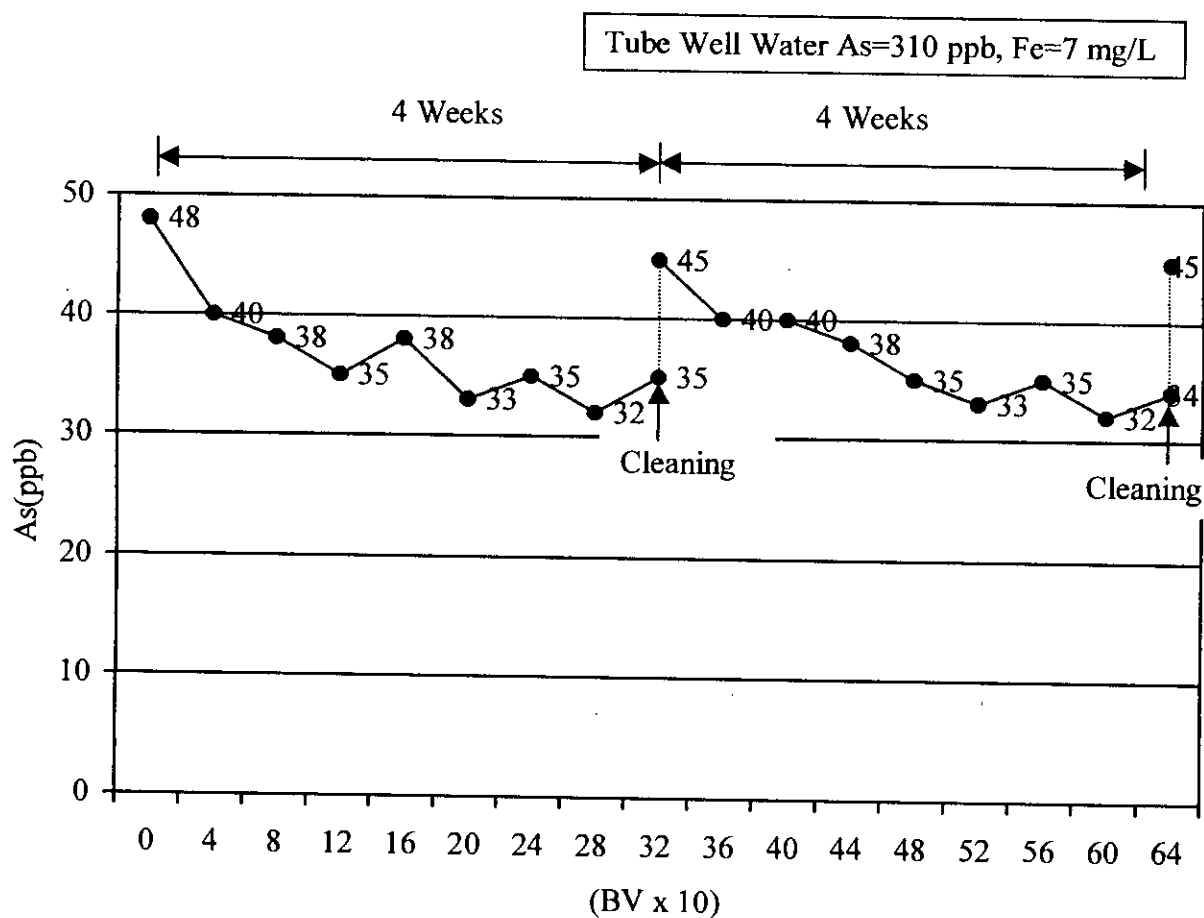


Fig.5.5 Variation of Arsenic in Treated Water with Bed Volume (AIRU-5)

Summary of As Removal Efficiency:

The initial concentration of arsenic in the treated water of the first two units were found less than 30ppb indicating a minimum removal efficiency over 70% without using any chemicals. Effluent arsenic concentration decreased with the passage of time due to gradual deposition of iron flocs on gravel surfaces.

The flow also reduced significantly (around 50%) due to clogging of the interstices of coarse media with time when the bed was cleaned before the break through curve reached the maximum concentration level (MCL). In the first unit on an average 200 bed volumes were achieved and length of run between cleaning was 4 weeks in the first three cycles of operation. Where as in the second unit due to the increase of adsorption surfaces through reduction of number of chambers from three to two, the length of run between cleaning was longer (around 5 weeks) and around 320 bed volume was achieved before the flow reduced to less than 50% of its influent flow.

However, in the third and fourth units due to the presence of very high concentration of arsenic (over 400 ppb) the break through curve reached to the maximum contaminant level (MCL) due to gradually avoiding the intermittent bleaching powder dosages before the effluent flow reduced significantly to 50% of the influent flow. Although further modifications were made in those two units to increase the flow of water through reduction of head loss, on an average 425 bed volume was achieved before significant reduction of flow and the length of run between cleaning was around 6 weeks.

In the fifth unit a smaller size of AIRU was considered for economic reason and thus a higher face velocity (approximately 1.5 m/hr) was allowed through coarse media roughing filter. As a result the arsenic concentration in the treated water was found fluctuating because of carrying over micro-flocs of iron hydroxides on which arsenic might adsorbed.

The result indicates that around 70% arsenic removal can be achieved directly through the AIRU without using any chemicals but for tube wells with acute arsenic problem (approximately over 200 ppb) intermittent dosage of bleaching powder is required to maintain the effluent arsenic concentration within the allowable limit.

5.2 VARIATION OF IRON CONCENTRATIONS WITH BED VOLUME

AIRU-1 (Sonargaon):

Appreciable iron removal efficiency was noticed from the very beginning of the commissioning of AIRU. The concentration of iron in the treated water was found less than 0.5mg/L indicating a minimum removal efficiency over 80%. The iron removal efficiency increased with the passage of time (over 90%) due to gradually deposition of iron flocs on the gravel surfaces and in the interstices. However, due to clogging of the interstices of coarse media the flow also reduced significantly (around 50%) with time when the bed was cleaned to reduce the head loss and to recover the flow of water from the plant. Fig.5.6 shows first three cycles of filter run which indicates that the length of filter run between cleaning were not uniform and reduced in successive cycles due to the presence of previously deposited iron precipitates which was not cleaned completely. This frequent clogging problem had been minimized through design modification in the subsequent treatment units.

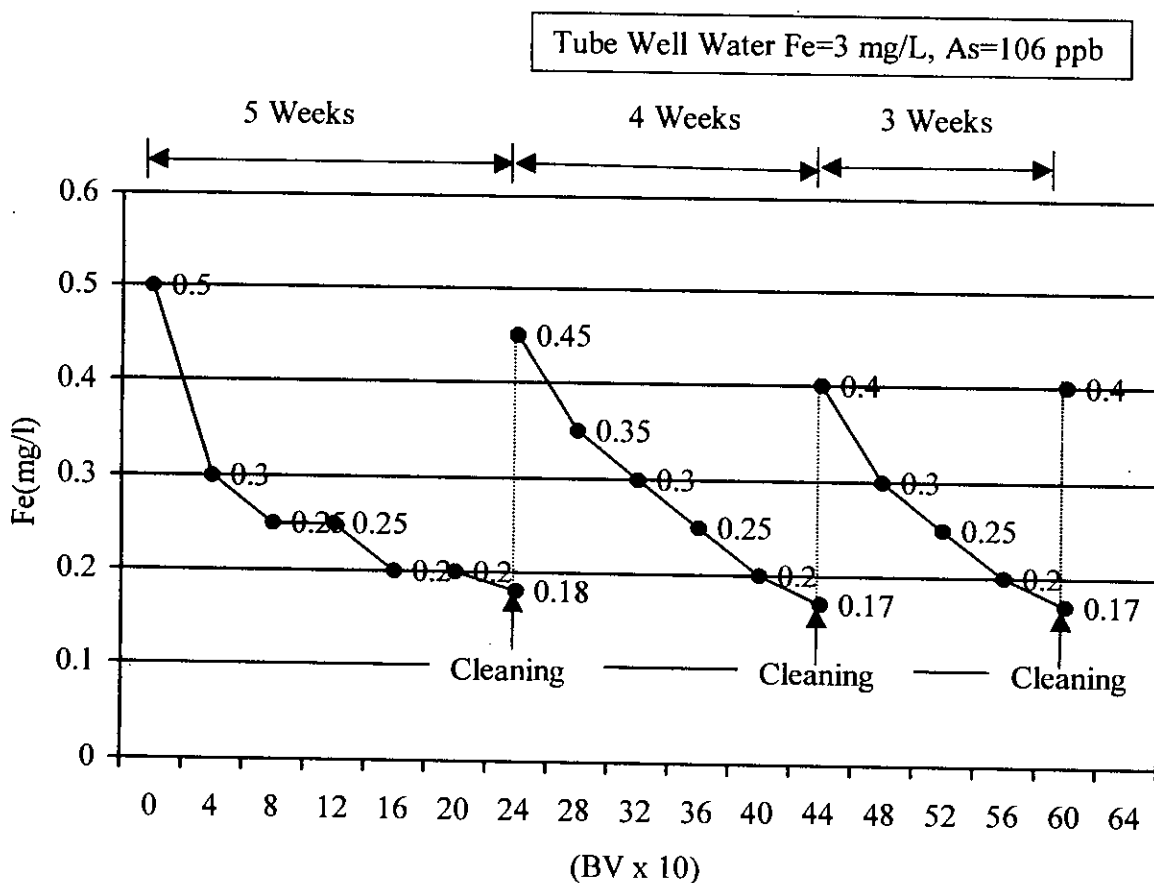


Fig.5.6 Variation of Iron in Treated Water with Bed Volume (AIRU-1)

AIRU-2 (Jhikorgacha):

Although the influent iron concentration was comparatively higher in the second unit the removal performance was found better in comparison to the first unit. The iron concentration in the treated water was found less than 0.6 mg/L indicating over 85% removal efficiency. Since the raw water iron concentration was higher there were more deposition of iron precipitates on coarse media from the very beginning and as a result more iron precipitates from water were removed. The iron removal efficiency increased with the passage of time (over 95%) due to gradually deposition of iron flocs on the gravel surfaces and in the interstices. During the second cycle of operation the initial iron concentration was found 0.45 mg/L. This was due to the presence of previously deposited iron precipitates which was not removed completely during cleaning.

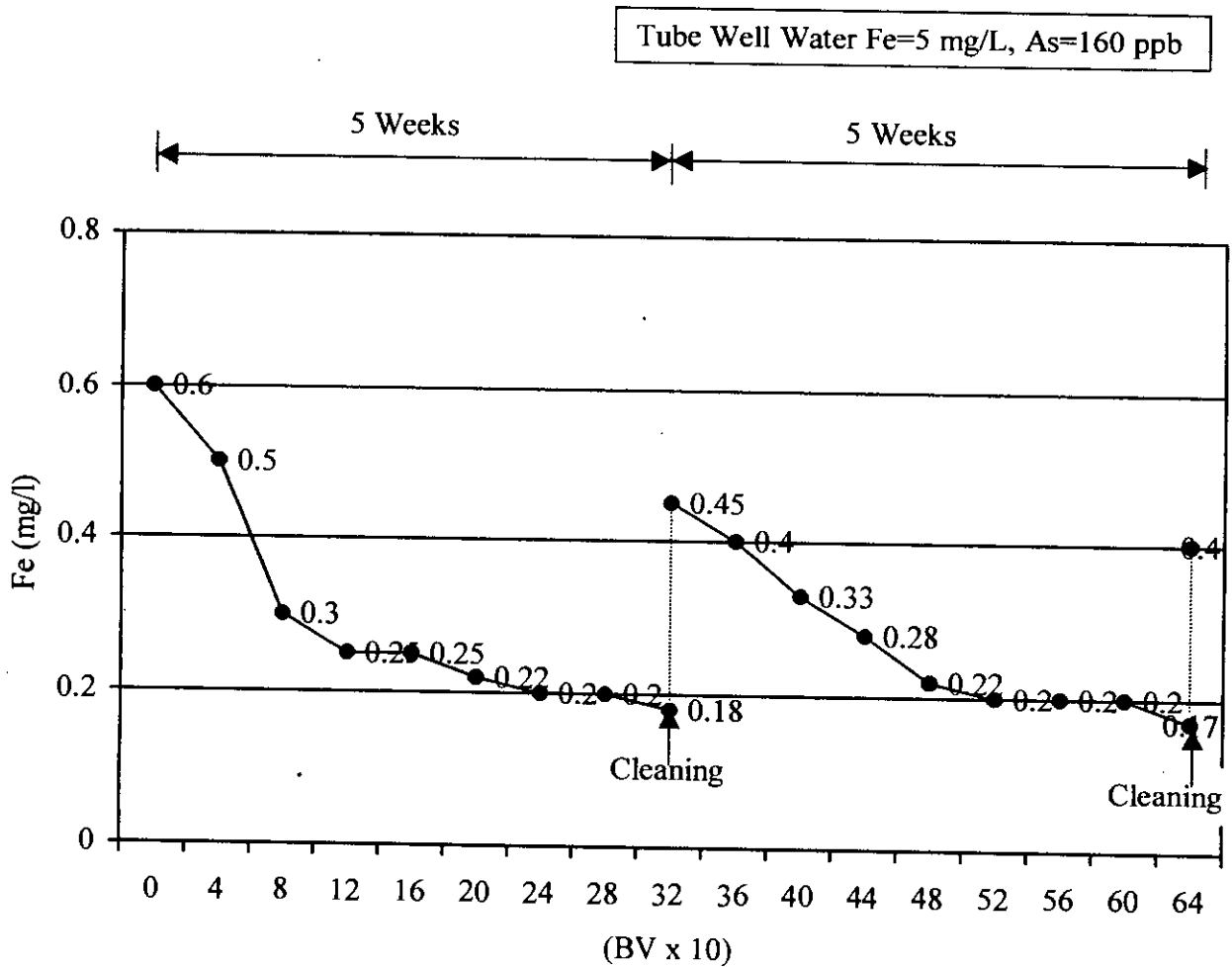


Fig.5.7 Variation of Iron in Treated Water with Bed Volume (AIRU-2)

AIRU-3 (Chougacha):

Although raw water iron concentration of both the second and third units were same; the initial iron concentration was found slightly higher (0.8 mg/l) in the effluent of third unit indicating a removal efficiency around 85%. The effluent iron concentration initially reduced with the passage of time, however, after 4 weeks of run the effluent iron concentration again started to increase. This was because the flow of tube well water was comparatively higher and as a result contact time was comparatively less and due to shearing forces sloughing of precipitated iron particles might be occurred. The bed was cleaned only when the flow reduced to 50% of its influent flow. However, at that stage the effluent iron concentration was found below the maximum contaminant level of 1 mg/L.

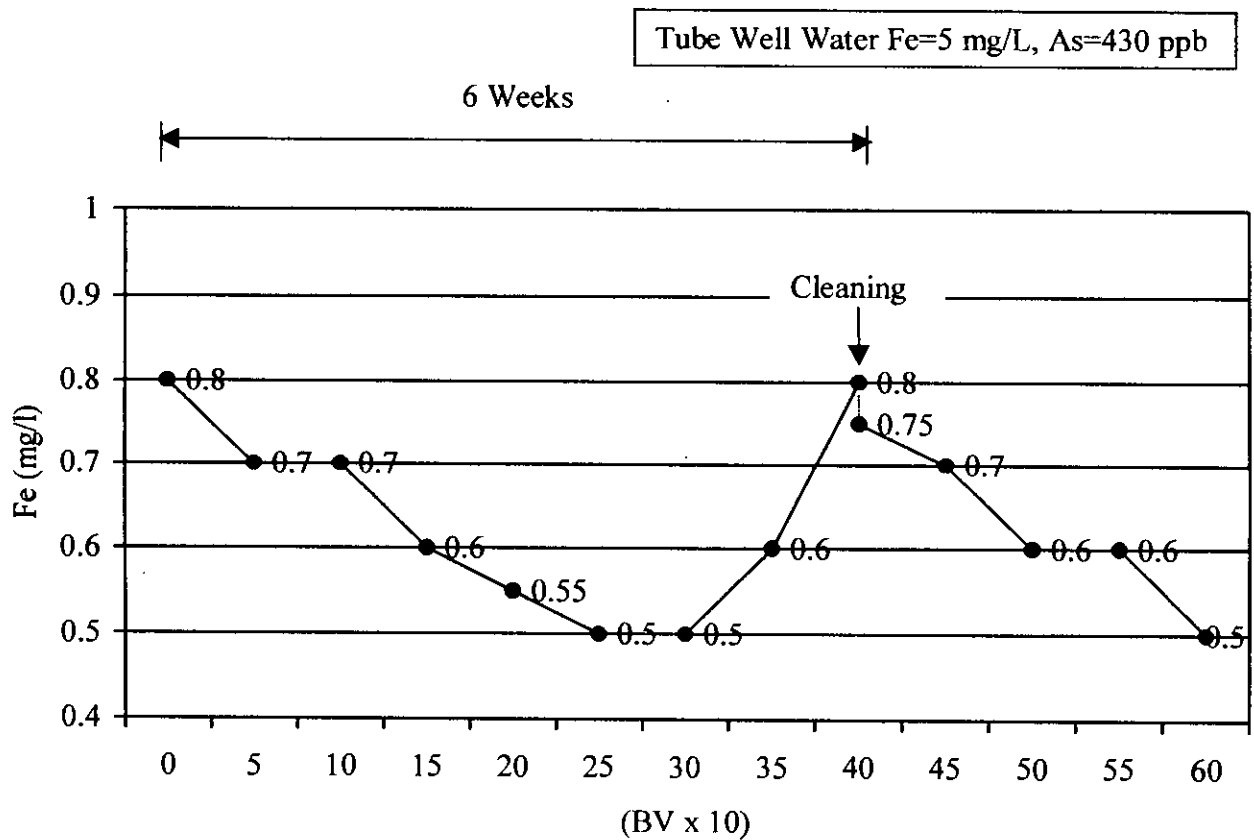


Fig.5.8 Variation of Iron in Treated Water with Bed Volume (AIRU-3)

AIRU-4 (Avoy nagar):

Although the raw water iron concentration was comparatively less than the third unit the iron removal efficiency was around 80% which indicates that lower the raw water iron concentration smaller the iron removal efficiency. However, the removal efficiency pattern was analogous to the third unit. The effluent iron concentration initially reduced with the passage of time, however, after 3.5 weeks of run the effluent iron concentration again started to increase.

This was because the flow of tube well water was comparatively higher and as a result contact time was comparatively less and due to higher pore velocity shearing forces caused sloughing of precipitated iron particles which ultimately appeared with the effluent water.

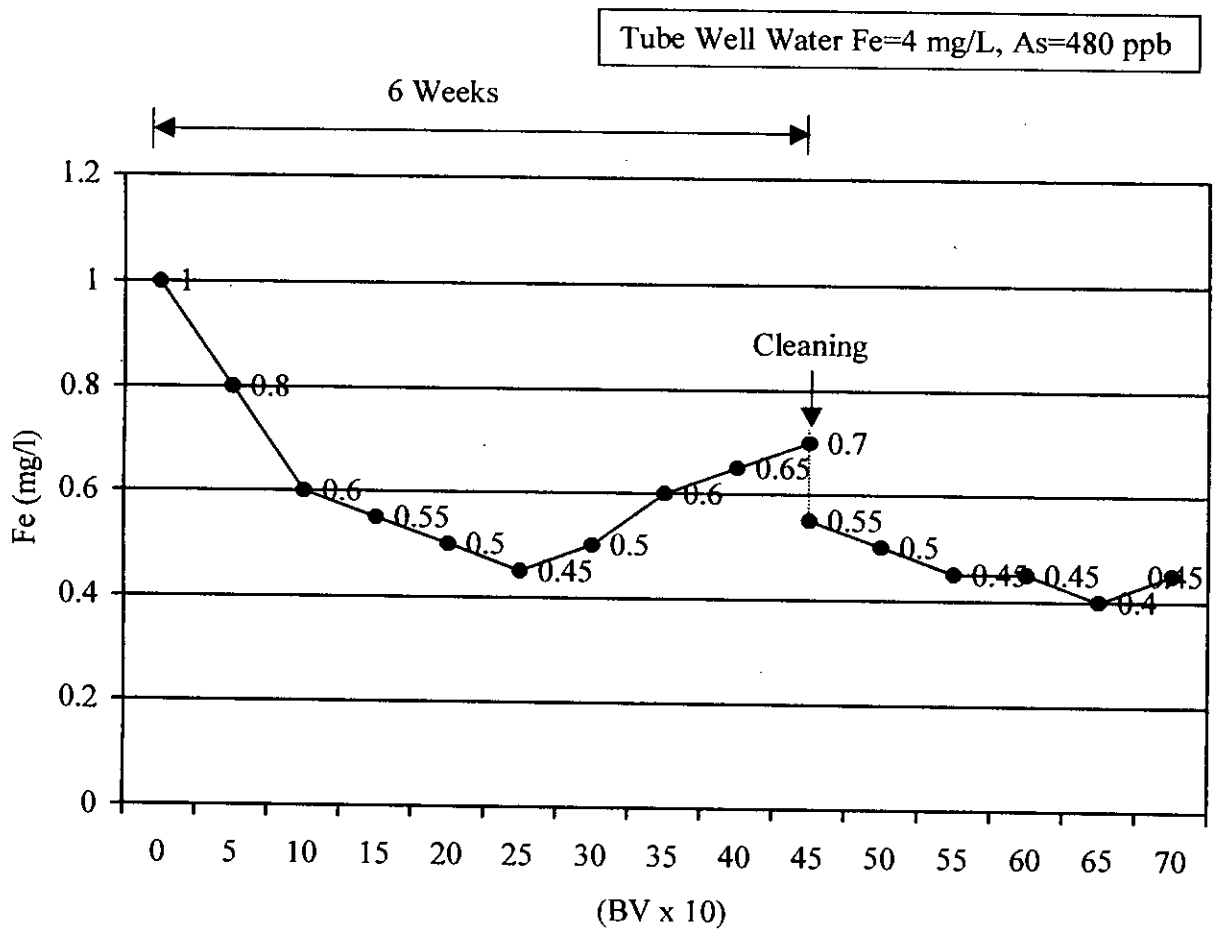


Fig.5.9 Variation of Iron in Treated Water with Bed Volume (AIRU-4)

AIRU-5 (Jhikorgacha):

The influent iron concentration was comparatively higher (7 mg/l) in this unit. The iron concentration in the treated water was found varied in the range of (1.2 ~0.6)mg/L indicating removal efficiency from (83 ~91)%. The effluent iron concentration initially reduced with the passage of time, however afterwards it fluctuated. This was because the face velocity through the course media roughing filter was comparatively higher (around 1.5 m/hr) in this unit and as a result contact time was comparatively less and due to shearing forces sloughing of precipitated iron particles might be occurred. The bed was cleaned only when the flow reduced to 50% of its influent flow at comparatively less bed volume of around 320 BV. This was because the raw water iron content was high, which causes greater deposition of precipitates in the interstices of the course media and eventually caused less filter run.

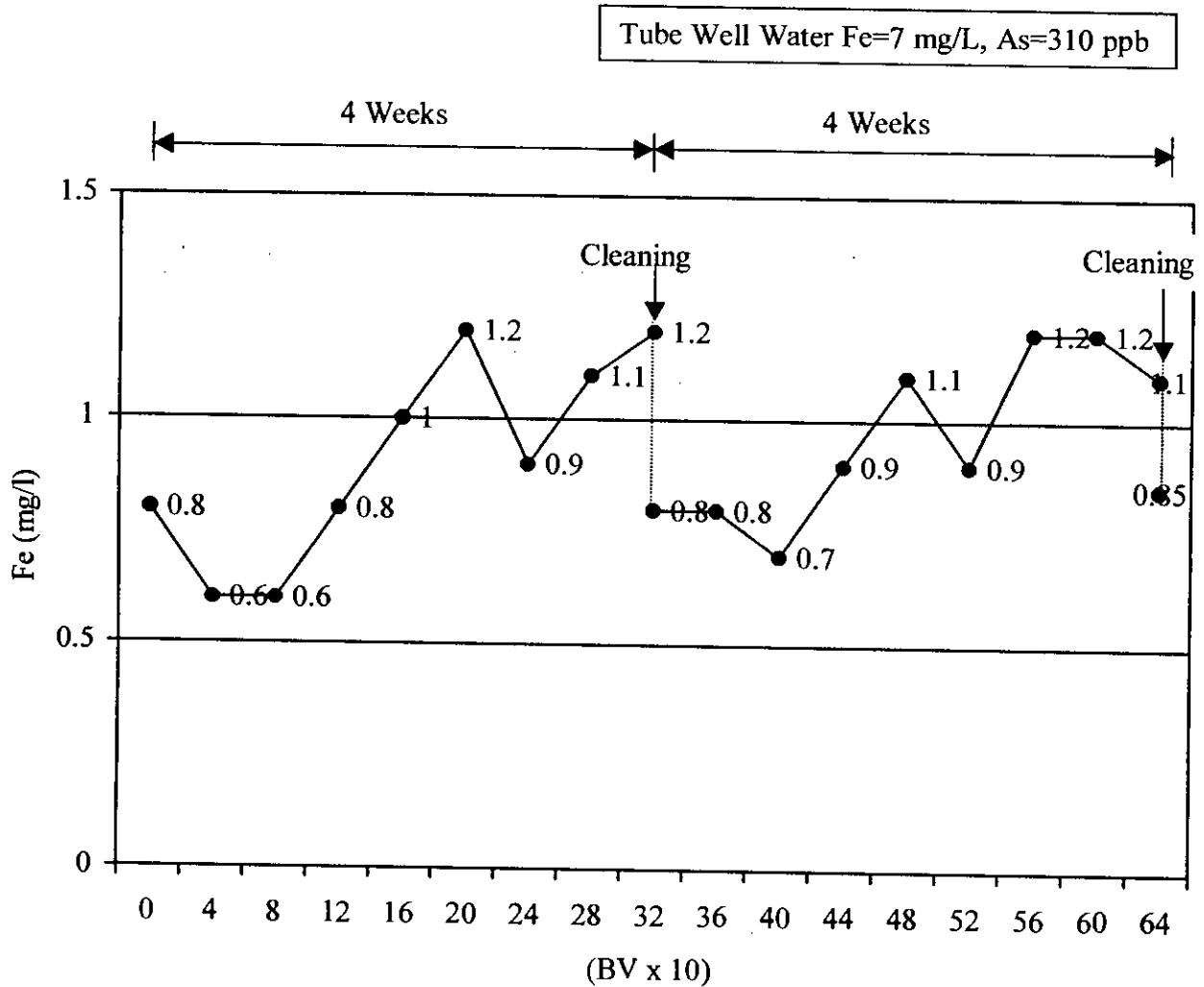


Fig.5.10 Variation of Iron in Treated Water with Bed Volume (AIRU-5)

Summary of Iron Removal Efficiency:

Appreciable iron removal efficiency was noticed from the very beginning of the commissioning of all the AIRUs. The initial concentrations of iron in the treated water of the first and second units were found less than 0.6mg/L indicating a minimum removal efficiency over 85%. The iron removal efficiency increased with the passage of time (over 90%) due to gradually deposition of iron flocs on the gravel surfaces and in the interstices. More removal was observed in case of comparatively higher raw water iron concentration.

However, due to clogging of the interstices of coarse media the flow of water reduced with the passage of time and when the flow reduced significantly (around 50%) the bed was cleaned to reduce the head loss and to recover the flow of water from the plant. The length of filter run between cleaning were not uniform and reduced in successive cycles due to the presence of previously deposited iron precipitates which was not cleaned completely.

Iron removal performance of the third and fourth units were analogous and differ from the first two units. Although effluent iron concentration of the third and fourth units were within the maximum contaminant level of 1 mg/L the removal efficiencies were comparatively less than the first two units. Moreover, the effluent iron concentration initially reduced with the passage of time, however, after 3.5 to 4 weeks of run the effluent iron concentration again started to increase. This was because the flow of tube wells water were comparatively higher and as a result contact time was comparatively less and due to higher pore velocities shearing forces caused sloughing of precipitated iron particles which ultimately appeared with the effluent water. For the same reason arsenic concentration also increased with the increase of iron concentration because arsenic adsorbed and co-precipitated with iron.

In case of fifth unit the iron content in the treated water was found fluctuating due to high face velocity (approximately 1.5 m/hr) through coarse media roughing filter and as a result carrying over of micro-flocs of iron hydroxides in the effluent water.

The results revealed that face velocity is an important parameter determining the removal performance of AIRU. The optimum face velocity of water was found around 0.5 m/hour.

5.3 CORRELATION BETWEEN ARSENIC AND IRON REMOVAL IN THE AIRU(S)

Table 5.1: Combined Arsenic and Iron Removal Performances of Different AIRU(s)

| Location | Raw Water As (ppb) | Raw Water Fe (ppm) | As Removal (%) | Fe Removal (%) | Fe/As (by wt.) ratio |
|----------|-----------------------|-----------------------|-------------------|-------------------|-------------------------|
| AIRU-1 | 106 | 3 | 70 | 85 | 28.30 |
| AIRU-2 | 160 | 5 | 80 | 88 | 31.25 |
| AIRU-3 | 430 | 5 | 80 | 85 | 11.63 |
| AIRU-4 | 480 | 4 | 75 | 80 | 8.33 |
| AIRU-5 | 310 | 7 | 80 | 88 | 22.58 |

The above mentioned table shows that the arsenic and iron removal performances through the AIRU(s) are close to the following correlation between Fe and As removal in treatment plants (Ahmed and Rahman, 2000).

$$\text{As Rem. (\%)} = 0.8718 \times \text{Fe Rem. (\%)} + 0.4547 \quad \text{Where, } R^2 = 0.6911$$

In case of AIRU-2 the iron and arsenic removal efficiency was observed higher in comparison to AIRU-1 because of higher Fe/As ratio in raw water and here the treatment processes were performed without using any chemicals.

For, AIRU-3, 4 and 5 the raw water arsenic concentrations were high and thus bleaching powder was used in the treatment processes as an oxidizing agent in order to convert As(III) to As(V). The highest removal of iron and arsenic among these three units were found in AIRU-5 where the raw water Fe/As ratio was higher in comparison to other two units.

5.4 VARIATION OF FLOW, NUMBER OF USERS AND CONSUMPTION PATTERN IN AIRU(S)

5.4.1 Variation of Flow with Time:

AIRU-1 (Sonargaon):

A thin sand filter bed was used in the 3rd chamber of this unit and as a result abrupt changes of head loss of water occurred from the very beginning of the filter run. The initial flow of effluent water was 42% of the tube well water flow and within the next few days the flow further reduced down to 34% of the tube well water flow. It was decided to discard the sand bed to increase the flow and as a result the flow recovered again up to 45% of the tube well water flow. After this modification the changes of flow with time was gradual and after 5 weeks of run when the flow reduced down to one third of its influent flow it was decided to clean the bed. Fig.5.11 shows first three cycles of filter run which indicates that the length of filter run between cleaning were not uniform and reduced in successive cycles.

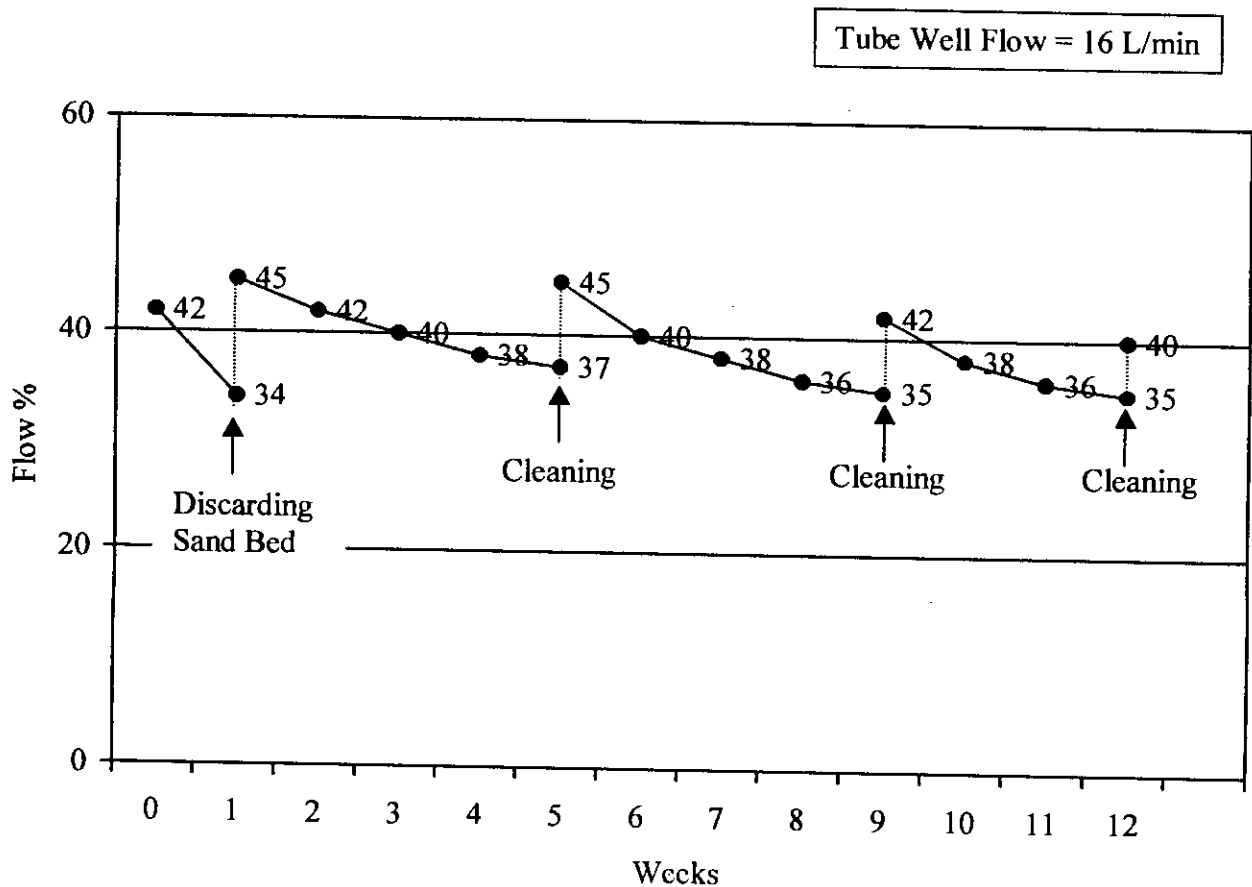


Fig.5.11 Variation of Flow of Treated Water (as a % of Tubewell Flow) with Time (AIRU-1 at Sonargaon)

AIRU-2 (Jhekorgacha):

Major design modification was made in the second unit to minimize the head loss and the unit was constructed with two chambers in place of three chambers. As a result initial effluent flow of 65% of the influent flow was achieved. The effluent water flow then gradually reduced down with time and reached to 50% of its influent flow within 5 weeks of filter run. Cleaning operation was done at this stage and the flow again recovered up to 63% of the tube well water (influent) flow. Cleaning operation was done at this stage and the flow again recovered up to 63% of the tube well water (influent) flow.

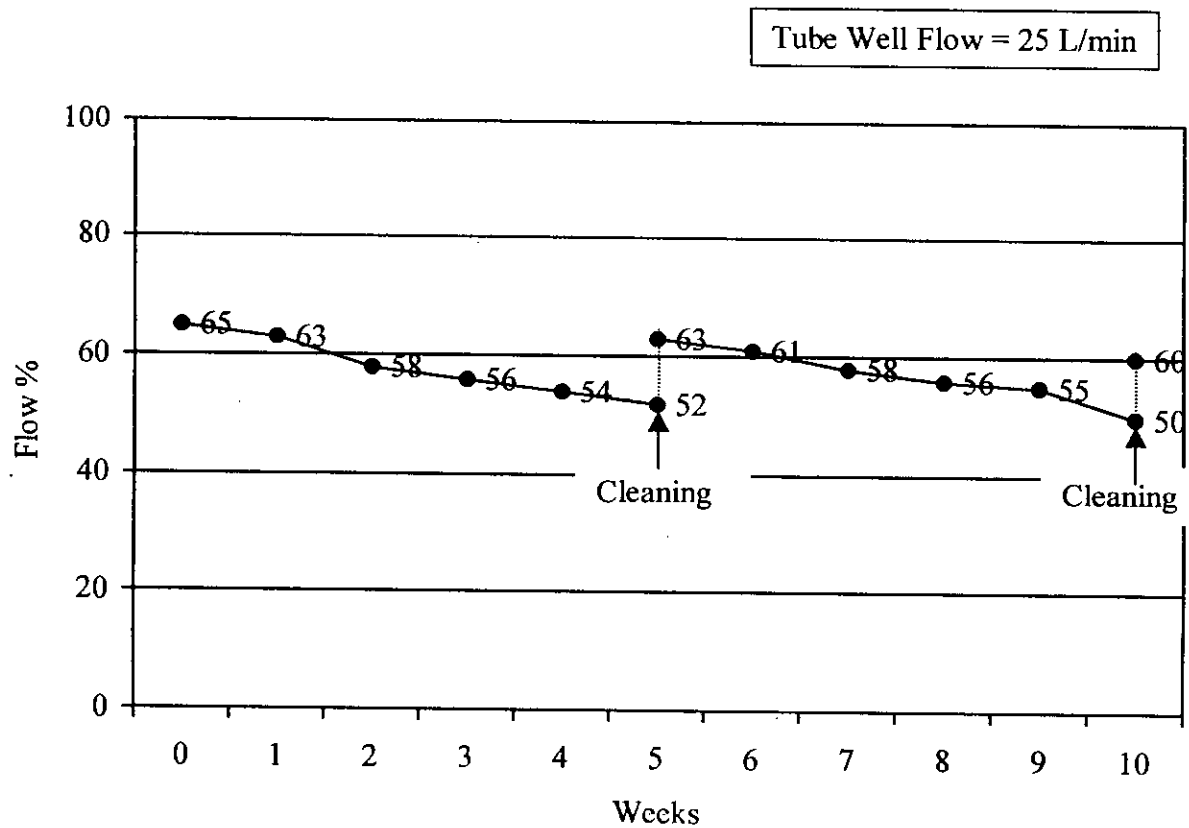


Fig.5.12 Variation of Flow of Treated Water (as a % of Tubewell Flow) with Time (AIRU-2 at Jhikorgacha)

AIRU-3 (Chougacha):

Further modification was made in the third unit to minimize the head loss through placing coarser gravel materials at the bottom of the first chamber and making bigger holes in the perforated slab. The flow of effluent water from this unit was found 75% of the tube well water (influent) flow at the beginning stage of operation and then reduced gradually due to deposition of iron flocs on the gravel surfaces and in the interstices of the filter bed. The flow reduced to 58% after 6 weeks of filter run when cleaning operation was done and the flow again recovered up to 74% of the tube well water flow.

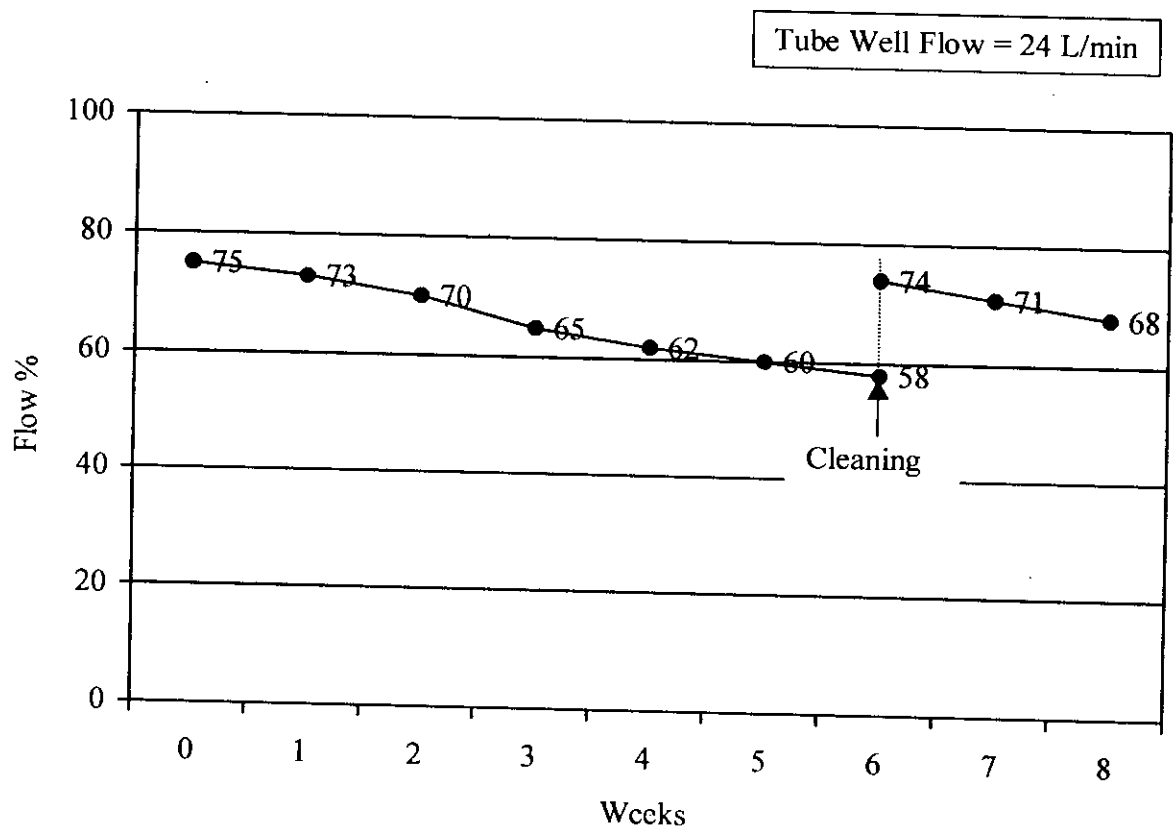


Fig.5.13 Variation of Flow of Treated Water (as a % of Tubewell Flow) with Time (AIRU-3 at Chougacha)

AIRU-4 (Avoynagar):

The interconnecting pipes between the first and second chamber were increased in the fourth unit for getting increased flow of treated water. The highest flow of treated water was obtained in this unit and the initial effluent water flow was 82% of the tube well water flow. This flow gradually reduced down to 63% of the influent flow after 6 weeks of filter run. Cleaning operation was done at that stage and the flow recovered up to 80% of the tube well water (influent) flow.

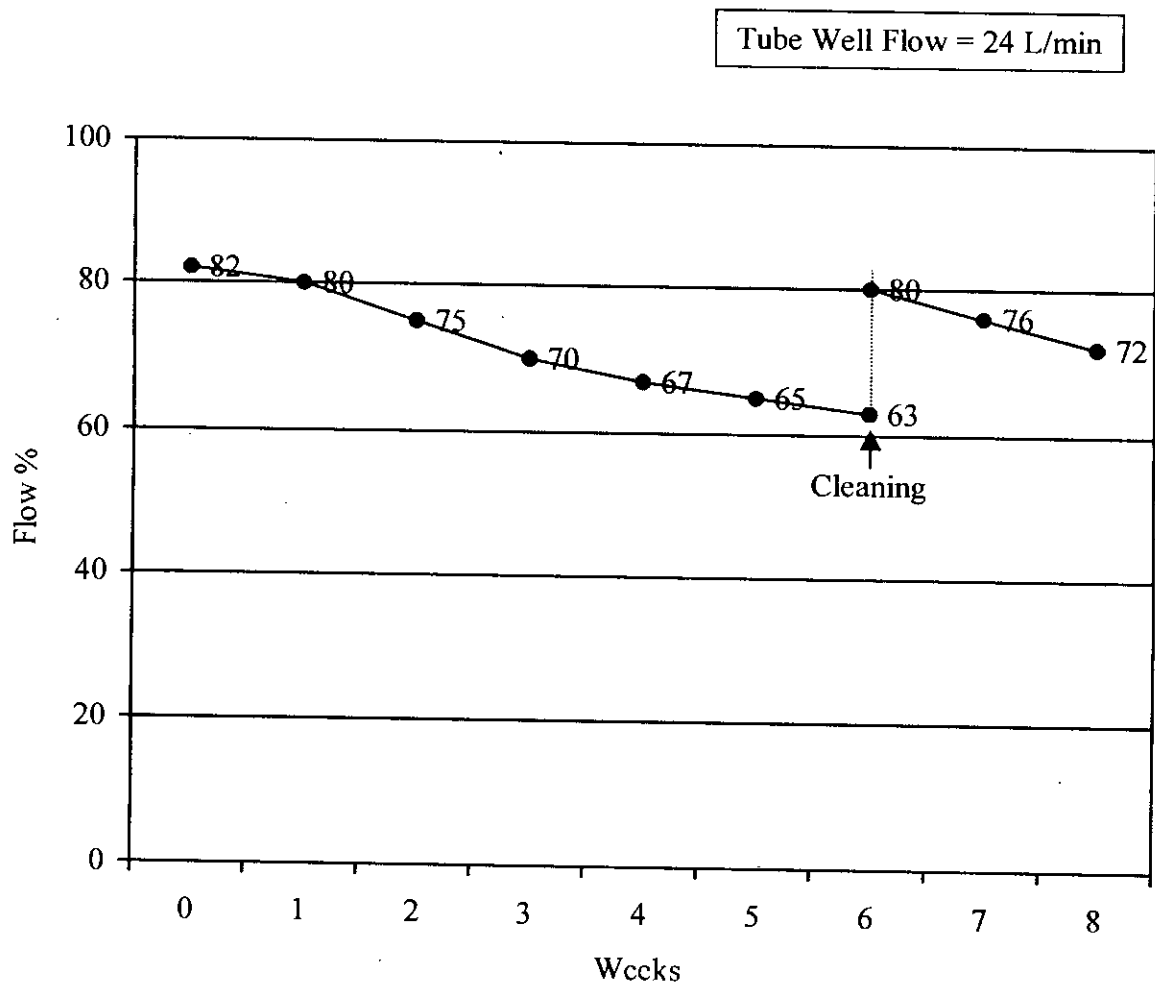


Fig.5.14 Variation of Flow of Treated Water (as a % of Tubewell Flow) with Time (AIRU-4 at Avoynagar)

AIRU-5 (Jhikorgacha):

This unit was comparatively smaller in size and the raw water iron content was high in this case. As a result the effluent flow of water from the AIRU was found less and again the flow was reduced significantly around 55% of the influent flow after 4 weeks of filter run. After cleaning operation it was found that the flow was recovered fully in the second cycle of filter run. Comparatively very easier cleaning operation was experienced in this unit.

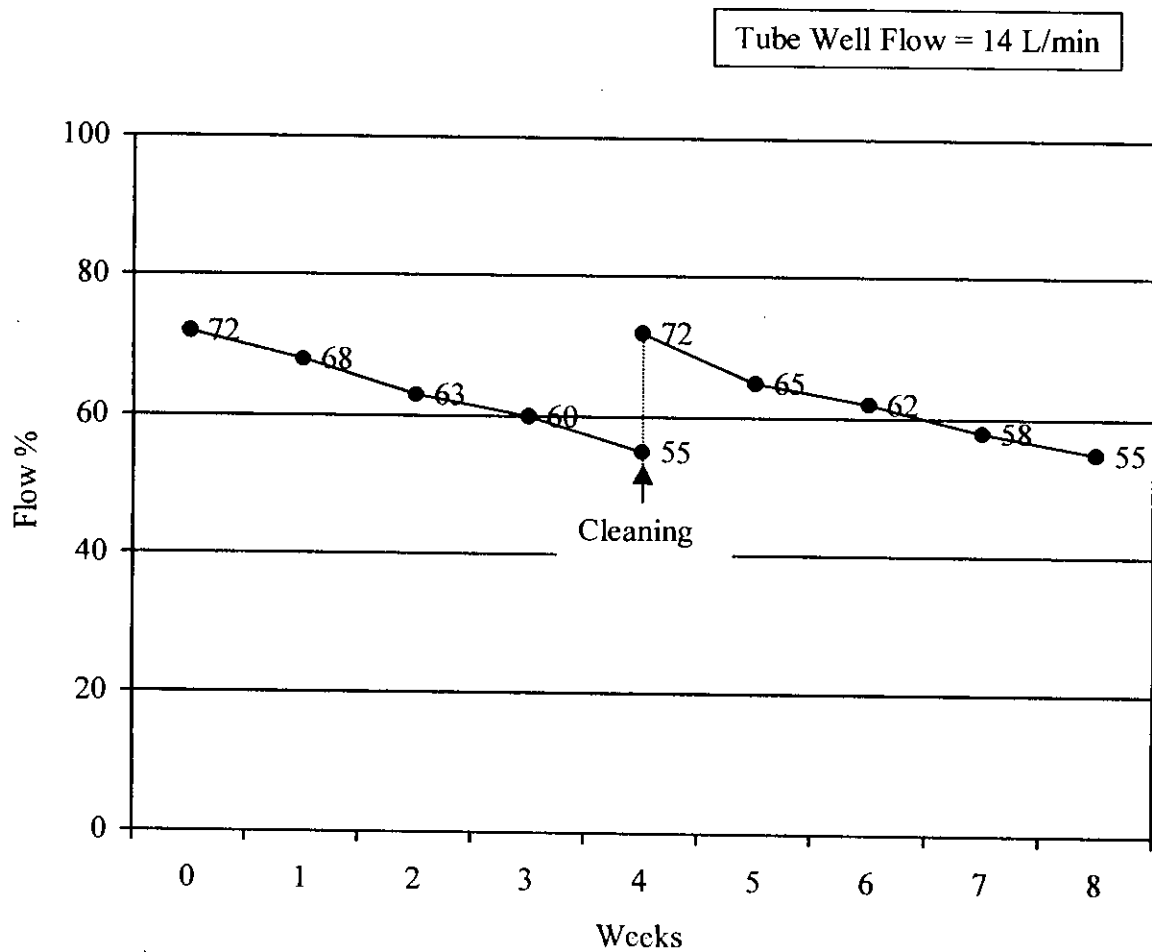


Fig.5.15 Variation of Flow of Treated Water (as a % of Tubewell Flow) with Time (AIRU-5 at Jhekorgacha)

Summary of Flow Variation in Treated Water with Time

Using of a thin sand filter bed in the AIRU-1 caused an abrupt increase of head loss of water which results a decrease of effluent water flow around 42% of the tube well water flow. Within few days of operation this flow further reduced down to 34% of the tube well water (Influent) flow. Elimination of this sand layer caused an increase of flow up to 45%.

Major design modification was made in the AIRU-2 through constructing two chambers in place of three chambers to minimize the head loss and as a result initial effluent flow of 65% of the influent flow was achieved.

Further modification was made in the AIRU-3 through placing coarser gravel materials at the bottom of the first chamber and making bigger holes in the perforated slab. The flow of effluent water from this unit was found 75% of the tube well water flow.

The interconnecting pipes between the first and second chamber were increased in the AIRU-4 for getting further increased flow of treated water around 82% of the tube well water flow.

Although the fifth unit was smaller in size and the raw water iron content was high in this case, the initial treated water flow was found 72% of the original tube well water flow due to following all the previous modifications. The flow of effluent water was reduced significantly around 55% of the influent flow after 4 weeks of filter run and after cleaning operation it was found that the flow was recovered fully. Comparatively very easier cleaning operation was experienced in this unit.

The length of filter run between cleaning were not uniform and reduced in successive cycles due to the presence of previously deposited iron precipitates which was not cleaned completely. The cleaning operation was done simply through opening the bottom outlet valves and flushing the deposited sludge with water through hydrostatic pressure. It was observed that three successive flushing can recover about 98% of the initial flow of water. No removing and replacing of gravel are required and chances of contamination can be avoided.

5.4.2 Flow Recovery of the AIRU in Cleaning Operation:

The clogging and maintenance of the AIRU was not frequent and the cleaning procedures were simple. Cleaning was performed without removing the coarse media and simply through opening the gate valve at the bottom layer of the AIRU and flushing out the settled sludge within the interstices of the gravel bed media through back washing by hydro-static pressure. Satisfactory flow recovery (as a % of initial flow) of the treated water from the AIRU was observed during the cleaning operations. After the 1st, 2nd and 3rd flushing it was found that the flow was recovered up to 85%, 95% and 98% respectively from the clogging condition of 50% flow from the AIRU.

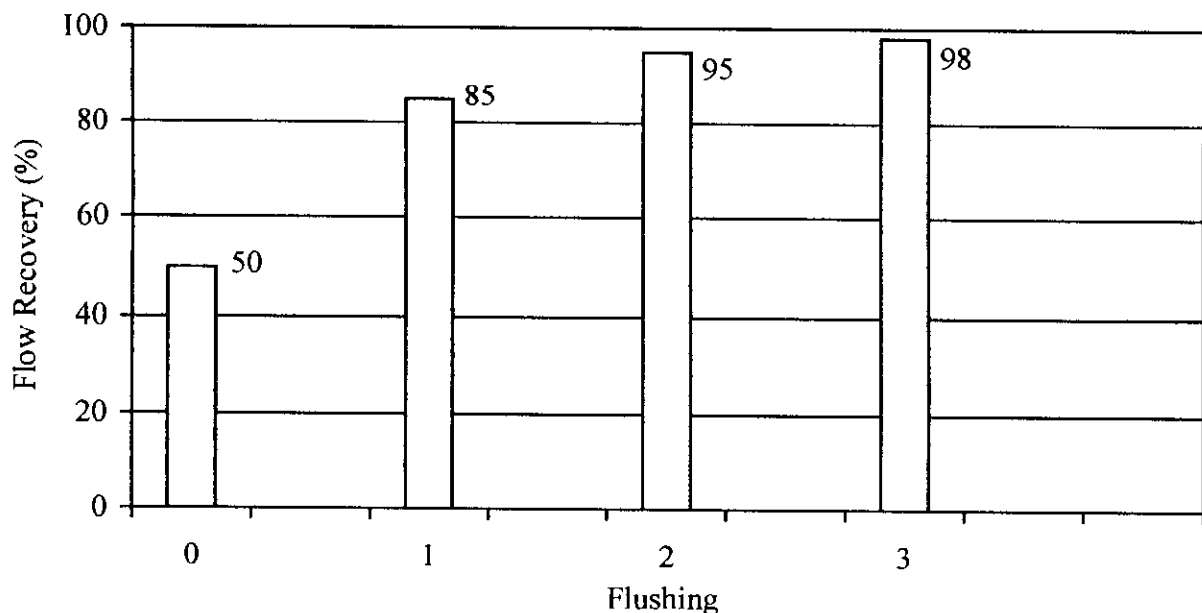


Fig.5.16 Flow Recovery of Treated Water (as a % of Initial Flow) with Successive Flushing in Cleaning Operation

5.4.3 Effect of the AIRU on Water Use:

Due to high arsenic concentrations in tube wells water, beneficiaries were afraid to use it for domestic purposes. Moreover, presence of iron discouraged the beneficiaries to use it for all domestic purposes. It was reported that before the construction of the AIRU(s) the tube wells were used only for toilet and cleaning purposes. After the construction of the AIRU(s), the local people were attracted by the treated water quality and consequently the number of users

increased depending on the existing local environmental conditions. In the first site (AIRU-1) there were some alternative sources of safe drinking water in the locality and as a result the increase of users was not significant. In the second site (AIRU-2) there were no alternative safe water sources in the vicinity and as consequence people from distant places started coming to fetch water from the AIRU-2. In the third and fourth sites (AIRU-3, 4) both the arsenic and iron concentrations were very high in the tube well water and as a result people from the vicinity were inclined to use the treated water from the AIRUs, although few safe deep tube well sources were present at distant places. When there was an increase of iron concentration in AIRUs water there was a drop of water uses for some time, however, after the improvement of water quality the numbers of beneficiaries again increased. In case of AIRU-5 appreciable number of users were found from the very beginning of the commissioning of the unit and this condition was prevailing till the last report was reached.

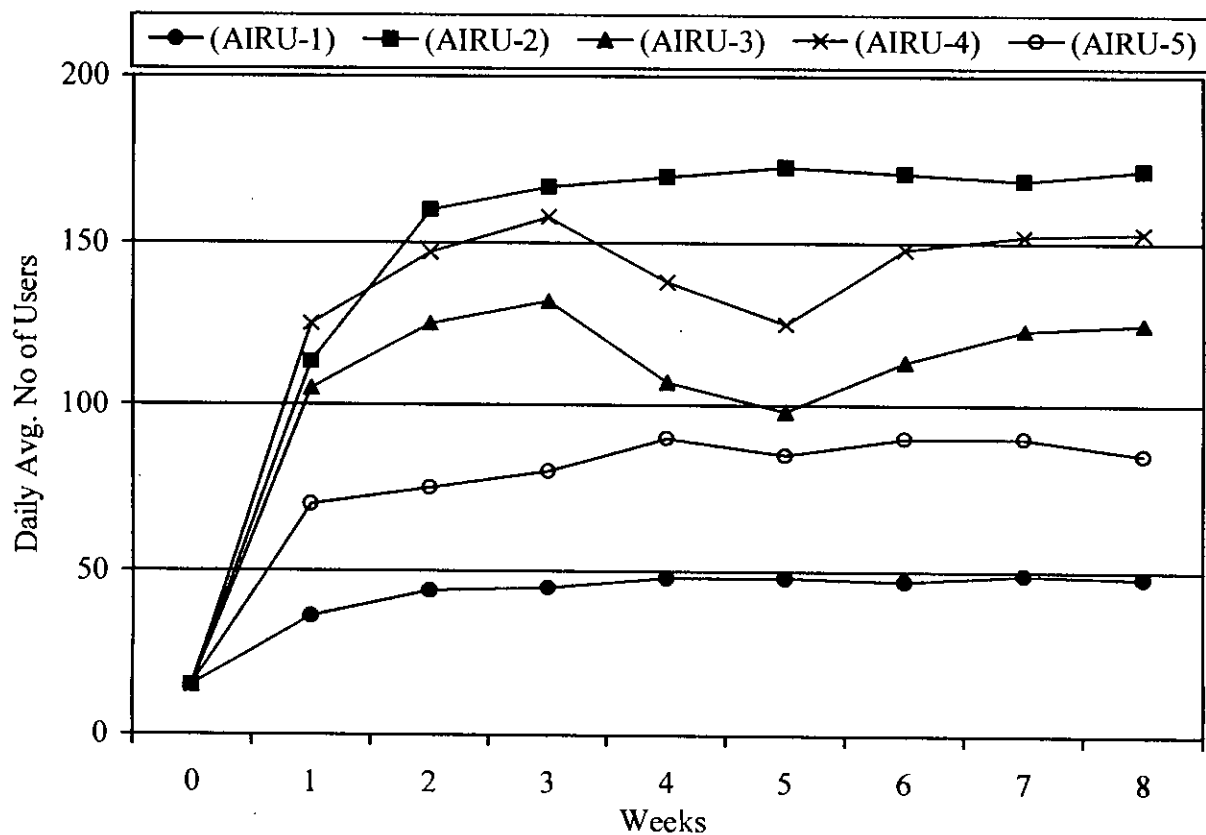


Fig.5.17 Variation of AIRU Users with Time (5 Units)

5.4.4 Effect of the AIRU on Water Consumption:

Since, both the iron and arsenic concentrations were high in the project areas, beneficiaries were afraid and reluctant to use the tube well water for all domestic purposes and on an average the water collection from tube well was limited to approximately 300 liters per day for cleaning and washing purposes only. After the construction of the AIRU(s), the physical quality of water improved significantly through the decrease of iron concentration and the local people started feeling confident to use low arsenic content water and as a result consumption of tube well water for other domestic purposes including drinking, cooking increased significantly depending on the prevailing local environmental conditions. Where there were no alternative sources of safe water in the locality consumption of tube well water for all domestic purpose were very significant, however, where there were alternative other water sources the increase of water consumption was moderate.

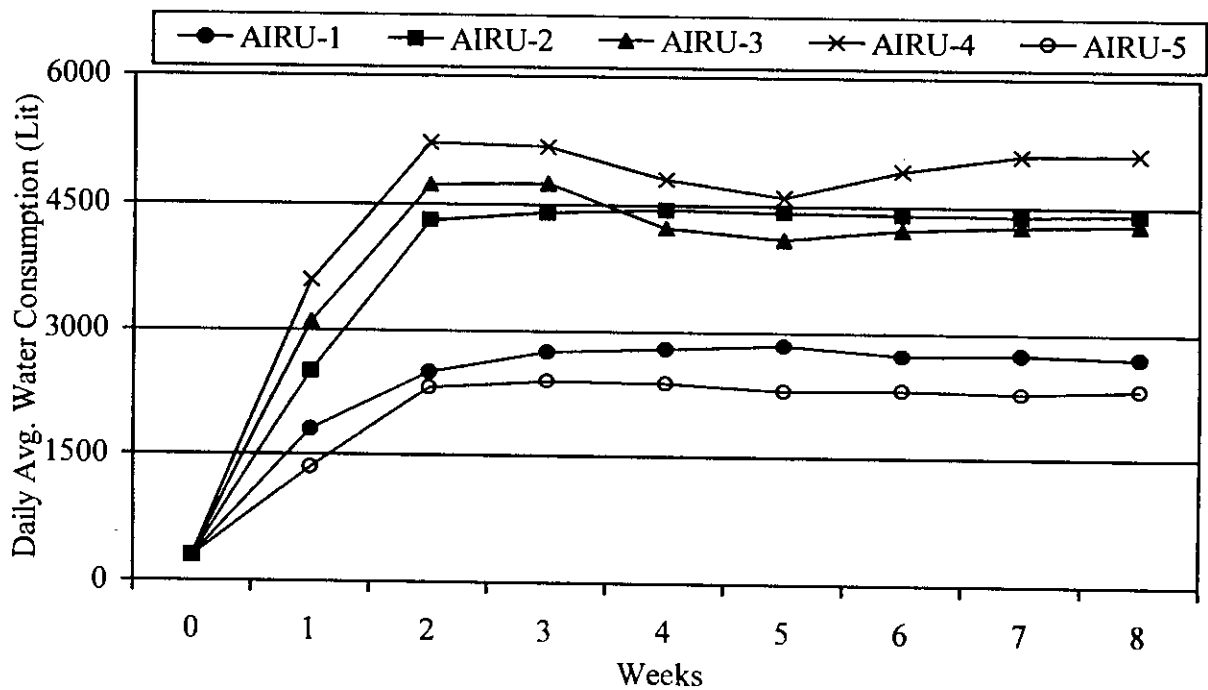


Fig.5.18 Variation of Water Consumption with Time (5 Units)

5.5 USER OPINION REGARDING THE AIRU(S)

Beneficiaries were interviewed about their opinion regarding the performance and operation of the AIRUs. A questionnaire as shown in the Annex-1 was used for the collection of household details and beneficiaries opinion. The approach was very polite, frank and intimate while collecting the field information. The family members were found very interested in giving their opinions. A sense of ownership of the AIRUs in operation and maintenance works also observed among them. 100% users felt that water quality has been improved dramatically particularly iron. Operations of AIRU(s) were not very much difficult, however, reduction of flow with time was a concern. They were capable to clean the unit through opening the bottom valves of the AIRU. The following table represents beneficiaries' opinion.

Table 5.2: Beneficiaries Opinion as a % of the Total Users of the AIRU(s)

| | Water Quality | | | Operation and Maintenance | | |
|--------|---------------|------|-----|---------------------------|------|-----|
| | Excellent | Good | Bad | Excellent | Good | Bad |
| AIRU-1 | 64 | 36 | - | - | 55 | 45 |
| AIRU-2 | 60 | 40 | - | 27 | 63 | 10 |
| AIRU-3 | 25 | 70 | 5 | 35 | 60 | 5 |
| AIRU-4 | 32 | 65 | 3 | 38 | 62 | - |
| AIRU-5 | 58 | 30 | 12 | 45 | 50 | 5 |

Excellent water quality in AIRU-(1 and 2) was observed because of using no chemicals in the treatment processes. The raw water arsenic concentrations were very high (around 400 ppb) in AIRU-(3,4 and 5) and thus bleaching powder was used as an oxidizing agent to ensure higher adsorption of arsenic on iron which hampered the quality of treated water due to unusual smell. The iron content in treated water was found fluctuating in AIRU-5 due to high face velocity (1.5 m/hr) which resulted bad water quality because of aesthetic reason.

Operation and maintenance was found bad in AIRU-1 due to using sand filter and consequent reduction of flow of treated water. The operation and maintenance were observed comparatively better for the subsequent AIRUs due to gradual modifications.

5.6 READ-F ADSORBENT COLUMN ATTACHMENT WITH EXISTING AIRU:

For acute arsenic problem areas intermittent dosage of bleaching powder was used as an oxidizing agent for maintaining the ultimate product water arsenic concentration within the acceptable limit of Bangladesh Standard. It was reported that the beneficiaries number of using tube well water for drinking purpose were getting short due to obnoxious smell of bleaching powder.

Thus, an attempt was taken to minimize the problem by launching an additional Read-F adsorbent attachment column with the existing AIRU and totally discarding the use of any other chemicals. Two different attachments of 1½ and 3 inch diameter PVC pipes containing 9 inch depth Read-F adsorbent bed has been put into trial with the existing AIRUs at Avoy nagor and Jhekorgacha respectively and their performance were also monitored.

Table 5.3: Arsenic Concentrations of Raw and Treated Water from AIRU
(Without Using Any Chemicals)

| Sl. | Location | Arsenic Concentration (ppb) | |
|-----|-------------|-----------------------------|------------|
| | | Raw Water | AIRU Water |
| 1 | Avoy nagor | 480 | 120 |
| 2 | Jhekorgacha | 310 | 80 |

Table 5.4: Variation of Arsenic Concentration with Bed Volume of Read-F

| Location | Read-F Treated water Bed Volume⇒ | 0 | 1000 | 2000 | 3000 | 4000 |
|-------------|----------------------------------|---|------|------|------|------|
| Avoy nagor | Treated Water As Conc. (ppb) ⇒ | 0 | 0 | 5 | 10 | 10 |
| Jhekorgacha | Treated Water As Conc. (ppb) ⇒ | 0 | 0 | 0 | 0 | 0 |

Although Read-F adsorbent is costly but using it in combination with the existing AIRU would be able to enhance its active life in a great extent due to reduction of 70% arsenic and 90% iron from raw tubewell water passing through AIRU. Koch (1987) has mentioned a typical domestic water consumption pattern for different purposes in his study.

Table 5.5: Treatment Units Involved for Different Purposes of Domestic Water Consumption (Koach, 1987)

| Purpose of Domestic Use | Percent of Daily Consumption | Treatment Required for Tubewell Water | Treatment Units Involved |
|-------------------------|------------------------------|---------------------------------------|------------------------------------|
| Drinking | 5% | As and Fe Treatment | READ-F Column Attachment With AIRU |
| Cooking | 10% | | |
| Washing Cloths | 20% | Mainly Fe Treatment | Only Using AIRU |
| Bathing | 30% | | |
| Washing Utensils | 15% | Without Treatment | Direct Tubewell Water |
| Sanitary & Cleaning | 20% | | |

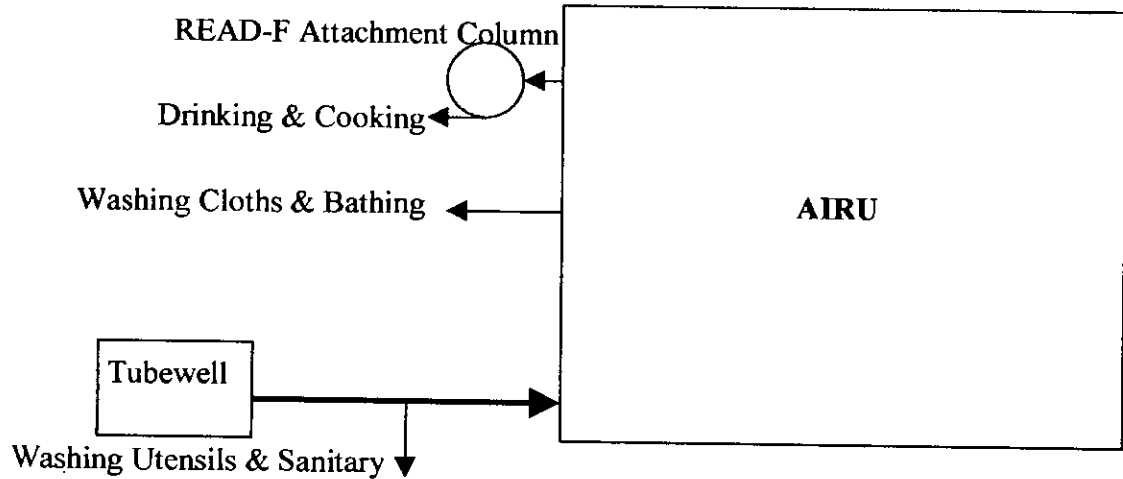


Figure 5.19: Schematic Diagrams of Treatment Units Involved for Different Purposes of Domestic Water Consumption

5.7 MODIFICATION AND RE-DESIGN OF THE AIRU(S)

At first two AIRU(s) were constructed in two different water quality sites and their performance were monitored for a period of three months. Moreover, beneficiaries were interviewed to understand the suitability and to determine the practical problems of operation and maintenance with the unit.

The field data was analyzed carefully and necessary modifications were made in the design of the AIRU for different water quality conditions.

Three more modified designed AIRU(s) were constructed in three different water quality sites of the country and their performances were monitored for a period of three months. Water consumption survey and beneficiaries interview regarding treated water quality, operation and maintenance problems of the AIRU was continued.

5.7.1 Problems Encountered:

Flow Reduction:

In case of AIRU-1, although appreciable removal of both arsenic and iron were observed due to use of sand as final filter media, the flow of water reduced significantly with time.

Difficulty in Pumping the Tube well :

The tube wells were uplifted about two feet, for ensuring gravity flow through the AIRU(1,2), resulting hard pumping due to increased suction head and consequently operating platform / pumping base became high which caused great difficulty for pumping tube wells.

Insufficient Sludge Drainage Facility :

Only one sludge drainage / wash out pipe was installed at the base level for both down-flow and up-flow chambers for AIRU-1, which caused insufficient sludge drainage facility in cleaning operation.

Uncontrolled flow of sludge :

Blind plugs were used as end cap for sludge drains in AIRU-1, which caused uncontrolled flow of sludge through the sludge drain when the plugs were opened in the time of cleaning operation.

Difficulty in Sludge Management :

At first, for AIRU-1, unconfined sand trap along with brick khoa soak pit arrangement were made for sludge disposal system. Which was found to be risky considering the high toxicity of the sludge.

Difficulty in Pre-cast (PC) Slab Construction:

R.C.C Perforated PC slabs were used in the 2nd up-flow chamber of the AIRU(s) to retain the gravel and again PC ferrocement (FC) slabs were used for cover plate and aeration purposes. These PC slabs constructions were found difficult in the rural environment.

5.7.2 Modifications Made for Different AIRU(s)

Table 5.6: Presentation of Design Modifications for Different AIRU(s)

| Sl | Purpose | Activity | AIRU-1 | AIRU-2 | AIRU-3 | AIRU-4 | AIRU-5 |
|----|----------------------------------|--|----------------|----------------|----------------|----------------|----------------|
| 1. | To Increase the Flow | Total Number of Chambers | 3 | 2 | 2 | 2 | 2 |
| | | Size of 1 st Chamber | 1'x1'-4" | 1'x3'-6" | 1'x3'-6" | 1'x3'-6" | 1'x2' |
| | | Gravel Size at Bottom Layer | Finer | Finer | Coarser | Coarser | Coarser |
| | | Pore Size of Perforated Slab | Smaller | Smaller | Bigger | Bigger | Bigger |
| | | No. of Inter-connecting Pipes | 3 | 5 | 5 | 6 | 6 |
| 2. | Easy Pumping | Height of Operating Platform | 2' | 2' | 1'-6" | 1'-6" | 1'-6" |
| 3. | Sufficient Sludge Drainage | No. of Sludge Drainage/Wash Out Pipes at the Base Level | 1 | 2 | 2 | 2 | 2 |
| 4. | Controlled Flow of Sludge | Flow Protection and Control Device Attached with Sludge Drain Pipe | Blind Plugs | Gate Valves | Gate Valves | Gate Valves | Gate Valves |
| 5. | Safe Sludge Disposal | Type of Installation (Unconfined/ Confined) of the Sludge Disposal Unit | Un Conf. | Conf. | Conf. | Conf. | Conf. |
| 6. | Solution of Pre-Casting Problems | Cover Plate for Protecting External Contamination | FC- PC Slabs | FC- PC Slabs | FC- PC Slabs | FC- PC Slabs | P. Wood Plate |
| | | Perforated Plate at the Inlet for Aeration | FC- PC Slabs | FC- PC Slabs | FC- PC Slabs | FC- PC Slabs | P. Wood Plate |
| | | Perforated Slabs in the 2 nd Up-Flow Chamber for Retaining the Gravel | R.C.C PC Slabs | R.C.C PC Slabs | R.C.C PC Slabs | R.C.C PC Slabs | P. Wood Plates |

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 GENERAL

The present study focussed on the development of a community based arsenic-iron removal unit (AIRU). Detailed laboratory model analysis and tests were carried out to determine some important optimum design parameters of the AIRU for practical application. In order to simulate the field conditions in Bangladesh as closely as possible, five such treatment units were constructed and their performances were monitored in different water quality conditions of the country. The performances of the AIRU(s) were studied in respect of arsenic and iron removal efficiency, flow pattern, increased number of users and increased water consumption. Beneficiaries' opinion for determining the practical problems of operation and maintenance of the unit has been mentioned and subsequent design modifications of the AIRU(s) were described. Performance of Read-F adsorbent column attachment with the existing AIRU was also studied.

6.2 CONCLUSIONS

Major results obtained from this study are summarized below:

- Over 75% arsenic removal can be achieved without using any chemicals through adsorption on to natural iron oxides surfaces provided that the raw water arsenic concentration is within 200ppb and the iron-arsenic concentration ratio is around 30.
- For higher arsenic concentration above 200ppb and iron-arsenic concentration ratio less than 30; intermittent dosing of oxidizing agent is necessary to convert the As(III) into As(V) to ensure more adsorption of arsenic and hence maintaining the treated water within the acceptable limit.
- Use of an additional filter-attachment with the AIRU containing sorptive media (Activated Alumina, Read-F, Iron Coated Sand etc.) can eliminate the use of oxidizing agent. The active life of the sorptive media would be extended long due to major removal of As and Fe from raw tube well water passing through the AIRU.

- Appreciable iron removal efficiency over 90% can be achieved provided that the face velocity is less than $0.5 \text{ m}^3/\text{m}^2\text{-h}$. The removal is a function of raw water iron concentration and increases with the passage of time.
- Initial flow of water from the AIRU can be increased/recovered from 42% to 82% of tube well water flow through changes of filter materials and some modifications of chambers. The reduction of flow for the treated water was not significant in comparison to the tube well water flow initially 82% and approximately 50% after one month of operation at 300 Bed Volume.
- The clogging and maintenance were not frequent and the cleaning procedures were simple. Cleaning was performed without removing the coarse media and the chance of external bacterial contamination was almost negligible. After the 1st, 2nd and 3rd flushing it was found that the flow was recovered up to 85%, 95% and 98% respectively.
- Number of tube well water users increased about 10 folds after the installation of AIRU and collection of tube well water increased more than 10 times.
- Unit cost of construction of an AIRU is around Tk.500 per household (considering 20 household per AIRU) which can be reduced through reduction of the AIRU size.
- Construction can be performed through local mason and using locally available construction materials.

6.3 RECOMMENDATION

There is a wide variation of water quality conditions in Bangladesh. The most important process control water quality parameters like pH value, concentration of carbon-dioxide, alkalinity, phosphate, silica, nitrate, iron, arsenic, the oxidation state of iron and arsenic in groundwater and their concentration ratio are not same in all the places, rather vary significantly from place to place. Therefore, it is necessary to test the performance of the

recently developed AIRU under various water quality conditions to determine important design parameters before going for mass scale construction.

It was understood from the previous studies that removal of iron and arsenic were not the main problem in the water treatment units constructed earlier. The main concern was regular maintenance and cleaning through community participation. So it is necessary to design a unit, which is simple in operation, maintenance and which can avoid any contamination. Long term monitoring and extensive field investigation are necessary to decide on these matters.

Following are the major recommendations for future study:

- To conduct extensive field tests of the AIRU to study both iron and arsenic removal performances and to determine maximum removal capacity under different water quality conditions.
- To observe the influence of phosphate, silica, nitrate, chloride and other anions on the arsenic removal efficiency of this unit under variable water quality conditions of the country.
- To study the comparative performances of variable adsorbents (activated alumina, iron coated sand, Read-F etc.) column attachment with the AIRU in acute arsenic problem areas and to find out the most suitable combination.
- To study the performance of up-flow flocculator in stead of down-flow flocculator in combination with up-flow roughing filtration unit for the AIRU.
- To study the performance of using brick chips aggregate in stead of gravel for both flocculation and roughing filtration purpose and to find out the effective and economic solution.
- To modify the design of the AIRU, specially for less iron and high arsenic prone areas.

- To determine the effect of pH, alkalinity, iron and arsenic concentrations for removal of arsenic through co-precipitation with iron.
- To determine the maintenance and operation problems through long term monitoring of the unit and to find out probable solution through community participation for sustainable development of the unit.
- To modify the design of the unit on the basis of field needs considering the operation and maintenance aspects.
- To develop different options of the AIRU(s) considering the environmental, social and economic aspects.
- To develop a more suitable and safe sludge collection and disposal system of the unit.
- To assess the difficulties for active community participation in operation and maintenance aspects and finding out simple techniques for sustainable development of the unit.

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Annex-1

QUESTIONNAIRE FOR FIELD SURVEY

1. Name Of The Land Lord Of The Family:

| |
|--|
| |
|--|

2. Number Of Members In The Family:

| Sex | Below 12 Years | 12 To 60 Years | Above 60 Years |
|---------|----------------|----------------|----------------|
| Male: | | | |
| Female: | | | |

3. Water Use From AIRU:

| Container Type | Big (Above 20 Liters) | Medium (12 To 20 Liters) | Small (Below 12 Liters) |
|------------------|--------------------------|-----------------------------|----------------------------|
| Kolshi (No) | | | |
| Bucket (No) | | | |
| Others (No) | | | |
| Total (Liters) = | | | |

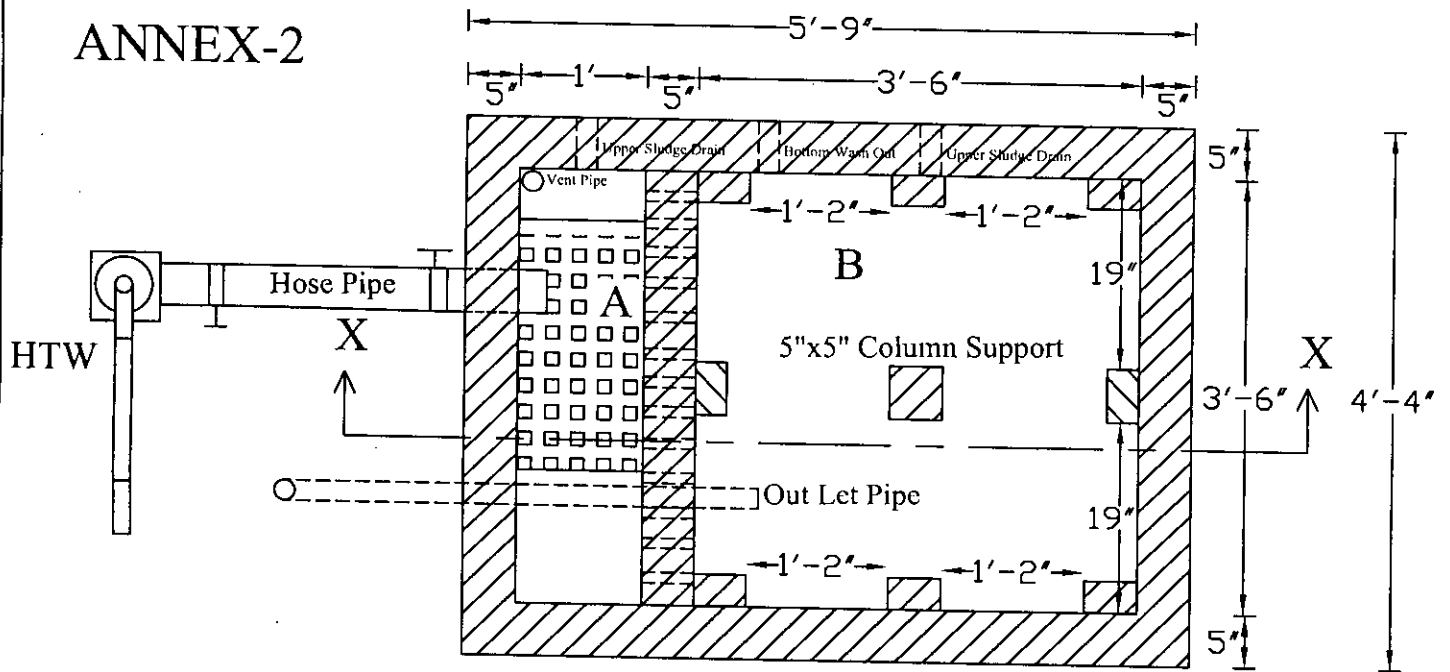
4. Number Of Persons Using AIRU For The Following Purposes:

| Drinking (2 L/Person) | Bathing (25 L/Person) | Cooking (3 L/Person) | Washing Cloths (20 L/Person) | Others () Liters |
|--------------------------|--------------------------|-------------------------|---------------------------------|----------------------|
| | | | | |
| Total (Liters) = | | | | |

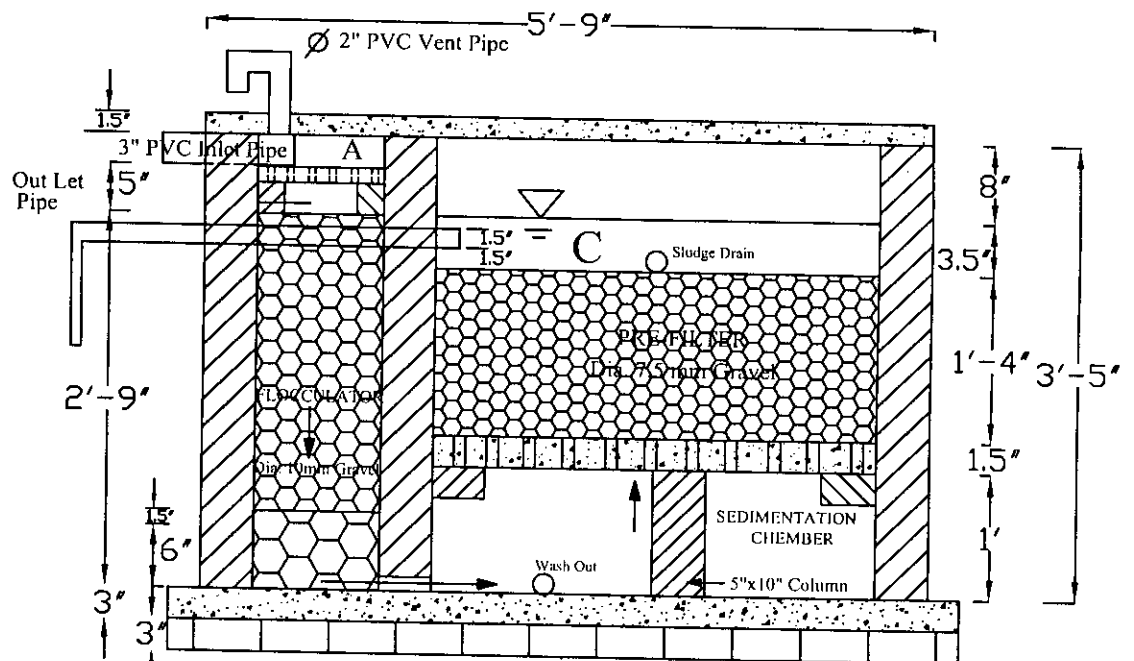
5. Beneficiaries Opinion (No):

| Water Quality | | | Operation And Maintenance | | |
|---------------|------|-----|---------------------------|------|-----|
| Excellent | Good | Bad | Excellent | Good | Bad |
| | | | | | |

ANNEX-2



TYPICAL PLAN OF AIRU



TYPICAL SECTION: (X-X) OF AIRU

Annex-3

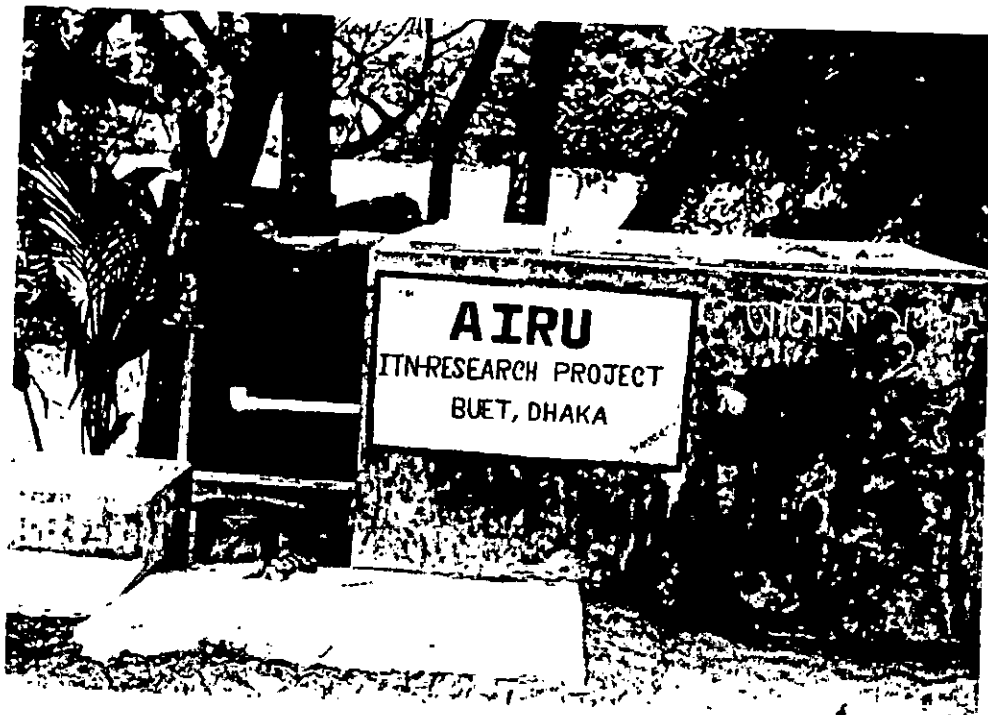
Construction Cost of Community Based Arsenic-Iron Removal Unit

| Sl. | Item | Sub-Item | Quant | Unit Pr (TK.) | Estimated Cost (TK.) |
|---------------------------|-------------|---|--------|---------------|----------------------|
| 1. | Bricks | Brick Flat Soling (BFS) | 100 No | 3 | 1650 |
| | | 5" Brick Wall | 450 No | | |
| 2. | Cement | 5" Brick Work & BFS | 4 bag | 250 | 1750 |
| | | R.C.C & C.C Works | 3 bag | | |
| 3. | Sand | 5" Brick Work & BFS | 25 cft | 7 | 245 |
| | | R.C.C & C.C Works | 10 cft | | |
| 4. | Khoa | R.C.C & C.C Works | 15 cft | 30 | 450 |
| 5. | M.S. Rod | R.C.C Works | 7 kg | 20 | 140 |
| 6. | Plumbing | 3" PVC Inlet pipe (4ft length) with end cap, Drain plug with socket (2 Nos), Delivery pipe fittings, Short piece connection for tubewell uplifting etc. | L.S. | - | 1000 |
| 7. | Gravel | Down-flow Flocculator and Up-flow Roughing Filter | 30 cft | 50 | 1500 |
| 8. | Cover Plate | Plastic Wood Sheet | L.S. | - | 1000 |
| 9. | Labour | Head Mason & Helper | 5 days | (150+100) | 1250 |
| 10. | Loc.Cary. | | L.S. | - | 1000 |
| TOTAL TK. / UNIT = | | | | | 9,985≈10,000 |

** For Read-F Column Attachment: Additional Tk/Unit (L.S.) = 1,000

Annex-4

Photographs of the AIRU(s) at the Field Level



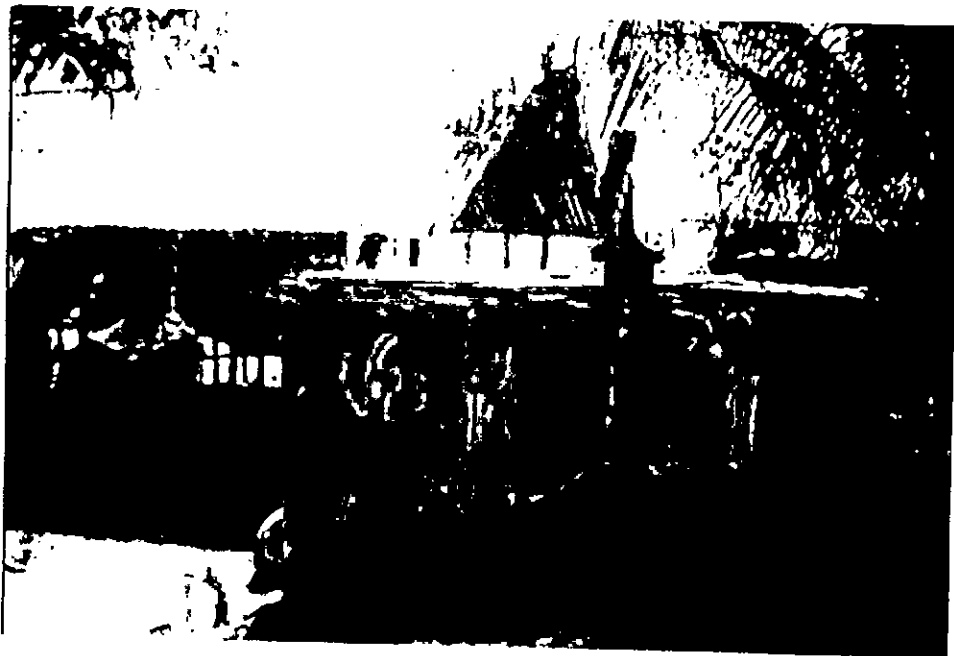
AIRU-1 at Sonargaon, Narayangong



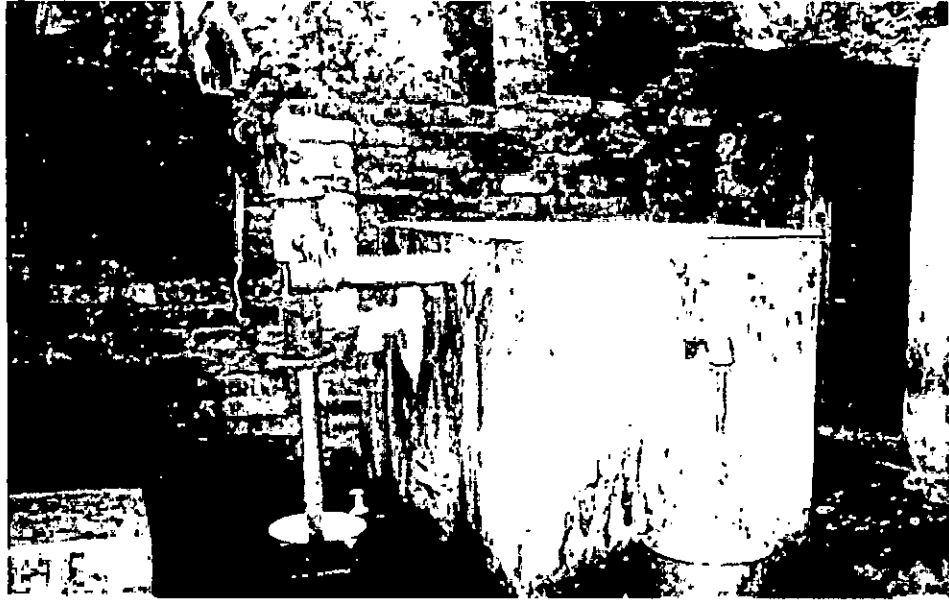
AIRU-2 at Jhekorgacha, Jessore



AIRU-3 at Chougacha, Jessore



AIRU-4 at Avoy nagor, Jessore



AIRU-5 at Jhekorgacha, Jessore

