DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

ARSENIC REMOVAL BY CHEMICAL TREATMENTS

by
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October, 2011
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ARSENIC REMOVAL BY CHEMICAL TREATMENTS

A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University In
Partial Fulfillment of the Requirements for the Degree of Master of Science in
Environmental Engineering, Environment Technology Program

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M.SC THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **“ARSENIC REMOVAL BY CHEMICAL TREATMENTS”** completed by **AHMET KÖKER** under supervision of **PROF. DR. NECDET ALPASLAN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science

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ACKNOWLEDGMENTS

I would like to express my gratitude to my advisor Prof. Dr. Necdet Alpaslan for his guidance, support and suggestions throughout this study.

I would like to express special my sincere gratitude to my working friends.

Above all I am most thankful to my parents, my niece Computer Engineer Zeynep Sönmez, and my friends from Petkim Petrochemical Industry, and from Karşıyaka Halk Sağlığı Laboratory especially Food Engineer Sultan Toksöz, Food Engineer Gül Sürücü and Chemist Zeynep Çavuşoğlu.

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ARSENIC REMOVAL BY CHEMICAL TREATMENTS

ABSTRACT

The problem of high levels of arsenic concentration in water (particularly drinking water) can be solved by two ways.

The first one is to find a new safe source of drinking water; and the second removing of arsenic from the contaminated source.

This research focuses to the latter alternative and aims to investigate arsenic removal capacity (efficiency) by chemical precipitation. In the thesis the different coagulants are used in order to remove high arsenic concentrations from distilled water and raw water. Different doses are applied under varying pH levels.

Result of the laboratory experiments indicated that, alum, ferric and calcium are the good coagulants which are capable to precipitate arsenic. The important part is the dose and pH levels which are examined in the thesis in detail.

Keywords: Arsenic, Drinking Water, Coagulants, Precipitation

KİMYASAL METOTLARLA ARSENİK UZAKLAŞTIRILMASI

ÖZ

İçme sularında yüksek miktardaki arsenik konsantrasyonu sorununu iki yöntemle çözebiliriz.

Birincisi yeni güvenilir içme suyu kaynaklarının bulunması, diğeri ise kirlenmiş kaynaktaki arseniğin giderilmesidir.

Bu çalışmanın amacı, kimyasal çökeltim ile arsenik giderme verimliliğinin incelenmesidir.

Bu çalışmada distile suda ve ham sudaki, yüksek arsenik konsantrasyonunu uzaklaştırmak farklı koagülantlar kullanıldı. Farklı pH değerlerinde farklı dozajlar uygulandı.

Laboratuar çalışmaları sonuçları, Alum, Demir-3klorür ve kireç kimyasal çökeltimle arsenik uzaklaştırılması için uygun koagülantlar olduğu gözlemlenmiştir. Dozaj ve pH seviyeleri tezin detaylarında incelenmiştir.

Anahtar sözcükler: Arsenik, İçme suyu, Koagülant, Çökeltim

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CHAPTER ONE

INTRODUCTION

1.1 Problems with Arsenic and Drinking Water

During the last century, steps have been taken to develop the technology and social policy to address questions of access to potable water and means of improving water quality. To date, problems still exist, even in developed countries, including the United States, Western European nations, and Japan, not to mention developing countries where drinking water supplies contain arsenic, other chemicals, and bacteria, just to mention a few. In the United State for example, fertilizers and pesticides spread on farms and lawns filter through the ground into the water table or wash into streams and lakes, which supply some of the nation's drinking water (Tibbetts, J., and 2000 February).

In many poor villages around the world, people have to rely on the water that's easiest to reach – groundwater, rivers, and streams. Thus, the effects of the introduction of arsenic contaminated water from industrial effluent cannot be underestimated. In well-oxygenated surface waters, arsenic (V) is the most common species present but, under reducing conditions such as those found in groundwater, pre dominant form is arsenic (III), which has increased solubility and high affinity for proteins, thereby making it more toxic. (Welch & others, 2000). Also, as pH rises, there is an increasing concentration of dissolved arsenic in water.

Another problem is the delayed health effects after exposure to arsenic (latency). This is of critical concern, and the Bangladesh example clearly gives an in-depth view into the problem globally. At the time that (groundwater) tube wells were encouraged (over twenty years ago), arsenic was not recognized as a problem in water supplies, and standard water testing procedures did not include a test for it.

The problem of arsenic exposure came to light when doctors first saw cases of arsenic induced skin lesions, in West Bengal, India in 1983.

Apart from the delayed health effects of exposure to arsenic, other major problems of global concern are; the lack of common definitions for arsenic toxicity and of awareness, as well as poor reporting in affected areas.

These form the stumbling blocks in determining the extent of the problem of arsenic in drinking water. To date, reliable data on exposure and health effects are scarce. In 1988, the British Geological Group surveyed sixty-one out of the sixty-four districts in Bangladesh with shallow tube wells and found that 46% of the samples had as levels greater than 0.01 mg/L and 27% were greater than 0.05 mg/L. The data estimated that people exposed to arsenic concentrations above 0.05 mg/L. was between 28 to 35 million and that of greater than 0.01 mg/L was 46 to 57 million cost of health care in the treatment and managing of arsenic toxicity, inability of affected persons to engage in productive activities and potential social isolation are important global consequences of economic and social behaviors associated with arsenic poisoning (Asideu-Stainer, M. & others, 2010).

Arsenic concentrations above accepted standards for drinking water have been demonstrated in many countries on all continents and this should therefore be regarded as a global issue. Arsenic has been reported in groundwater in the following countries, among others:

Table 1.1 Countries where arsenic has been reported in ground or surface waters

Asia	Bangladesh, Cambodia, China (including provinces of Taiwan and Inner Mongolia), India, Iran, Japan, Myanmar, Nepal, Pakistan, Thailand, Vietnam
Americas	Alaska, Argentina, Chile, Dominica, El Salvador, Honduras, Mexico, Nicaragua, Peru, United States of America
Europe	Austria, Croatia, Finland, France, Germany, Greece, Hungary, Italy, Romania, Russia, Serbia, United Kingdom
Africa	Ghana, South Africa, Zimbabwe
Pacific	Australia, New Zealand

Figure 1.1 Countries where arsenic has been reported in ground or surface waters

Recently, arsenic contamination has come into the spotlight, because of its negative impact on humans and the environment. As a result, the WHO and USEPA have strengthened standards against arsenic in drinking water at 10 ppb replacing the old standard of 50 ppb. Although this standard has been implemented, arsenic poisoning has been on the increase. Arsenic is introduced into the human body through drinking water and food, causing lung, liver, kidney and bladder cancer (Petrusevski, B., & others, March, 2007).

Turkey is a country facing and struggling with those emerging arsenic problems.

Stringent standards of drinking water were promulgated by Ministry of Health (MoH) in 2005, and arsenic level was lowered from 50 μg/L to 10 μg/L. The new standard has been enforced since February 2008 (Dölgen, D. & others, 2009).

1.2 Health and Social Problems with Arsenic in Drinking Water

Human exposure to arsenic can take place through ingestion, inhalation or skin adsorption; however, ingestion is the predominant form of arsenic intake. High doses of arsenic can cause acute toxic effects including gastrointestinal symptoms (poor appetite, vomiting, diarrhea, etc.), disturbance of cardiovascular and nervous systems functions (e.g. muscle cramps, heart complains) or death.

Arsenic toxicity strongly depends on the form in which arsenic is present. Inorganic arsenic forms, typical in drinking water, are much more toxic than organic ones that are present in sea food. Inorganic arsenic compounds in which arsenic is present in trivalent form are known to be the most toxic. The acute toxicity of a number of arsenic compounds is given in Table 1.2. Toxicity is expressed as the number of milligrams of the compound per kilogram of body weight that will result within a few days in the death of half of those who ingest it in a single dose. This concentration is known as LD50. Table 1.2 shows the amount of various arsenic compounds per kilogram of body weight required to reach LD50 (the higher the number, the less toxic the compound.) (Petrusvski B. & others, 2007 March).

Table 1.2 Acute toxicity for different arsenic compounds

Arsenic form	**Oral LD50** (mg/kg body weight**)**
Sodium Arsenite	15- 40
Arsenic Trioxide	34
Calcium arsenate	20-800
Arsenobetane	>10,000

1.3 The Aim and the Scope of the Study

Coagulation is the main treatment method for removal of suspended solids from drinking water, and waste water treatment, however, it also be applied for removing of heavy metals, particularly arsenic.

In this study, performance of coagulation methods for arsenic removal from drinking water is investigated.

In the conducted thesis the aims arsenic removal efficiency of chemical precipitation has been investigated.

The arsenic concentration of two different water, namely ‘Distilled water’ and ‘Raw Water’ (taken from the dam, prior the water treatment plant) is set to 50 ppb by adding As^{+5}. This is achieved by using different coagulants, and different doses.

$Al_2(SO_4)_3$, $FeCl_3$, and $Ca(OH)_2$ have been used as coagulant. Different doses, i.e. between 50-200 mg/lt have been applied to jar test analyses.

Similar experiments are also conducted by distilled water.

Results indicated that chemical precipitate can be considered as a good alternative for arsenic removal.

CHAPTER TWO
ARSENIC CHEMISTRY

Arsenic is the chemical element that has the symbol **As**, atomic number 33 and atomic mass 74.92. Arsenic was first documented by Albertus Magnus in 1250.

Arsenic is a semi-metal, a member of the nitrogen family. It occurs naturally in the earth and in the seas. It is odorless and tasteless. Arsenic that occurs in the earth's crust-rock, soil, all natural sources of exposure, or can be traced to deep water brines.

Alternatively, manmade processes such as industrial operations, containing arsenic include wood preservatives, paints, dyes, pharmaceuticals, herbicides, and semiconductors agricultural applications and mining can also contribute to the arsenic pollution when arsenic-contaminated waters are not properly treated before discharge to the environment.

Arsenic can combine with other elements to form inorganic and organic arsenicals. In general, inorganic derivatives are regarded as more toxic than the organic forms.

Arsenic compounds detected in the environment are listed on Figure 2.1

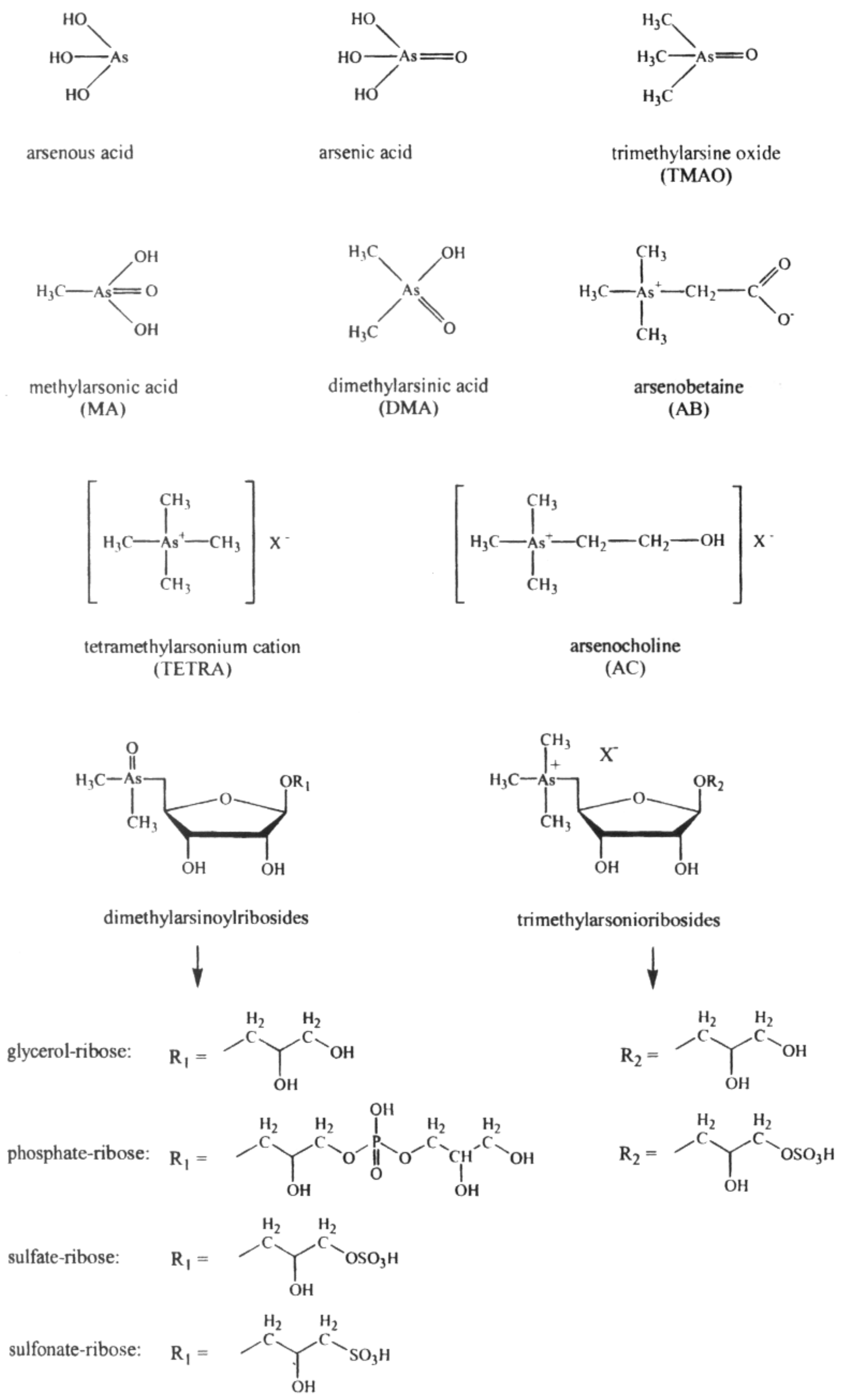


Figure 2.1 Structures of investigated arsenic compounds (Geiszinger. A., 1998)

Table 2.1 Major arsenic minerals occurring in nature (Smedley, P & Kinniburgh, G.,D., 2002).

Mineral	Composition	Occurrence
Native arsenic	As	Hydrothermal veins
Niciolite	NiAs	Vein deposits and norites
Realgar	AsS	Vein deposits, often associated with orpiment, clays and limestones, also deposits from hot springs.
Orpiment	As_2S_3	Hydrothermal veins, hot springs, volcanic sublimation products.
Cobaltite	CoAsS	High-temperature deposits, metamorphic rocks.
Arsenopyrite	FeAsS	The most abundant As mineral, dominantly in mineral veins.
Tennantite	$(Cu, Fe)_{12}As_4S_{13}$	Hydrothermal veins.
Enargite	Cu_3AsS_4	Hydrothermal veins.
Arsenolite	As_2O_3	Secondary mineral formed by oxidation of arsenopyrite, native arsenic and other As minerals.
Claudetite	As_2O_3	Secondary mineral formed by oxidation of realgar, arsenopyrite and other As minerals.
Scorodite	$FeAsO_4.2H_2O$	Secondary mineral
Annabergite	$(Ni,Co)_3(AsO_4)_2.8H_2O$	Secondary mineral
Hoernesite	$Mg_3(AsO_4)_2.8H_2O$	Secondary mineral, smelter wastes.
Haematilite	$(Mn,Mg)_4Al(AsO_4)(OH)_8$	
Conichalcite	$CaCu(AsO_4)(OH)$	Secondary mineral
Pharmacosiderite	$Fe_3(AsO_4)_2(OH)_3.5H_2O$	Oxidation product of arsenopyrite and other As minerals.

Arsenic exists in both organic and inorganic forms in nature; inorganic arsenic is mostly found in natural water systems. Generally, inorganic arsenic has two different oxidation states, that is, trivalent and pentavalent, in natural aqueous systems. The speciation of arsenic highly depends on solution pH. Pentavalent arsenic (As (V), arsenate) is stable in oxidative condition, while trivalent arsenic (As (III), arsenite) is stable in reductive condition (Wendy L.W & others, 2004, November).

Generally, inorganic arsenic is more toxic than organic arsenic, and As (III) is more toxic than As (V). In an aqueous system, heavy metals are easily removed by adsorption or pH adjustment while arsenic is not removed by pH control (Jeona, C.S, & Others).

The acute toxicity of arsenic at high concentrations has been known about for centuries. It was only relatively recently that a strong adverse effect on health was discovered to be associated with long-term exposure to even very low arsenic concentrations. Drinking water is now recognized as the major source of human intake of arsenic in its most toxic (inorganic) forms.

The presence of arsenic, even at high concentrations, is not accompanied by any change in taste, odor or visible appearance of water. The presence of arsenic in drinking water is therefore difficult to detect without complex analytical techniques (Petrusevski, B. & Others, 2007, March).

CHAPTER THREE
TECHNOLOGIES FOR ARSENIC REMOVAL

In some areas, arsenic-contaminated water will be abundant and arsenic-free sources scarce or polluted with other compounds. In these areas it may be most efficient to remove arsenic from the contaminated water, at least as a short term measure. Many technologies have been developed for the removal of arsenic. Most of the documented experience has been with large municipal treatment plants, but some of the same technologies can be applied at community or household levels.

This report identifies 13 technologies to treat arsenic in soil, waste, and water. Table 3.1 provides brief descriptions of these technologies. And table 3.2 summaries of Technologies for Arsenic Removal, and table 3.3 Applicability of Arsenic Treatment Technologies (EPA 2002).

All of the technologies for arsenic removal rely on a few basic chemical processes, which are summarized below:

Table 3.1 Arsenic treatment technology descriptions

Technology	**Description**
Technologies for Soil and Waste Treatment	
Solidification/ Stabilization	Physically binds or encloses contaminants within a stabilized mass and chemically reduces the hazard potential of a waste by converting the contaminants into less soluble, mobile, or toxic forms.
Vitrification	High temperature treatment that reduces the mobility of metals by incorporating them into a chemically durable, leach resistant, vitreous mass. The process also may cause contaminants to volatilize, thereby reducing their concentration in the soil and waste.
Soil Washing/ Acid Extraction	An ex situ technology that takes advantage of the behavior of some contaminants to preferentially adsorb onto the fines fraction of soil. The soil is suspended in a wash solution and the fines are separated from the suspension, thereby reducing the contaminant concentration in the remaining soil.
Pyrometallurgical Recovery	Uses heat to convert a contaminated waste feed into a product with a high concentration of the contaminant that can be reused or sold.
In Situ Soil Flushing	Extracts organic and inorganic contaminants from soil by using water, a solution of chemicals in water, or an organic extractant, without excavating the contaminated material itself. The solution is injected into or sprayed onto the area of contamination, causing the contaminants to become mobilized by dissolution or emulsification. After passing through the contamination zone, the contaminant-bearing flushing solution is collected and pumped to the surface for treatment, discharge, or reinjection.
Technologies for Water Treatment	
Precipitation/ Co precipitation	Uses chemicals to transform dissolved contaminants into an insoluble solid or form another insoluble solid onto which dissolved contaminants are adsorbed. The solid is then removed from the liquid phase by clarification or filtration.
Membrane Filtration	Separates contaminants from water by passing it through a semi-permeable barrier or membrane. The membrane allows some constituents to pass, while blocking others.
Adsorption	Concentrates solutes at the surface of a sorbent, thereby reducing their concentration in the bulk liquid phase. The adsorption media is usually packed into a column. As contaminated water is passed through the column, contaminants are adsorbed.
Ion Exchange	Exchanges ions held electrostatically on the surface of a solid with ions of similar charge in a solution. The ion exchange media is usually packed into a column. As contaminated water is passed through the column, contaminants are removed.
Permeable Reactive Barriers	Walls containing reactive media that are installed across the path of a contaminated groundwater plume to intercept the plume. The barrier allows water to pass through while the media remove the contaminants by precipitation, degradation, adsorption, or ion exchange.
Technologies for Soil, Waste, and Water Treatment	
Electrokinetic Treatment	Based on the theory that a low-density current applied to soil will mobilize contaminants in the form of charged species. A current passed between electrodes inserted into the subsurface is intended to cause water, ions, and particulates to move through the soil. Contaminants arriving at the electrodes can be removed by means of electroplating or electrodeposition, precipitation or co precipitation, adsorption, complexing with ion exchange resins, or by pumping of water (or other fluid) near the electrode.
Phytoremediation	Involves the use of plants to degrade, extract, contain, or immobilize contaminants in soil, sediment, and groundwater.
Biological Treatment	Involves the use of microorganisms that act directly on contaminant species or create ambient conditions that cause the contaminant to leach from soil or precipitate/co precipitate from water.

Table 3.2 Summary of technologies for arsenic removal (Johnston, R., Heijnen, H.)

Technology	Removal Efficiency		Institutional experience and issues
	As (III)	As (V)	
Coagulation with iron salts	++	+-H-	Well proven at central level, piloted at community and household levels. Phosphate and silicate may reduce arsenic removal rates. Generates arsenic -rich sludge. Relatively inexpensive.
Coagulation with alum		+++	Proven at central level, piloted at household levels. Phosphate and silicate may reduce arsenic removal rates. Optimal over a relatively narrow pH range. Generates arsenic -rich sludge. Relatively inexpensive
Lime softening	+	+++	Proven effective in laboratories and at pilot scale. Efficiency of this chemical process should be largely independent of scale. Chiefly seen in central systems in conjunction with water softening. Disadvantages include extreme pH and large volume of waste generated. Relatively inexpensive, but more expensive than coagulation with iron salts or alum because of larger doses required, and waste handling.
Ion exchange resins		+++	Pilot scale in central and household systems, mostly in industrialized countries. Interference from sulfate and TDS. High adsorption capacity, but long-term performance of regenerated media needs documentation. Waters rich in iron and manganese may require pre-treatment to prevent media clogging. Moderately expensive. Regeneration produces arsenic -rich brine.
Activated alumina	+/ ++	-H-+	Pilot scale in community and household systems, in industrialized and developing countries. Arsenite removal is poorly understood, but capacity is much less than for arsenate. Regeneration requires strong acid and base, and produces arsenic -rich waste. Long-term performance of regenerated media needs documentation. Waters rich in iron and manganese may require pre-treatment to prevent media clogging. Moderately expensive.
Membrane methods	_/ +++	+++	Shown effective in laboratory studies in industrialized countries. Research needed on removal of arsenite, and efficiency at high recovery rates, especially with low-pressure membranes. Pretreatment usually required. Relatively expensive, especially if operated at high pressures.
Fe-Mn Oxidation	9	+/++/ +++	Small-scale application in central systems, limited studies in community and household levels. More research needed on which hydrochemical conditions are conducive for good arsenic removal. Inexpensive.
Porous media sorbents (iron oxide coated sand, greensand, etc.)	+/ ++	++/ +++	Shown effective in laboratory studies in industrialized and developing countries. Need to be evaluated under different environmental conditions, and in field settings. Simple media are inexpensive, advanced media can be relatively expensive.
In-situ immobilization on	++	-H-+	Very limited experience. Long-term sustainability and other effects of chemical injection not well documented. Major advantage is no arsenic -rich wastes are generated at the surface, major disadvantage is the possibility of aquifer clogging. Should be relatively inexpensive.

Key :+++ Consistently > 90% removal ++Generally 60 - 90% removal
+ Generally 30 - 60% removal < 30% removal? Insufficient information

Table 3.3 Applicability of arsenic treatment technologies

Technology	Soil"	¤ Waste"	Water		
			Groundwater and Surface Water'	Drinking Water	Wastewater
Solidification/Stabilization	•	•	•	•	
Vitrification	•	•	•	•	
Soil Washing/ Acid Extraction	0				
Pyrometallurgical Treatment	*	•	o	•	
In Situ Soil Flushing	• •				
Precipitation/Co precipitation			•	o	•
Membrane Filtration			e	o	«
Adsorption				e	•
Ion Exchange			o		•
Permeable Reactive Barriers			• •		
Electrokinetics	«	•	•	•	•
Phytoremediation	•		•		•
Biological Treatment			•		

• «= Indicates treatment has been conducted at full scale.

a Soil includes soil, debris, sludge, sediments, and other solid phase environmental media.
b Waste includes non-hazardous and hazardous solid waste generated by industry.
c Groundwater and surface water also includes mine drainage.
d Wastewater includes nonhazardous and hazardous industrial wastewater and leachate.

The main arsenic removal technologies are presented below, along with a brief description of how removal efficiency is affected by arsenic concentration and speciation, pH, and the presence of other dissolved constituents.

3.1 Oxidation / Reduction

Most arsenic removal technologies are most effective at removing the pentavalent form of arsenic (arsenate), since the trivalent form (arsenite) is predominantly non-charged below pH 9.2 Therefore; many treatment systems include an oxidation step to convert arsenite to arsenate. Oxidation alone does not remove arsenic from solution, and must be coupled with a removal process such as coagulation, adsorption or ion exchange.

Arsenite can be directly oxidized by a number of other chemicals, including gaseous chlorine, hypochlorite, ozone, permanganate, hydrogen peroxide, and Fenton’s reagent (H_2O_2/Fe_2+). Some solids such as manganese oxides can also oxidize arsenic. Ultraviolet radiation can catalyze the oxidization of arsenite in the presence of other oxidants, such as oxygen. Direct UV oxidation of arsenite is slow, but may be catalyzed by the presence of sulfite, ferric iron or citrate. Chlorine is a rapid and effective oxidant, but may lead to reactions with organic matter, producing toxic trihalomethanes as a by-product. Chlorine is widely available globally, though if improperly stored it can lose its potency rapidly.

In Europe, and increasingly in the USA, ozone is being used as an oxidant. In developing countries, ozone has not been widely used. An ozone dose of 2 mg/L, contacted with the water for 1 minute prior to filtration, has been shown to be effective in oxidizing iron and manganese, at the same time removing arsenic and other metals to below detection limits. At a similar ozone dose, arsenite was shown to have a half-life of approximately 4 minutes. Ozone is also a potent disinfectant, but unlike chlorine, does not impart a lasting residual to treated water.

Permanganate effectively oxidizes arsenite, along with Fe (II) and Mn (II). It is a poor disinfectant, though it can produce a bacteriostatic effect. Potassium permanganate ($KMnO_4$) is widely available in developing countries, where it is used as a topical antibiotic for minor cuts. It is relatively stable with a long shelf life. Residual manganese in treated water should not exceed the WHO guideline of 0.5 mg/L (WHO, 1993). Hydrogen peroxide may be an effective oxidant if the raw water contains high levels of dissolved iron, which often occur in conjunction with arsenic contamination.

3.2 Precipitation

Causing dissolved arsenic to form a low-solubility solid mineral, such as calcium arsenate. This solid can then be removed through sedimentation and filtration. When coagulants are added and form flocks, other dissolved compounds such as arsenic can become insoluble and form solids, this is known as co precipitation. The solids formed may remain suspended, and require removal through solid/liquid separation processes, typically coagulation and filtration.

3.3 Adsorption and Ion Exchange

Various solid materials, including iron and aluminum hydroxide flocks, have a strong affinity for dissolved arsenic. Arsenic is strongly attracted to sorption sites on the surfaces of these solids, and is effectively removed from solution. Ion exchange can be considered as a special form of adsorption, though it is often considered separately. Ion exchange involves the reversible displacement of an ion adsorbed onto a solid surface by a dissolved ion. Other forms of adsorption involve stronger bonds, and are less easily reversed.

3.4 Solid / Liquid Separation

Precipitation, co-precipitation, adsorption, and ion exchange all transfer the contaminant from the dissolved to a solid phase. In some cases the solid is large and fixed (e.g. grains of ion exchange resin), and no solid/liquid separation is required. If the solids are formed in situ (through precipitation or coagulation) they must be separated from the water. Gravity settling (also called sedimentation) can accomplish some of this, but filtration is more effective. Most commonly, sand filters are used for this purpose.

Physical exclusion: some synthetic membranes are permeable to certain dissolved compounds but exclude others. These membranes can act as a molecular filter to remove dissolved arsenic, along with many other dissolved and particulate compounds.

3.5 Biological Removal Processes

Bacteria can play an important role in catalyzing many of the above processes. Relatively little is known about the potential for biological removal of arsenic from water.

Boiling does not remove arsenic from water.

Most of the established technologies for arsenic removal make use of several of these processes, either at the same time or in sequence. All of the removal technologies have the added benefit of removing other undesirable compounds along with arsenic – depending on the technology, bacteria, turbidity, color, odor, hardness, phosphate, fluoride, nitrate, iron, manganese, and other metals can be removed.

3.6 Coagulation and Filtration

Historically, the most common technologies for arsenic removal have been coagulation with metal salts, lime softening, and iron/manganese removal. Coagulation processes are sometimes unable to efficiently remove arsenic to these low levels. As a result, various alternate technologies have been developed or adapted that are capable of removing arsenic to trace levels. These advanced treatment options include ion exchange, activated alumina, and membrane methods such as reverse osmosis and nanofiltration. While these Technologies have all been shown to be effective in lab or pilot studies, there is still relatively little experience with full-scale treatment. In addition, a number of novel removal technologies are under development, some of which show great promise.

This treatment can effectively remove many suspended and dissolved constituents from water besides arsenic, notably turbidity, iron, manganese, phosphate and fluoride. Significant reductions are also possible in odor, color, and potential for trihalomethane formation. Thus coagulation and filtration to remove arsenic will improve other water quality parameters, resulting in ancillary health and esthetic benefits. However, the optimal conditions vary for removal of different constituents, and coagulation to remove arsenic may not be optimal for removal of other compounds, notably phosphate and fluoride.

Coagulation with ferric chloride works best at pH below 8. Alum has a narrower effective range, from pH 6-8. Ion exchange resins are commercially produced synthetic materials that can remove some compounds from water. These resins only remove arsenate. Activated alumina, like ion exchange resins, is commercially available in coarse grains. Activated alumina beds usually have much longer run times than ion exchange resins, typically several tens of thousands of beds can be treated before arsenic breakthrough.

Activated alumina works best in slightly acidic waters (pH 5.5 to 6). Membrane methods for arsenic removal include reverse osmosis and nanofiltration.

Arsenic removal with metal salts has been shown since at least 1934. The most commonly used metal salts are aluminum salts such as alum, and ferric salts such as ferric chloride or ferric sulfate. Ferrous sulfate has also been used, but is less effective. Excellent arsenic removal is possible with either ferric or aluminum salts, with laboratories reporting over 99% removal under optimal conditions, and residual arsenic concentrations of less than 1 μg/L. Full-scale plants typically report a somewhat lower efficiency, from 50% to over 90% removal.

During coagulation and filtration, arsenic is removed through three main mechanisms:

Precipitation: the formation of the insoluble compounds $Al(AsO_4)$ or $Fe(AsO_4)$

Co precipitation: the incorporation of soluble arsenic species into a growing metal hydroxide phase

Adsorption: the electrostatic binding of soluble arsenic to the external surfaces of the insoluble metal hydroxide.

All three of these mechanisms can independently contribute towards contaminant removal. In the case of arsenic removal, direct precipitation has not been shown to play an important role. However, coprecipitation and adsorption are both active arsenic removal mechanisms.

Numerous studies have shown that filtration is an important step to ensure efficient arsenic removal. After coagulation and simple sedimentation, HAO and HFO – along with their sorbed arsenic load – can remain suspended in colloidal form. Hering and others showed that coagulation and sedimentation without filtration achieved arsenate removal efficiencies of 30%; after filtration through a 1.0 micron filter, efficiency was improved to over 96%. Only marginal improvements were made by reducing the filter size to 0.1 micron. In field applications, some plants improve arsenic removal with two-stage filtration.

3.7 Ion-Exchange Resins

Ion exchange has been used to treat groundwater and drinking water containing arsenic. This technology typically can reduce arsenic concentrations to less than 0.050 mg/L and in some cases has reduced arsenic concentrations to below 0.010 mg/L. Its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It is used less frequently than precipitation/co precipitation, and is most commonly used to treat groundwater and drinking water, or as a polishing step for other water treatment processes.

Synthetic ion exchange resins are widely used in water treatment to remove many undesirable dissolved solids, most commonly hardness, from water. These resins are based on a cross-linked polymer skeleton, called the ‘matrix’. Most commonly, this matrix is composed of polystyrene cross-linked with divinylbenzene. Charged functional groups are attached to the matrix through covalent bonding, and fall into four groups:

- Strongly acidic (e.g. sulfonate, $–SO_3$ -)
- Weakly acidic (e.g. carboxylate, –COO-)
- Strongly basic [e.g. quaternary amine, $–N+(CH_3)3$]
- Weakly basic [e.g. tertiary amine, $–N(CH_3)2$]

The acidic resins are negatively charged, and can be loaded with cations (e.g. Na+), which are easily displaced by other cations during water treatment. This type of cation exchange is most commonly applied to soften hard waters.

Conversely, strongly basic resins can be pretreated with anions, such as Cl-, and used to remove a wide range of negatively charged species. Clifford gives the following relative affinities of some common anions for a type 1 strong-base anion resins (Clifford, 1999):

$CrO^{-2}_4 >> SeO^{-2}_4 >> SO\ ^{-2}_4 >> HSO^-_4 >> NO^-_3 >> Br^- >> HASO_4\ ^{-2} >> SeO^{-2}\ _3 >> HSO^{-3}_3 >> NO^-_2 >> Cl^-$

Different resins will have differing selectivity sequences, and resins have been developed specifically to optimize removal of sulfate, nitrate, and organic matter. Various strong-base anion exchange resins are commercially available which can effectively remove arsenate from solution, producing effluent with less than 1 μg/L arsenic.

3.8 Membrane Methods

Synthetic membranes are available which are selectively permeable: the structure of the membrane is such that some molecules can pass through, while others are excluded, or rejected. Membrane filtration has the advantage of removing many contaminants from water, including bacteria, salts, and various heavy metals.

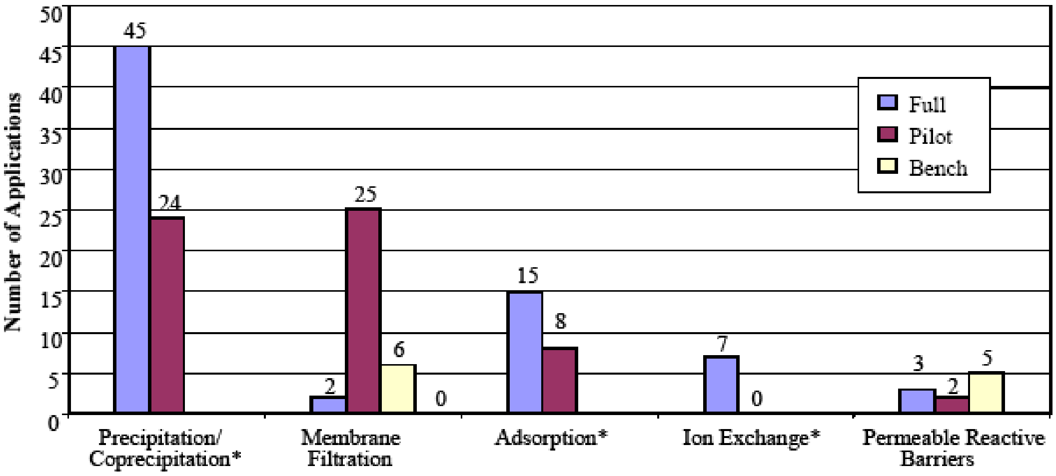
3.9 Emerging Technologies

In recent years, a tremendous amount of research has been conducted to identify novel technologies for arsenic removal, particularly low-cost, low-tech systems that can be applied in rural areas. Most of these technologies rely on oxidation of arsenite, followed by filtration through some sort of porous material, where arsenic is removed through adsorption and co precipitation. Many of these systems make use of iron compounds, which have a very strong affinity for arsenic. A brief review of some of the most documented technologies is given below.

3.10 Fe-Mn Oxidation

Conventional iron and manganese removal can result in significant arsenic removal, through co precipitation and sorption onto ferric or manganic hydroxides. The mechanisms involved are the same as in coagulation and filtration. Most low-cost technologies for arsenic and manganese removal rely on aeration and filtration through porous media such as sand and gravel. Any technology that effectively removes iron and manganese could be evaluated to see if arsenic is also removed effectively. In this respect arsenic removal is more convenient than that of fluoride, which does not undergo oxidation, and is not removed by co precipitation with iron (Johntson R.& Heijnen H.).

Figure 3.1 shows the number of treatment projects identified for technologies applicable to water. For water containing arsenic, the most frequently used technology is precipitation/co precipitation. Based on the information gathered for this report, precipitation/co precipitation is frequently used to treat arsenic contaminated water, and is capable of treating a wide range of influent concentrations to the revised MCL (Maximum Contaminant Level) for arsenic. The effectiveness of this technology is less likely to be reduced by characteristics and contaminants other than arsenic, compared to other water treatment technologies. It is also capable of treating water characteristics or contaminants other than arsenic, such as hardness or heavy metals. Systems using this technology generally require skilled operators; therefore, precipitation/ co precipitation is more cost effective at a large scale where labor costs can be spread over a larger amount of treated water produced Figure 3.2 shows the number of treatment projects identified for technologies applicable to soil, waste, and water. Three arsenic treatment technologies are generally applicable to soil, waste, and water: electro kinetics, phytoremediation, and biological treatment. These technologies have been applied in only a limited number of applications.



- Bench-scale data not collected for this technology.

Figure 3.1 Number of identified applications of arsenic treatment technologies for water (EPA, September 2002)

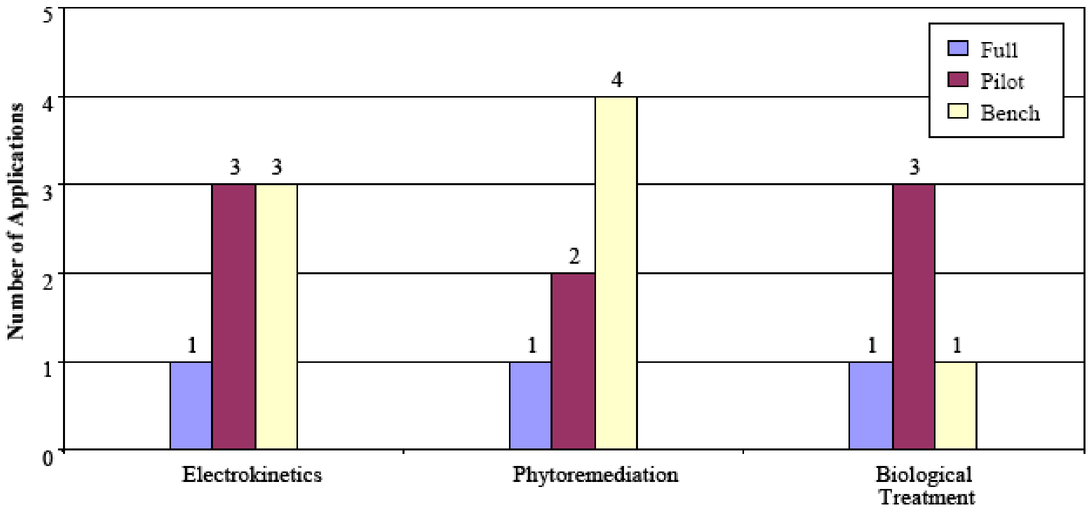


Figure 3.2 Number of identified applications of arsenic treatment technologies for soil, waste, and water

Some of treatment systems performance data's are given in from Table 3.4 to 3.7

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic

Industry or Site Type	**Waste or Media**	**Scale"**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process*'**
Landfill	Groundwater	Full	Winthrop Landfill Superfund Site, Winthrop, ME	0.300 mg/L	O.005 mg/L		Treatment train consisting of pH adjustment, oxidation, flocculation/ clarification, air stripping, and sand-bed filtration
Metal ore mining and smelting	Surface water, 32176 m^3	Full	Tex-Tin Superfund Site, OU 1,TX				Precipitation by pH adjustment followed by filtration
Herbicide application	Groundwater	Full		0.005 - 3.8 mg/L	O.005 - 0.05 mg/L	<5 mg/L (TCLP)	Iron Coprecipitation followed by membrane filtration
Power substation	Groundwater, 166558 m^3	Full	Ft. Walton Beach, FL	0.2-1.0 mg/L	O.005 mg/L		Iron Coprecipitation followed by ceramic membrane filtration
Chemical mixing	Groundwater, 162,8 m^3/d	Full	Baird and McGuire Superfund Site, Holbrook, MA				Treatment train consisting of air stripping, precipitation (ferric chloride, lime slurry, phosphoric and sulfuric acids, and ammonium sulfate), filtration, and carbon adsorption.

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale"**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process**
Wood preserving wastes	Groundwater	Full	Silver Bow Creek/Butte Area Superfund Site - Rocker Timber Framing And Treatment Plant OU, MT				In situ treatment of contaminated groundwater by injecting a solution of ferrous iron, limestone, and potassium permanganate
Metal ore mining and smelting activities	Collection pond water	Pilot	Ryan Lode Mine, AK	4.6 mg/L	0.027 mg/L		Enhanced iron co-precipitation followed by filtration
Herbicide application	Groundwater	Pilot		1 mg/L (TWA)	O.005 mg/L (TWA)		Iron coprecipitation followed by ceramic membrane filtration
Metal ore mining	Acid mine water	Pilot	Susie Mine/Valley Forge site, Rimini, MT	12.2 -16.5 mg/L	0.017-0.053 mg/L	8,830-13,300 mg/kg 0.0051-0.0076 mg/L (TCLP)	Photo-oxidation of arsenic followed by iron coprecipitation
Metals processing	Leachate from nickel roaster flue dust disposal area	Pilot	Susie Mine/Valley Forge site, Rimini, MT	423 - 439 mg/L	<0.32 mg/L	102,000 mg/kg 0.547-0.658 mg/L (TCLP)	Photo-oxidation of arsenic followed by iron coprecipitation
—	"Superfund wastewater"	Full	—	0.1-1 mg/L	0.022 mg/L	—	Chemical precipitation
-	Groundwater	Full	-	100 mg/L	< 0.2 mg/L	-	Precipitation
	"Superfund wastewater"	Full		0.1-1 mg/L	0.1 10 mg/L		Chemical precipitation

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale^3**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process''**
	Groundwater	Full		100 mg/L	<0.010mg/L		Reductive Precipitation (additional information not available)
Chemical manufacturing wastes, groundwater	Groundwater	Full	Peterson/Puritan Inc. Superfund Site-OU 1, PAC Area, RI				In-situ treatment of arsenic-contaminated groundwater by injecting oxygenated water
Chemical manufacturing	Groundwater, 246 m^3/d	Full	Greenwood Chemical Superfund Site, Greenwood, VA				Treatment train consisting of metals precipitation, filtration, UV oxidation and carbon adsorption
Waste disposal	Groundwater, 163 m^3/d	Full	Higgins Farm Superfund Site, Franklin Township, NJ				Treatment train consisting of air stripping, metals precipitation, filtration, and ion exchange
Wood preserving	Groundwater, 11 m^3/d	Full	Saunders Supply Company Superfund Site, Chuckatuck, VA				Treatment train consisting of metals precipitation, filtration, and carbon adsorption.
Herbicide manufacturing	RCRA waste codeK0 117746 m^3/d	Full	Vineland Chemical Company Superfund Site, Vineland, NJ				Metals precipitation followed by filtration

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale**^{3}	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process''**
Veterinary feed additives and Pharmaceuticals manufacturing	Groundwater, 189-378 lt/min.	Full	Whitmoyer Laboratories Superfund Site	100 mg/L	0.025 mg/L		Neutralization and flocculation by increasing pH to 9
	Drinking water, 6057 m^3 /d	Full		0.0203 mg/L (TWA)	0.0030 mg/L (TWA)	<5 mg/L (WET)	Ferric coprecipitation followed by zeolite softening
—	Drinking water, 5300 m^3/d	Full		0.0485 mg/L (TWA)	0.01 13 mg/L (TWA)	<5 mg/L (WET)	Ferric coprecipitation
	Drinking water	Full	McGrath Road Baptist Church, AK	0.370 mg/L	<0.005 mg/L		Enhanced iron co - precipitation followed by filtration
	Drinking water, 2271240 m^3/d	Full		0.0026-0.0121 mg/L	0.0008 - 0.006 mg/L	806-880 mg/kg O.05-0.106 mg/L (TCLP)	Ozonation followed by coagulation with iron- and aluminum-based additives and filtration
	Drinking water, 236588 m^3/d	Full		0.015-0.0239 mg/L	0.0015-0.0118 mg/L	293-493 mg/kg 0.058-0.114 mg/L (TCLP)	Coagulation with iron and aluminum based additives, sedimentation, and filtration
	Drinking water	Full		Plant A: 0.02 mg/L Plant B: 0.049 mg/L	Plant A: 0.003 mg/L Plant 8:0.012 mg/L		Adsorption and coprecipitation with iron hydroxide precipitates
-	Drinking water	Pilot	—	—	<0.002 mg/L Arsenic (V)	—	Iron coagulation with direct filtration

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale[3]**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process**
	Drinking water, 20 lt	Pilot	Bhariab & Sreenagar Thana, Bangladesh	0.28 - 0.59 mg/L	<0.03 - 0.05 mg/L	1194mg/kg	Iron co - precipitation followed by filtration
	Drinking water	Full	5 facilities, identification unknown		<0.003 mg/L (TWA)	<5 mg/L (TCLP)	Lime softening at pH >10.2
	Drinking water, lOmgd	Full		0.0159-0.0849 mg/L	0.0063-0.0331 mg/L	1 7.0-35.3 mg/kg <0.05 mg/L (TCLP)	Oxidation followed by lime softening and filtration
	Drinking water	Pilot	Harian Village Rajshaji District Bangladesh	0.092-0.120 mg/L	0.023 - 0.036 mg/L		Naturally-occurring iron at 9 mg/L facilitates precipitation, followed by sedimentation, filtration and acidification
	Drinking water	Pilot	West Bengal, India	0.300 mg/L	0.030 mg/L		Precipitation with sodium hypochlorite and alum, followed by mixing, flocculation, sedimentation, and up-flow filtration
	Drinking water, 40 liters per day	Pilot	Noakhali, Bangladesh	0.12 -0.46 mg/L	<0.05 mg/L		Coagulation with potassium permanganate and alum, followed by sedimentation and filtration

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale[3]**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process**
	Drinking water, 3,8 – 4,2 l/min.	Pilot	Spiro Tunnel Water Filtration Plant, Park City, UT	0.0609-0.146 mg/L	0.0012 - 0.0345 mg/L		Precipitation with ferric chloride and sodium hypochlorite, followed by filtration
	Drinking water, 20 liters per day	Pilot	West Bengal, India				Precipitation by ferric salt, oxidizing agent, and activated charcoal, followed by sedimentation and filtration
Veterinary Pharmaceuticals	K084, wastewater	Full	Charles City, Iowa	399-1, 670 mg/L (TWA)	Calcium arsenate, 60.5 - 500 mg/L (TWA)	45,200 mg/kg (TWA) 2,200 mg/L (TCLP)	Calcium hydroxide
	Wastewater	Full		4.2 mg/L (TWA)	0.51 mg/L (TWA)		Lime precipitation followed by sedimentation
	Wastewater	Full		4.2 mg/L (TWA)	0.34 mg/L (TWA)		Lime precipitation followed by sedimentation and filtration
	Wastewater	Full	BP Minerals America			Calcium arsenate and calcium arsenite, 1,900-6,900 mg/kg (TWA) 0.2 - 74.5 mg/L (EP Tox)	Lime

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale"**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process**
Veterinary Pharmaceuticals	K084, wastewater	Full	Charles City, Iowa	125 - 302 mg/L (TWA)	Manganese arsenate, 6.02 -22.4 mg/L (TWA)	47,400 mg/kg (TWA) 984 mg/L (TCLP)	Manganese sulfate
Metals processing	Spent leachate from the recovery of Cu, Ag, and Sb from ores (amount not available)	Full	Equity Silver Mine, Houston, British Columbia, Canada			95 to 98% recovery of arsenic	Acid addition, chemical precipitation with copper sulfate, and filtration
Metals processing	Leachate from filter cake from purification of zinc sulfate electrowinning solution (amount not available)	Full	Texasgulf Canada, Timmons, Ontario, Canada			98% recovery of arsenic	Acid addition, chemical precipitation with copper sulfate, and filtration
	Wastewater from wet scrubbing of incinerator vent gas (D004, P011)	Full	American NuKem	69.6 - 83.7 mg/L (TWA)	O.02 - 0.6 mg/L (TWA)		Chemical oxidation followed by precipitation with ferric salts
Veterinary Pharmaceuticals	K084, wastewater	Full	Charles City, Iowa	15 -107 mg/L (TWA)	Ferric arsenate, 0.163-0.580 mg/L (TWA)	9,760 mg/kg (TWA) 0.508 mg/L (TCLP)	Ferric sulfate

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale"**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process**
	Wastewater	Full		<0.1 -3.0 mg/L (TWA)	0.1 8 mg/L (average, TWA)		Chemical reduction followed by precipitation, sedimentation, and filtration
Centralized waste treatment industry	Wastewater	Full		57 mg/L (TWA)	0.1 81 mg/L (TWA)		Primary precipitation with solids-liquid separation
Centralized waste treatment industry	Wastewater	Full		57 mg/L (TWA)	0.246 mg/L (TWA)		Primary precipitation with solids-liquid separation followed by secondary precipitation with solids-liquid separation
Centralized waste treatment industry	Wastewater	Full		57 mg/L (TWA)	0.084 mg/L (TWA)		Primary precipitation with solids-liquid separation followed by secondary precipitation with solids-liquid separation and multimedia filtration
Centralized waste treatment industry	Wastewater	Full		57 mg/L (TWA)	0.011 mg/L (TWA)		Selective metals precipitation, solids-liquid separation, secondary precipitation, solids-liquid separation, tertiary precipitation, and solid-liquid separation

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale”**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process^{0,}**
Chemical and allied products	Wastewater	Full	—	O^{b} -O.lmg/L (TWA)	0.0063 mg/L (TWA)	—	Chemically assisted clarification
—	Domestic wastewater	Full	—	O^{b} -O.lmg/L (TWA)	0.00 15 mg/L (TWA)	—	Chemical precipitation
Transportation equipment industry	Wastewater	Full		0.1-1 mg/L (TWA)	<0.002 mg/L (TWA)		Chemical precipitation and filtration
Chemicals and allied products	Wastewater	Full	—	0.1-1 mg/L (TWA)	0.028 mg/L (TWA)	—	Chemically assisted clarification
WR Metals Industries (WRMI) arsenic leaching process Metals processing	Leachate from arsenical flue-dusts from non-ferrous smelters (amount not available)	Full	WR Metals Industries (location not available)	110,000-550,000 mg/kg (TWA)			Chemical precipitation and filtration
Metals processing	Spent leachate from the recovery of Ag from ores (amount not available)	Full	Sheritt Gordon Mines, LTD., Fort Saskatchewan, Alberta, Canada				Chemical precipitation and filtration
Metallurgie-Hoboken-Overpelt (MHO) solvent extraction process Metals processing	Spent electrolyte from Cu refining (amount not available)	Full	Olen, Belgium			99.96% recovery of arsenic	Chemical precipitation and filtration
Electric, gas, and sanitary	Wastewater	Pilot	—	O^{b}'- 0.1 mg/L (TWA)	0.0028 mg/L (TWA)	—	Chemically assisted clarification
Primary metals	Wastewater	Pilot	—	O^{b} -0.1 mg/L (TWA)	<0.0015 mg/L (TWA)	•-	Chemical precipitation

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale[3]**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process*'**
	Wastewater bearing unspecified RCRA listed waste code	Pilot		O[b]-- 0.1 mg/L (TWA)	0.001 mg/L (TWA)		Chemical precipitation, activated carbon adsorption, and filtration
–	Domestic wastewater	Pilot	—	O[b]--0.1 mg/L (TWA)	0.001 mg/L (TWA)	—	Chemical precipitation
	Wastewater bearing unspecified RCRA listed waste code	Pilot		0.1 - 1 mg/L (TWA)	0.0 12 mg/L (TWA)		Chemical precipitation, activated carbon adsorption, and filtration
	Wastewater bearing unspecified RCRA listed waste code	Pilot		0.1-1 mg/L (TWA)	0.0 12 mg/L (TWA)		Chemical precipitation, activated carbon adsorption, and filtration
	Wastewater bearing unspecified RCRA listed waste code	Pilot		0.1 - 1 mg/L (TWA)	0.006 mg/L (TWA)		Chemical precipitation, activated carbon adsorption, and filtration
Landfill	Hazardous leachate, F039	Pilot		0.1 - 1 mg/L (TWA)	0.008 mg/L (TWA)		Chemical precipitation, activated carbon adsorption, and filtration
	Wastewater bearing unspecified RCRA listed waste code	Pilot		0.1 - 1 mg/L (TWA)	0.0 14 mg/L (TWA)		Chemical precipitation, activated carbon adsorption, and filtration

Table 3.4 Arsenic precipitation/co precipitation treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale^3**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Precipitate Arsenic Concentration**	**Precipitating Agent or Process''**
Municipal landfill	Leachate	Pilot		1 – l0 mg/L (TWA)	8 mg/L (TWA)		Chemical precipitation, activated carbon adsorption, and filtration
Metals processing	Scrubber water from lead smelter	Pilot		3,300 mg/L	0.007 mg/L		Mineral-like precipitation (additional information not available)
Metals processing	Thickener overflow from lead smelter	Pilot		5.8 mg/L	0.003 mg/L		Mineral-like precipitation (additional information not available)
	Industrial wastewater	Pilot		5.8 mg/kg	< 0.5 mg/kg		

a Excluding bench-scale treatments.

b Detection limit not provided.

c The information that appears in the "Precipitating Agent or Process" column, including the chemicals used, the descriptions of the precipitation/ *co precipitation processes, and whether the process involved precipitation or co precipitation, were prepared based on the information reported in the cited references. This information was not independently checked for accuracy or technical feasability. In some cases the term "precipitation" may be applied to a process that is actually* co precipitation.

EPT = Extraction procedure toxicity test
mg/L = milligrams per liter
RCRA = Resource Conservation and Recovery Act
WET = Waste extraction test
mg/kg = milligrams per kilogram
— = Not available
TWA = Total waste analysis
gpd = gallons per day
mgd = million gallons per day
TCLP = Toxicity characteristic leaching procedure

Table 3.5 Membrane filtration treatment performance data for arsenic

Media or Waste	**Scale**	**Site JVame or Location**	**Initial Arsenic Concentration**	**Percent Arsenic Removal" or Final Arsenic Concentration**	**Membrane or Treatment Process**
Groundwater	Pilot	Tarrytown, NY	0.038-0.154mg/L	95%	--
Groundwater	Pilot	Tarrytown, NY	0.038-0.154mg/L	95%	-
Groundwater with low DOC (Img/L)	Pilot			60%	Single element, negatively charged membrane
Groundwater with high DOC(llmg/L)	Pilot			80%	Single element, negatively charged membrane
Groundwater with high DOC(llmg/L)	Pilot			75% initial, 3- 16% final	Single element, negatively charged membrane
Arsenic spiked surface water	Pilot			Arsenic (III) 20% Arsenic (V) > 95%	Single element membrane
Arsenic spiked surface water	Pilot		—	Arsenic (III) 30% Arsenic (V) > 95%	Single element membrane
Arsenic spiked surface water	Pilot	—	—	Arsenic (III) 52% Arsenic (V) > 95%	Single element membrane
Arsenic spiked DI water	Bench			Arsenic (III) 12% Arsenic (V) 85%	Single element, negatively charged membrane
Arsenic spiked lake water	Bench			Arsenic (V) 89%	Single element, negatively charged membrane
Arsenic spiked DI water	Bench		—	Arsenic (V) 90%	Flat sheet, negatively charged membrane

Table 3.5 Membrane filtration treatment performance data for arsenic (continued)

Media or Waste	**Scale**	**Site Maine or Location**	**Initial Arsenic Concentration**	**Percent Arsenic Removal" or Final Arsenic Concentration**	**Membrane or Treatment Process**
Surface water contaminated with wood preserving wastes	Full		24.4 mg/L	Arsenic removal, 99% reject stream, 57.7 mg/L treated effluent stream, 0.0394 mg/L	Treatment train consisting of RO followed by ion exchange. Performance data are for RO treatment only.
Groundwater	Pilot	Charlotte Harbor, FL	–	Arsenic (III) 46-84% Arsenic (V) 96-99%	
Groundwater	Pilot	Cincinnati, OH	-	Arsenic (III) 73%	-
Groundwater	Pilot	Eugene, OR	-	50%	-
Groundwater	Pilot	Fairbanks, AL	-	50%	-
Groundwater	Pilot	Hudson, NH	--	40%	--
Groundwater with low DOC	Pilot			> 80%	Single element, negatively charged membrane
Groundwater with high DOC	Pilot			> 90%	Single element, negatively charged membrane
Arsenic spiked surface water	Pilot	"		Arsenic (III) 60% Arsenic (V) > 95%	Single element membrane
Arsenic spiked surface water	Pilot	–	–	Arsenic (III) 68% Arsenic (V) > 95%	Single element membrane
Arsenic spiked surface water	Pilot		–	Arsenic (III) 75% Arsenic (V) > 95%	Single element membrane
Arsenic spiked surface water	Pilot			Arsenic (III) 85% Arsenic (V) > 95%	Single element membrane
Groundwater	Pilot	San Ysidro, NM	-	91%	-
Groundwater	Pilot	San Ysidro, NM		99%	Hollow fiber, polyamide membrane
Groundwater	Pilot	San Ysidro, NM	—	93-99%	Hollow fiber, cellulose acetate membrane

Table 3.5 Membrane filtration treatment performance data for arsenic (continued)

Media or Waste	**Scale**	**Site Name or Location**	**Initial Arsenic Concentration**	**Percent Arsenic Removal or Final Arsenic Concentration**	**Membrane or Treatment Process**
Groundwater	Pilot	Tarrytown, NY	--	86%	-
Arsenic spiked lake water	Bench	~		Arsenic (III) 5% Arsenic (V) 96%	"
Arsenic spiked DI water	Bench		¯	Arsenic (III) 5% Arsenic (V) 96%	
Arsenic spiked DI water	Bench	--	-	Arsenic (V) 88%	-
Drinking water	Pilot	Park City Spiro Tunnel Water Filtration Plant, Park City, Utah	0.065 mg/L	0.0005 mg/L	
Groundwater	Full		0.005 - 3.8 mg/L	O.005 - 0.05 mg/L	Iron coprecipitation followed by membrane filtration
Groundwater	Pilot		0.2 - 1 .0 mg/L	<0.005 mg/L	Iron coprecipitation followed by ceramic membrane filtration

a Percent arsenic rejection is 1 minus the mass of arsenic in the treated water divided by the mass of arsenic in the influent times 100 [(l-(mass of arsenic influent/mass of arsenic effluent))* 100]. DI = Deionized
DOC = Dissolved organic carbon — = Not available NF = Nanofiltration RO = Reverse Osmosis

Table 3.6 Adsorption treatment performance data for arsenic

Industry or Site Type	**Waste or Media**	**Scale-**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Adsorption Process Description***
—	Groundwater	Full	—	—	<0.05 mg/L	Activated alumina. Flow rate: 300 liters/hour.
—	Groundwater	Pilot	—	—	<0.05 mg/L	Activated alumina adsorption at pH 5
	Solution containing trivalent arsenic	Pilot		Trivalent arsenic, 0. 1 mg/L	Trivalent arsenic, 0.05 mg/L	Activated alumina adsorption at pH 6.0 of solution containing trivalent arsenic. 300 bed volumes treated before effluent exceeded 0.05 mg/L arsenic.
—	Solution containing pentavalent arsenic	Pilot	—	Pentavalent arsenic, 0. 1 mg/L	Pentavalent arsenic, 0.05 mg/L	Activated alumina adsorbent at pH 6.0 of solution containing pentavalent arsenic. 23,400 bed volumes treated before effluent exceeded 0.05 mg/L arsenic.

Table 3.6 Adsorption treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale'**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Adsorption Process Description**
Wood preserving	Groundwater	Full	Mid-South Wood Product Superfund Site, Mena, AS	0.018mg/L	.005mg/L(29of35 monitoring wells)	Treatment train consisting of oil/water separation, filtration, and carbon adsorption. Performance data are for the entire treatment train.
Wood Preserving	Groundwater, 102 m^3/d	Full	North Cavalcade Street Superfund Site Houston, TX			Treatment train consisting of filtration followed by carbon adsoiption
Wood Preserving	Groundwater, 11,4 m^3/d	Full	Saunders Supply Company Superfund Site, Chuckatuck, VA			Treatment train consisting of metals precipitation, filtration, and carbon adsorption
Wood Preserving	Groundwater, 15 m^3/d	Full	McCormick and Baxter Creosoting Co. Superfund Site, Portland, OR			Treatment train consisting of filtration, ion exchange, and carbon adsoiption
Chemical mixing and batching	Groundwater, 163 m^3/d	Full	Baird and McGuire Superfund Site, Holbrook, MA			Treatment train consisting of air stripping, metals precipitation, filtration, and carbon adsorption
Chemical Manufacturing	Groundwater, 246 m^3/d	Full	Greenwood Chemical Superfund Site, Greenwood, VA			Treatment train consisting of metals precipitation, filtration, UV oxidation and carbon adsorption

Table 3.6 Adsorption treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale-**	**Site Name or Location**	**Initial Arsenic Concentration**	**Final Arsenic Concentration**	**Adsorption Process Description***[1]
Landfill	Groundwater	Pilot			0.027 mg/L	Treatment train consisting of precipitation from barite addition followed by an iron filings and sand media filter. Performance data are for the entire treatment train.
	Groundwater, 13,6 m^3/d	Pilot	CA	0.018mg/L	<0.002 mg/L	Fixed-bed adsorber with sulfur-modified iron adsorbent; 13,300 bed volumes put through unit
	Drinking water	Full		0.063 mg/L	<0.003 mg/L	Two activated alumina columns in series, media replaced in one column every 1 .5 years
—	Drinking water	Full	—	0.034 - 0.087 mg/L	<0.05 mg/L	Activated alumina
—	Drinking water	Full	Project Earth Industries, Inc.	0.34 mg/L	0.01 -0.025 mg/L	Activated alumina
	Drinking water	Full		0.049 mg/L	<0.003 mg/L	Two activated alumina columns in series, media replaced in column tank every 1 .5 years
—	Drinking water, 53 m^3/d	Full	Bow, NH	0.057 - 0.062 mg/L	0.050 mg/L	Activated alumina
	Drinking water	Full	Harbauer GmbH & Co., Berlin, Germany	0.3 mg/L	0.01 mg/L	Granular ferric hydroxide

Table 3.6 Adsorption treatment performance data for arsenic (continued)

Industry or Site Type	Waste or Media	Scale'	Site Name or Location	Initial Arsenic Concentration	Final Arsenic Concentration	Adsorption Process Description[11]
	Drinking Water	Pilot		0.1- 0.18 mg/L	<0.01 mg/L	Fixed bed adsorber with ferric hydroxide-coated newspaper pulp; 20,000 bed volumes treated before effluent exceeded 0.01 mg/L arsenic
—	Drinking water	Pilot	—	0.180mg/L	0.010 mg/L	Granular ferric hydroxide
—	Drinking water	Full	—	0.02mg/L	0.003 mg/L	Fixed bed adsorber with ferric oxide granules
-	Drinking water	Full	--	5 mg/L	0.01 mg/L	Copper-zinc granules
	Drinking water	Pilot	ADI International			Adsorption in pressurized vessel containing proprietary media at pH 5. 5 to 8.0

a Excluding bench-scale treatments.

b Some processes employ a combination of adsorption, ion exchange, oxidation, precipitation/coprecipitation, or filtration to remove arsenic from water.

AA = activated alumina EPT = Extraction procedure toxicity test mg/L = milligrams per liter RCRA = Resource Conservation and Recovery Act

TCLP = Toxicity characteristic leaching procedure mg/kg = milligrams per kilogram

— = Not available TWA = Total waste analysis WET = Waste extraction test

Table 3.7 Ion Exchange treatment performance data for arsenic

Industry or Site Type	**Waste or Media**	**Scale**	**Site Name or Location**	**Ion Exchange Media or Process**	**Untreated Arsenic Concentration**	**Treated Arsenic Concentration**	**Ion Exchange Media Regeneration Information**
	Drinking Water	Full		Treatment train consisting of potassium permanganate greensand oxidizing filter followed by a mixed bed ion exchange system	0.040 - 0.065 mg/L[a]	<0.003 mg/L"	Bed regenerated every 6 days
	Drinking Water	Full		Treatment train consisting of a solid oxidizing media filter followed by an anion exchange system	0.019-0.055 mg/L"	O.005 - 0.080 mg/L[a]	
	Drinking Water	Full		Strongly basic gel ion exchange resin in chloride form	0.045 - 0.065 mg/L	0.0008 - 0.0045 mg/L	Resin regenerated every four weeks
	Drinking Water	Full		Chloride-form strong-base resin anion-exchange process		0.002 mg/L	Spent NaCl brine reused to regenerate exhausted ion-exchange bed
Wood Preserving, spill of chromated copper arsenate	Surface water	Full	Vancouver, Canada (site name unknown)	Anion and cation resins	0.0394 mg/L	0.0229 mg/L	
Waste disposal	Groundwater, 162 m^3/d	Full	Higgins Farm Superfund Site, Franklin Township, NJ	Treatment train consisting of air stripping, metals precipitation, filtration, and ion exchange			

Table 3.7 Ion Exchange treatment performance data for arsenic (continued)

Industry or Site Type	**Waste or Media**	**Scale**	**Site Name or Location**	**Ion Exchange Media or Process**	**Untreated Arsenic Concentration**	**Treated Arsenic Concentration**	**Ion Exchange Media Regeneration Information**
Wood preserving	Groundwater, 15 m^3/d	Full	McCormick and Baxter Creosoting Co. Superfund Site, Portland, OR	Treatment train consisting of filtration, ion exchange, and carbon adsorption			

a Data are for entire treatment train, including unit operations that are not ion exchange.
-- = Not available.
TWA = Total waste analysis.
mg/L = milligrams per liter.

CHAPTER FOUR

TECHNOLOGY SELECTION FACTORS

Major Decision Factors Considered in the Technology Selection Process is listed table 4–1(Wang, L.& Others, EPA, November, 2004).

Table 4.1 Major decision factors considered in the technology selection process

Decision Factor	**Issues**
Water Quality	Impact of water quality on performance and pretreatment requirements
Residuals Generation	Quantity and characteristics
Residuals Disposal	Available disposal methods; state requirements
Complexity of System Operation	Operational complexity or level of operator oversight
Cost	Capital and operational costs (excluding residual disposal)
Other	Adaptability for expansion or new technology conversion

4.1 Water Quality

A number of drinking water treatment technologies are available to reduce arsenic concentrations in source water to below the new MCL of 10 μg/L, including adsorption, ion exchange, membrane processes such as reverse osmosis and nanofiltration, and coagulation/filtration-related processes. Many of the most effective arsenic removal processes available are iron-based treatment technologies such as chemical coagulation/filtration with iron salts, and adsorptive media with iron-based products. These processes are particularly effective at removing arsenic from aqueous systems because iron surfaces have a strong affinity for adsorbing arsenic.

4.2 Complexity of System Operation

For small systems, complexity of system operation is always a concern. Complex systems often require more experienced and skilled operators to operate the systems. During technology selection, questions often raised by system operators include the frequency of backwashing, chemical addition requirements (pH adjustment, chlorine addition, etc.), and the frequency of media replacement. The level of automation available for system operation and data collection can significantly decrease the complexity, and thus can save time.

4.3 Cost

With limited resources available, operational cost is always an issue for most small systems, and thus is a major consideration in technology selection. For this demonstration study, the capital costs were generally less emphasized by the 12 water systems because the capital investment for the treatment systems is funded by EPA. However, the capital costs of treatment systems will be a major concern for most utilities when selecting technologies in the future. Information on the capital costs of the 12 treatment systems is reported in an EPA report, entitled Capital Costs of Arsenic Removal Technologies: U.S. EPA Arsenic Removal Technology Demonstration Program Round 1 (EPA, 2004b). Table 4-2 shows Available Arsenic Treatment Cost Data.

Table 4.2 Available arsenic treatment cost data

Site	**Amount Treated**	**Capital Cost**	**Annual O&M Cost**	**Unit Cost**	**Total Cost**	**Cost Explanation**
				$60 - $290 per ton		• Cost is for S/S of metals and is not arsenic-specific • Cost year not specified
Electrical Substation in Florida	2523 m^3	-	-	$85 per 0,765 m^3	-	• Excludes Disposal Costs • Costs in 1995 Dollars
Parsons Chemical Superfund Site	2294 m^3	$350,000 $550,000		$375 - $425 per ton		• Capital cost includes pilot testing, mobilization, and demobilization • Unit cots are for operation of vitrification equipment only • Cost year nor specified
King of Prussia Superfund Site	9787 m^3	-	-	$400 per ton	-	• Cost year not specified
-	-	-	-	$100 -$300 per ton	-	• Cost year not specified
-	-	-	-	$65 per ton	-	• Cost year not specified
-	306 m^3	-	-	$80 per ton	-	• Cost year not specified
-	38,000 tons	-	-	$203 per ton	$7.7 million	• Cost year not specified
-	-	-	-	$208 to $458 per ton	-	• Cost is not arsenic-specific • Costs in 1991 dollars
Vineland Chemical Company	5,3 m^3/ min	-	$4 million	-	-	• Cost year not specified
Winthrop Landfill	2,46 l/min	$2 million	$250,000	-	-	• Cost year not specified
Energized Substation in Florida	166558 m^3	-	-	$0.0006 per 3,7854 l	-	• Cost year not specified

Table 4.2 Available arsenic treatment cost data (Continued)

Site	**Amount Treated**	**Capital Cost**	**Annual O&M Cost**	**Unit Cost**	**Total Cost**	**Cost Explanation**
				\$0.003 - \$0.76 per 3,785 m^3		Cost year not specified
-	-	\$9,000	-	-	-	Cost year not specified
Monticello Mill Tailings	-	\$1.2 million	-	-	-	Cost year not specified
Pederok Plant, Kwint, Loppersum, Netherlands	248,5 m^3	-	-	\$70 per ton	-	Cost year not specified
Blackwater River State Forest, FL	-	-	-	\$883 per ton	-	Cost year not specified
	48562.28 m^2				\$200,000	1998 dollars Cost is for phytoextraction of lead from soil
	4,047 m^2, 50,80 centimeters deep				\$60,000 - \$100,000	Cost year not specified • Cost is for phytoextraction from soil • Contaminant was not specified
				\$2 - \$6 per 1,000 gallons		Cost is for ex situ treatment of water containing radionuclides Cost year not specified
				\$0.02 - \$.76 per cubic yard		Cost year not specified • Cost is for phytostabilization of metals, and is not arsenic-specific
-	-	-	-	\$0.50 per 1,000 gallons	-	Cost year not specified
-	-	-	-	\$2 per 1,000 gallons	-	Cost year not specified

- = Data nor provided

Table 4.3 Summary of cost data for treatment of arsenic in drinking

Technology	Design Flow Rate					
	378,54 m^3/d		3785,4 m^3/d		37854 m^3/d	
	Capital Cost ($)	Annual O&M Cost ($)	Capital Cost (S)	Annual O&M Cost (S)	Capital Cost (S)	Annual O&M Cost ($)
Precipitation/Co precipitation (coagulation-assisted microfiltration)	142,000	22,200	463,000	35,000	2,010,000	64,300
Adsorption (greensand filtration)	12,400	7,980	85,300	13,300	588,000	66,300
Adsorption (activated alumina, influent pH 7 - 8)	15,400	6,010	52,200	23,000	430,000	201,000
Ion exchange (anion exchange, influent <20 mg/L sulfate)	23,000	5,770	54,000	12,100	350,000	52,200

a. Costs are rounded to three significant figures and are in September 1998 dollars. Costs do not include pretreatment or management of treatment residuals. Costs for enhanced coagulation/filtration and enhanced lime softening are not presented because the costs curves for these technologies are for modification of existing drinking water treatment systems only (Ref. 3.4), and are not comparable to other costs presented in this table, which are for new treatment systems.

O&M = operating and maintenance

mg/L = milligrams per liter

< = less than

CHAPTER FIVE
EXPERIMENTAL STUDIES

Efficiency of chemical precipitation has been investigated. The arsenic concentration, of two different water samples, namely;

a-Distilled water

b-Raw water from dam, prior to water treatment plant.

The As concentration of both water samples have been set to 50 ppb by adding standard As^{+5} solution.

Three different coagulants have been used for simulating chemical precipitation by jar test.

$Al_2(SO_4)_3$

$FeCl_3$

$Ca(OH)_2$

have been used as coagulant.

Different doses, i.e. between 50-200 mg/lt coagulant have been applied to jar test analyses.

Arsenic concentration have been measured after jar test in laboratory and evaluated in the thesis.

After adding coagulant material, 60 seconds rapid mixing with blade type agitator, 15 minutes slow mixing and after 90 minutes delaying, water sample taken, and measurement arsenic value by ICP.

During test with distilled water, pH adjusted to 7,0.

In second steps coagulation tests applied at different pH values, 6; 7; 8; 9

Conducted results indicated that, all three type of coagulant are capable in arsenic removal, during chemical precipitation process. Among them $FeCl_3$ reflected the most effective results.

Doses of 50-100 mg/lt $Al_2(SO_4)_3$ and $FeCl_3$ generally have reflected better efficiency than the lower and higher doses for $Ca(OH)_2$,any recommended dose have not been achieved.

Therefore, using of $FeCl_3$, for arsenic removal is recommended as the anticipated conclusion of the thesis.

Table 5.1 Comparison of common coagulants (Corbill, A., R.)

Coagulant	Advantage	Disadvantage
Aluminum Sulfate	Easily to handle and apply, most commonly used, produces less sludge than lime, most effective between pH 6.8-7.5	Adds dissolved solids(salts)to water: effective over a limited pH range
Ferric Chloride	Effective between pH 4–11 also makes sludge dewatering easier	Adds dissolved solids(salts)to water
Lime	Commonly used, very effective: may not increased TDS (Total Dissolved Solids):sludge dewaters easily	Very pH dependent: produces large quantities of sludge overdose can result in poor effluent quality

Properties of coagulant materials

Table 5.2 Properties of alum

Chemical Formula	$Al_2 (SO_4)_3 .12 H_2O$
Molecular Weight	558
Commercial Form	Crystal, Powder

Table 5.3 Properties of ferric chloride

Chemical Formula	$FeCl_3$
Molecular Weight	161
Density	Crystal, Liquid

Table 5.4 Properties of calcium hydroxide

Chemical Formula	$Ca(OH)_2$
Molecular Weight	74
Density	Powder

5.1 Test Results with distilled water

Arsenic removal with $Al_2(SO_4)_3$

Arsenic removal efficiency with Alum at pH 7 data's and graphic are given on table 5.5 and figure 5.1.

Table 5.5 Arsenic removal data's with $Al_2(SO_4)_3$

Concentration of $Al_2(SO_4)_3$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
50	34	32
75	26	48
100	14	72
150	7	86

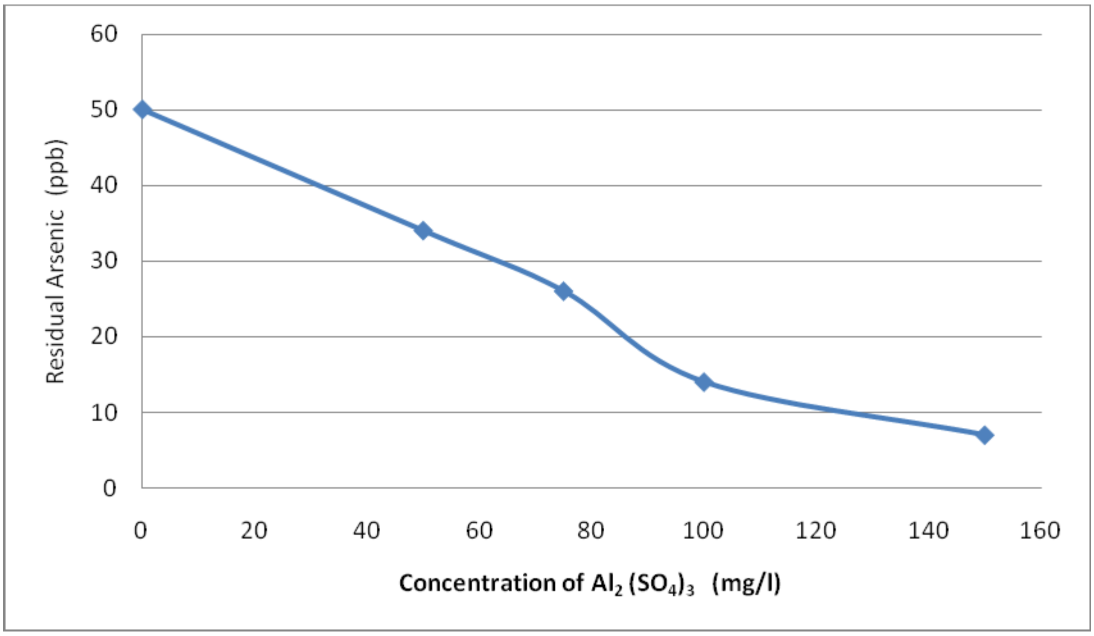


Figure 5.1 Arsenic removal with $Al_2(SO_4)_3$ with distilled water

Arsenic removal with $Al_2(SO_4)_3$ is effected, over 125 mg/lt $Al_2(SO_4)_3$ concentration, arsenic concentration becomes, less than 10 mg/lt.

Arsenic removal with $FeCl_3$

Arsenic removal efficiency with ferric chloride at pH 7 data's and graphic are given on table 5.6 and figure 5.2.

Table 5.6 Arsenic removal data's with $FeCl_3$

Concentration of $FeCl_3$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
50	29	42
75	21	58
100	11	78
150	4	92

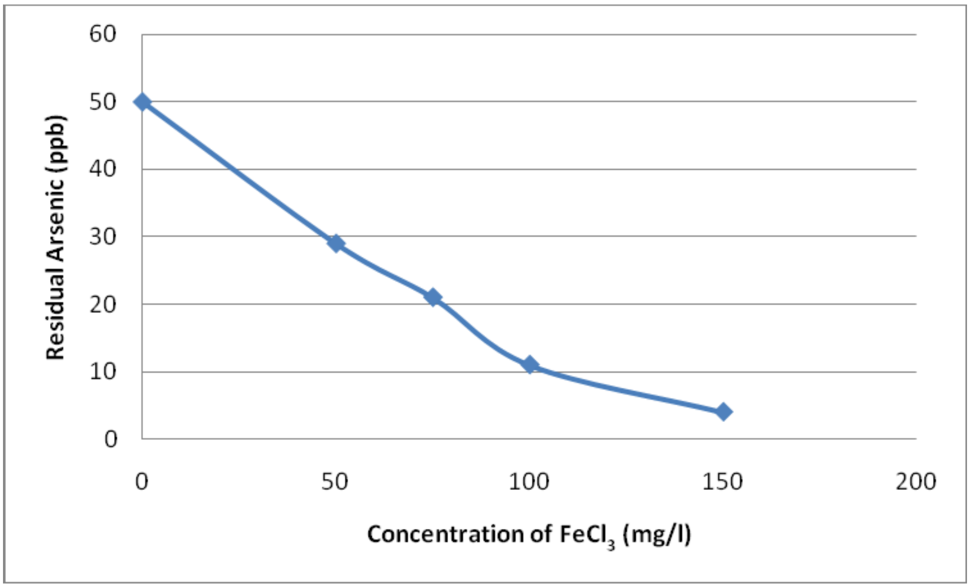


Figure 5.2 Arsenic removal with $FeCl_3$ with distilled water

Arsenic removal with $FeCl_3$ is effective, over 100 mg/lt $FeCl_3$ concentration

Arsenic removal with $Ca(OH)_2$

Arsenic removal efficiency with calcium hydroxide pH 7 data's and graphic are given on table 5.7 and figure 5.3.

Table 5.7 Arsenic removal data's with $Ca(OH)_2$

Concentration of $Ca(OH)_2$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
75	42	16
100	38	24
150	32	36
200	27	46

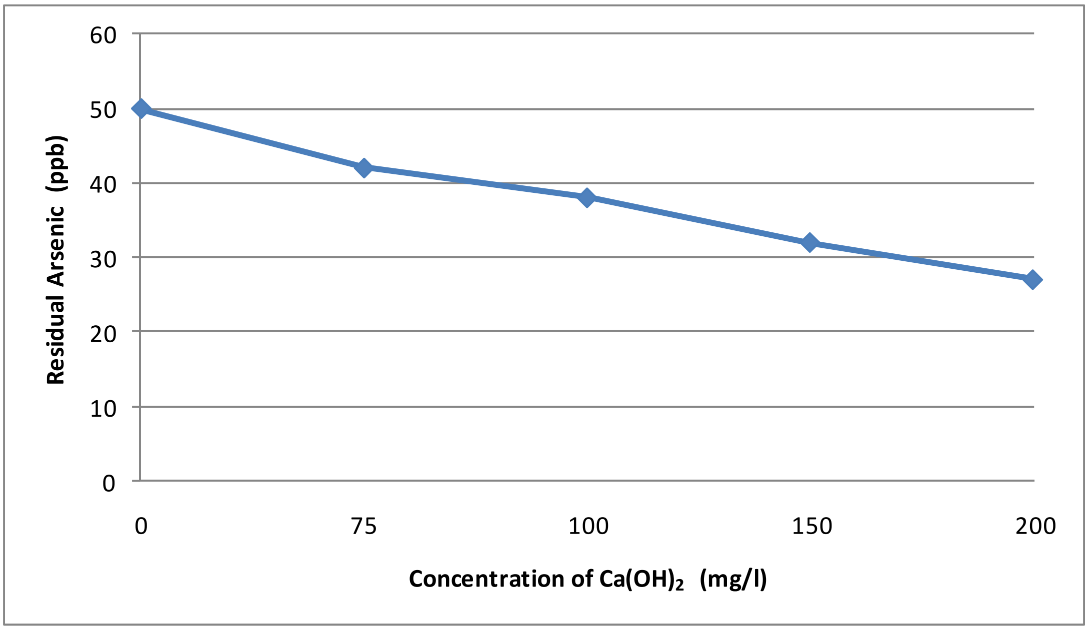


Figure 5.3 Arsenic removal with Ca $(OH)_2$ with distilled water

In this experiment, arsenic concentration decreasing according to $Ca(OH)_2$ concentration. Higher $Ca(OH)_2$ concentration becomes effective for increasing arsenic concentration.

5.2 Test Results with Raw Water

Efficiency of chemical precipitation has been investigated with raw water, was taken from the dam prior.

Test applied with different pH values, 6; 7; 8; 9 and different coagulant dosages.

Table 5.8 Properties of raw water

pH	7,5
Suspended Solids	70 mg/lt

Arsenic removal at pH 6 with $Al_2(SO_4)_3$

Arsenic removal efficiency with Alum at pH 6 data's and graphic are given on table 5.9 and figure 5.4.

Table 5.9 Arsenic removal data's with $Al_2(SO_4)_3$ at pH 6

Concentration of $Al_2(SO_4)_3$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
50	35.53	28.9
100	32.38	35.2
150	28.45	43.1
200	26.06	47.8

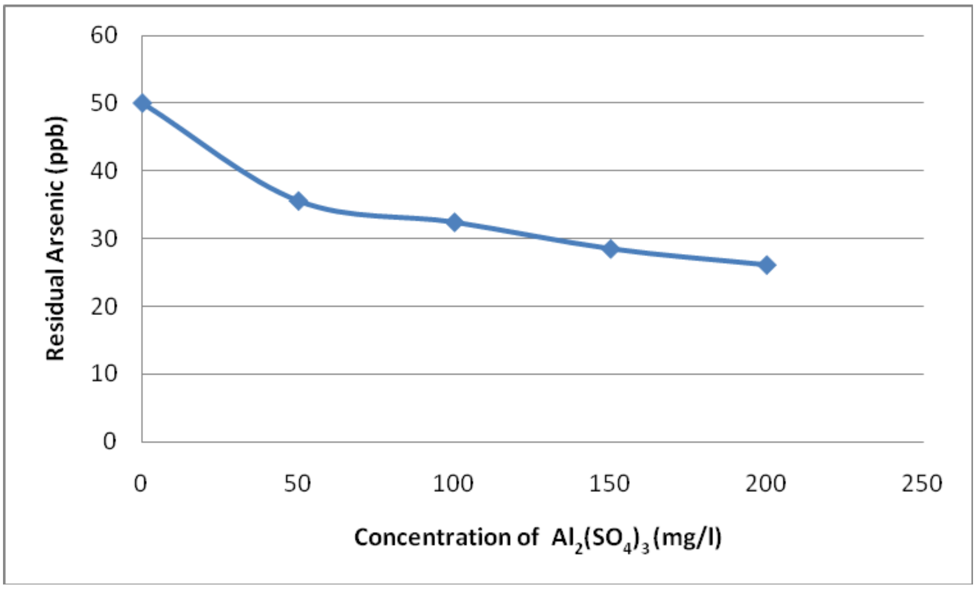


Figure 5.4 Arsenic removal with $Al_2(SO_4)_3$ at pH 6

Arsenic removal at pH 6, weak flocculation observed, over 250 mg/lt alum concentration may become effective.

At pH 7 with $Al_2(SO_4)_3$

Arsenic removal efficiency with Alum at pH 7 data's and graphic are given on table 5.10 and figure 5.5.

Table 5.10 Arsenic removal data's with $Al_2(SO_4)_3$ pH 7

Concentration of $Al_2(SO_4)_3$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
50	30.77	38.4
100	28.32	43.4
150	8.97	84
200	13.17	72.6

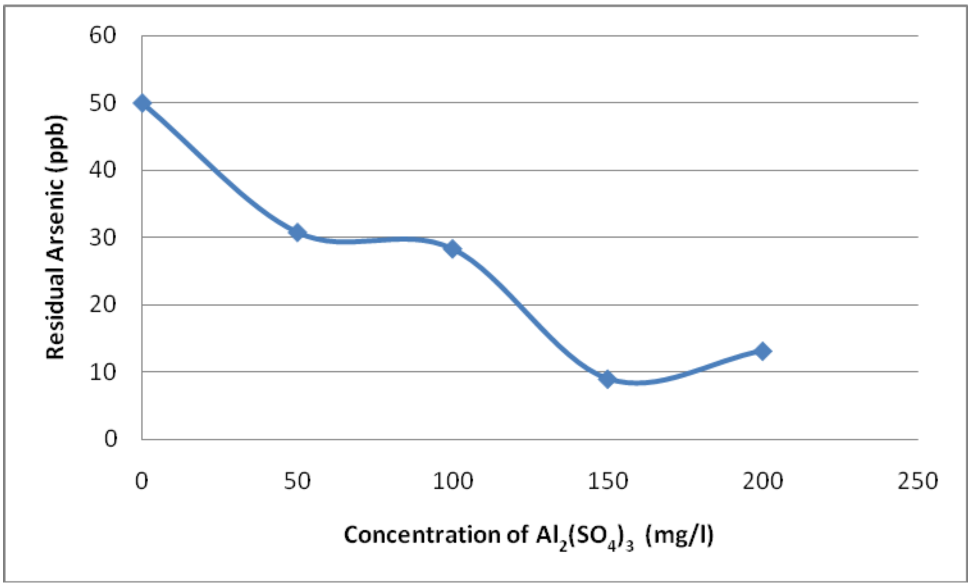


Figure 5.5 Arsenic removal with $Al_2(SO_4)_3$ at pH 7

At pH 7 arsenic removal with $Al_2(SO_4)_3$; in this experiment between 150-180 mg/l $Al_2(SO_4)_3$ concentration effective removal arsenic concentration less than 10 mg/l. But it is limited effective.

At pH 8 with $Al_2(SO_4)_3$

Arsenic removal efficiency with Alum at pH 8 data's and graphic are given on table 5.11 and figure 5.6.

Table 5.11 Arsenic removal data's with $Al_2(SO_4)_3$ at pH 8

Concentration of $Al_2(SO_4)_3$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
50	11.25	77.5
100	16.84	66.3
150	19.51	61
200	22.61	54.8

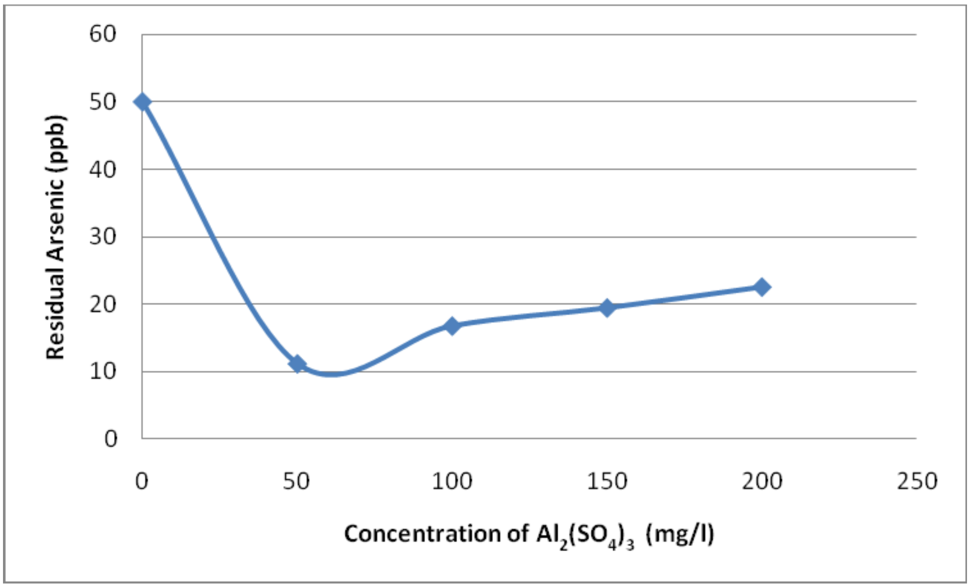


Figure 5.6 Arsenic removal with $Al_2(SO_4)_3$ at pH 8

In this experiment $Al_2(SO_4)_3$ concentration is effective for removing arsenic concentration. Approximately at 80 mg/l arsenic concentration, decrease to 10 mg/l. But over 100 mg/l $Al_2(SO_4)_3$ concentration, arsenic removal is not efficiency.

At pH 6 with $FeCl_3$

Arsenic removal efficiency with ferric chloride at pH 6 data's and graphic are given on table 5.12 and figure 5.7.

Table 5.12 Arsenic removal data's with $FeCl_3$ at pH 6

Concentration of $FeCl_3$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
50	16.34	67.3
100	18.21	63.6
150	28.24	43.5
200	23.63	52.7

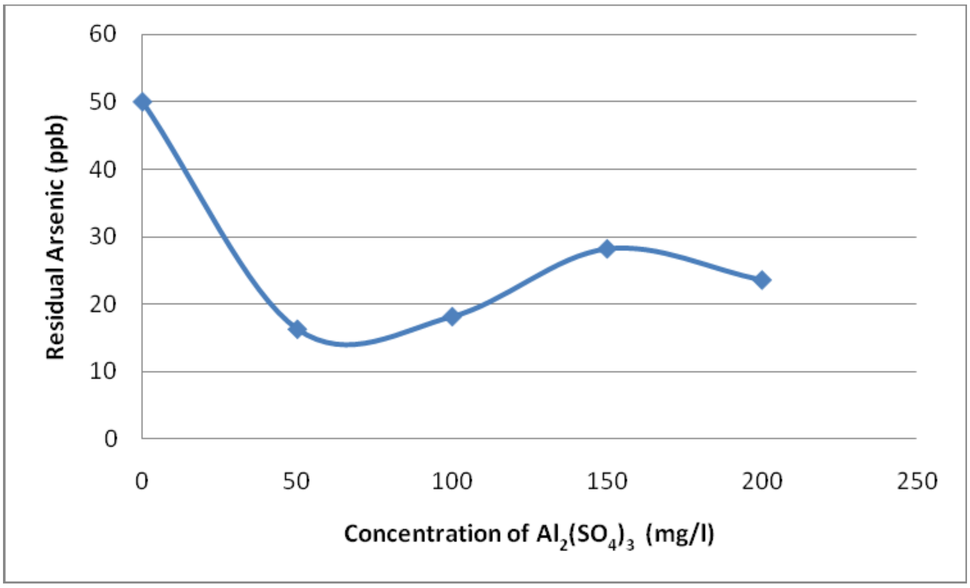


Figure 5.7 Arsenic removal with $FeCl_3$ at pH 6

In this study $FeCl_3$ not much effective for removal arsenic concentration at acidic condition. Over 100 mg /lt $FeCl_3$ weak flocculation and less arsenic removal observed.

At pH 7 with $FeCl_3$

Arsenic removal efficiency with ferric chloride at pH 7 data's and graphic are given on table 5.13 and figure 5.8.

Table 5.13 Arsenic removal data's with f $FeCl_3$ erric chloride at pH 7

Concentration of $FeCl_3$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
50	4.42	91.2
100	11.56	76.8
150	1.897	96.2
200	2.53	94.9

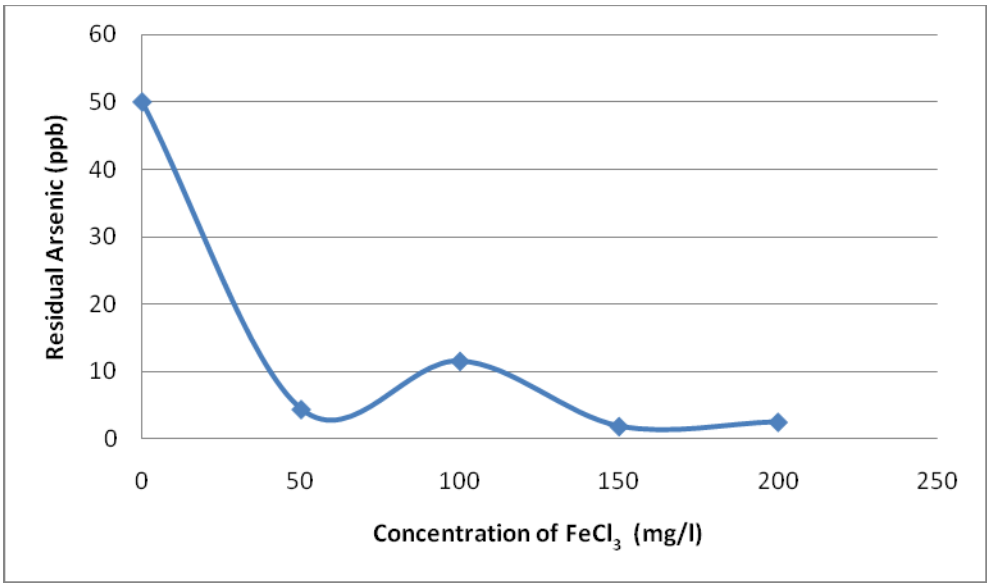


Figure 5.8 Arsenic removal with $FeCl_3$ at pH 7

Arsenic removal with $FeCl_3$ at pH 7 usually gives good results. Over 60 mg/lt $FeCl_3$ concentration reduce Arsenic concentration less than 10 mg/lt. I observed around 100 mg/lt $FeCl_3$ weak flocculation occurred. Approximately with 150 mg/lt $FeCl_3$ concentration arsenic concentration observed less than 5 mg/lt.

At pH 8 with $FeCl_3$

Arsenic removal efficiency with ferric chloride at pH 6 data’s and graphic are given on table 5.14 and figure 5.9.

Table 5.14 Arsenic removal data’s with $FeCl_3$ at pH 8

Concentration of $FeCl_3$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
50	4.65	90.7
100	5.94	88.1
150	5.62	88.8
200	4.83	90.3

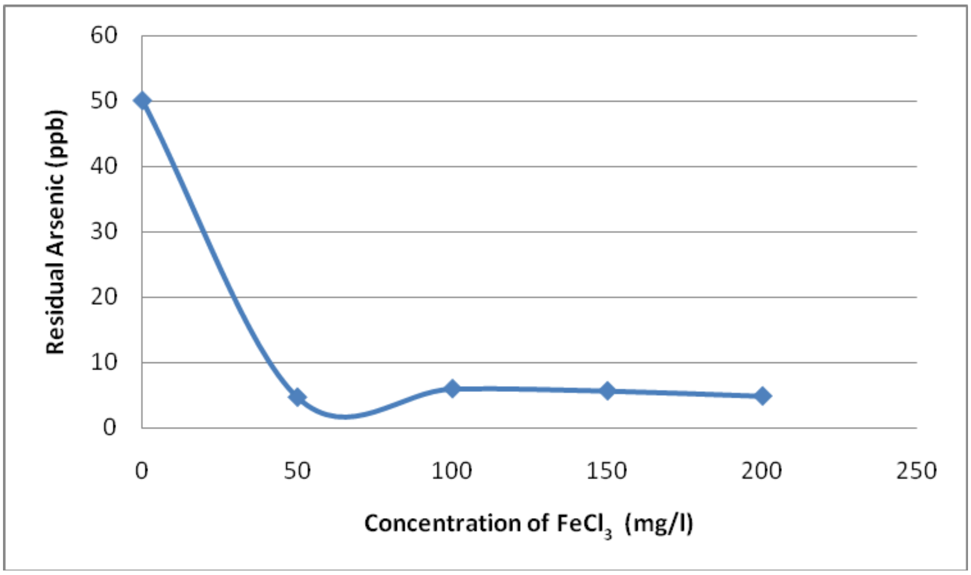


Figure 5.9 Arsenic removal with $FeCl_3$ at pH 8

In this experiment, 50-100 mg/l $FeCl_3$ concentration, effective removing arsenic, approximately 80-100 mg/l, arsenic concentration less than 5 mg/l, but after removal arsenic to make pH adjustment for drinking water.

At pH 9 with $FeCl_3$

Arsenic removal efficiency with ferric chloride at pH 9 data's and graphic are given on table5.15 and figure 5.10.

Table 5.15 Arsenic removal data's with $FeCl_3$ at pH 9

Concentration of $FeCl_3$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
50	29.14	41.72
100	14.932	70.13
150	7.72	84.86
200	4.864	90.27

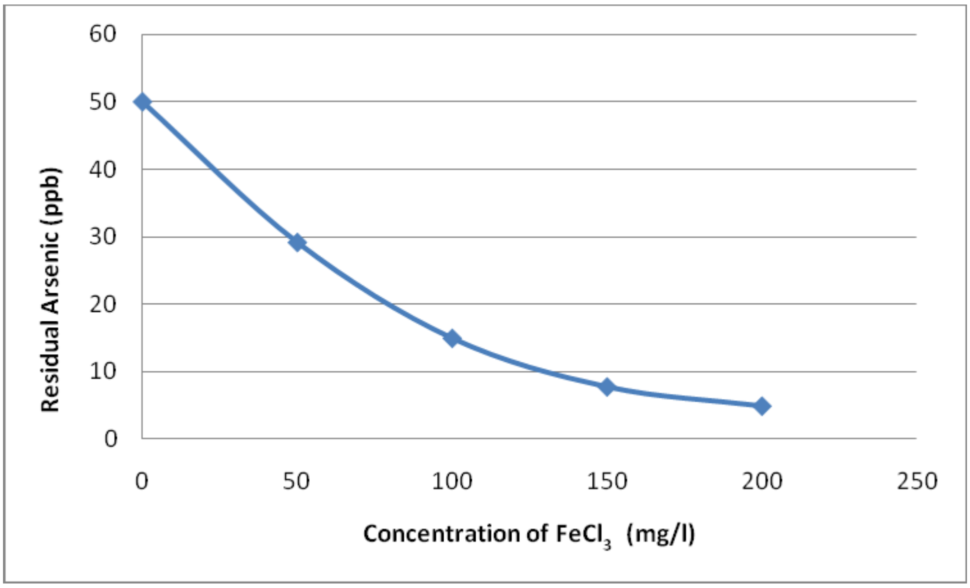


Figure 5.10 Arsenic removal with $FeCl_3$ at pH 9

In this experiment, over 100 mg/l $FeCl_3$ concentration, effective removing arsenic, but after removal arsenic to make pH adjustment for drinking water.

At pH 6 with $Ca(OH)_2$

Arsenic removal efficiency with calcium hydroxide pH 6 data's and graphic are given on table 5.16 and figure 5.11.

Table 5.16 Arsenic removal data's with $Ca(OH)_2$ at pH 6

Concentration of $Ca(OH)_2$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
75	38.4	23.2
100	35.4	29.2
150	30.7	38.6
200	28.6	42.8

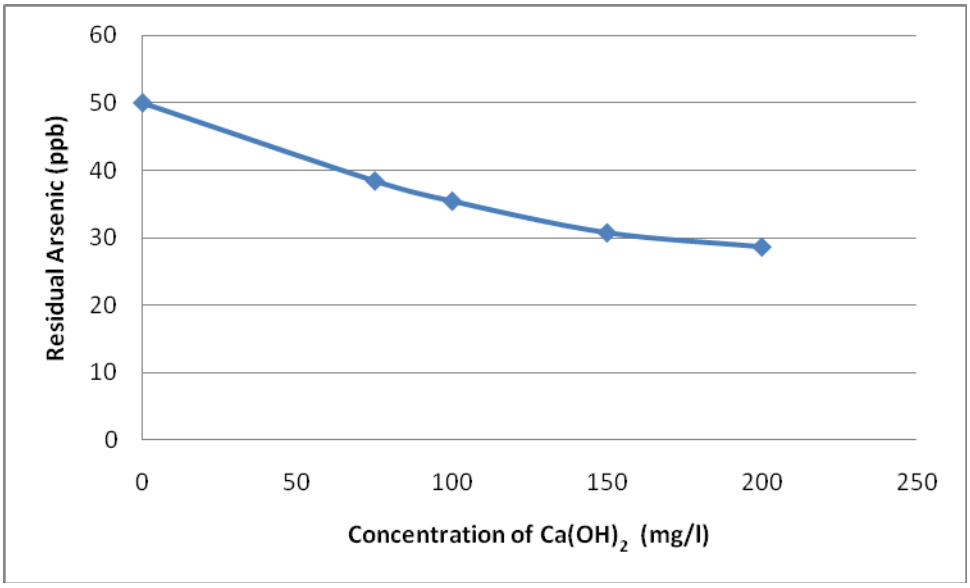


Figure 5.11 Arsenic removal with $Ca(OH)_2$ at pH 6

In this experiment, arsenic concentration decreasing according to $Ca(OH)_2$ concentration. Higher $Ca(OH)_2$ concentration becomes effective for increasing arsenic concentration.

At pH 7 with $Ca(OH)_2$

Arsenic removal efficiency with calcium hydroxide at pH 7 data's and graphic are given on table 5.17 and figure 5.12.

Table 5.17 Arsenic removal data's with $Ca(OH)_2$ at pH 7

Concentration of $Ca(OH)_2$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
75	38.17	23.6
100	35.32	29.4
150	28.17	43.7
200	23.75	52.5

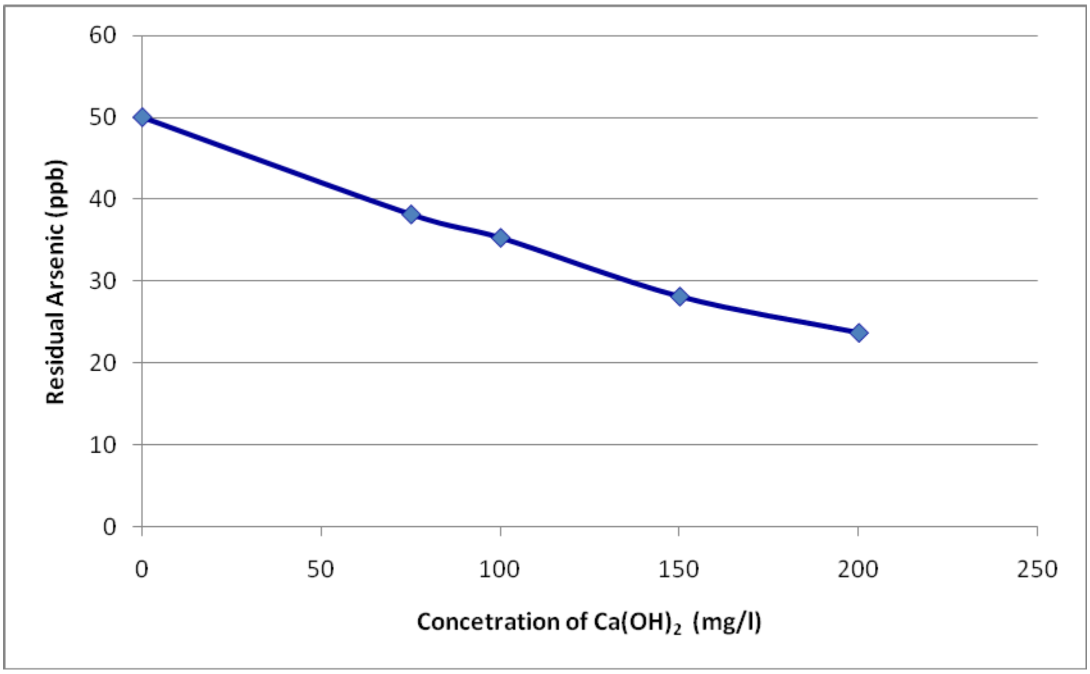


Figure 5.12 Arsenic removal with $Ca(OH)_2$ at pH 7

In this experiment, arsenic concentration decreasing according to $Ca(OH)_2$ concentration. Over 250 mg/lt $Ca(OH)_2$ concentration becomes effective for increasing arsenic concentration.

At pH 8 with $Ca(OH)_2$

Arsenic removal efficiency with calcium hydroxide at pH 8 data's and graphic are given on table and 5.18 figure 5.13.

Table 5.18 Arsenic removal data's with $Ca(OH)_2$ at pH 8

Concentration of $Ca(OH)_2$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
75	33.15	33.7
100	27.14	45.7
150	23.63	52.7
200	21.16	57.7

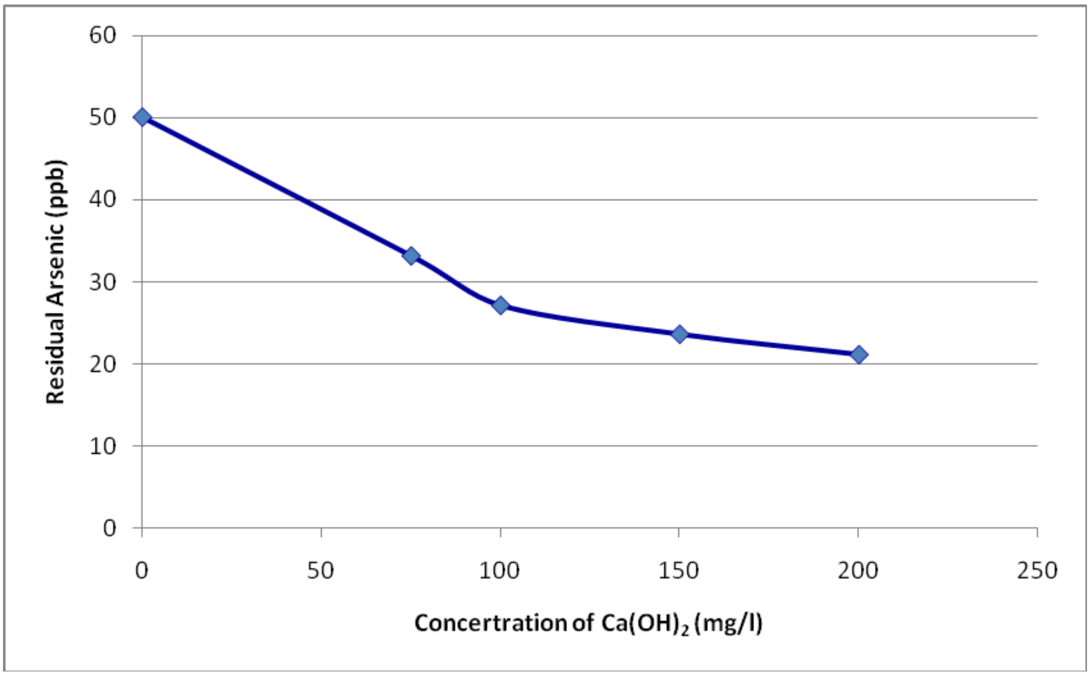


Figure 5.13 Arsenic removal with $Ca(OH)_2$ at pH 8

In this experiment, arsenic concentration decreasing according to $Ca(OH)_2$ concentration. Over 250 mg/lt $Ca(OH)_2$ concentration becomes effective for increasing arsenic concentration.

At pH 9 with $Ca(OH)_2$

Arsenic removal efficiency with calcium hydroxide at pH 9 data's and graphic are given on table 5.19 and figure 5.14.

Table 5.19 Arsenic removal data's with $Ca(OH)_2$ at pH 9

Concentration of $Ca(OH)_2$ (mg/l)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0
75	35.54	28.9
100	32.17	35.7
150	24.12	51.8
200	19.56	80.1

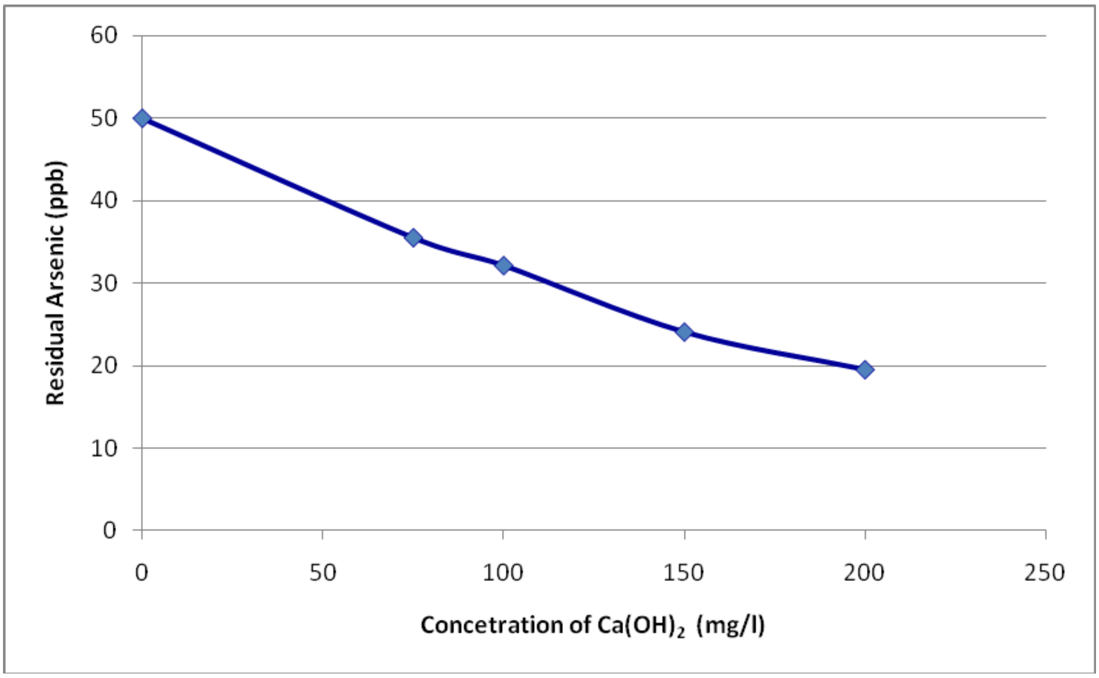


Figure 5.14 Arsenic removal with Ca $(OH)_2$ at pH 9

In this experiment, arsenic concentration decreasing according to $Ca(OH)_2$ concentration. Over 250 mg/lt $Ca(OH)_2$ concentration becomes effective for increasing arsenic concentration.

CHAPTER SIX

EVALUATION OF RESULTS

Comprehension of Alum efficiency with distilled water and raw water data's and graphic are given at table 6.1 and graphic 6.1.

Table 6.1 Comprehension of Alum efficiency with Distilled Water and Raw water

Concentration of $Al_2(SO_4)_3$ (mg/l)	Residual Arsenic (ppb)		Removing Efficiency (%)	
	Distilled water	Raw water*	Distilled water	Raw water*
0	50	50	0	0
50	34	30,77	32	28,9
75	-	-	-	-
100	26	28,32	48	35,2
150	14	8,97	72	43,1
200	7	13,17	86	47,8

*at pH 7

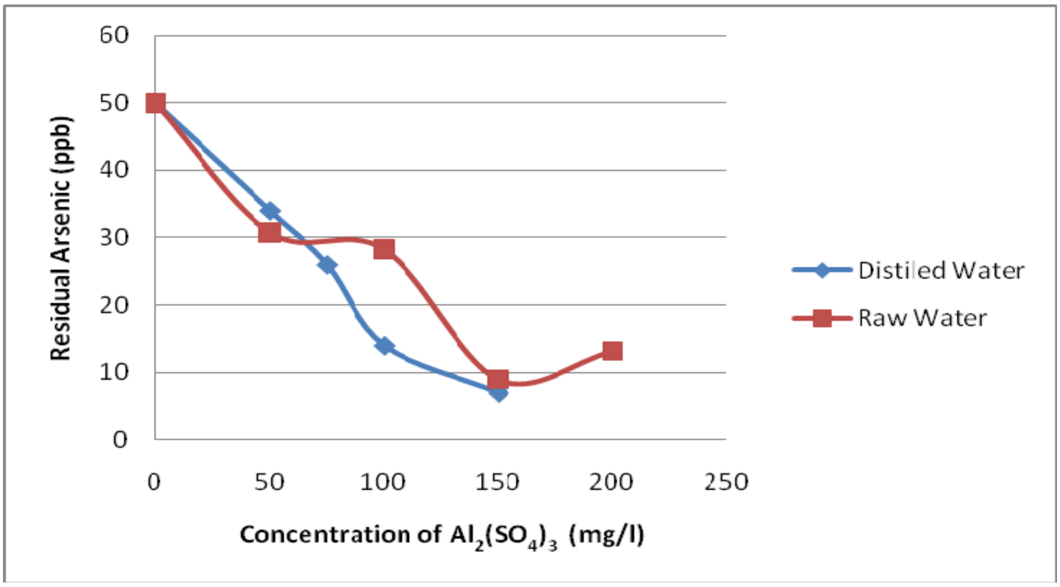


Figure 6.1 Comprehension of Alum efficiency with Distilled Water and Raw water

Comprehension of $FeCl_3$ efficiency with distilled water and raw water data’s and graphic are given at table 6.2 and graphic 6.2.

Table 6.2 Comprehension of $FeCl_3$ efficiency with Distilled Water and Raw water

Concentration of $FeCl_3$ (mg/l)	Residual Arsenic (ppb)		Removing Efficiency (%)	
	Distilled water	Raw water*	Distilled water	Raw water*
0	50	50	0	0
50	29	4,42	42	91,2
75	-	-	-	-
100	21	11,56	58	76,8
150	11	1,897	78	96,2
200	4	2,53	92	94,9

*at pH 7

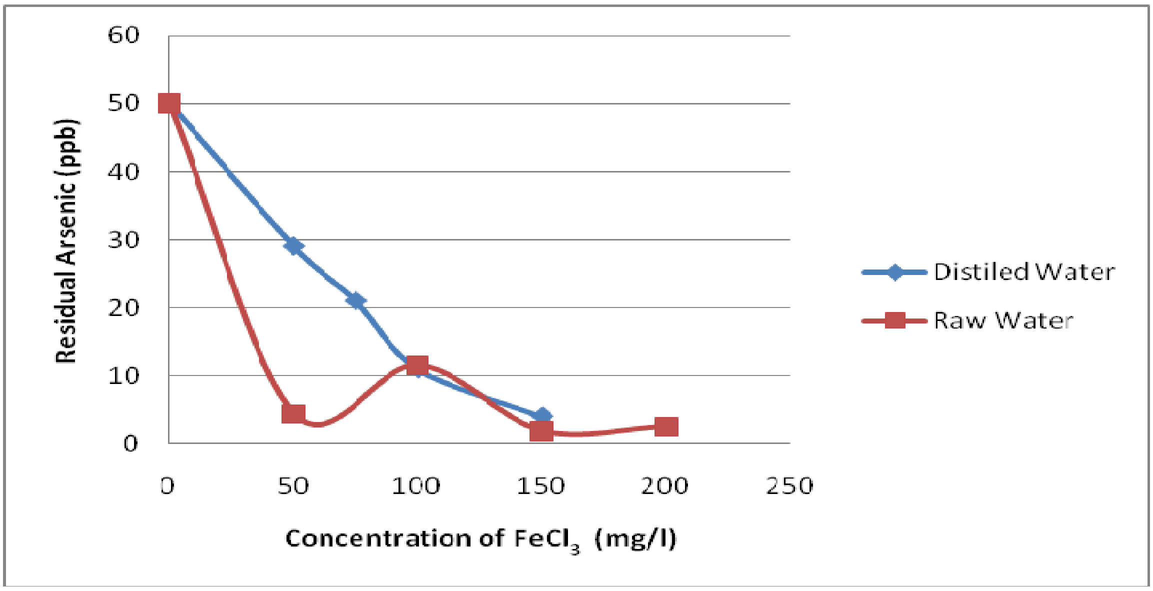


Figure 6.2 Comprehension of $FeCl_3$ efficiency with Distilled Water and Raw water

Comprehension of $Ca(OH)_2$ efficiency distilled water and raw water data's and graphic are given at table 6.3 and graphic 6.3.

Table 6.3 Comprehension of $Ca(OH)_2$ efficiency with Distilled Water and Raw water

Concentration of $Ca(OH)_2$ (mg/l)	Residual Arsenic (ppb)		Removing Efficiency (%)	
	Distilled water	Raw water*	Distilled water	Raw water*
0	50	50	0	0
75	29	4,42	42	91,2
100	21	-	58	-
150	11	11,56	78	76,8
200	4	1,897	92	96,2

*at pH 7

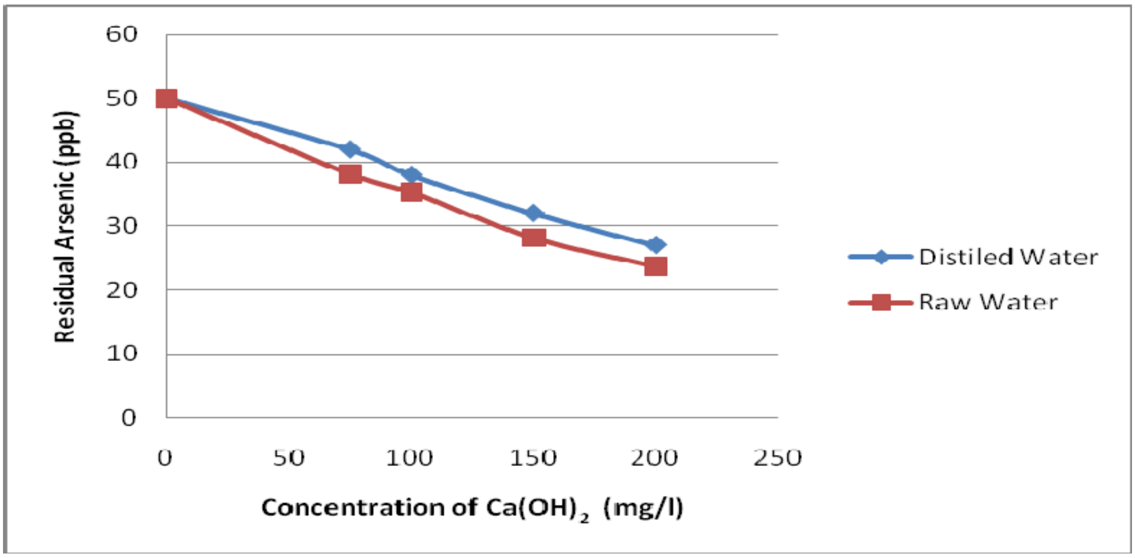


Figure 6.3 Comprehension of $Ca(OH)_2$ efficiency with Distilled Water and Raw water

Comprehension of coagulants efficiency at pH 6 data’s and graphic are given table 6.4 and graphic 6.4.

Table 6.4 Comprehension of Coagulants Efficiency at pH 6

Concentration of coagulant (mg/l)	$Al_2(SO_4)_3$		$FeCl_3$		$Ca(OH)_2$	
	Residual Arsenic (ppb)	Removing Efficiency (%)	Residual Arsenic (ppb)	Removing Efficiency (%)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0	50	0	50	0
50	35,53	28,9	16,34	67,3	-	-
75	-	-	-	-	38,4	23,2
100	32,38	35,2	18,21	63,6	35,4	29,2
150	24,5	43,1	28,24	43,5	30,7	38,6
200	26,06	47,8	23,63	52,7	200	42,8

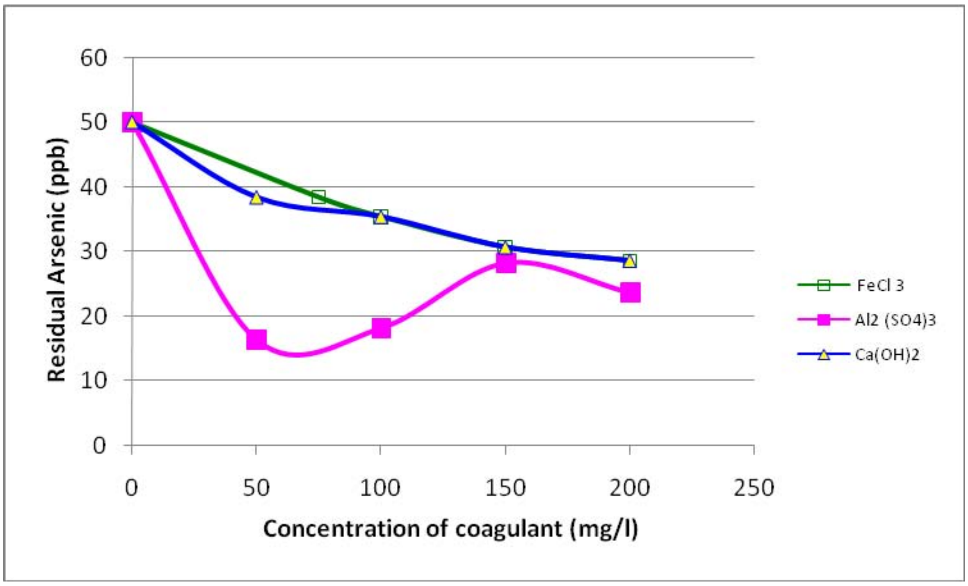


Figure 6.4 Comprehension of Coagulants Efficiency at pH 6

Comprehension of coagulants efficiency at pH 7 data’s and graphic are given table 6.5 and graphic 6.5.

Table 6.5 Comprehension of Coagulants Efficiency at pH 7

Concentration of coagulant (mg/l)	$Al_2(SO_4)_3$		$FeCl_3$		$Ca(OH)_2$	
	Residual Arsenic (ppb)	Removing Efficiency (%)	Residual Arsenic (ppb)	Removing Efficiency (%)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0	50	0	50	0
50	30,77	38,4	4,42	91,2	-	-
75	-	-	-	-	38,17	23,6
100	28,32	43,4	11,56	76,8	35,32	29,4
150	8,97	84	1,897	96,2	28,17	43,7
200	13,17	72,6	2,53	94,9	23,75	52,5

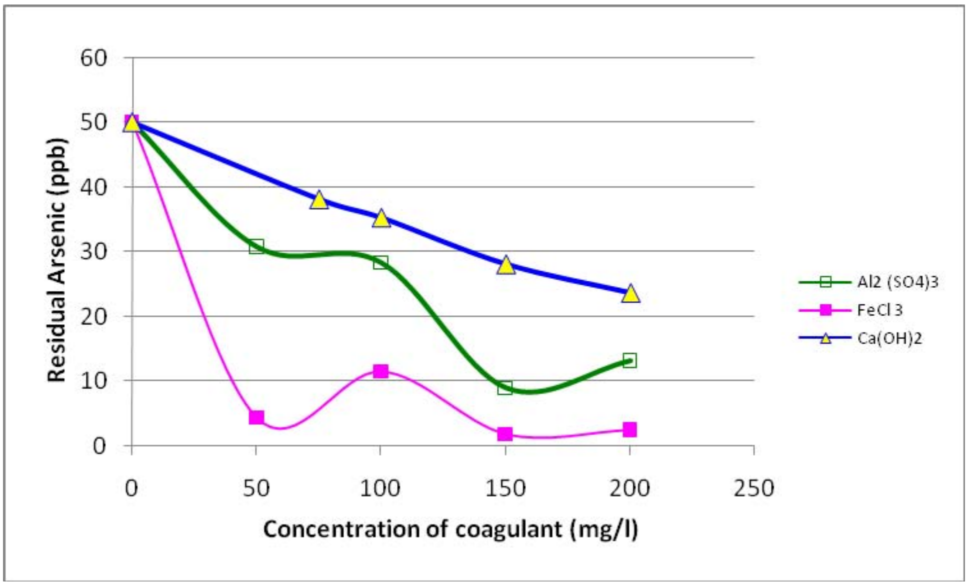


Figure 6.5 Comprehension of Coagulants Efficiency at pH 7

Comprehension of coagulants efficiency at pH 8 data’s and graphic are given table 6.6 and graphic 6.6.

Table 6.6 Comprehension of Coagulants Efficiency at pH 8

Concentration of coagulant (mg/l)	$Al_2(SO_4)_3$		$FeCl_3$		$Ca(OH)_2$	
	Residual Arsenic (ppb)	Removing Efficiency (%)	Residual Arsenic (ppb)	Removing Efficiency (%)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0	50	0	50	0
50	11,25	77,5	4,65	90,7	-	-
75	-	-	-	-	33,15	33,7
100	16,84	66,3	5,94	88,1	27,14	45,7
150	19,51	61	5,62	88,8	23,63	52,7
200	22,61	54,8	4,83	90,3	21,6	57,7

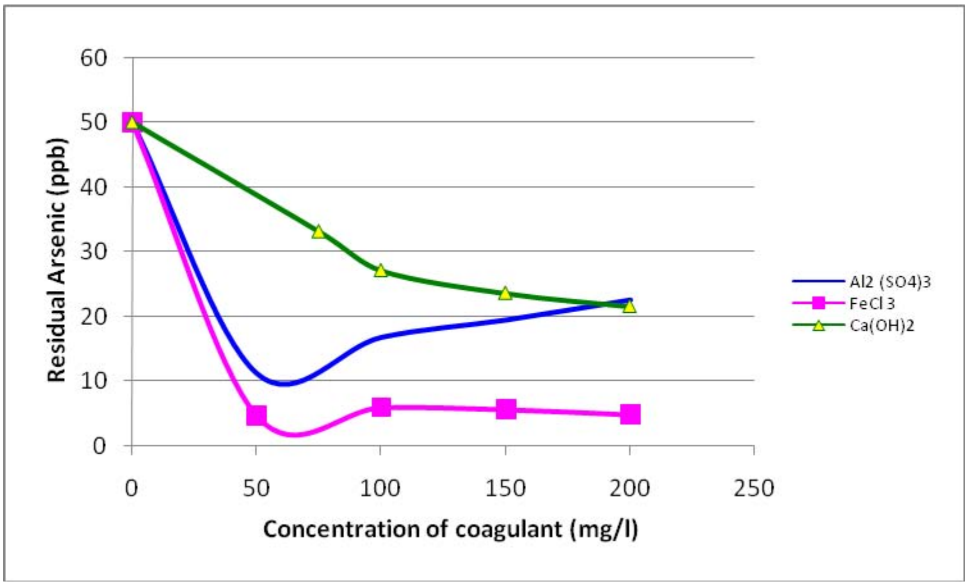


Figure 6.6 Comprehension of Coagulants Efficiency at pH 8

Comprehension of $FeCl_3$ and $Ca(OH)_2$ Efficiency at pH 9 data's and graphic are given table 6.7 and graphic 6.7.

Table 6.7 Comprehension of $FeCl_3$ and $Ca(OH)_2$ Efficiency at pH 9

Concentration of coagulant (mg/l)	$FeCl_3$		$Ca(OH)_2$	
	Residual Arsenic (ppb)	Removing Efficiency (%)	Residual Arsenic (ppb)	Removing Efficiency (%)
0	50	0	50	0
50	29,4	41,72	-	-
75	-	-	35,54	28,9
100	14,93	70,13	32,17	35,7
150	7,72	84,86	24,12	51,8
200	4,86	90,27	19,56	80,1

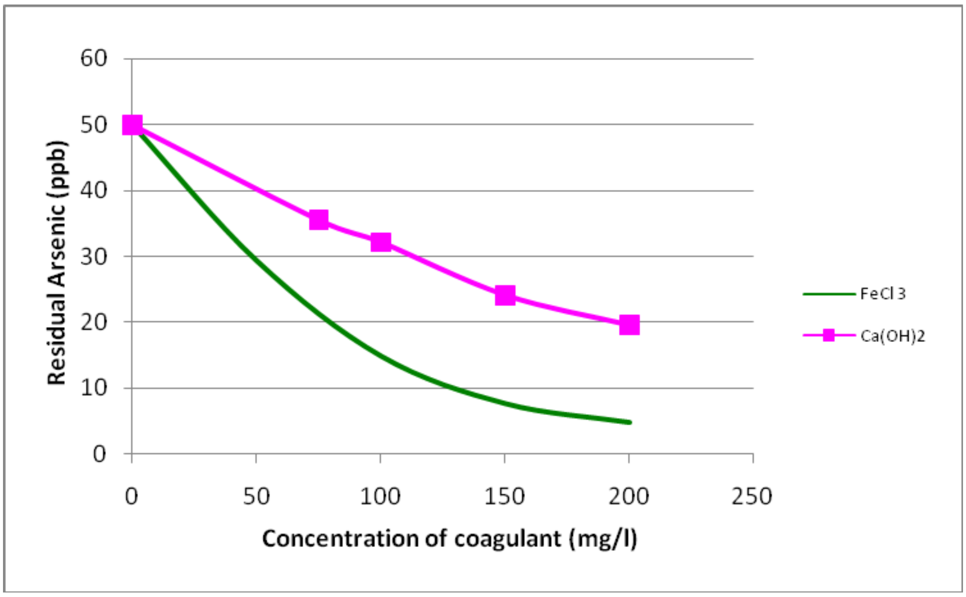


Figure 6.7 Comprehension of $FeCl_3$ and $Ca(OH)_2$ Efficiency at pH 9

CHAPTER SEVEN
CONCLUSION

It is obviously clear that high level of arsenic in drinking water has dangerous for human life. In areas where the drinking water supply contains unsafe levels of arsenic, the immediate concern is finding a safe source of drinking water. There are two main options: finding a new safe source, and removing arsenic from the contaminated source. In either case, the drinking water supplied must be free from harmful.

There are various methods for arsenic removal. One of the well known methods was chemical precipitation.

In the conducted research chemical precipitation method has been simulated by using jar test.

Results indicated that it is a good alternative method for arsenic removal.

$FeCl_3$ is found as the best coagulant for arsenic removal, the set concentration around 50 mg $FeCl_3$/ lt is recommended.

However, for difference water similar jar test studies should be conducted to achieve more reliable doses.

In all cases, technologies should meet several basic technical criteria. Water supply option must first of all be to produce water of required quality, both chemical and bacteriological. Systems should also be able to supply water in adequate quantity, throughout different seasons. Technologies should be updateable.

It is important that operational safety be ensured. Finally, technologies should not have an undue adverse effect on the environment.

Coagulation processes are sometimes unable to efficiently remove arsenic to these low levels. As a result, various alternate technologies have been developed or adapted that are capable of removing arsenic to trace levels. These advanced treatment options include ion exchange, activated alumina, and membrane methods such as reverse osmosis and nanofiltration. While these Technologies have all been shown to be effective in lab or pilot studies, there is still relatively little experience with full-scale treatment.

Comparison arsenic removal from distillated water and raw water; distillated water gives better results (efficiency) than raw water. This may due to the interferences of other suspended particles in the raw water. In other words, certain amount of coagulants is consumed by those suspended particles for precipitation.

There one may note, arsenic removal in pure water by coagulation is easier than raw water.

Alum and ferric chloride are more efficiency than lime.

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