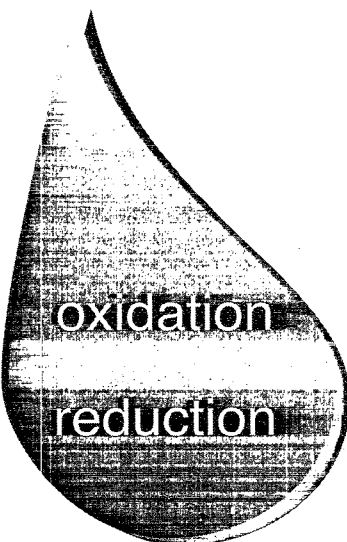


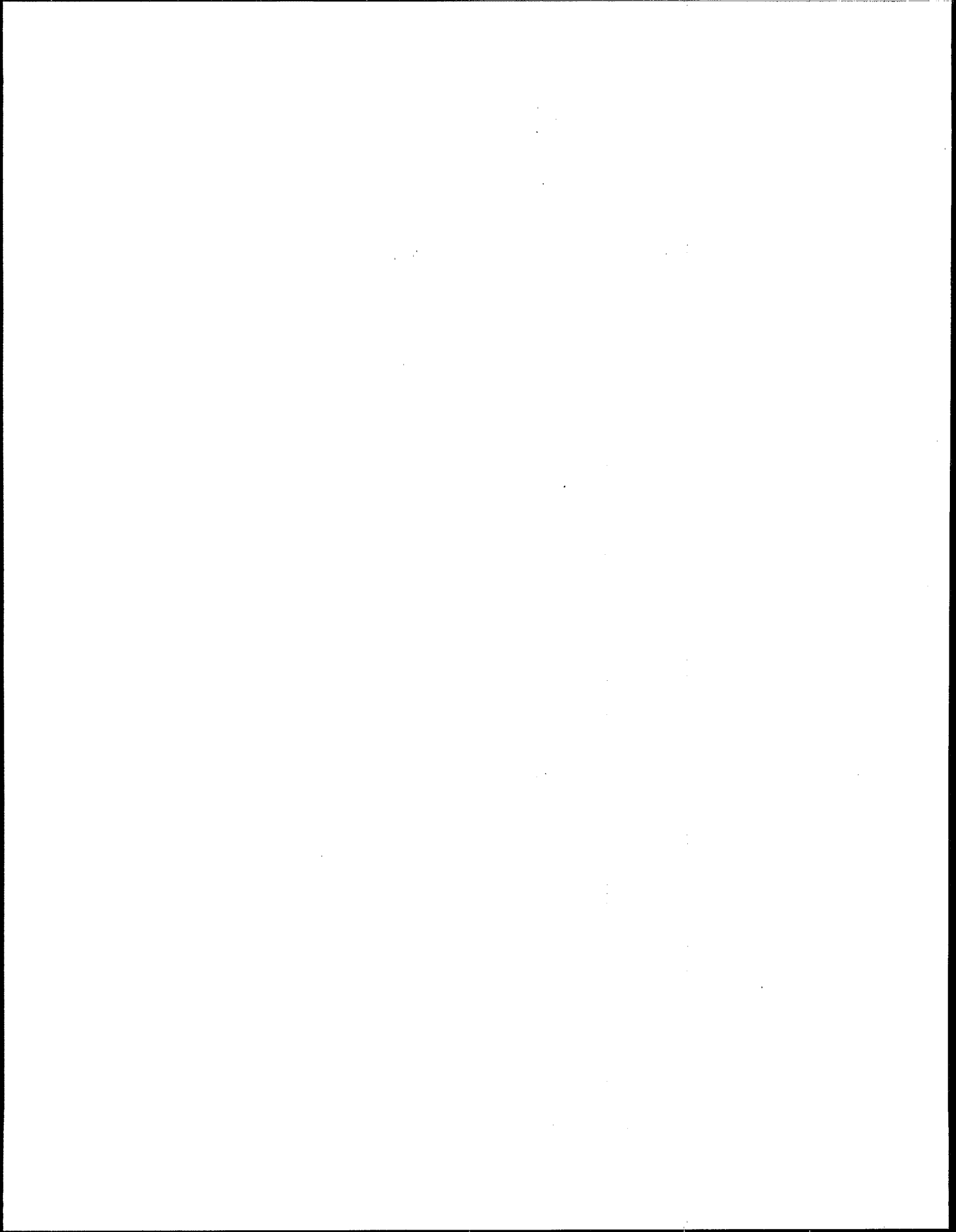


# Arsenic Removal from Drinking Water by Coagulation/Filtration and Lime Softening Plants

As (III)



As (V)



# **Arsenic Removal from Drinking Water by Coagulation/Filtration and Lime Softening Plants**

by

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## Foreword

The United States Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement action leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for prevention and control of pollution to air, land, water, and sub-surface resources: protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air. The goal of this research effort is to evaluate the performance on a full-scale level of five processes, including coagulation/filtration, lime softening, iron oxidation/filtration, ion exchange, and activated alumina, to consistently remove arsenic over a sustained period of time (1 year).

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director  
National Risk Management Research Laboratory

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## Abstract

This report documents treatment plant information as well as results of sampling and analysis at two coagulation/filtration plants (referred to in this document as Plants A and B) and one lime softening plant (referred to as Plant C). The objective of sampling and analysis was to evaluate the effectiveness of the water treatment plants to consistently remove arsenic (As) from source water. Additionally, data were collected in this study to evaluate the characteristics of the residuals produced by the treatment processes.

The study was divided into three phases: source water sampling, preliminary sampling, and long-term evaluation. The first phase, source water sampling, was conducted to evaluate source water characteristics at each plant. The second phase, preliminary sampling, consisted of a four-week sampling period to refine procedures prior to implementing the long-term evaluation phase. The third phase, long-term evaluation, consisted of weekly sample collection and analysis for approximately 1 year. Sludge samples also were collected at each facility during a single sampling event from settling lagoons/ponds during a two-month period. Samples of recycle supernatant water (Plant A) and supernatant discharge water (Plants B and C) were collected monthly beginning in November 1998 and continuing until June 1999.

Long-term evaluation of Plants A and B demonstrated that conventional coagulation/filtration can consistently achieve low levels of arsenic in the treated water (i.e., less than 5 µg/L). The total arsenic concentrations at Plant A were reduced by an average of 52%, which represents a decrease of average arsenic concentrations from 7.5 µg/L in the source water to 3.5 µg/L in the finished water. Average total arsenic removal efficiency at Plant B was 79%, with an average source water concentration of 19.1 µg/L and an average finished water concentration of 4.0 µg/L. Adsorption and coprecipitation of As(V) with iron and aluminum flocs are believed to have been the primary arsenic removal mechanisms at these plants.

The lime softening facility, Plant C, was not able to consistently reduce arsenic to low levels in treated water. The average total arsenic concentration in Plant C source water was 32.0 µg/L, and the lime softening plant reduced the average total arsenic concentration to 16.6 µg/L in the finished water, which equals a 45% removal efficiency. As(III) was the primary species of soluble arsenic in the raw water and was almost completely oxidized to As(V) as a result of two chlorination steps that occurred prior to softening and prior to filtration. The primary mechanism of arsenic removal was likely adsorption and coprecipitation of As(V) with iron that was present in the source water. Plant C operated at a pH of 9.6, a level at which arsenic removal by coprecipitation with calcium carbonate is reported to be less than 10% (Sorg and Logsdon, 1978; McNeill and Edwards, 1997b).

None of the sludge samples collected at Plants A, B, and C qualified as a hazardous waste based on Toxicity Characteristic Leaching Procedure (TCLP) testing for metals. Therefore, nonhazardous waste landfills should be able to accept the sludge generated by these treatment processes.

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## Acronyms and Abbreviations

AF	after-filtration sampling location
AWWA	American Water Works Association
DI	distilled
EDR	electrodialysis reversal
EPA	United States Environmental Protection Agency
GFAAS	graphite-furnace atomic-absorption spectrophotometer
GI	gastrointestinal
gpm	gallons per minute
HDPE	high-density polyethylene
ICP-MS	inductively coupled plasma-mass spectrometry
ID	identification
IN	inlet sampling location
MCL	maximum contaminant level
MDL	method detection limit
mgd	million gallons per day
MS	matrix spike
MSD	matrix spike duplicate
ND	not detected
NOM	natural organic matter
NTU	nephelometric turbidity units
PAC	powdered activated carbon
PAX-18	liquid polyaluminum chloride
PF	before filtration (prefiltration) sampling location
POC	point of contact
QA	quality assurance
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/Quality Control
RPD	relative percent difference
SDWA	Safe Drinking Water Act
STLC	soluble threshold limit concentration
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids

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TOC	total organic carbon
TSS	total suspended solids
WA	work assignment
WAM	work assignment manager
%R	percent recovery

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## **Acknowledgments**

Sincere appreciation is extended to the three water treatment facilities that participated in this study. The staff from each facility contributed greatly to this project by collecting samples every week for more than 12 months. The success of this study depended on the personnel of these plants, and all performed exceptionally well. Their work on this project was uncompensated, making their superb efforts even more remarkable. Personnel from all plants are thanked for their hard work and dedication throughout the duration of this project.

## 1. Introduction

This project consisted, in part, of a field study to collect samples from various locations throughout the treatment processes at two coagulation/filtration plants and one lime softening plant. These samples were analyzed and used to evaluate the effectiveness of conventional coagulation/filtration and lime softening processes to consistently reduce arsenic (As) in source water to low levels. This project also includes the collection of process residual samples that were used to determine the quantity and chemical characteristics of the residuals produced by these treatment processes. This report describes the design and operation of the three treatment plants and presents the results of the analyses of the water samples collected from the plants during one year of operation.

### 1.1 Background

The Safe Drinking Water Act (SDWA) of 1994 mandates that the United States Environmental Protection Agency (EPA) identify and regulate drinking water contaminants that may have an adverse human health effect and that are known or anticipated to occur in public water supply systems. Arsenic is a naturally occurring contaminant that has known adverse human health effects. Excessive amounts of arsenic can cause acute gastrointestinal (GI) and cardiac damage. Chronic doses can cause vascular disorders such as blackfoot disease (Chen, S.L., et al., 1994), and epidemiological studies have linked arsenic to skin and lung cancer (Tate and Arnold, 1990). In 1975, under the SDWA, EPA established a maximum contaminant level (MCL) for arsenic at 0.05 mg/L. Since that time, revision of the MCL has been considered a number of times, but no change has been made. The SDWA was amended in 1996 and these amendments required that the EPA develop an arsenic research strategy and publish a proposal to revise the arsenic MCL by January 2000.

A draft arsenic research plan was prepared by the EPA in December 1996 and was finalized in February 1998 based upon a technical review by the EPA's Board of Scientific Counselors (EPA, 1998). The plan identifies the research needed by the EPA to support a proposed

revision of the arsenic MCL. The plan also identifies a number of treatment methods available for arsenic removal and recognizes the need to determine the capability of these technologies to reduce arsenic to a level significantly lower than the current MCL. This study was conducted as part of the EPA's arsenic research strategy to determine the ability of conventional water treatment processes to consistently remove arsenic from drinking water.

#### 1.1.1 General Chemistry of Arsenic

Arsenic is a common, naturally occurring drinking water contaminant that originates from arsenic-containing rocks and soil and is transported to natural waters through erosion and dissolution. Arsenic occurs in natural waters in both organic and inorganic forms. However, inorganic arsenic is predominant in natural waters and is the most likely form of arsenic to exist at concentrations that cause regulatory concern (Edwards et al., 1998).

The valence and species of inorganic arsenic are dependent on the oxidation-reduction conditions and the pH of the water. As a general rule of thumb, the reduced, trivalent form [As(III)] normally is found in ground water (assuming anaerobic conditions) and the oxidized, pentavalent form [As(V)] in surface water (assuming aerobic conditions), although this does not always hold true for ground water, where both forms have been found together in the same water source. Arsenate exists in four forms in aqueous solution based on pH:  $\text{H}_3\text{AsO}_4$ ,  $\text{H}_2\text{AsO}_4^-$ ,  $\text{HAsO}_4^{2-}$ , and  $\text{AsO}_4^{3-}$ . Similarly, arsenite exists in five forms:  $\text{H}_4\text{AsO}_3^+$ ,  $\text{H}_3\text{AsO}_3$ ,  $\text{H}_2\text{AsO}_3^-$ ,  $\text{HAsO}_3^{2-}$ , and  $\text{AsO}_3^{3-}$ . As shown in Figure 1-1, which contains solubility diagrams for As(III) and As(V), ionic forms of arsenate dominate at pH >3, while arsenite is neutral at pH <9 and ionic at pH >9. Conventional treatment technologies used for arsenic removal, such as coagulation/filtration and lime softening, rely on adsorption and coprecipitation of arsenic to metal hydroxides. Therefore, the valence and species of soluble arsenic are very significant in evaluating arsenic removal.

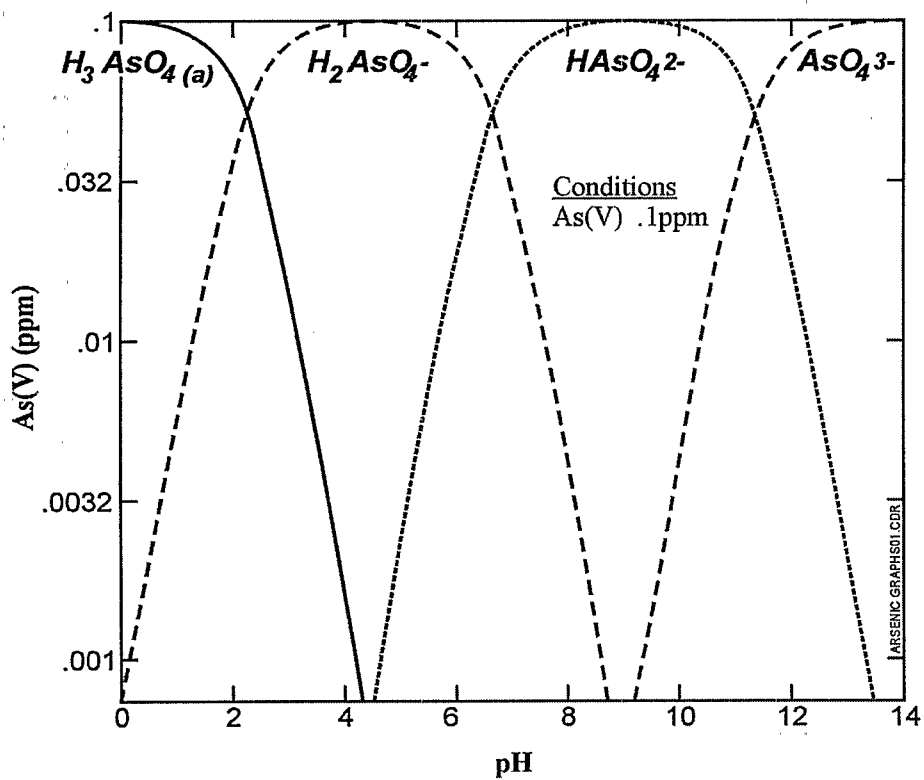
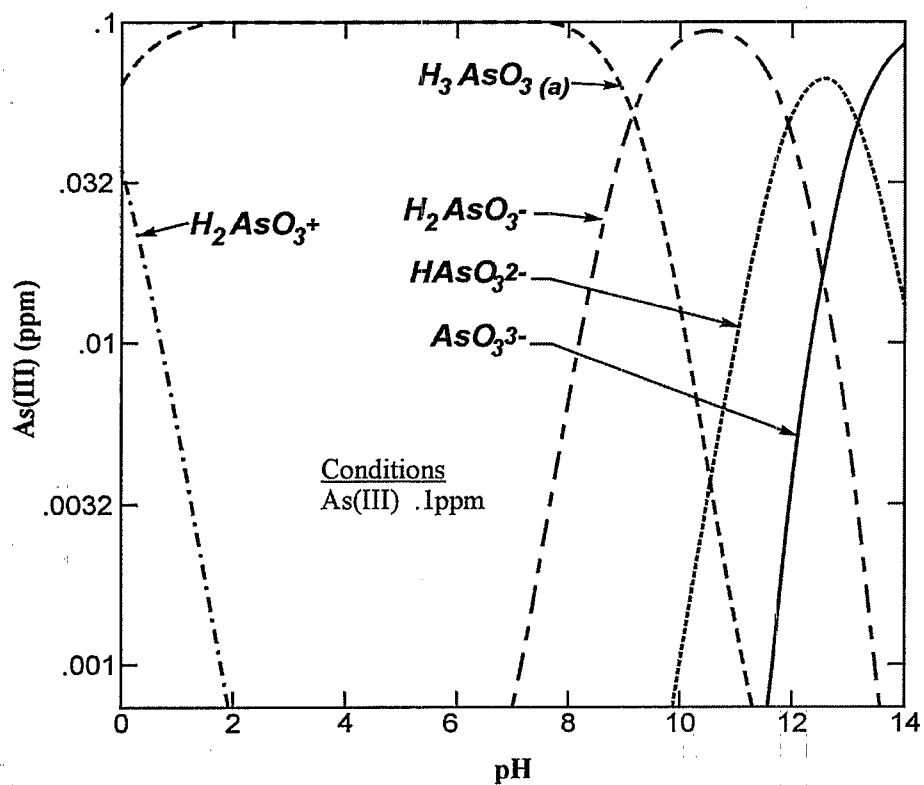


Figure 1-1. Solubility Diagrams for As(III) and As(V)



Although soluble arsenic species typically make up the majority of the total arsenic concentration in natural waters, some research indicates that particulate arsenic can exist at significant concentrations. Studies by Chen et al. (1994) and Hemond (1995) measured particulate arsenic at levels of 17 and 50% of the total arsenic concentration, respectively, in the subject source waters. Therefore, determination of the particulate arsenic concentration is important because it can provide insight into the arsenic removal mechanisms that occur during treatment.

### **1.1.2 Determination of Arsenic Species**

Although total arsenic can be effectively preserved in field samples, presently no method exists to consistently preserve inorganic arsenic species in field samples. Preservation of total arsenic is accomplished by acidifying the sample to  $\text{pH} < 2$  in the field. However, a high level of ambiguity exists when acids such as nitric acid ( $\text{HNO}_3$ ) or hydrochloric acid ( $\text{HCl}$ ) are used to preserve inorganic species of arsenic. Interconversion of  $\text{As(III)}$  and  $\text{As(V)}$  in samples preserved with 0.05 N  $\text{HCl}$  have been reported to occur within one day (Andreae, 1977). Another laboratory study conducted by Eaton et al. (1997) examined preservation of arsenic using humic acid, ascorbic acid, and  $\text{HCl}$ ; the study concluded that no effective methods exist for preserving  $\text{As(III)}$  and  $\text{As(V)}$  in water samples. Some researchers have used freezing of samples as a means of preserving the inorganic species of arsenic. However, freezing is neither a cost-effective nor a practical method for field sampling.

In response to the lack of techniques available for adequately preserving arsenic species, field speciation protocols have been developed by Ficklin (1982), Clifford et al. (1983), and Edwards et al. (1998). In each of these studies, an anion exchange resin column is used for field speciation of arsenic. Ficklin (1982) used a strong anion exchange resin (Dowex 1  $\times$  8, 100-200 mesh, acetate form) in a 10 cm  $\times$  7 mm glass column to separate  $\text{As(III)}$  from  $\text{As(V)}$  in water samples that had been filtered through a 0.45- $\mu\text{m}$  membrane filter and acidified with 1%  $\text{HCl}$ . The resin was supplied in chloride form and was converted to the acetate form. However, in the protocol by Clifford et al. (1983), a chloride-form strong base anion resin (ASB-2, 30-60 mesh) was used to separate  $\text{As(III)}$  from  $\text{As(V)}$ . In this method, the sample was not filtered or preserved with acid. Both Ficklin and Clifford used a graphite-furnace atomic-absorption spectrophotometer (GFAAS) to determine the arsenic concentration.

More recently, Edwards et al. (1998) made the following modifications to Ficklin's method: (1) substituted 50- to 100-mesh resin for the 100- to 200-mesh resin to allow faster sample flow; (2) used 12-cm  $\times$  15-mm polypropylene

columns to improve safety and speed of sample treatment; (3) Used 0.05%  $\text{H}_2\text{SO}_4$  instead of 1%  $\text{HCl}$  to acidify samples prior to resin treatment. Edwards et al.'s use of  $\text{H}_2\text{SO}_4$  helped to prevent potential problems associated with overacidification of the sample, and also helped to prevent  $\text{Cl}^-$  from interfering with the inductively coupled plasma/mass spectrometry (ICP-MS) analysis. The reported recoveries of  $\text{As(III)}$  and  $\text{As(V)}$  ranged from 80 to 120% by Ficklin (1982), 95 to 117% by Clifford et al. (1983), and 100 to 105% by Edwards et al. (1998). For this study, the decision was made to utilize a field speciation technique similar to that used by Edwards et al. (1998).

### **1.1.3 Treatment Technologies for Arsenic Removal**

Several common treatment technologies are used for removal of inorganic contaminants, including arsenic, from drinking water supplies. Large-scale treatment facilities often use conventional coagulation with alum or iron salts followed by sedimentation and filtration to remove arsenic. Lime softening is another common, conventional treatment process that can potentially remove arsenic from source waters. Smaller-scale systems and point-of-entry systems often use anion exchange resins or activated alumina. Other arsenic removal technologies include manganese greensand, reverse osmosis, electrodialysis reversal (EDR), nanofiltration, and adsorption on activated carbon. This report focuses on the two conventional treatment processes commonly used for arsenic removal at large-scale operations: coagulation/filtration and lime softening. Two additional reports will be developed that focus on (1) iron removal plants and (2) anion exchange and activated alumina plants.

#### **1.1.3.1 Coagulation/Filtration**

Conventional coagulation/filtration is a common water treatment methodology used to remove suspended and dissolved solids from source water. The coagulation process promotes aggregation of the suspended solids to form flocs, which then can be removed through sedimentation and/or filtration. Coagulation is typically described as a process consisting of three steps: coagulant formation, particle destabilization, and interparticle collisions. The first two steps, coagulant formation and particle destabilization, occur during rapid mixing, and the third step occurs during flocculation. Alum and iron (III) salts, such as ferric chloride, are the most common coagulants used for drinking water treatment (Amirtharajah and O'Melia, 1990).

Coagulation using alum and iron (III) salts can be used to remove dissolved inorganic drinking water contaminants, such as arsenic. Removal mechanisms for dis-

solved inorganics consist of two primary mechanisms: adsorption and occlusion (Benefield and Morgan, 1990). During the adsorption process, the dissolved contaminant attaches to the surface of a particle or precipitate. Occlusion occurs when the dissolved contaminant is adsorbed to a particle and then entrapped as the particle continues to agglomerate. Several factors affect the coagulation process, including coagulant dosage, pH, turbidity, natural organic matter (NOM), anions and cations in solution, zeta potential, and temperature (Amirtharajah and O'Melia, 1990).

Numerous bench- and pilot-scale studies and some short-term full-scale evaluations have been performed to evaluate arsenic removal using conventional coagulation/filtration using alum and iron (III) salts. Most of these studies have focused on removal of As(V) rather than As(III) because better As(V) removal can be achieved under comparable conditions, and As(III) can easily be converted to As(V) using a strong oxidant such as chlorine (Hering et al., 1996; Sorg, 1993). Ferric and alum coagulation are equally effective on a molar basis (Edwards, 1994). However, on a weight basis (e.g., mg/L of ferric chloride vs. mg/L of alum), coagulation with iron (III) salts achieves better removal than coagulation with aluminum salts (Sorg and Logsdon, 1978; Sorg, 1993; Chen, R.C., et al., 1994; Scott et al., 1995). These results are observed primarily because iron hydroxide is less soluble than aluminum hydroxide over a wider pH range (Benefield and Morgan, 1990). McNeill and Edwards (1997a) observed that aluminum flocs with sorbed arsenic could pass through filters and that arsenic removal increased when capture of aluminum flocs increased. Other research indicates that As(V) removal is not pH dependent between pH 5.5 to 8.5 when iron coagulants are used, although As(V) removal efficiency decreases above pH 7 using alum (Sorg, 1993).

Previous studies also indicate that arsenic removal is directly correlated with coagulant dosage (i.e., more coagulant increases arsenic removal) (Sorg and Logsdon, 1978; Sorg, 1993; Hering et al., 1996; Gullett and O'Conner, 1973). Also, arsenic removal efficiency appears to be independent of initial arsenic concentration at levels of interest to drinking water treatment (Hering et al., 1996; Chen, R.C., et al., 1994; Edwards, 1994). Although no correlation between turbidity removal and arsenic removal has been established, turbidity removal is a prerequisite for arsenic removal (Chen, R.C., et al., 1994).

#### 1.1.3.2 Lime Softening

Lime softening commonly is used to reduce hardness in source waters. Hardness is due primarily to the presence of calcium and magnesium ions. The lime provides hydroxide ions that increase pH, which results in calcium

and magnesium removal due to the formation of  $\text{CaCO}_3$  and  $\text{Mg(OH)}_2$  precipitates. Also, lime softening has been used for removal of heavy metals, radionuclides, dissolved organics, and viruses (Benefield and Morgan, 1990) through adsorption and occlusion with calcium carbonate and magnesium hydroxide. The typical lime softening treatment process train includes rapid mixing of the lime, flocculation of solids, and sedimentation. These three processes are often combined into a single unit referred to as a solids-contact softener (Benefield and Morgan, 1990). Filtration usually follows these three processes. Lime and lime-soda typically are used for softening, and selection is dependent on the type of hardness. Lime alone is used for source waters that contain little or no noncarbonate hardness, while high noncarbonate hardness may require both lime and lime soda. Caustic soda is sometimes used instead of lime and lime-soda to decrease sludge production (increases dissolved solids, but produces less sludge).

Only a few studies have been conducted to evaluate arsenic removal during lime softening. Bench-scale and pilot-scale studies by Sorg and Logsdon (1978) indicate that arsenic removal during lime softening is pH dependent. Removal of As(III) and As(V) are low at pH less than 10; however, As(V) removal approaches 100% and As(III) removal approaches 75% at pH greater than 10.5. As part of a survey of full-scale water treatment plants by McNeill and Edwards (1995), lime softening plants were able to achieve up to 90% arsenate removal if pH was high enough to precipitate magnesium hydroxide (i.e., near pH 11). When only  $\text{CaCO}_3$  precipitated, As(V) removal was between 0 and 10%; however, when  $\text{CaCO}_3$  and  $\text{Mg(OH)}_2$  were precipitated, As(V) removals were between 60 and 95% (McNeill and Edwards, 1995). Coprecipitation of As(V) with  $\text{Mg(OH)}_2$  appears to be the primary arsenic removal mechanism for As(V) during lime softening.

McNeill and Edwards published results from bench-scale experiments designed to evaluate the basic mechanisms of arsenic removal during lime softening (McNeill and Edwards, 1997b). Consistent with previous findings, greater than 90% arsenate removal was observed at above pH 11 where  $\text{Mg(OH)}_2$  was precipitated (McNeill and Edwards, 1997b). Also, it was determined that trace amounts of orthophosphate and the presence of carbonate could limit arsenate removal by  $\text{Mg(OH)}_2$ . If manganese was present in the source water, some As(V) removal could be achieved through sorption with  $\text{Mn(OH)}_2$ , although  $\text{Mn}_3(\text{AsO}_4)_2$  precipitate formation was not determined to be a major mechanism (McNeill and Edwards, 1997b). Other findings from the same study indicated that arsenate removal percentages were relatively constant for arsenic concentrations between 5 to 75  $\mu\text{g/L}$ . Also, addition of iron before softening could increase

arsenic removal; however, competition between arsenic and carbonate for sorption sites on the iron hydroxide reduced the removal efficiency to levels below those normally achieved with a conventional coagulation/filtration process using iron (III) salts (McNeill and Edwards, 1997b).

#### **1.1.4 Data Gaps**

The removal of arsenic from drinking water by conventional coagulation/filtration has been extensively studied at the laboratory and pilot-scale level. To a lesser degree, arsenic removal by lime softening has been studied at the laboratory and pilot-scale level. Although some short-term full-scale evaluations have been performed for both treatment processes, little data exist on the capability of these processes in full-scale applications to reduce arsenic on a sustained basis. Thus, a need exists to determine the effectiveness of coagulation/filtration and lime softening to produce drinking water low in arsenic on a long-term basis, under varying operational and seasonal conditions.

Another data gap that exists concerning conventional drinking water treatment processes is the production and disposal of residuals. Currently, little or no data exist on the amounts and the chemical composition of residuals generated by the arsenic removal processes and the methods that are environmentally acceptable for their disposal. Therefore, information needs to be collected on the quality and the chemical characteristics of the wastes produced by the coagulation/filtration and lime softening plants.

## **1.2 Objectives**

One objective of this project was to evaluate the effectiveness of conventional coagulation/filtration and lime softening to consistently reduce arsenic concentrations in source water to low levels. This report presents the results of weekly monitoring for approximately one year at two coagulation/filtration plants and one lime softening plant.

Another objective of this study was to examine the residuals produced during treatment at conventional coagulation/filtration and lime softening plants. Information was collected on the quality and chemical characteristics of the wastes produced by these drinking water treatment processes.

## **1.3 Report Organization**

Section 1.0 provides background information for the field study and project objectives. Section 2.0 of this report presents the conclusions from the study of the two conventional coagulation/filtration plants and the lime softening plant. Section 3.0 describes the materials and methods used to conduct this study. Section 4.0 discusses the results of the study and Section 5.0 provides specific information on quality assurance/quality control (QA/QC) procedures. Section 6.0 is a list of references cited in the text. Appendices A, B, and C present the complete set of analytical data collected at Plants A and B (the two coagulation/filtration plants), and C (the lime softening plant), respectively, during long-term sampling.

## 2. Conclusions

The U.S. EPA currently is in the process of revising the arsenic MCL, and it is anticipated that the revised standard will be significantly lower than the existing MCL of 0.05 mg/L. Therefore, there is a need to determine the ability of existing treatment processes to consistently remove arsenic to low levels. The primary objectives of this project were to document arsenic removal at two conventional coagulation/filtration plants and one lime softening plant, and to characterize the residuals (sludge and supernatant water) at these treatment plants.

The study was divided into three major phases: source water sampling (February 1998), preliminary sampling (April and May 1998), and long-term evaluation (June 1998 through June 1999). For the first phase, Battelle staff traveled to each facility to conduct source water sampling, which provided information on source water characteristics. The second phase, preliminary sampling, consisted of a 4-week sampling period to refine the sampling approach before implementing the long-term evaluation phase. Battelle staff again traveled to each facility to coordinate the first sampling event and train plant personnel in sampling procedures for subsequent events. The third phase, long-term evaluation, consisted of weekly sample collection and analysis at each of the water treatment plants, sludge sampling (November and December 1998), and recycle supernatant water (Plant A) and supernatant discharge (Plants B and C) sampling (November 1998 through June 1999). During the long-term evaluation phase, plant personnel conducted sampling and Battelle staff coordinated sampling logistics.

The primary focus of this study was the long-term performance of two coagulation/filtration plants and one lime softening plant. The two coagulation/filtration plants demonstrated the ability to consistently achieve low levels of arsenic in the treated water (i.e., less than 5 µg/L). Adsorption and coprecipitation of As(V) with metal hydroxides, such as iron hydroxide and alum hydroxide, are believed to be the primary arsenic removal mechanisms in coagulation/filtration plants. As(III) removal during coagulation/filtration was not observed during this study because both plants had surface water

source where the soluble arsenic was primarily arsenate. Interestingly, Plant B conducted a 6-week test wherein the coagulant was changed from alum to liquid poly-aluminum chloride (i.e., PAX-18). During this test, arsenic removal was negatively impacted. Average removal efficiency using alum was 84% compared to 43% using PAX-18. The difference in removal efficiencies may be the result of the difference in pH achieved with each coagulant.

The lime softening plant (Plant C) evaluated for this project was not able to consistently reduce arsenic to low levels in the treated water. The plant did not operate at a significantly high pH to precipitate magnesium hydroxide, and the arsenic removal by coprecipitation with calcium carbonate is low (<10%) (Sorg and Logsdon, 1978; McNeill and Edwards, 1997b). However, arsenic removal efficiency at Plant C was approximately 45%. It is believed that the primary mechanism of arsenic removal is coprecipitation of As(V) with iron that is present in the source water. Prior research indicates that arsenic removal by iron oxides during lime softening can be hindered by competition for sorption sites with carbonate (McNeill and Edwards, 1997b). Also, little research exists on the coprecipitation of arsenic and iron hydroxide at pH values greater than 8.

The secondary focus of this study was on residual production and the chemical characteristics of the residuals. None of the sludge sampled during this study qualified as a hazardous waste based on the Toxicity Characteristic Leaching Procedure (TCLP) tests for metals. Therefore, the sludge generated by these treatment processes should be accepted by nonhazardous waste landfills. However, stricter requirements in California regarding hazardous waste classification were not met by Plant A based on total arsenic concentrations. Supernatant water from sludge lagoons was either discharged to surface water bodies under state permits (Plants B and C) or recycled back to the inlet (Plant A). The recycle supernatant did not appear to contain high concentrations of arsenic. The ecological risks associated with discharging these waters were not assessed.

### 3. Materials and Methods

This section discusses the materials and methods used for performing the source water, preliminary, and long-term sampling and data collection at two coagulation/filtration plants and one lime softening plant. Section 3.1 describes the general project approach. Section 3.2 describes the preparation of arsenic speciation kits and sample coolers. Section 3.3 provides detailed sampling procedures. Section 3.4 discusses pertinent analytical procedures.

#### 3.1 General Project Approach

Several consecutive tasks were performed to accomplish the project objectives described in Section 1.2. These tasks involved the following activities:

- Select treatment plants and conduct an initial site visit to collect source water samples at each selected plant
- Prepare a preliminary sampling and data collection plan for each plant
- Finalize the sampling and data collection plan after completion of four weekly preliminary sampling events at each plant
- Implement the final sampling and data collection plan with weekly sampling events at each plant for one full year.

For initial plant selection, a list of potential treatment plant candidates was compiled. Plant operators or other key personnel were contacted via telephone to obtain/confirm information and solicit interest in participating in the project. Each facility was evaluated, in order of importance, on source water arsenic concentrations, source water type, available manpower to conduct the year-long study, availability of historical arsenic data, and plant size. Battelle recommended the selection of two coagulation/filtration plants (designated as Plants A and B) and one lime softening plant (designated as Plant C) for initial site visits and source water sampling. These recommendations were later approved by the

EPA Work Assignment Manager (WAM). The information collected during the site visits, including the concentration and speciation of arsenic in each source water, was tabulated and used as the basis for the final plant selection.

Following the final plant selection (Plants A, B, and C again were selected), a preliminary sampling and data collection plan was prepared for each plant to document the plant's operation and performance for arsenic removal and the critical parameters that would impact the removal. Each preliminary plan also described the data collection effort to characterize the residuals produced by the treatment process. The approved preliminary plans were implemented at Plants A, B, and C during a 4-week trial period. A Battelle staff member revisited the plants during the first week of the trial period to observe plant operations, perform sampling, conduct training of plant support personnel, and establish/coordinate all required logistics (such as receiving/shipping of sample coolers, chain-of-custody coordination, communication methods, and emergency/contingency plans). The remaining three sampling events during the preliminary sampling were performed by a designated point of contact (POC) or an alternate at each plant. The experience gained during the trial period was used to finalize the long-term sampling and data collection plans.

All water and residual samples were collected and analyzed in accordance with the Category III Quality Assurance Project Plan (QAPP) prepared by Battelle (1998) for this project. Water samples were collected weekly at Plants A, B, and C at three locations: (1) the inlet to the treatment plants (IN); (2) before the filtration process (PF); and (3) after the filtration process/at the plant outlet (AF). During the preliminary and long-term sampling phases, field arsenic speciation was conducted once every four weeks. Starting from November 1998, samples of recycle supernatant water (from the settling pond at Plant A) or supernatant discharge water (from lagoons at Plants B and C) were collected once every four weeks from each plant. Three sludge samples also

were collected from either the settling pond or lagoons during one sampling event at each of the three plants.

All sample containers and arsenic speciation kits were prepared by Battelle and sent in coolers on a weekly basis to each plant via Federal Express. The coolers were returned to Battelle immediately after the sample collection had been completed. Analyses of arsenic, aluminum, iron, and manganese in water were conducted by Battelle's ICP-MS laboratory. Wilson Environmental Laboratories in Westerville, OH, was subcontracted to perform all other chemical analyses. Battelle coordinated all sampling logistics.

### 3.2 Preparation of Sampling Kits and Sample Coolers

All arsenic speciation kits, recycle supernatant water/supernatant discharge sampling kits, and sample coolers were prepared at Battelle. The following sections describe the relevant preparation procedures.

#### 3.2.1 Preparation of Arsenic Speciation Kits

The arsenic field speciation method used an anion exchange resin column to separate the soluble arsenic species, As(V) and As(III). A 250-mL bottle (identified as bottle A) was used to contain an unfiltered sample, which was analyzed to determine the total arsenic concentration (both soluble and particulate). The soluble portion of the sample was obtained by passing the unfiltered sample through a 0.45- $\mu$ m screw-on disc filter to remove any particulate arsenic and collect the filtrate in a 125-mL bottle (identified as bottle B). Bottle B contained 0.05% (volume/volume) ultra-pure sulfuric acid to acidify the sample to about pH 2. At this pH, As(III) was completely protonated as  $\text{H}_3\text{AsO}_3$ , and As(V) was present in both ionic (i.e.,  $\text{H}_2\text{AsO}_4^-$ ) and protonated forms (i.e.,  $\text{H}_3\text{AsO}_4$ ) (see Figure 1-1). A portion of the acidified sample in bottle B was run through the resin column. The resin retains the As(V) and allowed As(III) (i.e.,  $\text{H}_3\text{AsO}_3$ ) to pass through the column. (Note that the resin will retain only  $\text{H}_2\text{AsO}_4^-$  and that  $\text{H}_3\text{AsO}_4$ , when passing through the column, will be ionized to  $\text{H}_2\text{AsO}_4^-$  due to elevated pH values in the column caused by the buffer capacity of acetate exchanged from the resin.) The elute of the column was collected in another 125-mL bottle (identified as bottle C). Samples in bottles A, B, and C were analyzed for total arsenic using ICP-MS. As(III) concentration was the total arsenic concentration of the resin-treated sample in bottle C. As(V) concentration was calculated by subtracting As(III) from the total soluble arsenic concentration of the sample in bottle B.

Arsenic speciation kits were prepared in batch at Battelle based on a method modified from Edwards et al. (1998). Each arsenic speciation kit contained the following:

- Two anion exchange resin columns
- Primary and duplicate A, B, and C bottles
- One 400-mL disposable beaker
- Two 60-mL disposable syringes
- Several 0.45- $\mu$ m syringe-adapted disc filters.

Each speciation kit was packed in a plastic zip-lock bag along with latex gloves and a step-by-step speciation sampling instruction sheet. All chemicals used for preparing the kits were of analytical grade or higher. The arsenic speciation kits were prepared according to the following procedures:

- **Resin Preparation.** Before packing into columns, the anion exchange resin (Dowex 1-X8, 50-100 mesh) was converted from the chloride form (as supplied by Supelco) to the acetate form according to the method used by Edwards et al. (1998). First, 1 kg of the resin was placed in a 3-L beaker. One liter of 1N sodium hydroxide (NaOH) then was added to the resin, stirred for an hour using an overhead stirrer, and drained. This NaOH rinse was repeated sequentially three times. The NaOH-treated resin was then rinsed with two 1-L batches of reagent grade water, followed by three acetic acid rinses. Each acetic acid rinse consisted of adding 1 L of 1N reagent grade acetic acid to the resin, stirring for 5 minutes, and draining the spent acid. The acetic acid-treated resin was subsequently rinsed with 3-L batches of reagent-grade water. The resin slurry was stored in a 2-L bottle and kept moist until use.
- **Anion Exchange Column Preparation.** The resin columns used were 12 cm  $\times$  15 mm in size and made of polypropylene (Bio-Rad Laboratories, CA). Each column was slurry packed with about 20 g (drained weight) of the prepared resin, yielding a resin depth of approximately 10.5 cm. The column was sealed with two plastic caps (one each on top and bottom) to prevent contamination and retain moisture prior to use.
- **Sample Bottles.** VWRbrand™ TraceClean™ high-density polyethylene (HDPE) sample bottles (250 and 125 mL) were used to prepare bottles A, B, and C. Bottles A and C were spiked with 500 and 250  $\mu$ L of concentrated ultra-pure nitric acid ( $\text{HNO}_3$ ), respectively; and bottle B was spiked with 1.25 mL of 5% (volume/volume) ultra-pure sulfuric acid ( $\text{H}_2\text{SO}_4$ ).  $\text{H}_2\text{SO}_4$  was used to acidify the sample in bottle B because chloride ( $\text{Cl}^-$ ) in HCl could interfere with the ICP-MS arsenic detection

and  $\text{HNO}_3$  (an oxidizing agent) could damage the resin or form nitric acid-arsenic redox couples (Edwards et al., 1998).

- **Beaker, Syringes, and Filters.** One 400-mL disposable plastic beaker was used to collect a water sample. Samples were filtered using 60-mL disposable plastic syringes with 0.45- $\mu\text{m}$  screw-on disc filters. All disposable beakers, syringes, and filters were rinsed with distilled (DI) water and air-dried before being packed into the sampling kits.

### 3.2.2 Preparation of Recycle Backwash Water/Supernatant Discharge Sampling Kits

The recycle backwash water/supernatant discharge samples were collected for pH, hardness (Plant C only), total and soluble As, Al, Fe, and Mn measurements. Each sampling kit contained the following items:

- Primary and duplicate A and B bottles (both preserved with  $\text{HNO}_3$ ) to contain unfiltered and filtered samples for total and soluble As, Al, Fe, and Mn analyses
- One 400-mL disposable beaker

- Two 60-mL disposable syringes
- Several 0.45- $\mu\text{m}$  screw-on disc filters
- Bottles provided by Wilson Environmental Laboratories used for pH and hardness (Plant C only) analyses.

The sampling kit was prepared in a similar way as the arsenic speciation kit except that bottle B was preserved with  $\text{HNO}_3$  instead of  $\text{H}_2\text{SO}_4$ . The sampling kit was packed in a plastic zip-lock bag along with latex gloves and a step-by-step sampling instruction sheet.

### 3.2.3 Preparation of Sample Coolers

Sample containers for analysis of all water quality parameters except for total As, Al, Fe, and Mn were provided by Wilson Environmental Laboratories. These containers were new, rinsed with DI water, allowed to air dry, and contained appropriate preservatives before being delivered to Battelle. These bottles were labeled with the letter D, E, F, or G, designating the specific analysis to be performed. Table 3-1 lists the sample container size and type (for water and sludge samples), sample preservation used, analysis to be performed, and holding time. All sample containers were labeled prior to shipment.

**Table 3-1.** Sample Containers and Preservation Methods

Container Size	Container Type	Preservation Method	Analyte	Hold Time
<b>Arsenic Speciation Samples</b>				
250 mL (A)	certified clean HDPE bottles	4°C, $\text{HNO}_3$ for pH <2	Total As, Al, Fe, Mn	6 months
125 mL (B)	certified clean HDPE bottles	4°C, 0.05 % $\text{H}_2\text{SO}_4$	Dissolved As, Al, Fe, Mn	6 months
125 mL (C)	certified clean HDPE bottles	4°C, $\text{HNO}_3$ for pH <2	Dissolved As, Al, Fe, Mn	6 months
<b>Recycle Backwash Water/Supernatant Discharge Samples</b>				
250 mL (D)	plastic	4°C	pH TSS	immediate 7 days
250 mL (A)	certified clean HDPE bottles	4°C, $\text{HNO}_3$ for pH <2	Total As, Al, Fe, Mn	6 months
250 mL (B)	certified clean HDPE bottles	4°C, $\text{HNO}_3$ for pH <2	Dissolved As, Al, Fe, Mn	6 months
<b>Water Quality Parameter Samples</b>				
250 mL (D)	plastic	4°C	Alkalinity pH	14 days immediate
250 mL (D)	plastic	4°C	Turbidity Sulfate	48 hours 28 days
250 mL (E)	plastic	4°C, $\text{HNO}_3$ for pH <2	Fluoride	28 days
250 mL (F)	plastic	4°C, $\text{H}_2\text{SO}_4$ for pH <2	Hardness	6 months
500 mL (G)	glass	4°C, $\text{H}_2\text{SO}_4$ for pH <2	$\text{NO}_3^-/\text{NO}_2^-$ TOC	28 days 14 days
<b>Sludge Samples</b>				
8 oz (SL1)	glass jar	4°C	Total As, Al, Fe, Mn	6 months
4 oz (SL2)	glass jar	4°C	Water content, pH, TCLP metals	14 days
4 oz (SL2)	glass jar	4°C	Water content, pH, TCLP metals	14 days

TOC = total organic carbon.

TSS = total suspended solids.

Figure 3-1 presents an example sample bottle label. The sample identification (ID) consisted of five parts, including a two-letter code for a water treatment plant, the sampling date (mm/dd/yy), a two-letter code for a specific sampling location (e.g., IN for inlet water, PF for before the filtration process, and AF for after the filtration process or at the plant outlet), a one-letter code designating the analyses to be performed (see Table 3-1), and a code indicating whether the sample is a primary sample or a field duplicate sample. A field duplicate was identified by adding a "dup" to the label and a primary sample used no additional coding.

<b>AC-02/15/98-PF-B-DUP</b>	
<b>Date:</b> 02/15/98	<b>Time:</b> 11am
<b>Collector's Name:</b> Sample Collector	
<b>Location:</b> Any City WTP	
<b>Sample ID:</b> AC-02/15/98-PF-B-DUP	
<b>Send to:</b> Battelle	
<b>Analysis Required:</b> Total As, Al, Fe, and Mn	
<b>Preservative:</b> 0.05% sulfuric acid	

**Figure 3-1.** Example of Sample Bottle Label

After the sample bottles were labeled, they were placed in coolers subdivided into three compartments, each corresponding to a specific sampling location at each plant. Color coding was used to identify sampling locations and all associated sample bottles. For example, red, blue, and yellow were used to designate sample locations for raw water at the plant inlet, before the filtration process, and after the filtration process (or at the plant outlet), respectively. Other sampling and shipping-related materials, including latex gloves, chain-of-custody forms, prepaid Federal Express air bills, sampling instructions, ice packs, and bubble wrap, also were packed into coolers. Arsenic speciation kits or recycle supernatant water/discharge sampling kits were included in the cooler when the arsenic speciation or recycle supernatant water/discharge samples were collected. After preparation, sample coolers were sent to all plants every Thursday via Federal Express for the following week's sampling activity. Figure 3-2 shows photographs of a sample cooler with three sample compartments and a color-coded instruction sheet placed under the lid of the cooler.

### 3.3 Sampling Procedures

#### 3.3.1 General Approach and Sampling Schedules

One or two Battelle staff members traveled to each plant to collect source water samples, meet plant operators, solicit interest in participating in this year-long sampling

program, and obtain plant design and operating information and historical water quality data. After the plant selection, one Battelle staff member returned to each plant to collect samples at selected sampling locations and train the plant operator or a designated POC to perform sampling and field arsenic speciation. The remaining three preliminary sampling events and long-term sampling events then were conducted by the trained plant personnel. Residuals sampling, including a single sludge sampling event and the monthly collection of recycle supernatant water or supernatant samples from either a settling pond or lagoon also were collected by the designated plant employees with detailed instructions provided by Battelle over the telephone. Table 3-2 summarizes the sampling activities at Plants A, B, and C.

During the preliminary and long-term sampling, the sample collection was conducted on a 4-week cycle, with each week having unique sampling requirements. Tables 3-3 (Plants A and B) and 3-4 (Plant C) summarize the schedules for the initial source water, the preliminary, the long-term, and the sludge sampling.

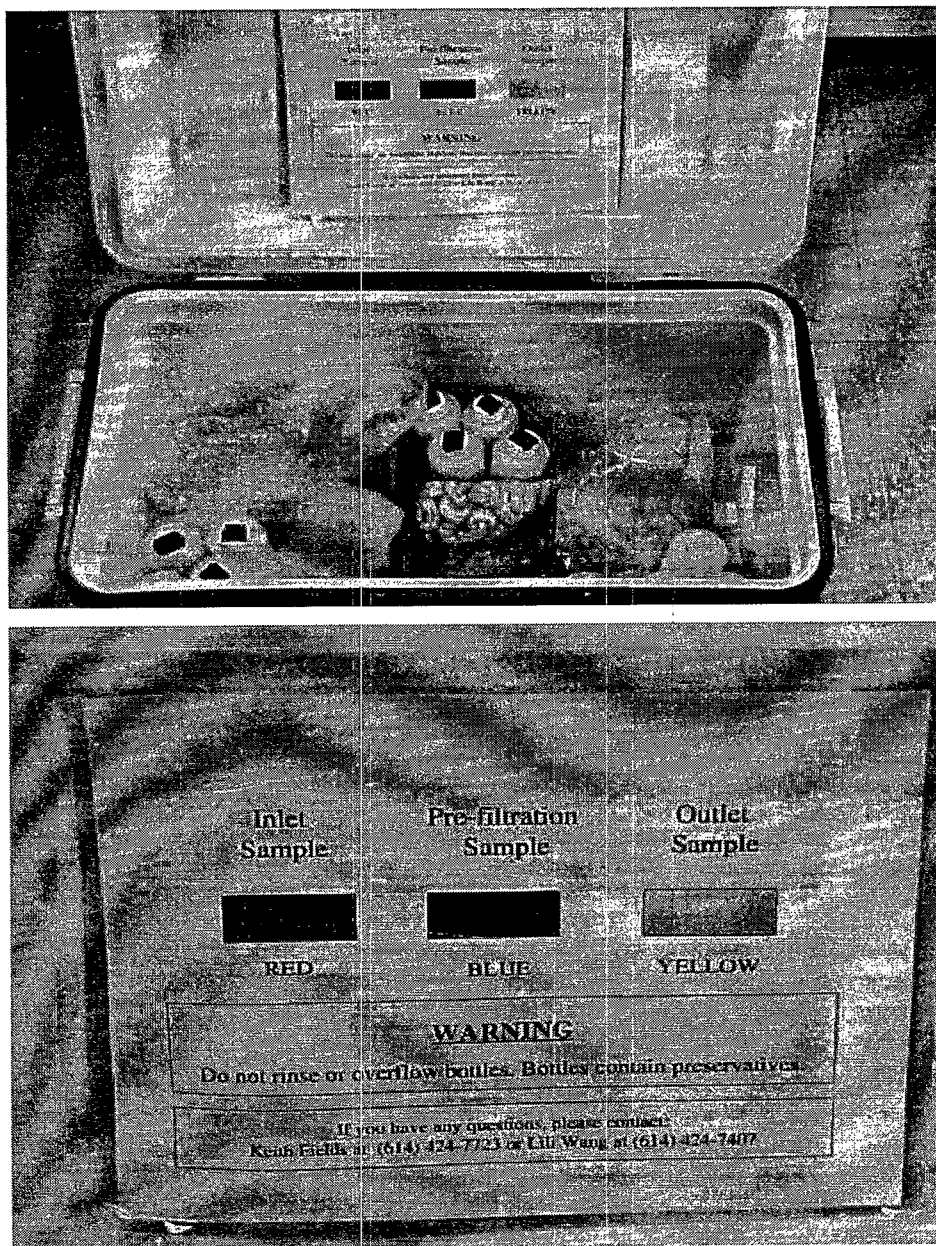
After receipt of the weekly sample coolers, plant personnel began sampling activities at the selected locations on the scheduled dates. Upon completion, all sample bottles were sealed with tape and placed in the same coolers for return shipment to Battelle by Federal Express. Upon receipt of the samples, the designated Battelle sample custodian immediately examined and compared the conditions of all sample bottles with those indicated in the chain-of-custody forms. Samples then were distributed to Battelle's ICP-MS laboratory and Wilson Environmental Laboratories for chemical analyses.

Throughout the duration of the study, Battelle staff maintained frequent telephone contact with each plant to ensure that all sampling activities were carried out as planned. For example, after scheduled arrival of sample coolers, one Battelle staff member would call to confirm the receipt of the coolers, answer any questions, discuss irregular plant operations and unusual observations, and propose/suggest corrective actions. When available, results of the chemical analyses also were discussed over the telephone and data sheets were sent quarterly to the plants for review. Further, plant operational and water quality data (such as plant flowrate, chlorine addition rate, ferric chloride or alum dosage [Plants A and B], lime dosage [Plant C], pH, hardness [Plant C], and turbidity) were sent along with sample coolers or transmitted via facsimile to Battelle for information/evaluation.

#### 3.3.2 Arsenic Field Speciation Procedure

The procedures for performing field arsenic speciation are shown in Figure 3-3 and are described as follows ("steps" refer to Figure 3-3):





**Figure 3-2.** Photographs of a Typical Sample Cooler (with Three Sample Compartments) and a Color-Coded Instruction Sheet

- **Bottle A:** A 400-mL disposable plastic beaker was rinsed thoroughly with the water to be sampled. The beaker then was used to collect a water sample and to fill bottle A with an aliquot of that sample (step 3). If necessary, additional sample water was added to the beaker after bottle A was filled to complete arsenic speciation sampling.
- **Bottle B:** A 60-mL disposable plastic syringe was rinsed thoroughly with the water in the plastic

beaker by completely filling and emptying the syringe (step 4). After attaching a 0.45- $\mu$ m disc filter and wasting about 10 drops of the filtrate, the syringe was used to filter the water sample from the beaker and fill bottle B. Bottle B then was tightly capped and vigorously shaken for about 15 seconds to allow thorough mixing of the filtered water and sulfuric acid (step 5).

**Table 3-2. Summary of Sampling Activities at Plants A, B, and C**

Sampling Activities	Sampling Frequency	Plant A	Plant B	Plant C
Initial source water sampling	Once	02/03/98	02/05/98	02/27/98
Preliminary sampling	Weekly	04/09/98 through 04/30/98	04/23/98 through 05/14/98	04/27/98 through 05/18/98
Long-term sampling	Weekly <sup>(a)</sup>	06/24/98 through 06/16/99	06/25/98 through 06/17/99	06/22/98 through 06/14/99
Sludge sampling	Once	12/02/98	12/15/98	11/16/98
Recycle water sampling	Weekly	11/11/98 through 06/16/99	11/12/98 through 06/17/99	11/09/98 through 06/14/99

(a) Except for the weeks of 11/23/98, 12/21/98, and 12/28/98.

**Table 3-3. Summary of Sampling Schedule for Plants A and B**

Analyte	Initial Source Water Sampling (Once)	Water Sampling								Sludge Sampling (Once)
		Preliminary Sampling Cycle				Long-Term Sampling Cycle				
		Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	
As (total)	W <sup>(a)</sup>	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W, R <sup>(a)</sup>	W	
As (total soluble)	W <sup>(a)</sup>	W <sup>(a)</sup>				W <sup>(a)</sup>		R <sup>(a)</sup>		
As (particulate)	W <sup>(a)</sup>	W <sup>(a)</sup>				W <sup>(a)</sup>		R <sup>(a)</sup>		
As(III)	W <sup>(a)</sup>	W <sup>(a)</sup>				W <sup>(a)</sup>				
As(V)	W <sup>(a)</sup>	W <sup>(a)</sup>				W <sup>(a)</sup>				
Al (total)	W <sup>(a)</sup>	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W, R <sup>(a)</sup>	W	
Fe (total)	W <sup>(a)</sup>	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W, R <sup>(a)</sup>	W	
Mn (total)	W <sup>(a)</sup>	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W, R <sup>(a)</sup>	W	
Al (dissolved)						W <sup>(a)</sup>		W, R <sup>(a)</sup>		
Fe (dissolved)						W <sup>(a)</sup>		W, R <sup>(a)</sup>		
Mn (dissolved)						W <sup>(a)</sup>		W, R <sup>(a)</sup>		
Alkalinity	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W	
Sulfate	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W	
NO <sub>3</sub> -NO <sub>2</sub> (N)	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W	
TOC	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W	
Turbidity	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W	
pH	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W, R <sup>(a)</sup>	W	
Hardness	W <sup>(a)</sup>									
Ca Hardness	W <sup>(a)</sup>									
Mg Hardness	W <sup>(a)</sup>									
TCLP Metals										S
Percent Moisture										S
pH										S
As (total)										S
Fe (total)										S

(a) = Duplicate samples collected and analyzed.

W = Water samples collected from the inlet, prefiltration, and after filtration locations.

R = Recycle supernatant water sample collected at Plant A; Supernatant discharge water sample collected at Plant B.

S = Sludge sample; three sludge samples were collected at each of Plants A and B.

Empty cells indicate no samples taken.

- Bottle C:** The protective caps on the top and bottom of a resin column were removed and approximately 40 mL of the water in bottle B was wasted through the column. This initial 40 mL was used to displace the water in the resin column and to ensure attainability of a representative sample from the column. The resin column then was positioned over bottle C, and the water from bottle B was passed through the column until approximately 20 mL of the resin-treated sample had been collected in bottle C (step 6).
- The procedure as described under the above three bullets was repeated to obtain duplicate bottles A, B, and C.
- Upon completion, the individual performing the speciation signed on a chain-of-custody form (step 7). All sample bottles (for arsenic speciation and other water quality parameters), along with the signed chain-of-custody form, were placed in the original cooler with ice packs and shipped via Federal Express to Battelle (step 8).

**Table 3-4.** Summary of Sampling Schedule for Plant C

		Water Sampling								Sludge Sampling (Once)
Analyte	Initial Source Water Sampling (Once)	Preliminary Sampling Cycle				Long-Term Sampling Cycle				
		Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	
As (total)	W <sup>(a)</sup>	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W, R <sup>(a)</sup>	W	
As (total soluble)	W <sup>(a)</sup>	W <sup>(a)</sup>				W <sup>(a)</sup>		R <sup>(a)</sup>		
As (particulate)	W <sup>(a)</sup>	W <sup>(a)</sup>				W <sup>(a)</sup>		R <sup>(a)</sup>		
As(III)	W <sup>(a)</sup>	W <sup>(a)</sup>				W <sup>(a)</sup>				
As(V)	W <sup>(a)</sup>	W <sup>(a)</sup>				W <sup>(a)</sup>				
Al (total)	W <sup>(a)</sup>	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W, R <sup>(a)</sup>	W	
Fe (total)	W <sup>(a)</sup>	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W, R <sup>(a)</sup>	W	
Mn (total)	W <sup>(a)</sup>	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W, R <sup>(a)</sup>	W	
Al (dissolved)						W <sup>(a)</sup>		W, R <sup>(a)</sup>		
Fe (dissolved)						W <sup>(a)</sup>		W, R <sup>(a)</sup>		
Mn (dissolved)						W <sup>(a)</sup>		W, R <sup>(a)</sup>		
Alkalinity	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W	
Sulfate	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W	
NO <sub>3</sub> -NO <sub>2</sub> (N)	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W	
TOC	W <sup>(a)</sup>									
Turbidity	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W	W	
pH	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W, R <sup>(a)</sup>	W	
Hardness	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W, R <sup>(a)</sup>	W	
Ca Hardness	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W, R <sup>(a)</sup>	W	
Mg Hardness	W <sup>(a)</sup>	W	W <sup>(a)</sup>	W	W	W	W <sup>(a)</sup>	W, R <sup>(a)</sup>	W	
TCLP Metals										S
Percent Moisture										S
pH										S
As (total)										S
Fe (total)										S

(a) = Duplicate samples collected and analyzed.

W = Water samples collected from the inlet, prefiltration, and after filtration locations.

R = Supernatant discharge water sample.

S = Sludge samples; three collected at Plant C.

Empty cells indicate no samples taken.

### 3.3.3 Recycle Supernatant Water/Supernatant Discharge Sampling Procedure

Figure 3-4 shows an instruction sheet for performing recycle backwash water and supernatant discharge sampling. Because both total and dissolved As, Al, Fe, and Mn were analyzed, the procedure for recycle supernatant water/supernatant discharge sampling was similar to that for arsenic speciation, except that the steps for collecting samples in bottle C were omitted.

### 3.3.4 Sampling Procedure for Other Water Quality Parameters

All other water quality parameters identified in Tables 3-3 and 3-4, were analyzed using samples either in bottles A, B, and C or in bottles provided by Wilson Environmental Laboratories (i.e., bottles D, E, F, and G). All bottles D, E, F, and G were filled directly from sample taps and preserved according to the respective analytical methods.

These sample bottles along with bottles A, B, and C were placed in the original coolers with ice packs and shipped via Federal Express to Battelle.

## 3.4 Analytical Procedures

The analytical procedures used for this project were described in Section 4.0 of the QAPP prepared by Battelle (1998). Table 3-5 presents a summary of all analytical methods used. All of the methods used are standard EPA methods. Analyses of As, Al, Fe, and Mn in water samples were accomplished by ICP-MS using EPA Method 200.8. ICP-MS was chosen as the method for As, Al, Fe, and Mn analyses because it had a low method detection limit (MDL) and was a relatively low-cost method (about \$35/sample). ICP-MS analyses were conducted on a Perkin Elmer Sciex Model 6000 equipped with a crossflow pneumatic nebulizer and an automatic sampler. Yttrium (<sup>88.9</sup>Y) was added to all samples as an internal standard to correct for instrument drift. Because arsenic is monoisotopic, all measurements were made at a mass/charge ratio of 75. To eliminate an appreciable

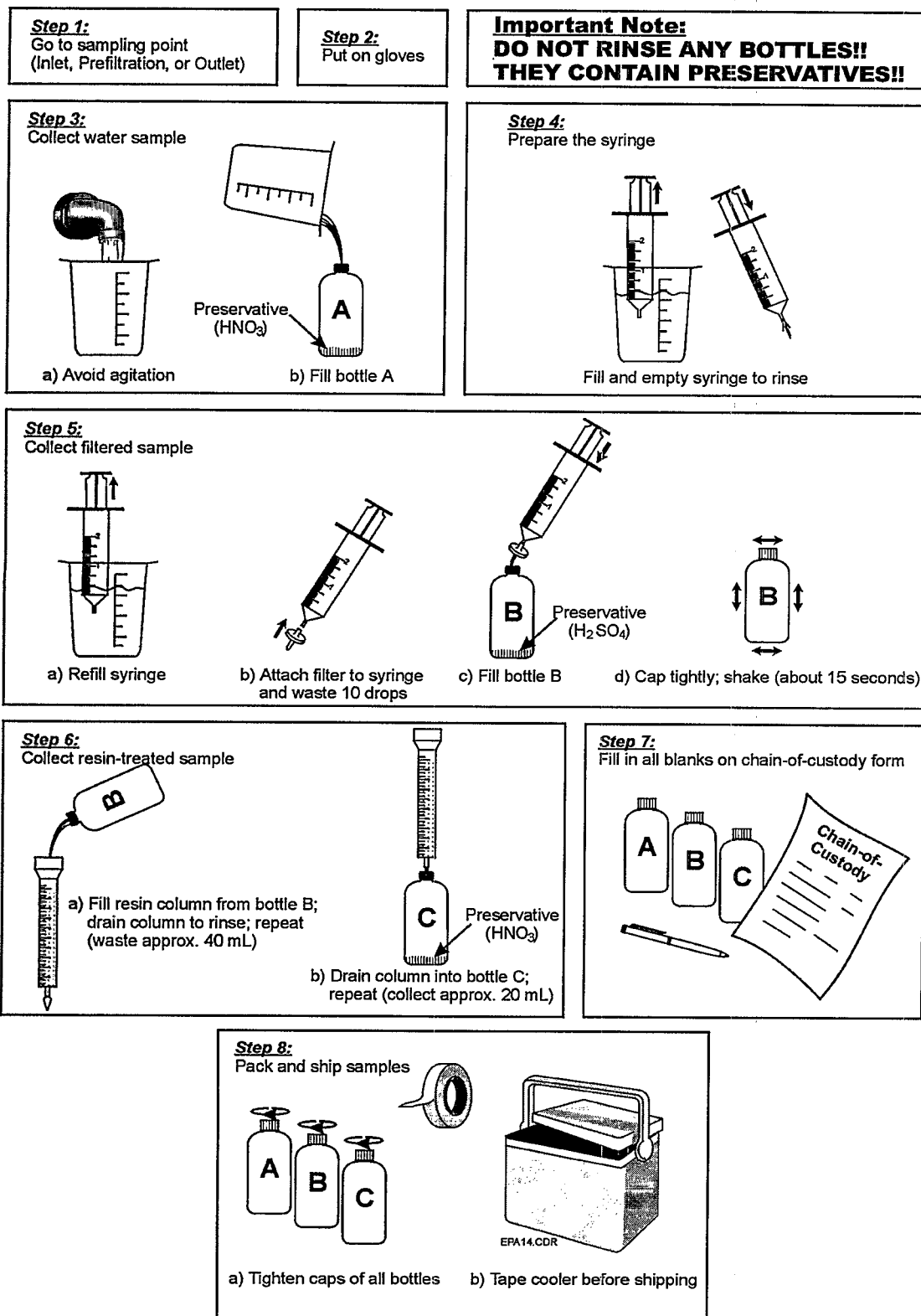


Figure 3-3. Instruction Sheet for Arsenic Field Speciation

**Step 1:**

Go to recycle backwash water  
or supernatant discharge  
sampling point

**Step 2:**

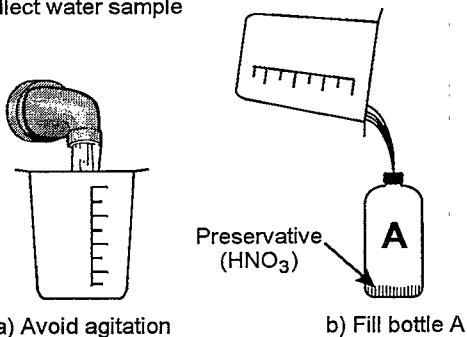
Put on gloves

**Important Note:**

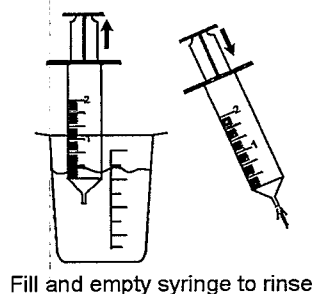
**DO NOT RINSE ANY BOTTLES!!  
THEY CONTAIN PRESERVATIVES!!**

**Step 3:**

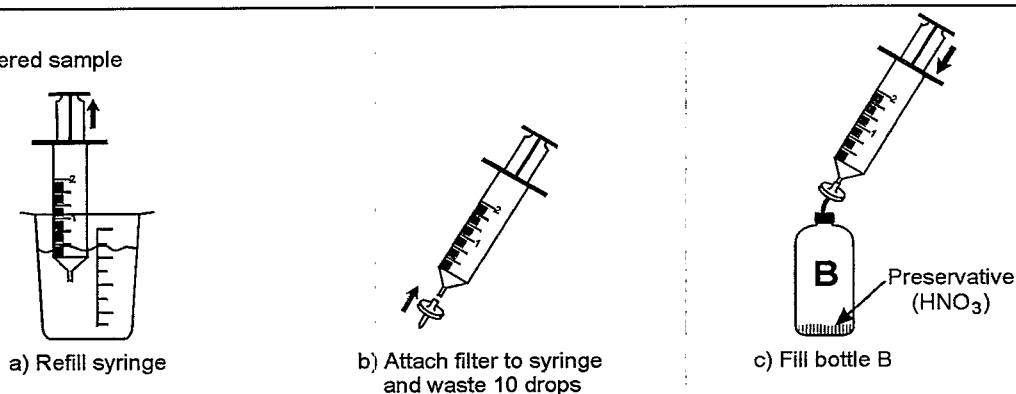
Collect water sample

**Step 4:**

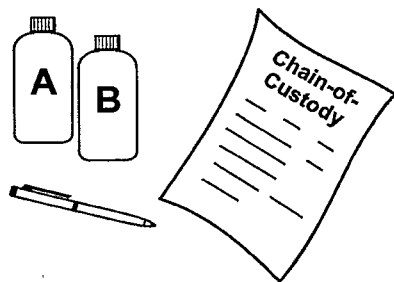
Prepare the syringe

**Step 5:**

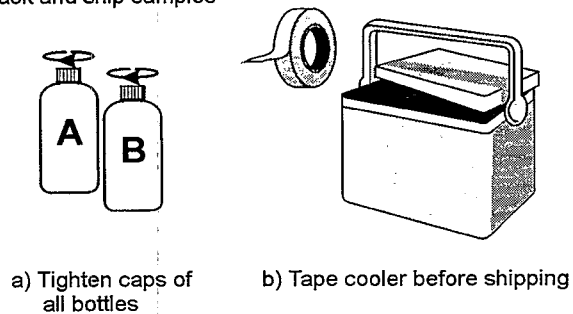
Collect filtered sample

**Step 6:**

Fill in all blanks on chain-of-custody form

**Step 7:**

Pack and ship samples



**Figure 3-4.** Instruction Sheet for Recycle Supernatant Water/Supernatant Discharge Sampling

**Table 3-5. Summary of Analytical Methods for Arsenic Treatment Study**

Sample Matrix	Analyte	Method	Analytical Laboratory
Aqueous (including samples collected at the plant inlet, before the filtration process, after the filtration process, and supernatant water from sludge settling ponds/lagoons that was recycled or discharged)	As (total)	EPA 200.8	Battelle ICP/MS
	Total Al	EPA 200.8	Battelle ICP/MS
	Total Fe	EPA 200.8	Battelle ICP/MS
	Total Mn	EPA 200.8	Battelle ICP/MS
	Alkalinity	EPA 310.1	Wilson Environmental
	pH	EPA 150.1	Wilson Environmental
	Turbidity	EPA 180.1	Wilson Environmental
	Hardness	EPA 215.1/242.1	Wilson Environmental
	SO <sub>4</sub> <sup>2-</sup>	EPA 375.4	Wilson Environmental
	TOC	EPA 415.1	Wilson Environmental
	NO <sub>3</sub> <sup>-</sup> /NO <sub>2</sub> <sup>-</sup>	EPA 353.2	Wilson Environmental
Sludge	Water content	ASTM D 2216	Wilson Environmental
	pH	SW-846 9045	Wilson Environmental
	TCLP metals	SW-846 1311	Wilson Environmental
	Total As	SW-846 3051, 6020	Wilson Environmental
	Total Fe	SW-846 3051, 6020	Wilson Environmental

interference from a chloride molecular species (<sup>40</sup>Ar<sup>35</sup>Cl), all ion current data at m/e 75 were corrected using chloride measurements in all samples, and the MDL was 0.1 µg/L As. All the unfiltered water samples (i.e., in bottle A) were digested using EPA Method 200.8 prior to analysis. Filtered water samples (i.e., in bottles B and C) were analyzed directly without digestion. Wilson Environ-

mental Laboratories in Westerville, OH, was subcontracted to perform all other chemical analyses. QA/QC of all methods followed the guidelines provided in the QAPP (Battelle, 1998) and the data quality in terms of precision, accuracy, MDL, and completeness is discussed in Section 5.0 of this report.

## 4. Results and Discussion

This section presents the results of the treatment plant selection process, which resulted in the selection of two coagulation/filtration plants, referred to as Plants A and B, and one lime softening plant, referred to as Plant C. In addition, results from water and residuals sampling and analysis at Plants A, B, and C are summarized and discussed. Complete analytical results from long-term water sampling at Plants A, B, and C are presented in Appendices A, B, and C, respectively.

### 4.1 Plant Selection

The plant selection process consisted of identifying potential treatment facilities, contacting these facilities via telephone, and conducting initial site visits during which source water samples were collected and analyzed. Initially, a list was prepared consisting of six potential coagulation/filtration treatment facilities and two lime softening facilities. These potential candidate facilities were contacted to discuss the study and determine details of plant operation. Each facility was evaluated and assigned an overall plant rating based, in order of importance, on source water arsenic concentrations, source water type, available manpower to conduct the year-long study, availability of historical arsenic data, and plant size. Selection was based primarily on source water arsenic concentrations, and preference was given to facilities with arsenic concentrations greater than 20 µg/L. Another major consideration was the availability of manpower, because the year-long study would require significant resources. Also, it was desirable to have historical arsenic analytical data, fairly large facilities (i.e., >20,000

people served), and to have a mix of plants using ground water and/or surface water sources.

From the eight initial plants, three plants (two coagulation/filtration and one lime softening) were selected for site visits and source water sampling (Plants A, B, and C in Table 4-1). The same plants that were selected for the initial site visits also were selected for the subsequent phases of the study. Results from source water sampling at each of the three facilities are presented in the sections that follow.

### 4.2 Plant A

Water and residual samples were collected and analyzed at Plant A, a coagulation/filtration plant, during three phases of the study. The first phase consisted of source water sampling used to help determine if the plant should be considered for additional phases. Source water sampling at Plant A was performed in February 1998. Following source water sampling, the second phase of the study was initiated. This second phase consisted of weekly water sampling for a 4-week period in April 1998 and was designed to determine if the sampling locations and proposed water quality analyses were appropriate for the third phase, long-term evaluation. The third phase was initiated in June 1998 and continued through June 1999. This long-term evaluation consisted of weekly sampling and analysis of process water at three locations throughout the treatment process. Also, arsenic speciation sampling was conducted every fourth week. The third phase of the study also included residual sample

**Table 4-1.** Initial List of Treatment Facilities Identified for the Study

Plant ID	Process	Source Water Arsenic Concentration, July 1994 (µg/L)	Source Water Arsenic Concentration, March 1995 (µg/L)	Population Served	Historical Data	Source Water Type
A	C/F	NS	66.9	2,500,000	Yes	SW
B	C/F	NS	33.2	65,000	Yes	SW
C	LS	33.2	52.5	35,000	Yes	GW

C/F = coagulation/filtration.      GW = ground water.      NS = not sampled.  
 LS = lime softening.                SW = surface water.

collection and analysis. Recycle supernatant water samples from the settling pond were collected monthly beginning in November 1998, and three sludge samples were collected during a single sampling event from a dewatered sludge pond.

#### 4.2.1 Plant A Description

Plant A began operation in December 1986 and can treat up to 600 million gallons of water per day (mgd). However, based on discussions with plant personnel, the average plant flowrate is approximately 420 mgd. This plant uses ozonation, coupled with coagulation/filtration for water treatment. Figure 4-1 is a schematic diagram of the treatment process at Plant A.

During treatment, the influent water is split into four treatment trains immediately prior to ozonation and the trains are recombined prior to distribution. At the design flowrate, the treatment process takes approximately 40 minutes. Typically, it takes approximately 1 hour for raw water to be processed. The treatment process consists of the following major elements:

- **Screening.** The raw water is passed through a screen with a 2-inch mesh to remove debris.
- **Ozonation.** Ceramic diffusers are used to feed 1.5 mg/L of ozone at the influent of the unit. There is approximately a 5-minute contact time. Ozonation is used for disinfection and microflocculation to improve filtration and control taste and odor. The plant produces approximately 13,000 lb/day of ozone with six generators.

- **Rapid Mixing.** 1 to 2 mg/L of ferric chloride and 1 to 5 mg/L of cationic polymer are mixed with the water.
- **Flocculation.** Flocculation occurs in three basins placed in series with approximately 8.5 minutes of contact time.
- **Filtration.** Filtration is accomplished with a high-rate filter (13.5 gpm/ft<sup>2</sup>). The filter media is anthracite coal (1.5 mm effective size) and a thin layer of pea gravel. Typically, backwashing occurs every 6 to 40 hours (average 20 hours) and the backwash water is sent to settling ponds. Supernatant water is fed into the water treatment plant influent. Backwashing accounts for approximately 2% of plant flow.
- **Chlorination.** Chlorine is added during the treatment process for disinfection. The treatment plant chlorinates in order to maintain approximately 2 mg/L of residual chlorine.

#### 4.2.2 Initial Source Water Sampling

Source water for Plant A is supplied primarily via an aqueduct system that carries ground water and surface water runoff from the Sierra Nevada Mountains. This water is collected and stored in a series of eight reservoirs. The aqueduct is enclosed for 200 miles between the last of the eight reservoirs and the water treatment plant. Due in part to the high arsenic concentrations in the source water, a water treatment facility was constructed in 1995 at the inlet of the last reservoir. This plant doses 3 to 7 mg/L of ferric chloride and a cationic

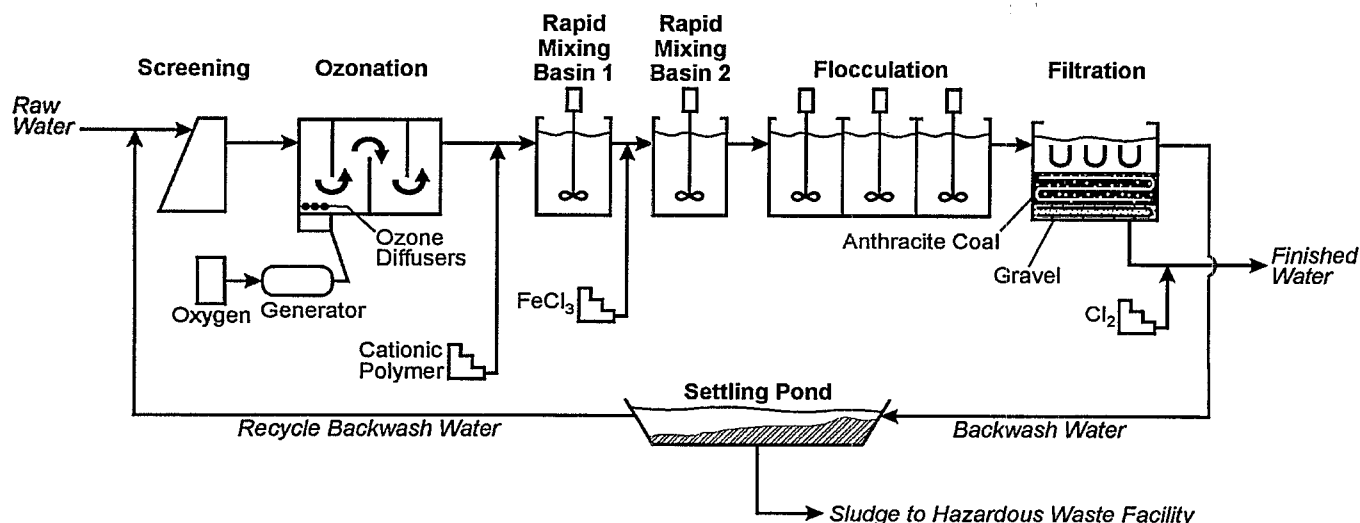


Figure 4-1. Schematic Diagram of Plant A Treatment Process



polymer into the reservoir, which is used as a large settling basin. The reservoir is relatively effective at removing arsenic. The long-term average arsenic concentration in the source water prior to entering the reservoir is approximately 25 µg/L and the reservoir effluent has an average arsenic concentration of 8 to 10 µg/L. The reservoir treatment plant is not considered part of Plant A and is not included in the sampling phases of this study.

An initial site visit to Plant A was conducted February 3, 1998, during which time source water samples were collected. The total arsenic concentration during the initial sampling event was 10.4 µg/L. Particulate arsenic accounted for 2.4 µg/L of the total arsenic concentration, and soluble arsenic, primarily arsenate, accounted for the remaining 8.0 µg/L of the total arsenic. The particulate arsenic is probably attached to the iron, which was detected at a concentration of 170 µg/L. The As(V) concentration was 7.9 µg/L and the As(III) concentration was 0.1 µg/L, which is consistent with what would be expected for a surface water source. Table 4-2 presents the analytical results from the source water sampling.

Although the total arsenic in the source water at this plant was below the desired concentration of 20 µg/L, it was selected for incorporation into the preliminary sampling and long-term evaluation phases. Selection of Plant A was based on the very large size and the availability of resources at the facility to conduct the long-term sampling.

#### 4.2.3 Preliminary Sampling

During the preliminary sampling phase of this study, water samples were collected at three locations within

the treatment plant: IN, PF, and AF. The IN samples were collected from a tap located after initial screening and after the supernatant from the sludge settling lagoons had been recycled. The PF and AF samples were collected from sample taps located on treatment train two of the four parallel trains at Plant A. The PF sampling tap was located after flocculation and just prior to filtration. The AF sampling tap was located after filtration and prior to final chlorine addition and distribution. Figure 4-2 is a process flowchart for Plant A that shows sampling locations within the treatment process and the associated sample analyses performed at each location.

Alkalinity, turbidity, pH, total aluminum, total iron, total manganese, TOC, and total arsenic analyses were performed on samples collected each of the four weeks at each of the three sampling locations. Arsenic speciation was conducted once during the preliminary study on samples collected from each sampling location. Soluble, and particulate were determined as part of the arsenic speciation, as well as the species (arsenite and arsenate) making up the soluble fraction of the total arsenic. Table 4-3 presents the results of the 4-week preliminary sampling period.

Results from the preliminary sampling events indicated that inlet total arsenic concentrations ranged from approximately 12 to 17 µg/L. As found during the initial source water sampling, the total arsenic in the source water was primarily As(V) and contained only minor concentrations of As(III) and particulate arsenic. As would be expected, the species of arsenic did not vary during the treatment process. The average total arsenic removed by Plant A was approximately 48% during preliminary

**Table 4-2.** Source Water Analytical Results at Plant A (February 3, 1998)

Parameter	Unit	Primary Sample	Duplicate Sample	Average Concentration
Alkalinity	mg/L <sup>(a)</sup>	98	95	97
Sulfate	mg/L	44	44	44
Turbidity	NTU	0.67	0.68	0.68
pH	—	8.1	8.1	8.1
Hardness	mg/L <sup>(a)</sup>	104	93.5	98.8
Ca Hardness	mg/L <sup>(a)</sup>	74	65	70
Mg Hardness	mg/L <sup>(a)</sup>	29	29	29
Total Al	µg/L	<400	<400	<400
Total Fe	µg/L	160	180	170
Total Mn	µg/L	<20	<20	<20
NO <sub>3</sub> -NO <sub>2</sub> (N)	mg/L <sup>(b)</sup>	0.12	0.13	0.13
TOC	mg/L	1	2	1.5
As (total)	µg/L	11.1	9.6	10.4
As (total soluble)	µg/L	7.3	8.6	8.0
As (particulate)	µg/L	3.8	1.0	2.4
As(III)	µg/L	ND	0.2	0.1
As(V)	µg/L	7.3	8.4	7.9

(a) As CaCO<sub>3</sub>.

(b) Combined NO<sub>3</sub>-N and NO<sub>2</sub>-N.

ND = not detected.

NTU = nephelometric turbidity units.



**Table 4-3.** Analytical Results from Preliminary Sampling at Plant A (April 9, 1998 through April 30, 1998)

Parameter	Units	4/9/98 <sup>(a)</sup>						Sampling Date/Location					
		IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(b)</sup>	113 111	108 108	107 107	112	110	110	116	115	115	124	119	116
Turbidity	NTU	1.6 1.6	2.1 2.1	0.1 0.1	2.5	7.1	0.2	1.4	1.9	<0.1	1.1	7.5	<0.1
pH	—	8.1 8.1	7.8 7.8	7.7 7.7	8.4	8.2	8.0	7.9	7.9	7.8	8.3	8.1	8.0
Total Al	µg/L	<400 <400	<400 <400	<400 <400	<400	<400	<400	<400	<400	<400	<400	<400	<400
Total Fe	µg/L	280 300	780 720	60 60	460	1,040	40	250	940	100	170	1,190	50
Total Mn	µg/L	30 30	40 40	<20 <20	70	70	50	50	70	50	<20	60	<20
TOC	mg/L	2 3	3 3	2 2	2	3	2	3	3	2	2	3	2
As (total)	µg/L	13.6 12.1	8.6 8.5	6.1 6.1	14.5	16.2	7.3	14.2	15.6	7.2	16.6	19.3	9.5
As (total soluble)	µg/L	12.0 12.0	7.8 7.8	6.4 6.5	NA	NA	NA	NA	NA	NA	NA	NA	NA
As (particulate)	µg/L	1.6 0.1	0.8 0.7	ND ND	NA	NA	NA	NA	NA	NA	NA	NA	NA
As (III)	µg/L	0.2 0.3	0.2 0.2	0.1 0.2	NA	NA	NA	NA	NA	NA	NA	NA	NA
As (V)	µg/L	11.8 11.7	7.6 7.6	6.3 6.3	NA	NA	NA	NA	NA	NA	NA	NA	NA

(a) Duplicate samples were taken on 4/9/98.

(b) As CaCO<sub>3</sub>.

IN = inlet; PF = prefiltration; AF = after filtration.

NA = not applicable.

ND = not detected.

sampling, reducing the finished water total arsenic concentration to 6.1 to 9.5 µg/L. Plant A does not have a sedimentation step following flocculation; therefore, the majority of the arsenic removal occurred during filtration. The As(V) attaches to iron flocs and is then removed during filtration, which is why the PF sampling location consistently has higher total arsenic concentrations.

McNeill and Edwards (1997a) developed the following simplified model for predicting arsenic removal at iron and alum coagulation facilities based on raw water Fe and Al concentrations:

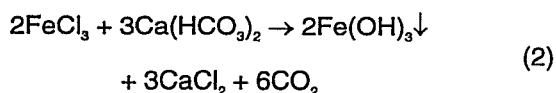
$$\text{Arsenic Sorbed(\%)} = 100 \times \frac{K \times [\text{Fe} + \text{Al}] \text{mM}}{(1 + K \times [\text{Fe} + \text{Al}] \text{mM})} \quad (1)$$

where  $K = 78 \text{ mM}^{-1}$

This model was based on data collected at over 14 full-scale facilities, and was able to accurately predict arsenic removal within  $\pm 13\%$  (90th percentile confidence interval). Applying this model to the preliminary results from Plant A, the predicted removal ranged between 51 and 62% compared to actual removals ranging from 43 to 52%. During the first sampling event, the actual and predicted arsenic removal percentages were very close (51% predicted and 52% actual). However, a 19% difference in arsenic removal was observed during the last sampling event in which the calculated removal was 62% and the actual removal was 43%. Estimated arsenic removal percentages for the other two sampling events were within  $\pm 13\%$  of the actual removal observed. Therefore, the simplified model appeared to approximate the arsenic removal at Plant A fairly well.

Other water quality parameters were analyzed to support understanding of the mechanisms of arsenic removal. TOC and pH concentrations were relatively constant throughout the treatment process during the preliminary sampling phase. Also, the pH was approximately 8.0 and in the range where no effect on arsenic removal efficiency using iron (III) salts has been observed in previous studies (Sorg and Logsdon, 1978; Sorg, 1993; Hering et al., 1996).

A slight decrease in alkalinity was observed after the addition of the ferric chloride coagulant (i.e., at the PF sampling location). This decrease in alkalinity is a result of a chemical reaction with ferric chloride:



Total aluminum concentrations were below detection limits at all three locations during each sampling event

and were not considered to play a role in arsenic removal; however, the detection limits were relatively high (400 µg/L). Total manganese concentrations ranged from <20 to 70 µg/L in the inlet and <20 to 50 µg/L in the outlet. The total iron concentrations averaged 293 µg/L at the inlet, 980 µg/L at the prefiltration sampling location, and 63 µg/L at the after-filtration sampling location. The increase at the prefiltration location is due to the addition of  $\text{FeCl}_3$  as a coagulant. The iron then is removed in the filters. It appears that the primary arsenic removal mechanism at Plant A is adsorption and coprecipitation of As(V) with the iron flocs.

Based on the results of the preliminary sampling effort, only minor changes were made to the approach for the long-term evaluation. Sampling locations and primary analytes remained unchanged. However, aluminum, iron, and manganese analysis was modified to achieve lower detection limits by using ICP-MS. Also, it was determined that part of the sample in bottle B from the arsenic speciation kits would be used to determine dissolved aluminum, iron, and manganese concentrations.

## 4.2.4 Long-Term Sampling

Long-term sampling and analysis consisted of 49 weeks of sampling with 12 arsenic speciation sampling events. During the long-term sampling phase of this study, water samples were collected at the same three locations that were used during the preliminary sampling phase: IN, PF, and AF. Alkalinity, turbidity, pH, total aluminum, total iron, total manganese, TOC, and total arsenic analysis was performed on samples collected each week. Arsenic speciation sampling was conducted 12 times during the long-term sampling phase on samples collected from each sampling location. Dissolved aluminum, iron, and manganese concentrations at each sampling location were determined monthly using a sample from bottle B of the arsenic speciation kits. Additionally, residual sampling was performed during this phase and consisted of collection and analysis of recycle supernatant water and sludge from the settling pond. The following subsections summarize the analytical results for arsenic, other water quality parameters, and residuals. Figure 4-2 is a process flow diagram for Plant A that indicates sampling locations during the long-term evaluation and the analyses performed on samples from each location.

### 4.2.4.1 Arsenic

Table 4-4 provides a summary of the arsenic analytical results collected at the three treatment process locations at Plant A. Total arsenic concentrations at the inlet ranged from 2.6 µg/L to 12.1 µg/L with an average concentration of 7.5 µg/L. These concentrations are slightly lower than what was observed during the initial source water and preliminary sampling phases of this study.

**Table 4-4.** Summary of Arsenic Analytical Results at Plant A (June 1998–June 1999)

Parameter	Sample Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	Inlet	µg/L	49	2.6	12.1	7.5	2.1
	Prefiltration	µg/L	49	2.0	23.4	8.7	3.9
	After filtration	µg/L	48	0.8	6.0	3.5	1.1
As (total soluble)	Inlet	µg/L	12	5.1	10.9	7.7	1.7
	Prefiltration	µg/L	12	2.7	6.0	4.3	1.1
	After filtration	µg/L	12	2.0	4.8	3.5	0.9
As (particulate)	Inlet	µg/L	12	<0.1	1.9	0.5	0.6
	Prefiltration	µg/L	12	1.7	7.8	4.3	1.8
	After filtration	µg/L	12	<0.1	0.5	0.2	0.2
As(III)	Inlet	µg/L	12	0.3	2.0	0.7	0.5
	Prefiltration	µg/L	12	<0.1	2.1	0.6	0.6
	After filtration	µg/L	12	<0.1	1.9	0.6	0.5
As(V)	Inlet	µg/L	12	4.8	10.2	6.9	1.7
	Prefiltration	µg/L	12	2.2	5.4	3.6	0.9
	After filtration	µg/L	12	1.6	4.3	3.0	0.7

One-half of the detection limit was used for nondetect samples for calculations.  
 Primary and duplicate samples were averaged for calculations.

These results are due to a general trend of slightly higher arsenic concentrations that occur seasonally during the months of February through July. Total arsenic concentrations at the PF sampling location ranged from 2.0 to 23.4 µg/L, with an average of 8.7 µg/L. Therefore, in general, no reduction of arsenic was observed between the inlet and prefiltration sampling locations. In fact, the data indicated that a slight increase in total arsenic concentration occurred due to the formation of iron flocs which sorbed the arsenate. The flocs accumulated just prior to the filtration step where the PF samples were collected. Samples collected at the after-filtration location contained total arsenic concentrations ranging from 0.8 µg/L to 6.0 µg/L with an average concentration of 3.5 µg/L.

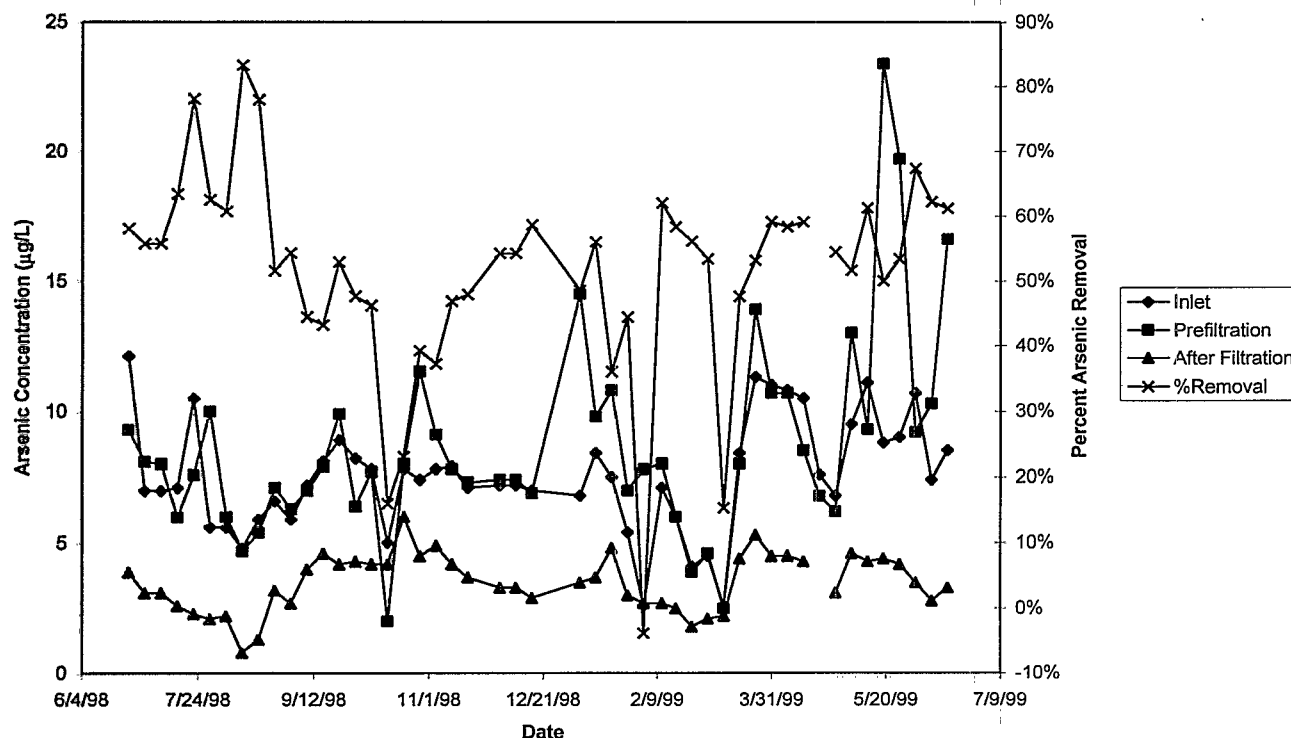
The average removal percentage of total arsenic between the inlet and after-filtration sampling locations was 53%. The average arsenic removal predicted by the McNeill and Edwards (1997a) sorption model was 43%, which is within the 90th percentile confidence interval of the model. However, individual sampling events showed differences in actual and predicted arsenic removals as high as 63% and the average difference was approximately 20%, which is outside of the 90th percentile confidence interval for the model. The discrepancies between the actual and predicted values may be due to temperature and competition for sorption sites by natural organic matter (McNeill and Edwards, 1997a). Also, the low arsenic concentration in the source water (average 7.5 µg/L) likely contributed to the discrepancy between the predicted and actual removal efficiencies. However, it appears that the difference is not a result of iron floc passing through the filter because the particulate arsenic and total iron concentrations at the outlet are very low. Figure 4-3 is a graph showing the total arsenic concentration recorded at each sampling location throughout

the study, as well as removal percentages calculated for each sampling event.

Particulate arsenic concentrations averaged 0.5 µg/L at the inlet, 4.3 µg/L at the prefiltration sampling location, and 0.2 µg/L at the after-filtration sampling location. The increase of particulate arsenic at the prefiltration sampling location is due to sorption and coprecipitation of arsenic on/with the iron flocs formed. This observation is supported by the decrease of particulate arsenic in the after-filtration sampling location.

As(III) and As(V) make up the soluble portion of the total arsenic concentration. Throughout the duration of the study and at each sampling location, As(V) made up the majority of the soluble arsenic. As(III) concentrations averaged 0.7 µg/L at the inlet, 0.6 µg/L at the prefiltration location, and 0.6 µg/L at the after-filtration location, indicating that As(III) was not removed by the treatment process. Although the As(III) concentrations were low, no apparent conversion to As(V) was observed after ozonation. Average As(V) concentrations were 6.9 µg/L at the inlet, 3.6 µg/L at the prefiltration location, and 3.0 µg/L at the after-filtration location. The As(V) concentration decreased at the prefiltration location due to coprecipitation/adsorption of the arsenic with iron flocs. This result correlates with the increase in particulate arsenic at this same location. The arsenic that was not removed with the coagulant passes through the system. Figure 4-4 provides charts showing the fractions of the total arsenic concentration made up by particulate arsenic, As(III), and As(V) throughout the long-term evaluation.

The Plant A water treatment system was able to consistently remove arsenic to low levels (i.e., average treated water total arsenic concentration is 3.5 µg/L).



**Figure 4-3.** Total Arsenic Analytical Results During Long-Term Sampling at Plant A

The primary arsenic removal mechanism appears to be coprecipitation/adsorption with iron flocs followed by filtration. The simplified sorption model developed by McNeill and Edwards (1997a) appears to approximate the arsenic removal process at Plant A reasonably well, although discrepancies were noted.

#### 4.2.4.2 Other Water Quality Parameters

In addition to arsenic analysis, other water quality parameters were analyzed to provide insight into the chemical processes occurring at the treatment facility. Table 4-5 summarizes the analytical results for several water quality parameters obtained during the long-term sampling at Plant A.

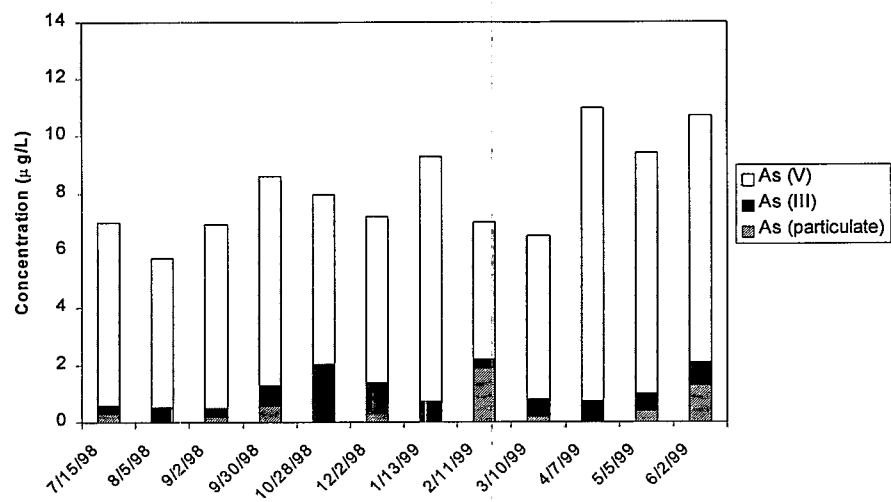
Alkalinity concentrations ranged from 45 mg/L to 112 mg/L (as  $\text{CaCO}_3$ ) in the inlet with an average of 89 mg/L. The analytical data indicated seasonal variations in alkalinity concentrations, with a dip occurring during July and August. This dip correlated with the snow melt in the Sierra Nevada mountains, which resulted in a higher percentage of the source water coming from lower-alkalinity melted snow. However, these data did not appear to correlate with arsenic analytical results or removal efficiencies at Plant A. Figure 4-5 plots the inlet alkalinity, turbidity, pH, and TOC concentrations throughout the duration of the study.

During long-term sampling, turbidity concentrations averaged 1.2 NTU at the inlet, 1.8 NTU at the prefiltration location, and <0.1 NTU at the after-filtration location. As seen in Figure 4-5, spikes in the inlet turbidity concentrations were observed during the study and are most likely due to precipitation events that increase suspended solids in the source water. The ferric chloride dosages are adjusted to account for the varying turbidity concentrations. The data show that Plant A effectively removes turbidity from the source water, although no correlation was observed regarding arsenic removal efficiency.

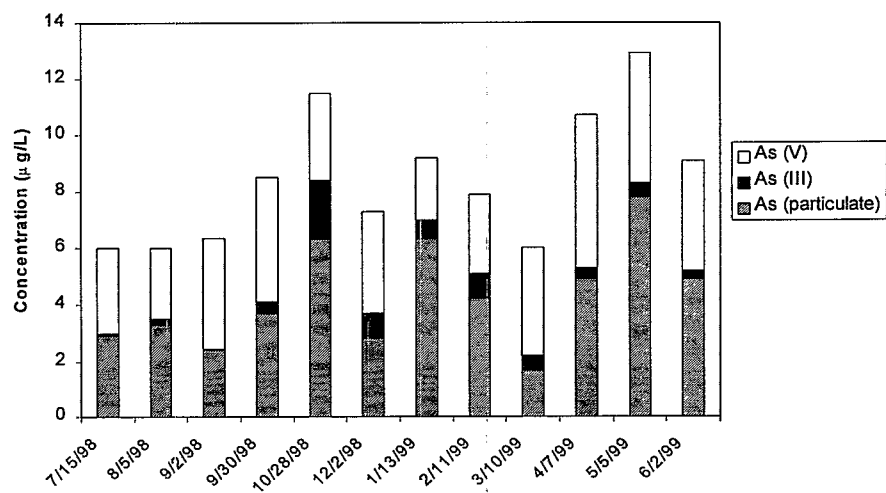
The average pH was 8.0 at the inlet, 7.9 just prior to filtration, and 7.8 in the finished water. These pH values are in the range (pH 5.5 to 8.5) where arsenic removal efficiency by iron oxides is not affected (Sorg, 1993). On March 24, 1999, a pH of 5.2 was reported; however, this figure is considered to be an outlier because plant operational data did not indicate any change in pH. TOC concentrations also were relatively constant, with averages of 2.4 mg/L, 2.7 mg/L, and 2.4 mg/L, at the inlet, prefiltration, and after-filtration sampling locations, respectively. TOC does not appear to impact arsenic removal efficiency.

Total iron concentrations at the inlet sampling location ranged from <30 to 767 µg/L and averaged 146 µg/L. At the prefiltration sampling location, total iron concentrations ranged from <30 to 2,646 µg/L and averaged 642 µg/L.

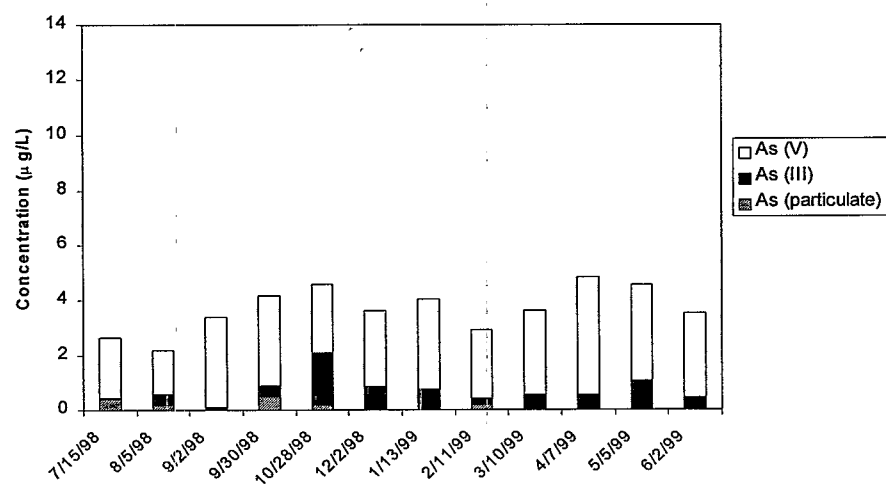
**Inlet**



**Prefiltration**



**After Filtration**



**Figure 4-4.** Arsenic Form and Species Analytical Results During Long-Term Sampling at Plant A

**Table 4-5. Summary of Water Quality Parameter Analytical Results at Plant A (June 1998–June 1999)**

Parameter	Sample Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Alkalinity	Inlet	mg/L	48	45	112	89	20.7
	Prefiltration	mg/L	48	43	111	88	20.6
	After filtration	mg/L	48	42	109	87	20.5
Turbidity	Inlet	NTU	48	0.3	5.5	1.2	1.0
	Prefiltration	NTU	48	0.4	18.5	1.8	2.7
	After filtration	NTU	48	<0.1	0.2	<0.1	0.04
pH	Inlet	—	48	5.2	8.3	8.0	0.4
	Prefiltration	—	48	7.5	8.1	7.9	0.1
	After filtration	—	48	7.4	8.0	7.8	0.2
TOC	Inlet	mg/L	47	1.5	4.8	2.4	0.6
	Prefiltration	mg/L	48	<1.0	12.0	2.7	1.5
	After filtration	mg/L	48	1.5	7.4	2.4	0.9
Total Al	Inlet	µg/L	49	<11	717	68	104.2
	Prefiltration	µg/L	49	18.2	246	64	48.8
	After filtration	µg/L	49	<11	39	12	7.6
Total Fe	Inlet	µg/L	49	<30	767	146	175.1
	Prefiltration	µg/L	49	<30	2,646	642	474.5
	After filtration	µg/L	49	<30	63.8	<30	14.7
Total Mn	Inlet	µg/L	49	4.4	112	20.9	20.0
	Prefiltration	µg/L	49	8.9	85.5	27.1	17.0
	After filtration	µg/L	49	<0.5	45.4	4.7	7.2
Dissolved Al	Inlet	µg/L	12	<11	22.6	<11	4.9
	Prefiltration	µg/L	12	<11	<11	<11	NA
	After filtration	µg/L	12	<11	18	<11	3.7
Dissolved Fe	Inlet	µg/L	12	<30	45.7	<30	8.9
	Prefiltration	µg/L	12	<30	<30	<30	NA
	After filtration	µg/L	12	<30	<30	<30	NA
Dissolved Mn	Inlet	µg/L	12	1.1	10.8	3.1	2.6
	Prefiltration	µg/L	12	1.4	69.7	8.7	19.2
	After filtration	µg/L	12	<0.5	5.8	2.3	2.3

One-half of the detection limit was used for nondetect samples for calculations.  
 Primary and duplicate samples were averaged for calculations.

The total iron concentration increased at the prefiltration location due to the addition of  $\text{FeCl}_3$  as a coagulant. The average total iron concentration at the after-filtration sampling location was <30 µg/L. Also, average dissolved iron concentrations were below the detection limit at the inlet, prefiltration, and after-filtration sampling locations. As stated previously, iron is the key factor in arsenic removal at Plant A. It is believed that the majority of the arsenic removal is through adsorption and coprecipitation of As(V) with iron hydroxides.

Total aluminum concentrations averaged 68 µg/L at the inlet, 64 µg/L at the prefiltration location, and 12 µg/L at the after-filtration location. The average dissolved aluminum concentration at all three locations was less than the detection limit. It did not appear that coprecipitation with aluminum hydroxide was a significant factor in the removal of arsenic at Plant A, because minor concentrations were present and almost all of the aluminum was in the particulate form at the inlet.

Total manganese concentrations averaged 20.9 µg/L, 27.1 µg/L, and 4.7 µg/L, at the inlet, prefiltration, and after-filtration sampling locations, respectively. Average dis-

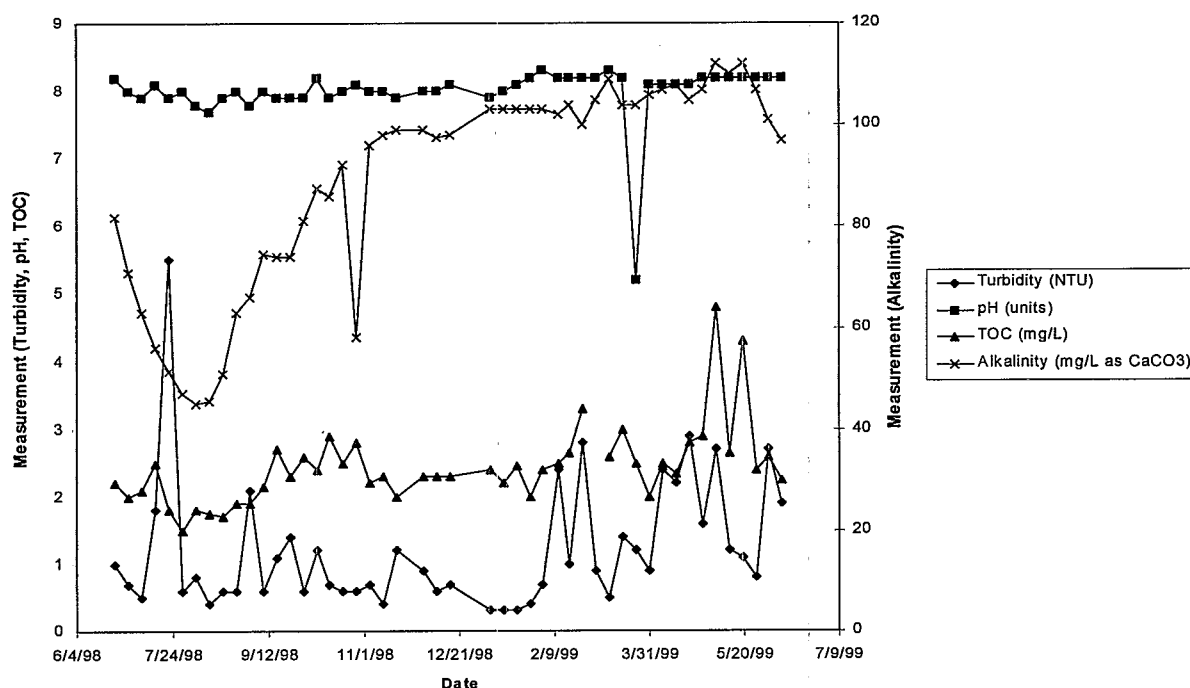
solved manganese concentrations were 3.1 µg/L at the inlet, 8.7 µg/L at the prefiltration location, and 2.3 µg/L at the after-filtration location.

#### 4.2.4.3 Recycle Supernatant Water

Approximately 2% of the total flow at Plant A is used for backwashing filters. The filter backwash water then is sent to a sludge settling pond and the supernatant is recycled. The supernatant water is added continuously to the source water and processed at the facility. Supernatant samples were collected from a sample tap in the piping that transports the water from the sludge settling pond to the source water inlet. Results of supernatant sampling are summarized in Table 4-6.

The soluble arsenic concentrations are approximately equal to those measured in the source water; however, the particulate arsenic is approximately 3.0 µg/L higher on average. This result would be expected because the backwash water contains some unsettled iron solids, which most likely contain sorbed arsenic. The low dissolved iron concentrations observed during the study support this assumption. Based on these results, it does not appear





**Figure 4-5.** Inlet Turbidity, pH, TOC, and Alkalinity Analytical Results at Plant A

that the recycle backwash water would impact the treatment process either positively or negatively.

#### 4.2.4.4 Sludge

Sludge is generated at Plant A from backwashing the anthracite coal/pea gravel filters. Typically, backwashing occurs every 6 to 40 hours (average 20 hours) and the backwash water is sent to settling ponds. Supernatant water from the settling ponds is recycled into plant influent. Approximately 2% of plant flow is used for backwashing.

Approximately once per year, or as required, the settling ponds are drained and the sludge is removed. Approximately 18,000 tons of sludge are removed per year. The sludge is considered California hazardous waste due to

elevated concentrations of arsenic and copper based on exceedances of regulatory levels for the soluble threshold limit concentration (STLC). Total arsenic and TCLP results have not exceeded regulatory levels for classification as California hazardous waste. Table 4-7 contains analytical results from sludge sampling conducted during three sampling events at Plant A in October 1996, March 1997, and May 1997.

During the long-term evaluation phase, sludge samples were collected on December 2, 1998, from three locations within a dewatered sludge pond. These sludge samples were analyzed for pH, percent moisture, total arsenic, and total iron. Also, a TCLP test was performed on each sample to determine the quantities of leachable arsenic,

**Table 4-6.** Summary of Analytical Results from Recycle Backwash Water Samples at Plant A (November 11, 1998–June 16, 1999)

Parameter	Units	Number of Sample Events	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	µg/L	8	3.7	19.7	10.2	5.1
As (soluble)	µg/L	8	3.8	10.9	7.1	2.6
As (particulate)	µg/L	8	<0.1	11.7	3.2	4.1
pH	—	7	7.6	7.9	7.8	0.1
Total Al	µg/L	8	<11	113	47	44
Total Fe	µg/L	8	174	1367	535	420
Total Mn	µg/L	8	52.8	572	169	174
Dissolved Al	µg/L	8	<11	<11	<11	NA
Dissolved Fe	µg/L	8	<30	127	37.9	39.3
Dissolved Mn	µg/L	8	33.2	235	78.3	67.0

**Table 4-7. Previous Analytical Results of Sludge Sampling at Plant A (1996–1997)**

Analyte	Description	October 1996	March 1997	May 1997
Total Arsenic	Number of samples	10	10	10
	Minimum concentration (mg/kg)	110	73	110
	Maximum concentration (mg/kg)	740	370	210
	80% UCL concentration (mg/kg)	418	265	180
	Regulatory level (mg/kg)	500	500	500
Arsenic-STLC	Number of samples	10	10	10
	Minimum concentration (mg/L)	4.1	5	9.5
	Maximum concentration (mg/L)	37	21	15
	80% UCL concentration (mg/L)	22	15	13
	Regulatory level (mg/L)	5	5	5
Arsenic-TCLP	Number of samples	10	10	10
	Minimum concentration (mg/L)	<0.2	<0.2	<0.2
	Maximum concentration (mg/L)	<0.2	0.3	0.3
	80% UCL concentration (mg/L)	NA	NA	NA
	Regulatory level (mg/L)	5	5	5

UCL = upper confidence level.

barium, cadmium, chromium, lead, mercury, selenium, and silver. The sample collected from location 2 did not have the same appearance as the samples from locations 1 and 3. It was reported to look more like soil than dried sludge. This difference in appearance probably accounts for the differences in measured arsenic and iron concentrations between the location 2 sample and the samples from locations 1 and 3. Assuming that the samples collected from locations 1 and 3 are more representative of the sludge produced by Plant A, total arsenic concentrations were 806 and 880 mg/kg dry, respectively, and total iron concentrations were 83,200 and 95,000 mg/kg dry, respectively. These total arsenic concentrations exceed the regulatory levels for total arsenic in California, which would classify this sludge as hazardous waste. Arsenic was detected in one sample leachate at a concentration of 0.106 mg/L, which was well below the regulatory limit of 5 mg/L. Table 4-8 presents the results of sludge analysis at each of the three sampling locations.

### 4.3 Plant B

Water and residual samples were collected and analyzed at Plant B, a coagulation/filtration plant, during three phases of the study: source water sampling, preliminary sampling, and long-term evaluation. Source water sampling at Plant B was performed in February 1998. Preliminary sampling consisted of weekly water sampling for a 4-week period in April/May 1998 and was designed to determine if the sampling locations and proposed water quality analysis were appropriate for the third phase, long-term evaluation. The third phase was initiated in June 1998 and continued through June 1999. Arsenic speciation sampling was conducted every fourth week. The third phase of this study also included residual sample collection and analysis. Supernatant water samples from the settling tank were collected monthly beginning in November 1998, and three sludge samples were collected during a single sampling event from a dewatered sludge lagoon.

**Table 4-8. Analytical Results of Sludge Sampling at Plant A (December 2, 1998)**

Parameter	Unit	DL	Location 1	Location 2	Location 3
As-TCLP	mg/L	0.05	0.106	<0.05	<0.05
Ba-TCLP	mg/L	1.0	1.1	1.1	<1.0
Cd-TCLP	mg/L	0.020	<0.020	<0.020	<0.020
Cr-TCLP	mg/L	0.030	<0.030	<0.030	<0.030
Pb-TCLP	mg/L	0.50	<0.50	<0.50	<0.50
Hg-TCLP	mg/L	0.0002	<0.0002	<0.0002	<0.0002
Se-TCLP	mg/L	0.05	<0.050	<0.050	<0.050
Ag-TCLP	mg/L	0.020	<0.020	<0.020	<0.020
TCLP extraction	NA	NA	Complete	Complete	Complete
pH	—	—	7.0	8.1	7.2
Percent moisture	%	0.1	31.6	14.6	38.6
Total As	mg/kg, dry	2.0	806	9.0 <sup>(a)</sup>	880
Total Fe	mg/kg, dry	1,370	83,200	17,600	95,000

(a) Confirmed by sample re-analysis. The sample looked like soil instead of dry sludge.

DL = Detection limit.

### 4.3.1 Plant B Description

Plant B is used to treat surface water for a population of approximately 65,000. The plant processes 6 to 8 mgd during the winter months and 30 to 35 mgd during the summer. The design flowrate is 62.5 mgd. The plant utilizes coagulation, sedimentation, and filtration for water treatment. Figure 4-6 is a schematic diagram of the treatment process used at Plant B.

The treatment process at Plant B consists of the following major elements:

- **Screening.** Screening is required to remove debris from the raw water at the river intake.
- **Pre-Chlorination.** Approximately 3 to 4 mg/L of chlorine is added to the raw water for disinfection and to provide residual chlorine for the distribution system.
- **Rapid Mixing.** Depending on influent turbidity, 25 to 30 mg/L of alum is added to the water. Also, 0.75 mg/L Cat Floc-TL polymer is used when water temperature is less than 10°C, typically October through April. Jar testing conducted by the treatment plant was used to develop relationships for estimating alum dosage based on influent turbidity.
- **Flocculation.** Flocculation of alum hydroxide and various contaminants, including arsenic, occurs

during this treatment process. During late summer, powdered activated carbon (PAC) may be added for taste and odor control.

- **Sedimentation.** Sedimentation of flocs occurs in primary and secondary clarifiers.
- **Filtration.** Additional solids removal is accomplished through filtration. Filtering is accomplished with a dual media consisting of anthracite and sand. Backwashing occurs approximately every 50 hours.
- **Clearwell Storage.** Ammonia is added prior to clearwell storage to form monochloramine. No posttreatment chlorination is performed.
- **Backwash.** Backwashing occurs approximately every 50 hours. The sludge eventually is sent to a landfill and the supernatant water from the sludge lagoon is discharged to the Missouri River under a state permit.

### 4.3.2 Initial Source Water Sampling

Plant B influent water is supplied from the Missouri River. Based on discussions with plant personnel, the turbidity ranges from 2 to 3 NTU in the winter and between 10 and 100 NTU during the spring and summer due to snow melt and rain. The primary source of arsenic in the source water is believed to come from the Yellowstone Basin that drains into the Madison River, the largest tributary of the Missouri River. Historically,

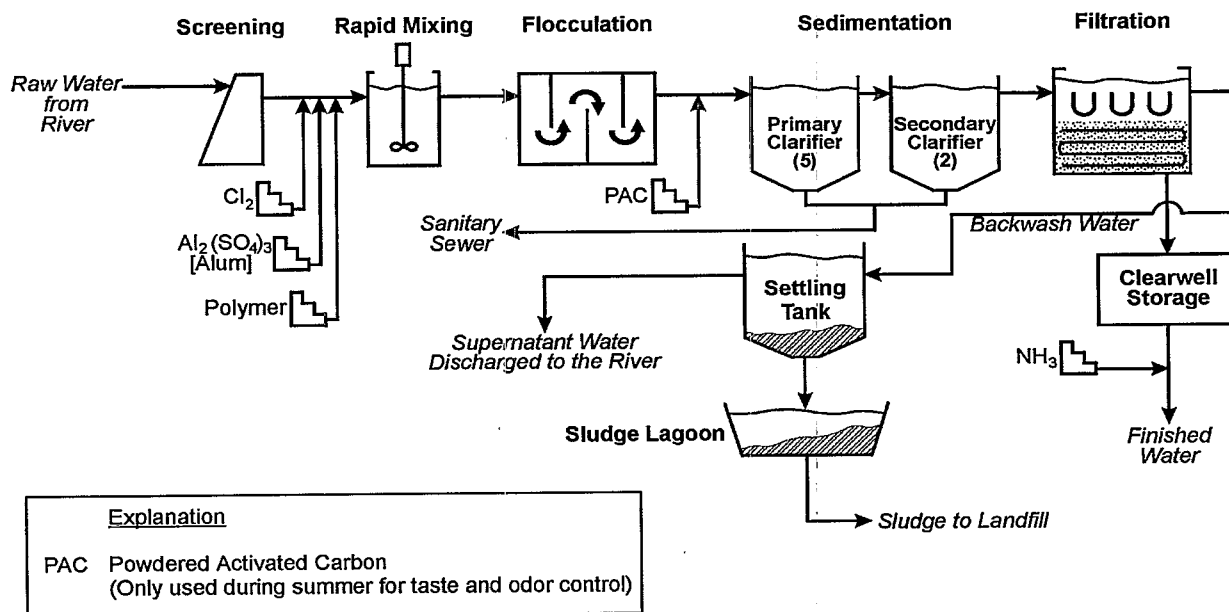


Figure 4-6. Schematic Diagram, Plant B

arsenic concentrations in the source water have ranged from 16 to 25 µg/L.

An initial site visit to Plant B was conducted on February 5, 1998, during which time source water samples were collected. During this sampling event, samples were collected and analyzed for arsenic (total, particulate, soluble, As[III], As[V]) and various other water quality parameters that may affect arsenic removal. Table 4-9 presents the analytical results from the source water sampling. The total arsenic concentration in the source water averaged 21.2 µg/L. Particulate arsenic averaged 1.4 µg/L of the total, and all of the soluble arsenic was As(V). The inlet iron concentration averaged 2,790 µg/L, which was relatively high and did not correlate well with the total iron data collected during the preliminary sampling and long-term evaluation phases. Aluminum concentrations were less than the detection limit, and manganese concentrations were 30 µg/L.

Alkalinity concentrations averaged 122 mg/L (as CaCO<sub>3</sub>) and total hardness concentrations averaged 281.5 mg/L (as CaCO<sub>3</sub>). Therefore, the source water would be classified as hard. Based on discussions with plant personnel, turbidity concentrations are typically in the range of 2 to 3 NTU in the winter. Consistent with this information, turbidity concentrations were relatively low during the source water sampling event conducted in February, averaging 1.1 NTU. The pH averaged 8.2, which is relatively high for effective arsenic removal using alum (Sorg and Logsdon, 1978; Sorg, 1993).

### 4.3.3 Preliminary Sampling

Water samples collected during the preliminary sampling phase of this study were taken at three locations within

the treatment plant: (1) the IN; (2) PF; and (3) AF. The IN and PF sampling locations were open channels transporting the raw and partially treated water to the various treatment processes in the plant. Therefore, a scoop was used to take grab samples at IN and PF sampling locations. The IN sample was collected from a channel immediately following initial screening. The PF sample was collected from the channel located after rapid mixing, flocculation and sedimentation. A sink facet located in the plant was used as the AF sampling location and represents the finished water entering the distribution system. Figure 4-7 is a process flow diagram for Plant B that shows sampling locations used during the preliminary sampling, as well as the analyses performed on samples collected from each location.

Alkalinity, turbidity, pH, total aluminum, total iron, total manganese, TOC, and total arsenic analysis was performed on all water samples collected at Plant B. Arsenic speciation sampling was conducted at each sampling location once during the preliminary study. Arsenic form (soluble and particulate) and species (arsenate and arsenite) were determined as part of the arsenic speciation. Table 4-10 presents the results of the 4-week preliminary sampling period.

Results from the preliminary sampling events indicated that inlet total arsenic concentrations ranged from approximately 20.9 to 23.3 µg/L. The total arsenic in the source water was primarily As(V) and contained only minor concentrations of As(III) and particulate arsenic. As would be expected, the species of arsenic did not vary significantly during the treatment process. The average total arsenic removal by Plant B was approximately 86% during preliminary sampling. In general, the majority of the arsenic removal occurred during sedimentation (average

Table 4-9. Source Water Analytical Results at Plant B (February 5, 1998)

Parameter	Units	Primary Sample	Duplicate Sample	Average Concentration
Alkalinity	mg/L <sup>(a)</sup>	122	122	122
Sulfate	mg/L	38	37	37.5
Turbidity	NTU	1.08	1.11	1.095
pH	—	8.2	8.2	8.2
Hardness	mg/L <sup>(a)</sup>	286	277	281.5
Ca Hardness	mg/L <sup>(a)</sup>	147	140	143.5
Mg Hardness	mg/L <sup>(a)</sup>	138	138	138
Total Al	µg/L	<400	<400	<400
Total Fe	µg/L	2,780	2,800	2,790
Total Mn	µg/L	30	30	30
NO <sub>3</sub> -NO <sub>2</sub> (N)	mg/L <sup>(b)</sup>	0.23	0.22	0.22
TOC	mg/L	3	3	3
As (total)	µg/L	22.5	20.0	21.2
As (total soluble)	µg/L	20.3	19.3	19.8
As (particulate)	µg/L	2.2	0.7	1.4
As(III)	µg/L	<0.1	<0.1	<0.1
As(V)	µg/L	20.3	19.3	19.8

(a) As CaCO<sub>3</sub>.

(b) Combined NO<sub>3</sub>-N and NO<sub>2</sub>-N.

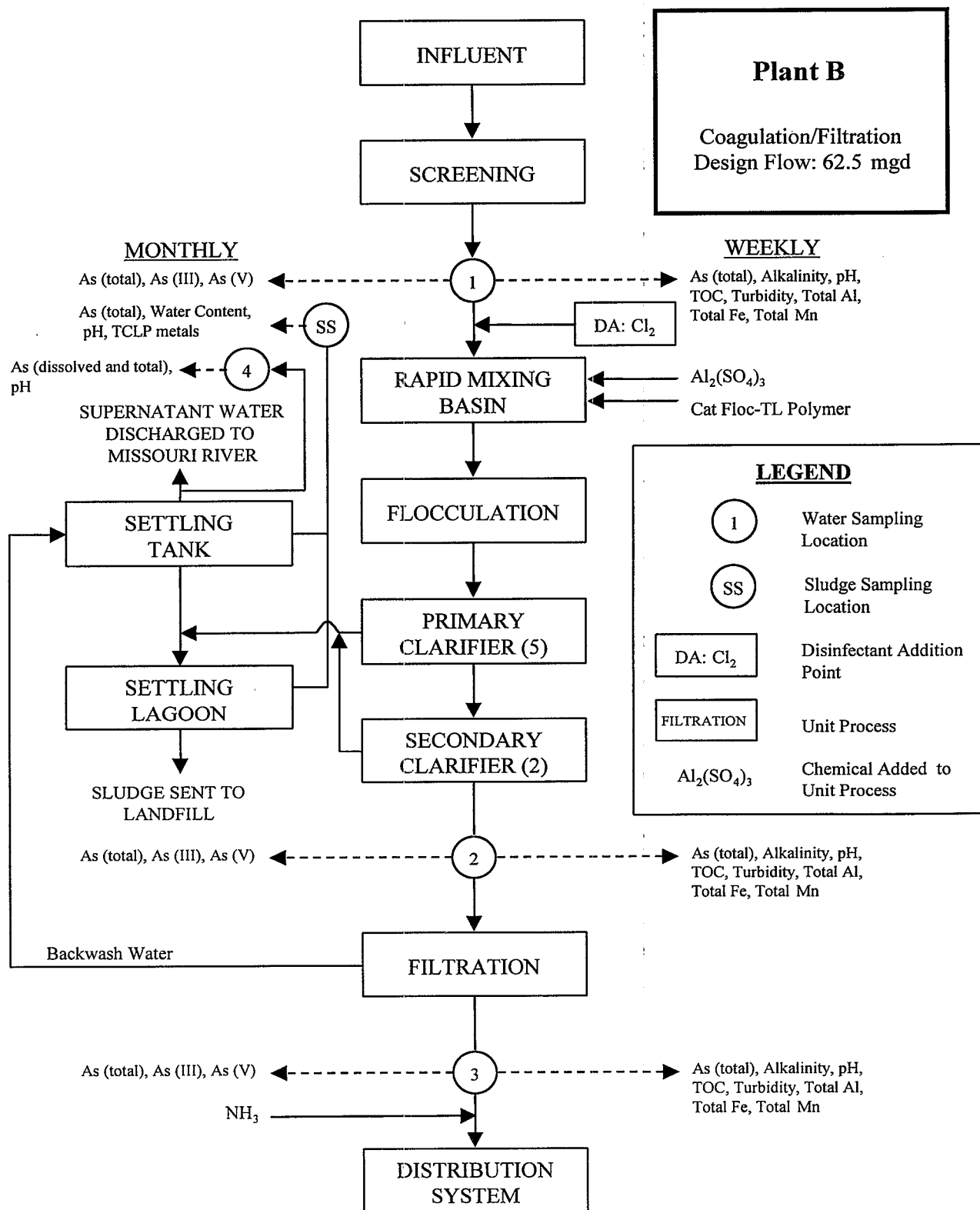


Figure 4-7. Process Flow Diagram and Sampling Locations at Plant B

**Table 4-10. Analytical Results from Preliminary Sampling at Plant B (April 23, 1998 through May 14, 1998)**

Parameter	Units	4/23/98 <sup>(a)</sup>						Sampling Date and Location					
		IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(b)</sup>	134	114	114	132	111	110	132	113	112	127	107	107
Turbidity	NTU	136	114	<0.1	6.3	<0.1	<0.1	7	1.0	<0.1	5.1	0.7	<0.1
pH	—	4	0.8	<0.1	8.5	7.4	7.5	8.7	7.4	7.3	8.5	7.5	7.4
Total Al	µg/L	8.5	7.4	7.4	500	600	<400	500	590	<400	450	530	<400
Total Fe	µg/L	<400	500	<400	440	40	<30	540	40	<30	400	50	<30
Total Mn	µg/L	500	50	40	60	<20	<20	40	<20	<20	50	40	30
TOC	mg/L	90	50	50	3	3	3	3	3	3	3	3	3
As (total)	µg/L	3	3	3	23.3	6.9	4.1	21.2	5.5	2.7	20.9	4.2	2.4
As (total soluble)	µg/L	23.3	6.1	3.4	NA	NA	NA	NA	NA	NA	NA	NA	NA
As (particulate)	µg/L	24.2	5.7	3.3	NA	NA	NA	NA	NA	NA	NA	NA	NA
As (III)	µg/L	26.3	4.2	4.4	NA	NA	NA	NA	NA	NA	NA	NA	NA
As (V)	µg/L	ND	1.9	ND	NA	NA	NA	NA	NA	NA	NA	NA	NA
		ND	0.3	0.3	NA	NA	NA	NA	NA	NA	NA	NA	NA
		0.8	0.4	0.4	NA	NA	NA	NA	NA	NA	NA	NA	NA
		0.7	3.9	4.1	NA	NA	NA	NA	NA	NA	NA	NA	NA
		23.4	3.6	4.2	NA	NA	NA	NA	NA	NA	NA	NA	NA

(a) Duplicate samples were taken on 4/23/98.

(b) As CaCO<sub>3</sub>.

NA = not applicable.

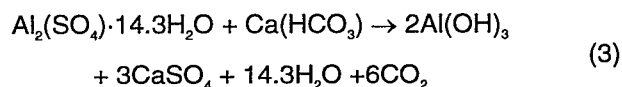
ND = not detected.

75%). Additional arsenic removal occurred during filtration to achieve the 86% average removal, leaving only 2.4 to 4.2 µg/L in the finished water.

Very good correlation with the sorption model proposed by McNeill and Edwards (1997a) was observed. Predicted arsenic removal ranged between 89 and 91%, while actual removals ranged between 82 and 89%. The largest deviation between the predicted and actual arsenic removal was 10%, which is within the 90th percentile confidence interval of the model. Therefore, this simplified sorption model appeared to approximate the system performance and was used in evaluating long-term data.

Other water quality parameters were analyzed to support understanding of the mechanisms of arsenic removal. TOC concentrations were relatively constant (i.e., 3 mg/L) throughout the treatment process, indicating no significant TOC removal by the plant. Similar to Plant A, the lack of TOC removal does not appear to impact arsenic removal.

During alum coagulation, the alum reacts with natural alkalinity to form aluminum hydroxide:



Therefore, alkalinity concentrations and pH values decreased between the inlet and prefiltration sampling locations. Average alkalinity concentrations decreased from 132 to 111 mg/L (as CaCO<sub>3</sub>) and average pH values decreased from 8.6 to 7.5. The alkalinity and pH then remained constant between the prefiltration and after-filtration sampling locations. Turbidity concentrations averaged 5.6 NTU during the preliminary sampling phase. These turbidity values are almost 6 times higher than the values observed during the preliminary sampling event; however, this would be expected due to snow melt and precipitation during the spring months.

Total aluminum concentrations ranged between <400 and 680 µg/L in the inlet and between 500 and 600 µg/L in the prefiltration location. Total aluminum was less than detection during all four sampling events at the after-filtration sampling location. An increase in aluminum concentration due to the addition of alum is not observed at the prefiltration sampling location because it is located after sedimentation. However, based on plant alum dosage data, the calculated aluminum concentration available for coagulation ranged between 2.5 and 4.1 mg/L. Total manganese concentrations ranged from 40 to 90 µg/L in the inlet and <20 to 50 µg/L in the prefiltration and after-filtration locations. The total iron concentrations averaged 460 µg/L at the inlet, 44 µg/L at the prefiltration sampling location, and <30 µg/L at the after-filtration

sampling location. The inlet iron concentrations were significantly lower than the concentration obtained during the source water sampling event and consistent with the concentrations observed during the long-term evaluation phase. It appears that arsenic removal is primarily achieved through adsorption and coprecipitation of As(V) with the aluminum flocs formed from the alum coagulant and the iron in the source water.

Based on the results of the preliminary sampling effort, only minor changes were made to the approach for the long-term evaluation. As with Plant A, sampling locations and primary analytes remained unchanged; however, aluminum, iron, and manganese analyses were modified to ICP-MS. Also, part of the sample in bottle B from the arsenic speciation kits was used to determine dissolved aluminum, iron, and manganese concentrations.

#### 4.3.4 Long-Term Sampling

Long-term sampling and analysis consisted of 49 weeks of water sampling at the same three locations used during the preliminary sampling phase. All weekly samples were analyzed for alkalinity, turbidity, pH, total aluminum, total iron, total manganese, TOC, and total arsenic. Arsenic speciation sampling was conducted at each sampling location 12 times during the long-term sampling phase on samples collected from each sampling location and included determination of dissolved aluminum, iron, and manganese concentrations. Supernatant discharge water and sludge sampling and analysis also was performed during this phase. The following subsections summarize the arsenic, other water quality parameters, and residuals analytical results.

##### 4.3.4.1 Arsenic

Table 4-11 provides a summary of the arsenic analytical results collected at the three sampling locations. Total arsenic concentrations at the inlet ranged from 15 to 23.9 µg/L with an average concentration of 19.1 µg/L. These arsenic concentrations correspond well with the historical data collected by the plant where total arsenic concentrations have ranged from 16 to 25 µg/L. Total arsenic concentrations at the prefiltration location ranged from 3.0 to 15.5 µg/L with an average of 6.4 µg/L. Therefore, an average arsenic removal rate of 66% occurred prior to filtration in the sedimentation basins. Samples collected after-filtration location contained total arsenic concentrations ranging from 1.5 to 11.8 µg/L with an average concentration of 4.0 µg/L. The average removal percentage of total arsenic (comparing raw water and finished water concentrations) was 79%. These removal percentages were calculated based on an average of all total arsenic data collected during the long-term evaluation, including the 6-week period when a polyaluminum

**Table 4-11. Summary of Arsenic Analytical Results at Plant B (June 1998–June 1999)**

Parameter	Sample Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	Inlet	µg/L	49	15	23.9	19.1	2.4
	Prefiltration	µg/L	49	3.0	15.5	6.4	2.7
	After filtration	µg/L	49	1.5	11.8	4.0	2.7
As (total soluble)	Inlet	µg/L	12	18.3	23.0	20.3	1.3
	Prefiltration	µg/L	12	2.1	12.1	4.3	3.1
	After filtration	µg/L	12	2.2	12.5	4.6	3.2
As (particulate)	Inlet	µg/L	12	<0.1	0.6	0.2	0.2
	Prefiltration	µg/L	12	0.6	4.5	2.6	1.2
	After filtration	µg/L	12	<0.1	0.3	<0.1	0.1
As(III)	Inlet	µg/L	12	0.1	1.2	0.6	0.3
	Prefiltration	µg/L	12	<0.1	1.2	0.4	0.3
	After filtration	µg/L	12	<0.1	0.8	0.4	0.2
As(V)	Inlet	µg/L	12	17.9	21.8	19.7	1.2
	Prefiltration	µg/L	12	1.8	11.8	3.9	3.2
	After filtration	µg/L	12	1.9	12.1	4.2	3.3

One-half of the detection limit was used for nondetect samples for calculations.  
Primary and duplicate samples were averaged for calculation.

chloride coagulant was used instead of alum. The removal efficiencies observed during the long-term evaluation correspond well with the removal percentages observed during the preliminary sampling phase (75% and 86% arsenic removal achieved at the PF and AF sampling locations, respectively). Figure 4-8 is a graph showing the total arsenic concentration recorded at each sampling location throughout the study.

Particulate arsenic concentrations averaged 0.2 µg/L at the inlet, 2.6 µg/L at the prefiltration sampling location, and <0.1 µg/L at the after-filtration sampling location. The increase of particulate arsenic at the prefiltration sampling location was attributed to the sorption and coprecipitation of the arsenic and the aluminum flocs. The decrease of particulate arsenic in the after-filtration sampling location supports this observation. The low levels of particulate arsenic at the after-filtration location indicated that the system effectively removes arsenic sorbed to metal flocs.

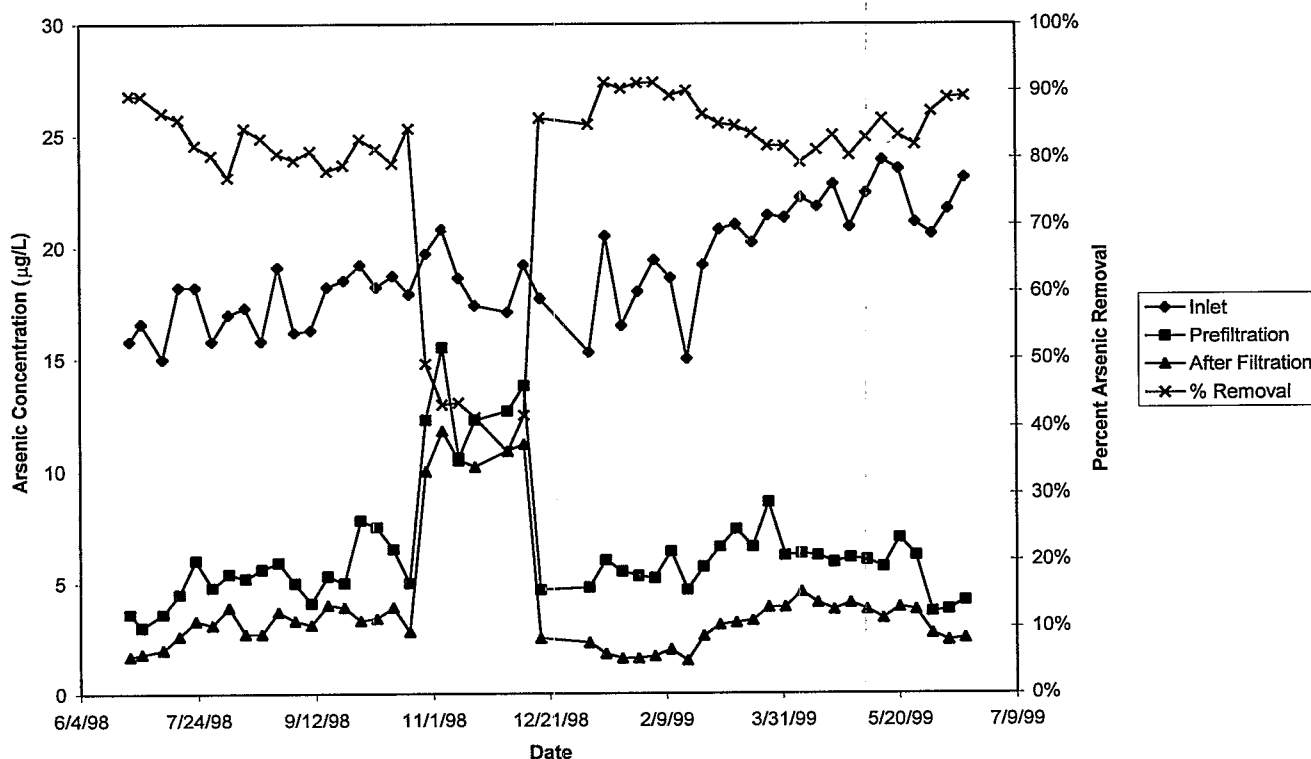
As(III) and As(V) make up the soluble portion of the total arsenic concentration. Throughout the duration of the study and at each sampling location, As(V) made up the majority of the soluble arsenic, averaging 97, 90, and 91% at the IN, PF, and AF sampling locations, respectively. As(III) concentrations averaged 0.6 µg/L at the inlet, 0.4 µg/L at the prefiltration location, and 0.4 µg/L at the after-filtration location. The treatment process removed approximately 33% of the inlet As(III). This removal was probably due to conversion of As(III) to As(V) during chlorination, followed by sorption/occlusion with alum flocs, sedimentation, and filtration. Average As(V) concentrations were 19.7 µg/L at the inlet, 3.9 µg/L at the prefiltration location, and 4.2 µg/L at the after-filtration location. The As(V) concentration decreased at the prefil-

tration location due to adsorption and coprecipitation of the arsenic with the aluminum flocs in the sedimentation basins. This result correlated with the increase in particulate arsenic at this same location. Figure 4-9 shows the fractions of the total arsenic concentration made up of particulate arsenic, As(III), and As(V).

As seen in Figure 4-9, a significant decrease in arsenic removal efficiency was observed beginning October 29, 1998, and continuing through December 10, 1998. This decrease in removal efficiency corresponded to an operational change at the plant. During this period, Plant B was testing an alternative coagulant to alum called PAX-18, which is a liquid polyaluminum chloride coagulant that is supposed to reduce the amount of sludge produced. During the six sampling events that occurred while this alternative coagulant was used, total arsenic concentrations averaged 18.8 µg/L at the inlet, 12.9 µg/L at the prefiltration location, and 10.8 µg/L at the after-filtration location. In comparison, results from total arsenic concentrations measured during the 43 sampling events when alum was used as the coagulant averaged 19.1 µg/L at the inlet, 5.5 µg/L at the prefiltration location, and 3.0 µg/L at the after-filtration location. These results correspond to arsenic removal efficiency of 43% when the PAX-18 coagulant was being used and 84% when the alum coagulant was used.

Removal efficiency using alum correlated very well to the simple sorption model (McNeill and Edwards, 1997a). In fact, the maximum deviation between the calculated and actual removal was 12%, which is within the 90th percentile confidence interval of the model. Based on the correlation, it is believed that arsenic removal is achieved through adsorption on and coprecipitation with the aluminum flocs. The iron concentrations in the source water,





**Figure 4-8.** Total Arsenic Analytical Results During Long-Term Sampling at Plant B

which were figured into the sorption model, also may contribute to arsenic removal because the particulate arsenic at the inlet is most likely attached to the iron.

Removal efficiency using the PAX-18 did not correlate well to the sorption model. Actual arsenic removal was 28 to 42% less than removal predicted by the model. Based on the arsenate results at the outlet, it appeared that significantly less As(V) attached to the aluminum flocs produced by the PAX-18 than the alum. Research indicates that arsenate removal efficiency decreases above pH 7 using alum (Sorg and Logsdon, 1978; Sorg, 1993). During operation with PAX-18, the average pH of the finished water increased from 7.4 to 7.8. This increase may explain the difference in removal efficiency. Additional research is needed to identify the mechanisms affecting removal of arsenic using polyaluminum chloride. However, this study indicated that removal efficiency using PAX-18 was significantly less than alum.

The Plant B water treatment system was able to consistently remove arsenic to low levels when alum is used as the coagulant (i.e., average treated water total arsenic concentration was 3.0 µg/L when alum was used as the coagulant). The primary arsenic removal mechanism was adsorption and coprecipitation with the alum coagulant followed by sedimentation and filtration. Based on the literature, increased arsenic removal could possibly

be achieved by lowering pH to 7 or below and by increasing coagulant dosage.

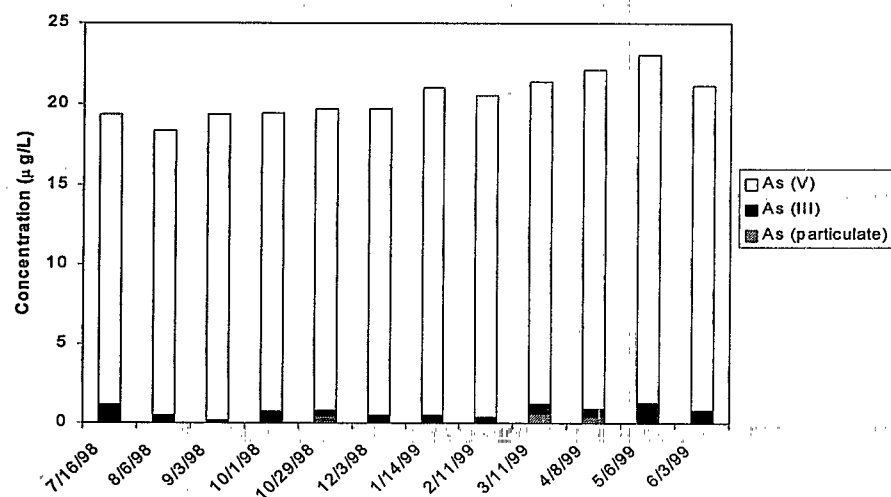
#### 4.3.4.2 Other Water Quality Parameters

Other water quality parameters also were analyzed to provide information regarding the ability of the treatment plant to remove arsenic. Table 4-12 summarizes the analytical results for several water quality parameters obtained during long-term sampling.

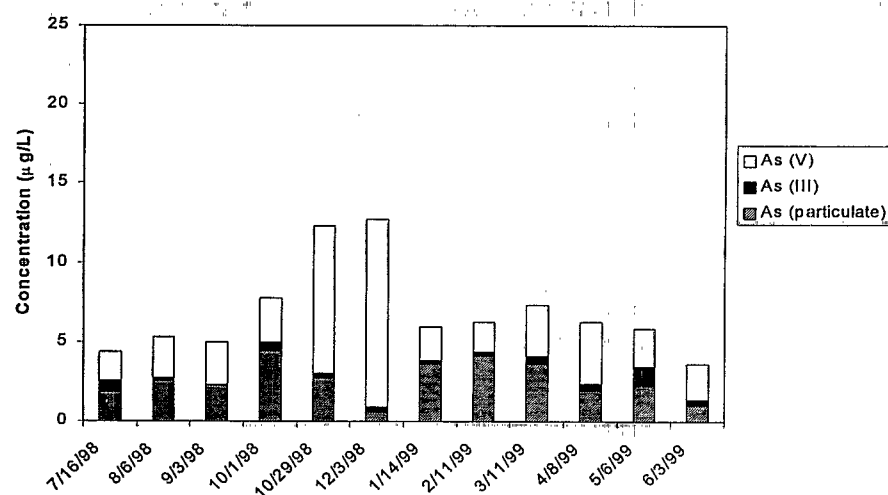
Alkalinity concentrations ranged from 119 to 146 mg/L (as CaCO<sub>3</sub>) in the inlet with an average of 131 mg/L. Figure 4-10 shows that alkalinity in the source water fluctuated slightly seasonally with the lowest concentrations in the late summer and the highest concentrations in the spring. Concentrations decreased between the inlet and prefiltration sampling location and remained relatively constant between the prefiltration and after-filtration locations. These data do not appear to correlate with arsenic analytical results or removal efficiencies.

During long-term sampling, turbidity concentrations averaged 3.4 NTU at the inlet, 0.8 NTU at the prefiltration location, and <0.1 NTU at the after-filtration location. Inlet turbidity concentrations ranged from 11.8 to 1.0 NTU and varied seasonally (see Figure 4-10). The highest turbidities were observed in the late spring, corresponding

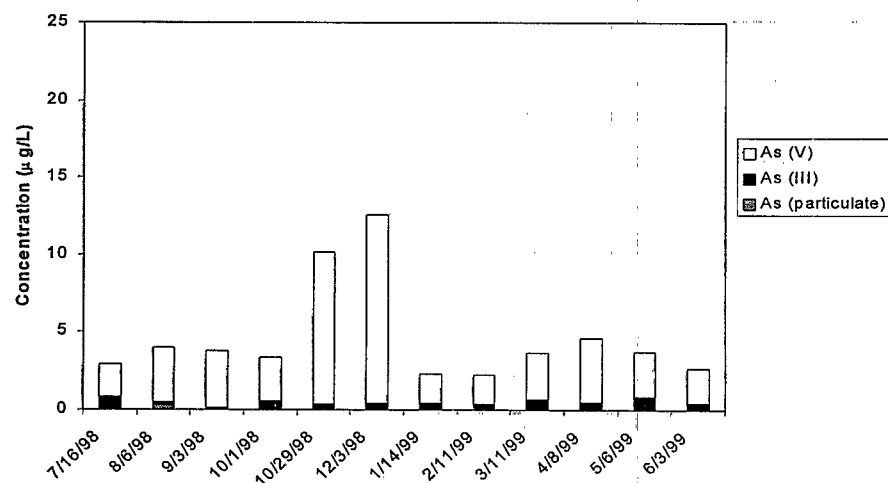
**Inlet**



**Prefiltration**



**After Filtration**



**Figure 4-9. Arsenic Form and Species Analytical Results During Long-Term Sampling at Plant B**

**Table 4-12.** Summary of Water Quality Parameter Analytical Results at Plant B (June 1998–June 1999)

Parameter	Sample Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Alkalinity	Inlet	mg/L	49	119	146	131	7.8
	Prefiltration	mg/L	49	96	132	114	10.2
	After filtration	mg/L	49	96	126	113	9.4
Turbidity	Inlet	NTU	49	1	11.8	3.4	2.3
	Prefiltration	NTU	49	0.3	1.2	0.8	0.2
	After filtration	NTU	49	<0.1	0.3	<0.1	0.04
pH	Inlet	—	49	7.9	8.6	8.4	0.1
	Prefiltration	—	49	7.2	8.1	7.5	0.2
	After filtration	—	49	7.2	8	7.4	0.2
TOC	Inlet	mg/L	49	2.8	9.8	3.7	1.0
	Prefiltration	mg/L	49	2.3	8.6	3.1	0.9
	After filtration	mg/L	49	1.7	8.7	3.1	0.9
Total Al	Inlet	µg/L	49	43.4	501	173	129.7
	Prefiltration	µg/L	49	67.6	809	493	145.3
	After filtration	µg/L	49	28.1	98	56	18.2
Total Fe	Inlet	µg/L	49	32.2	507	164	129.3
	Prefiltration	µg/L	49	<30	75.6	<30	14.1
	After filtration	µg/L	49	<30	57.4	<30	6.4
Total Mn	Inlet	µg/L	49	11.0	39.0	19.6	7.1
	Prefiltration	µg/L	49	0.6	18.2	9.3	3.7
	After filtration	µg/L	49	<0.5	5.8	0.7	0.8
Dissolved Al	Inlet	µg/L	12	<11	<11	<11	NA
	Prefiltration	µg/L	12	41.7	120	73	22.4
	After filtration	µg/L	12	25.7	77	43	17.1
Dissolved Fe	Inlet	µg/L	12	<30	<30	<30	NA
	Prefiltration	µg/L	12	<30	<30	<30	NA
	After filtration	µg/L	12	<30	<30	<30	NA
Dissolved Mn	Inlet	µg/L	12	1.8	7.5	4.0	1.9
	Prefiltration	µg/L	12	1.3	9.7	5.5	2.7
	After filtration	µg/L	12	<0.5	<0.5	<0.5	NA

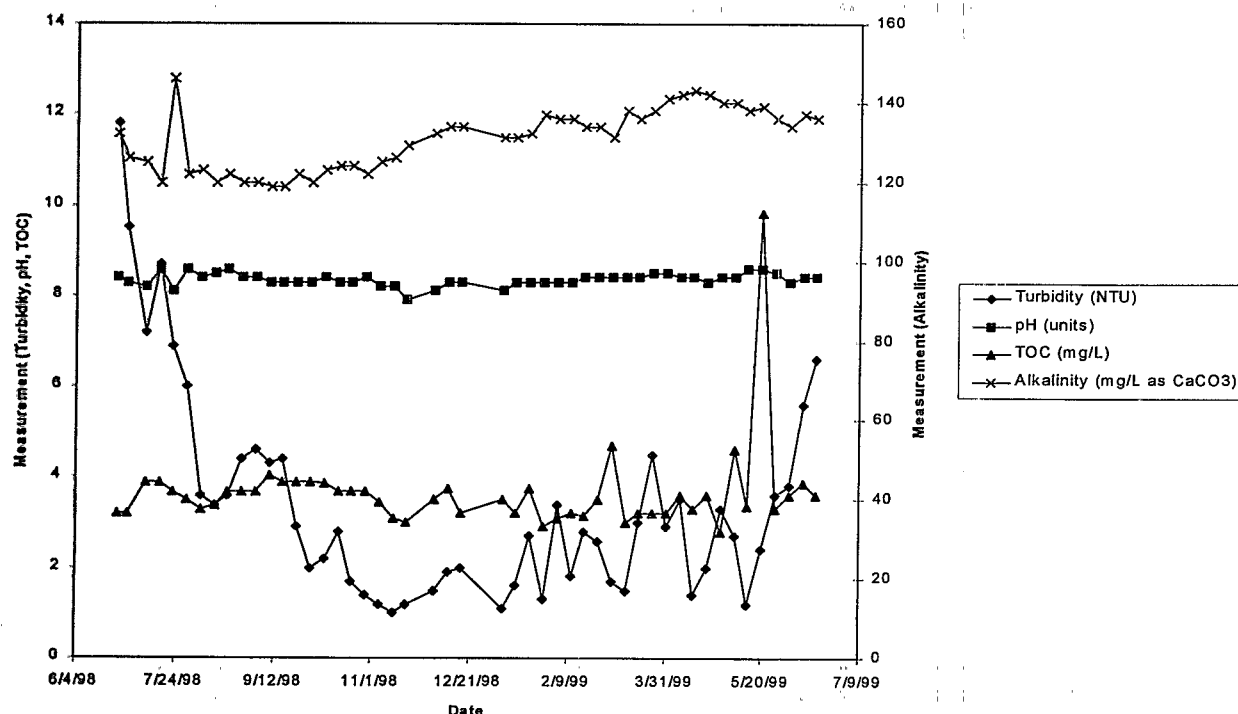
One-half of the detection limit was used for nondetect samples for calculations.  
 Primary and duplicate samples were averaged for calculations.

to snow melt and spring rains, while the lowest values were observed in the winter. Coagulant dosages were determined by the source water turbidity concentration and ranged from 29.0 to 44.7 lb/day (2.6 to 4.1 mg/L) when alum was used and 14.0 to 16.7 lb/day (1.3 to 1.5 mg/L) when PAX-18 was used. The data show that Plant B effectively removed turbidity from the source water; however, no correlation between turbidity removal and arsenic removal was observed. Turbidity removal was still very good (i.e., typically <0.1 NTU) when the plant was using PAX-18, although PAX-18 was used during the winter when turbidities were lowest.

The average pH was 8.4 at the inlet, 7.5 before filtration, and 7.4 after filtration. As seen in Figure 4-10, inlet pH was constant throughout the duration of the study. As stated previously, the pH increase, noted at the before- and after-filtration sampling locations, during usage of the PAX-18 may have adversely affected the arsenic removal efficiency. TOC concentrations were relatively constant (see Figure 4-10), with averages of 3.7 mg/L, 3.1 mg/L, and 3.1 mg/L at the inlet, prefiltration, and after-filtration sampling locations, respectively. A spike in

the TOC concentration was observed on May 20, 1999, although the cause is not known. Eliminating this data point would reduce the average TOC concentrations to 3.5, 3.0, and 3.0 mg/L at the IN, PF, and AF sampling locations, respectively. The decrease in TOC between the inlet and prefiltration sampling location is most likely due to the coagulation process followed by sedimentation. The decrease corresponded to an average 14% TOC removal.

Total aluminum concentrations averaged 173 µg/L at the inlet, 493 µg/L before filtration, and 56 µg/L after filtration. The average dissolved aluminum concentrations were <11 µg/L at the inlet, 73 µg/L at the prefiltration location, and 43 µg/L at the after-filtration location. The increase in total and dissolved aluminum at the prefiltration sampling location was due to the use of alum as the coagulant. Based on plant data, alum dosages ranged from 29 to 44.7 lb/day during the study, corresponding to aluminum concentrations ranging from 2,600 to 4,100 µg/L. The PAX-18 dosages ranged from 14 to 16.7 mg/L, corresponding to aluminum concentrations of 1,300 to 1,500 µg/L. These relatively high aluminum concentrations



**Figure 4-10. Inlet Turbidity, pH, TOC, and Alkalinity Analytical Results at Plant B**

were not observed at the prefiltration location because it was located after the sedimentation basin.

Total manganese concentrations averaged 19.6  $\mu\text{g/L}$ , 9.3  $\mu\text{g/L}$ , and 0.7  $\mu\text{g/L}$ , at the inlet, prefiltration, and after-filtration sampling locations, respectively. Average dissolved manganese concentrations were 4.0  $\mu\text{g/L}$  at the inlet, 5.5  $\mu\text{g/L}$  at the prefiltration location, and <0.5  $\mu\text{g/L}$  at the after-filtration location. These relatively minor manganese concentrations probably did not have a significant impact on arsenic removal efficiency.

Total iron concentrations at the inlet sampling location ranged from 32.2  $\mu\text{g/L}$  to 507  $\mu\text{g/L}$  and averaged 164  $\mu\text{g/L}$ . At the prefiltration sampling location, total iron concentrations ranged from <30 to 75.6  $\mu\text{g/L}$  and averaged <30  $\mu\text{g/L}$ . The average total iron concentration at the after-filtration sampling location was <30  $\mu\text{g/L}$ . Also, average dissolved iron concentrations were below the detection limit at the inlet, prefiltration, and after-filtration sampling locations. These data indicate that iron probably was not a major factor in As(V) removal during treatment operations. However, arsenic may have been attached to the iron particles in the raw water, showing up as particulate arsenic, which were subsequently removed.

#### 4.3.4.3 Supernatant Discharge Water

The filter backwash water at Plant B is sent to a sludge settling pond and the supernatant is discharged to the

adjacent river under a state permit. Supernatant discharge water samples were collected from a manhole located in the piping that transports the water from the sludge settling lagoon to the river. Total arsenic concentrations ranged from 4.6 to 56.1  $\mu\text{g/L}$  and averaged 14.0  $\mu\text{g/L}$ , approximately half of which was soluble and half particulate. Total aluminum concentrations ranged from 359 to 7,500  $\mu\text{g/L}$  and total iron concentrations ranged from <30 to 191.5  $\mu\text{g/L}$ . Results of supernatant discharge sampling are summarized in Table 4-13.

#### 4.3.4.4 Sludge

Sludge is generated at Plant B from sedimentation in primary and secondary clarifiers and from backwashing filters. For most of the year, wastewater and sludge from the clarifiers is sent directly to a sludge lagoon. However, the wastewater and sludge are sent directly to the sanitary sewer for 3 to 4 months in the winter due to freezing conditions in the lagoon.

Backwashing occurs approximately every 50 hours. Backwash water is sent to a sludge settling tank. Sludge is transferred from the settling tank and combined with the wastewater and sludge from the clarifiers prior to discharge into the sludge lagoon. Approximately once per year, the sludge lagoon is dewatered using an underdrain system and the dewatered sludge is sent to a landfill. The volume of sludge sent to the landfill has not been recorded, nor has metals analysis been performed.

**Table 4-13.** Summary of Analytical Results from Supernatant Discharge Water Samples at Plant B (November 12, 1998–June 17, 1999)

Parameter	Units	Number of Sampling Events	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	µg/L	8	4.6	56.1	14.0	17.6
As (soluble)	µg/L	8	2.5	19.2	6.7	5.8
As (particulate)	µg/L	8	0.2	44.9	7.3	15.2
pH		8	7.5	8.0	7.8	0.2
Total Al	µg/L	8	359	7,500	1,610	2,457
Total Fe	µg/L	8	<30	191.5	49.3	60.7
Total Mn	µg/L	8	7.1	160.5	32.5	52.1
Dissolved Al	µg/L	8	46.4	2,216.0	327.7	763.2
Dissolved Fe	µg/L	8	<30	62.7	<30	16.9
Dissolved Mn	µg/L	8	<0.5	22.5	4.0	7.6

Sludge samples were collected on December 15, 1998 from three locations from within a dewatered sludge lagoon. These sludge samples were analyzed for pH, percent moisture, total arsenic, and total iron. Also, a TCLP test was performed on each sample to determine the quantity of leachable arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. Total arsenic concentrations ranged from 293 to 493 mg/kg dry, and total iron concentrations ranged from 14,600 to 15,800 mg/kg dry. Arsenic was detected in leachate from all three samples at concentrations as high as 0.160 mg/L; however these concentrations were well below the regulatory limit of 5 mg/L. Table 4-14 presents the results of sludge analysis at each of the three sampling locations.

#### 4.4 Plant C

Water and residual samples were collected and analyzed at Plant C, a lime softening plant, during three phases of the study: initial source water sampling (February 1998), preliminary sampling (April and May 1998) and long-term evaluation (June 1998 to June 1999). Arsenic speciation sampling was conducted during the initial source water

sampling, once during preliminary sampling, and every fourth week during the long-term evaluation. The third phase also included residual sample collection and analysis. Supernatant discharge water samples were collected monthly beginning in November 1998, and three sludge samples were collected during a single sampling event from a dewatered sludge lagoon.

##### 4.4.1 Plant C Description

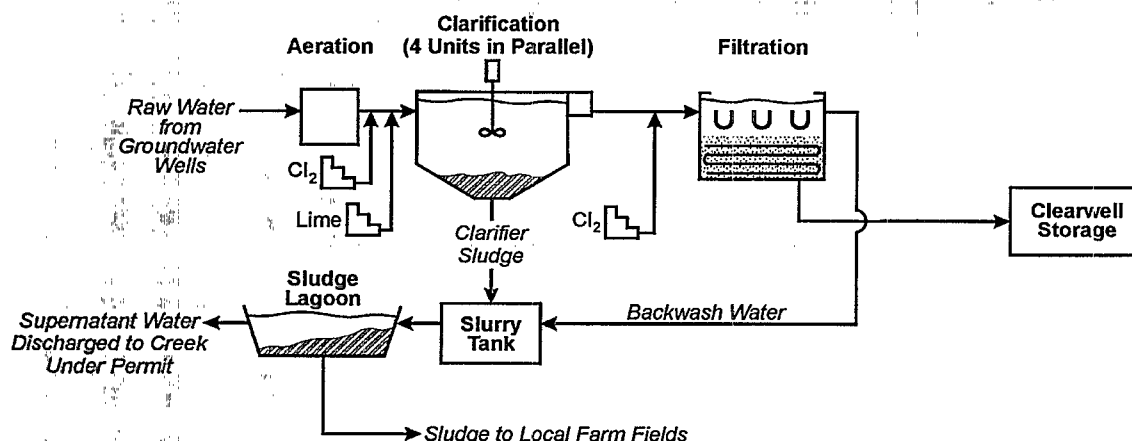
Plant C serves a population of approximately 35,000 (more than 14,000 taps). The plant processes approximately 6.1 mgd and the design flowrate is 10 mgd. The plant treats ground water using a lime softening process followed by sand filtration. Figure 4-11 is a schematic diagram of the treatment process used at Plant C.

The treatment process at Plant C consists of the following major elements:

- **Intake.** Raw ground water from multiple wells (up to 4) is combined in a common header.
- **Aeration.** Aeration is used to oxidize iron.

**Table 4-14.** Analytical Results of Sludge Sampling at Plant B (December 15, 1998)

Parameter	Units	DL	Location 1	Location 2	Location 3
As-TCLP	mg/L	0.05	0.058	0.160	0.114
Ba-TCLP	mg/L	1.0	1.3	1.2	1.2
Cd-TCLP	mg/L	0.020	<0.020	<0.020	<0.020
Cr-TCLP	mg/L	0.030	<0.030	<0.030	<0.030
Pb-TCLP	mg/L	0.20	<0.500	<0.500	<0.500
Hg-TCLP	mg/L	0.0002	<0.0002	<0.0002	<0.0002
Se-TCLP	mg/L	0.05	<0.050	<0.050	<0.050
Ag-TCLP	mg/L	0.020	<0.020	<0.020	<0.020
TCLP extraction	NA	NA	Complete	Complete	Complete
pH	—	—	7.0	6.9	6.9
Percent moisture	%	0.1	74.9	82.3	78.2
As (total)	mg/kg, dry	61	353	493	293
Fe (total)	mg/kg, dry	379	14,600	14,800	15,800



**Figure 4-11. Schematic Diagram, Plant C**

- Clarification.** Immediately after aeration, lime is added to the water in the middle section of each of four precipitators (solids-contact softeners) at a rate of 245 mg/L (dry lime stored on site in silos). In each of the precipitators, lime and water are mixed using a paddle-wheel mixer. The retention time in the precipitators is approximately 60 minutes. Sludge is collected from the bottom of the precipitators, sent to a slurry tank, and then placed in a sludge lagoon. Sludge from the lagoon is used on local farm fields.
- Chlorination.** Chlorine is added into each clarifier collection trough at a rate of approximately 100 to 200 lbs/day (correlating to approximately 15 mg/L).
- Filtration.** Filtering media consists of 10 inches of graded gravel and 2 feet of sand. There are 15 separate filtering units that are backwashed approximately every 80 hours. Backwashing includes a surface scour.
- Clearwell Storage.** Treated water is chlorinated prior to clearwell storage. The final chlorine concentration in finished water is approximately 6 mg/L (<0.5 mg/L free chlorine).
- Backwash.** Backwashing occurs every 80 hours and the backwash water is combined with sludge from the clarifiers, sent to a slurry tank, and then on to a sludge lagoon. Sludge from the lagoon is used on local farm fields. Approximately 230,000 gal/day of water goes to lagoons.

#### 4.4.2 Initial Source Water Sampling

The influent water is supplied from four deep (approximately 300 ft) ground water wells. Typically, only three

wells are used due to problems with the fourth well regarding, among other things, high arsenic concentrations. Based on plant records, the ground water hardness is approximately 350 to 400 mg/L (as  $\text{CaCO}_3$ ) and iron concentrations are approximately 2 to 2.5 mg/L. Also, the raw water contains 70 to 100 mg/L of  $\text{CO}_2$ . Based on samples collected and analyzed by the plant, arsenic concentrations observed in the source water wells range from <0.01 to 89  $\mu\text{g/L}$ . Arsenic concentrations in samples collected near Plant C on November 25, 1992, from each of the ground water wells are presented in Table 4-15.

**Table 4-15. Arsenic Concentrations in Ground Water Wells at Plant C (1992)**

Well Number	Arsenic Concentration ( $\mu\text{g/L}$ )
6	89
7	75
8	38
9	<0.01

On February 27, 1998, an initial site visit to Plant C was conducted and water samples were collected. The ground water supplying Plant C is hard (averaging 336.5 mg/L as  $\text{CaCO}_3$ ), with an average calcium hardness of 214.5 mg/L as  $\text{CaCO}_3$  and an average magnesium hardness of 121.5 mg/L as  $\text{CaCO}_3$ . Plant C also had relatively high turbidity, averaging 20.5 NTU during the source water sampling event. Consistent with plant records, the iron concentration was relatively high, averaging 2,370  $\mu\text{g/L}$ . As would be expected for a ground water source, the majority of the soluble arsenic existed as arsenite (83% of the soluble arsenic). As(V) was detected during the source water sampling at an average concentration of 2.0  $\mu\text{g/L}$ . Particulate arsenic was not detected in the

source water samples. Table 4-16 presents the analytical results from the source water sampling.

The average arsenic concentration detected during the source water sampling event was 9.4 µg/L. This concentration is lower than the minimum required for inclusion into the preliminary and long-term phases of the study. However, the historical data indicated that the source water concentrations were much higher (see Table 4-15). Therefore, the plant was included in the preliminary and long-term sampling phases of this study. It was determined during the preliminary sampling phase of the study that the sampling tap used during the initial source water sampling was not located properly (this issue is discussed in detail in Section 4.4.3).

#### 4.4.3 Preliminary Sampling

Water samples were collected at three locations (i.e., IN, PF, and AF) during the preliminary sampling phase of this study. Sampling taps were available at the IN and AF sampling locations; however, a scoop was used to collect samples at the PF location. The inlet sampling location represents a combined sample from the four ground water wells and was located in the manifold piping where the water from the wells is combined. The PF samples were taken from the channel surrounding precipitator (i.e., solids-contact softener) No. 3 that transports the softened water to the filtration vessels. Therefore, PF sampling location represents water that has been aerated and processed through the solids-contact softener. The AF sampling tap was located after the filtration units and represents water that enters the distribution system.

Figure 4-12 is a process flow diagram for Plant C that shows each of the sampling locations.

Consistent with Plants A and B, preliminary sampling at Plant C consisted of weekly sample collection and analysis of various parameters (alkalinity, turbidity, pH, hardness, total iron, total manganese, and total arsenic analysis). Arsenic speciation sampling, which included determination of soluble and particulate arsenic, was conducted once during the preliminary study on samples collected from each sampling location. Table 4-17 presents the results of the 4-week preliminary sampling period.

Results from the preliminary sampling events indicated that inlet total arsenic concentrations varied widely, ranging from approximately 2.4 to 83.4 µg/L. The influent samples collected on April 27 and May 11, 1998, contained relatively low concentrations of arsenic (i.e., 3.5 and 2.4 mg/L, respectively), when compared to concentrations in prefiltration and postfiltration samples. Reanalysis of samples confirmed the concentrations of the influent samples. Similarly, the inlet concentrations observed during the source water sampling event were relatively low. Subsequent discussion with plant personnel determined that the cause of the problem was the sample tap location. The sampling location was situated in the manifold piping downstream of wells 6 and 9 and upstream of wells 7 and 8. Review of the well operation log indicated that well 6 (producing the highest As concentration among the four wells) was not in operation during sampling on April 27 and May 11, 1999; however, well 6 was running on May 4 and May 18. As a result of this finding, a new sampling location downstream of all

**Table 4-16. Source Water Sampling Analytical Results at Plant C (February 27, 1998)**

Parameter	Units	Primary Sample	Duplicate Sample	Average Concentration
Alkalinity	mg/L <sup>(a)</sup>	400	397	398.5
Sulfate	mg/L	7	7	7
Turbidity	NTU	20	21	20.5
pH	—	7.2	7.2	7.2
Hardness	mg/L <sup>(a)</sup>	341	332	336.5
Ca Hardness	mg/L <sup>(a)</sup>	217	212	214.5
Mg Hardness	mg/L <sup>(a)</sup>	124	119	121.5
Total Al	µg/L	<400	<400	<400
Total Fe	µg/L	2,410	2,330	2,370
Total Mn	µg/L	200	210	205
NO <sub>3</sub> -NO <sub>2</sub> (N)	mg/L <sup>(b)</sup>	<0.02	<0.02	<0.02
TOC	mg/L	3	3	3
As (total)	µg/L	9.4	9.4	9.4
As (total soluble)	µg/L	12.0	12.0	12.0
As (particulate)	µg/L	ND	ND	ND
As(III)	µg/L	10.2	9.7	9.9
As(V)	µg/L	1.8	2.3	2.0

(a) As CaCO<sub>3</sub>.

(b) Combined NO<sub>3</sub>-N and NO<sub>2</sub>-N.

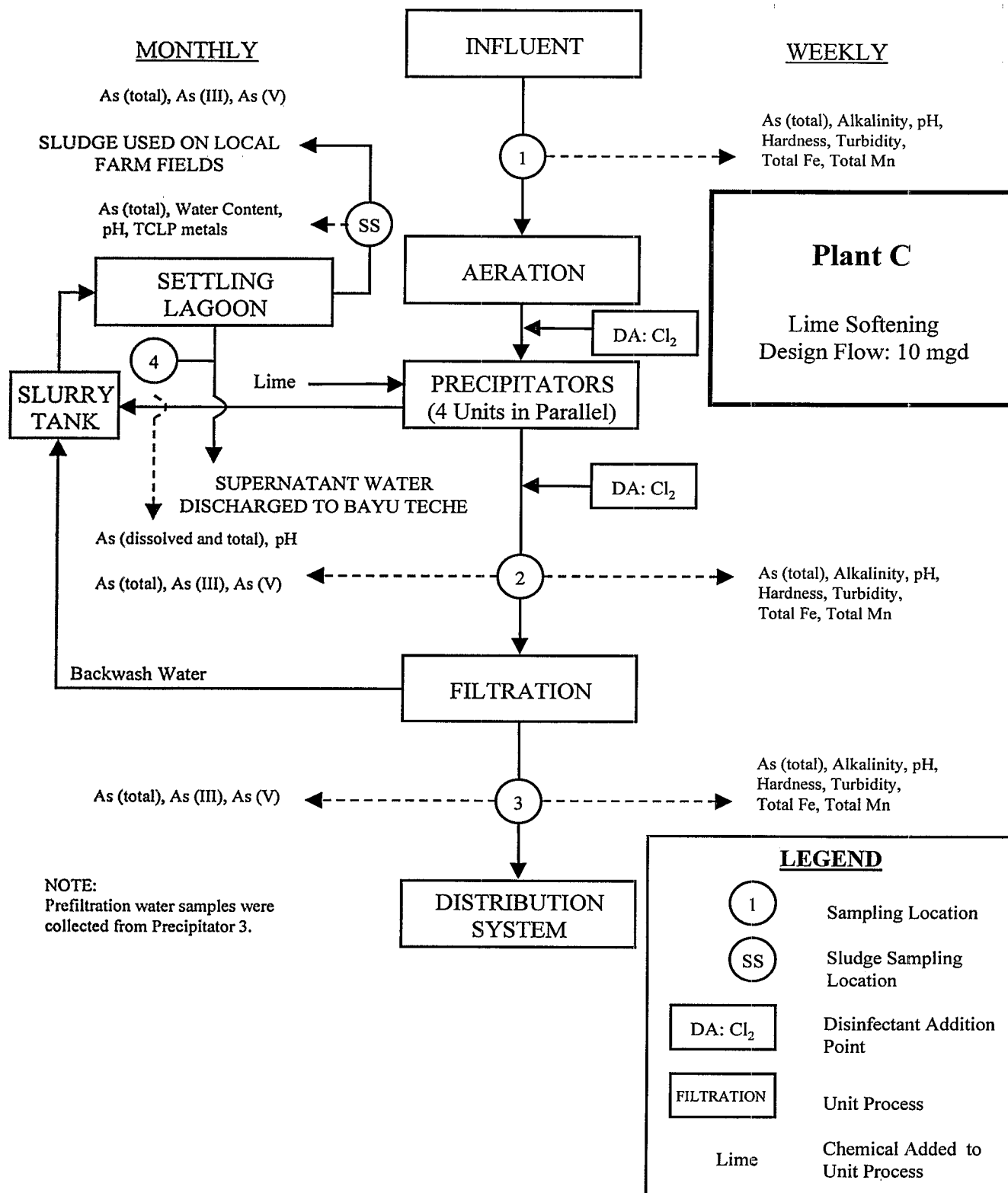


Figure 4-12. Process Flow Diagram and Sampling Locations at Plant C



**Table 4-17. Analytical Results from Preliminary Sampling at Plant C (April 27, 1998 through May 18, 1998)**

Parameter	Units	4/27/98 <sup>(a)</sup>						Sampling Date and Location					
		5/4/98			5/11/98			5/18/98					
		IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(b)</sup>	395 384	180 180	191 189	378	190	208	403	239	201	366	217	202
Turbidity	NTU	21 22	4.5 4.5	0.1 0.1	9.5	1.1	1.4	18.7	8.1	0.2	34	4.2	0.1
pH	—	7.2 7.2	9.1 9.2	8.5 8.4	7.3	9.1	8.5	7.3	8.6	8.6	7.2	8.8	8.8
Hardness	mg/L <sup>(b)</sup>	317 317	154 123	152 156	313	181	166	332	190	160	255	145	133
Ca Hardness	mg/L <sup>(b)</sup>	195 195	46.9 33.2	42.4 46.4	195	61.9	48.9	210	75.9	48.4	165	51.4	42.7
Mg Hardness	mg/L <sup>(b)</sup>	122 122	107 89.4	109 110	118	119	117	122	114	112	90.6	93.5	90.6
Total Fe	µg/L	2,100 2,090	590 590	90 100	3,440	640	<30	2,030	500	<30	3,840	440	40
Total Mn	µg/L	230 210	40 50	40 40	160	50	<20	160	<20	<20	130	<20	<20
As (total)	µg/L	3.5 3.7	31.4 36.6	24.4 28.8	43.6	35.5	18.8	2.4	43.3	22.6	83.4	51.0	41.6
As (total soluble)	µg/L	5.1 4.7	34.6 38.3	28.9 33.1	NA	NA	NA	NA	NA	NA	NA	NA	NA
As (particulate)	µg/L	ND ND	ND ND	ND ND	NA	NA	NA	NA	NA	NA	NA	NA	NA
As (III)	µg/L	3.9 4.1	2.3 <0.1	1.5 1.8	NA	NA	NA	NA	NA	NA	NA	NA	NA
As (V)	µg/L	ND 0.6	32.3 38.6	27.4 31.3	NA	NA	NA	NA	NA	NA	NA	NA	NA

(a) Duplicate samples were taken on 4/27/98.

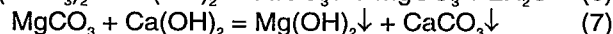
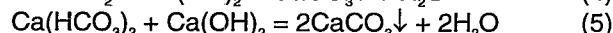
(b) As CaCO<sub>3</sub>.

wells (i.e., wells 6, 7, 8, and 9) was used for the long-term sampling phase of the study. This new sample tap was located just prior to aeration, the first treatment process implemented at Plant C.

The inappropriate sampling location used during the preliminary sampling events complicates evaluation of arsenic removal efficiency. However, some observations regarding the arsenic can be made. For example, the soluble arsenic in the raw water entering the treatment plant was approximately 94% As(III). This level would be expected for a ground water source. It appeared that the majority of the As(III) was oxidized to As(V) prior to filtration using two chlorine treatment steps. The average As(V) concentration observed at the sampling location situated after softening and chlorine addition made up approximately 97% of the soluble arsenic. The soluble arsenic in the finished water consisted of approximately 95% As(V). Particulate arsenic was not detected in any of the samples collected during the preliminary sampling.

Total arsenic concentrations in the finished water ranged between 18.8 µg/L and 41.6 µg/L and averaged 27.4 µg/L. Although arsenic removal efficiency could not be determined because of the raw water sampling location, the data indicate that Plant C was not able to reduce arsenic concentrations to low levels. Prior research indicates that As(V) removal approaches 100% and As(III) removal approaches 75% at pH 11 (Sorg and Logsdon, 1978); however, arsenic removal efficiency decreases rapidly below pH 11. McNeill and Edwards (1997b) showed that the primary arsenic removal mechanism during lime softening is adsorption and coprecipitation of As(III) and As(V) with magnesium hydroxide, which is precipitated near pH 11. Therefore, it appeared that pH limited arsenic removal at Plant C, where the average pH after lime softening was 8.9. This conclusion was further supported by the limited removal of magnesium hardness. The average magnesium hardness concentrations decreased from 113 mg/L in the raw water to only 107 mg/L in finished water.

Total hardness concentrations averaged 304 mg/L, 164 mg/L, and 153 mg/L (as CaCO<sub>3</sub>) in the IN, PF, and AF sampling locations, respectively. The plant did soften the raw water significantly; however, Plant C removed primarily calcium hardness, which was reduced an average of 76% during preliminary sampling. As stated in the previous paragraph, magnesium hardness was not effectively removed by Plant C, averaging only 5% removal. Alkalinity decreased after softening and then remained constant between the softening and after filtration. This decrease was expected due to the chemical reactions that occur during the lime softening process (for carbonate hardness only):



Similarly, pH increased between the inlet and prefiltration sampling locations due to the addition of lime; however, this pH is significantly less than the optimal pH for arsenic removal (i.e., pH 11).

Total manganese concentrations ranged from 130 to 230 µg/L in the inlet, <20 to 50 µg/L before filtration, and <20 to 40 µg/L after filtration. The total iron concentrations averaged 2,851 µg/L at the inlet, 543 µg/L at the prefiltration sampling location, and 41 µg/L at the after-filtration sampling location. The iron in the raw water is most likely in the reduced state since the soluble arsenic was primarily As(III) in the raw water. As observed in Plant A, arsenic removal by iron oxides can be significant. Therefore, the concentration of iron in the raw water was important and research indicates that this iron can positively impact arsenic removal efficiency (McNeill and Edwards, 1997b).

Similar to Plants A and B, the preliminary sampling effort at Plant C resulted in only minor changes to the long-term sampling approach. Dissolved aluminum, iron, and manganese concentrations would be determined every fourth week using leftover samples from the arsenic speciation kits. In addition, aluminum was added to the list of analytes and the inlet sampling location was changed to be downstream of all ground water well inflows.

#### 4.4.4 Long-Term Sampling

Weekly long-term sampling and analysis was performed for 49 weeks to determine concentrations of alkalinity, turbidity, pH, hardness, total aluminum, total iron, total manganese, and total arsenic. Long-term sampling also included 12 arsenic speciation sampling events that were used to determine arsenic form and species as well as dissolved metals (iron, manganese, and aluminum) at each sampling location. The same three sampling locations that were used during the preliminary sampling phase also were used during long-term sampling. Additionally, residual sampling was performed during this phase and consisted of collection and analysis of supernatant discharge water and sludge. Figure 4-12 shows the sampling locations during the long-term evaluation phase.

##### 4.4.4.1 Arsenic

Table 4-18 provides a summary of the arsenic analytical results collected at the three treatment process locations. Total arsenic concentrations at the inlet ranged from 15.9

**Table 4-18.** Summary of Arsenic Analytical Results at Plant C (June 1998–June 1999)

Parameter	Sample Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	Inlet	µg/L	49	15.9	84.9	32.0	10.5
	Prefiltration	µg/L	49	7.7	32.6	23.2	5.6
	After filtration	µg/L	49	6.3	33.1	16.6	4.2
As (total soluble)	Inlet	µg/L	12	21.9	40.8	33.8	6.0
	Prefiltration	µg/L	12	17.3	31.0	24.2	4.6
	After filtration	µg/L	12	13.9	22.5	17.1	2.4
As (particulate)	Inlet	µg/L	12	<0.1	7.3	1.2	2.2
	Prefiltration	µg/L	12	<0.1	4.0	1.0	1.5
	After filtration	µg/L	12	<0.1	1.1	0.3	0.4
As(III)	Inlet	µg/L	12	22	37.2	30.0	4.9
	Prefiltration	µg/L	12	<0.1	17.8	1.9	5.0
	After filtration	µg/L	12	<0.1	1.5	0.4	0.4
As(V)	Inlet	µg/L	12	<0.1	10.2	3.9	2.9
	Prefiltration	µg/L	12	12.6	29.9	22.3	4.9
	After filtration	µg/L	12	13.7	22.1	16.7	2.4

One-half of the detection limit was used for nondetect samples for calculations.  
 Primary and duplicate samples were averaged for calculations.

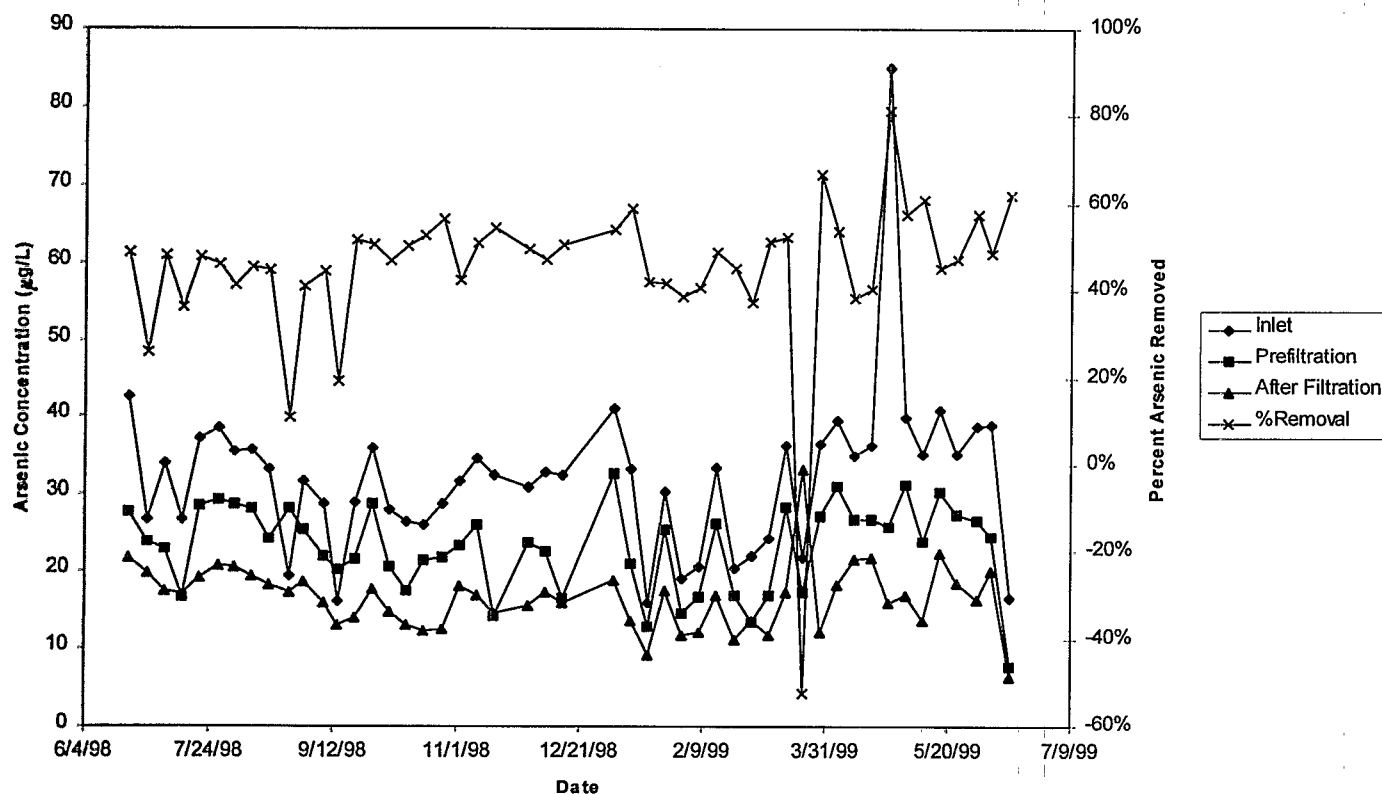
to 84.9 µg/L with an average concentration of 32.0 µg/L. Total arsenic concentrations at the prefiltration location (i.e., after softening and before filtration) ranged from 7.7 to 32.6 µg/L with an average of 23.2 µg/L. Samples collected after filtration contained total arsenic concentrations ranging from 6.3 to 33.1 µg/L with an average concentration of 16.6 µg/L. The total arsenic analytical results were relatively constant, with the exception of a peak in the raw water arsenic concentration that occurred on April 26, 1999. The cause of this peak is not known; however, it is likely due to the ground water wells operating during this sampling event (i.e., wells 6 and 7, which have much higher arsenic concentration, may have been contributing more to the influent flow). The average removal percentage of total arsenic between the inlet and prefiltration sampling locations was 28%. The average removal percentage of total arsenic between the inlet and after-filtration sampling locations was 48%. Total arsenic removal efficiency also was relatively constant during the long-term evaluation with the exception of March 22, 1999, when arsenic removal was a minus 53%. The explanation for this data point is not known but may be a result of well operation schedule, resulting in lower than normal inlet arsenic concentrations. Figure 4-13 is a graph showing the total arsenic concentration recorded at each sampling location throughout the study, as well as removal percentages calculated for each sampling event.

Particulate arsenic concentrations averaged 1.2 µg/L at the inlet, 1.0 µg/L at the prefiltration sampling location, and 0.3 µg/L at the after-filtration sampling location. This indicates that approximately 75% of the particulate arsenic is removed by the system, primarily during filtration. As(III) concentrations averaged 30.0 µg/L at the inlet, 1.9 µg/L at the prefiltration location, and 0.4 µg/L at the after-filtration location. Substantial conversion of As(III)

to As(V) occurred between the inlet and finished water due to the two chlorination steps. As(V) concentrations were 3.9 µg/L at the inlet, 22.3 µg/L at the prefiltration location, and 16.7 µg/L at the after-filtration location. The data were relatively consistent regarding As(III) and As(V) concentrations at each sampling location. One deviation occurred on August 3, 1998, where the As(III) concentration after the precipitators and before the filters was 17.8 µg/L and the As(V) concentration was 12.6 µg/L. The cause of this deviation is not known.

These data showed that the inlet water at Plant C contained primarily the reduced species of arsenic (i.e., As(III)) with only minor concentrations of As(V) and particulate arsenic. The As(III) was converted to As(V) during the aeration and chlorination step prior to clarification (softening) and the chlorination step prior to filtration. The arsenic in the finished water consists almost entirely of As(V). Figure 4-14 shows the fractions of the total arsenic concentration made up of particulate arsenic, As(III), and As(V).

Based on studies by Sorg and Logsdon (1978), arsenic removals should be low at Plant C due to the relatively low pH (average pH is 8.8 after lime softening) achieved during the softening process. Documented arsenic removal efficiencies when only calcium carbonate is precipitated are between 0 and 10% (McNeill and Edwards, 1995). However, the average arsenic removal at Plant C was 48%. This removal most likely is associated with the iron in the source water. Total iron concentrations in the source water averaged 2,303 µg/L, practically all of which was in reduced state. It is believed that adsorption and coprecipitation with the iron is the primary factor in arsenic removal at this plant. Based on the simple sorption model by McNeill and Edwards (1997a), estimated



**Figure 4-13.** Total Arsenic Analytical Results During Long-Term Sampling at Plant C

arsenic removals should average approximately 75% (approximately 30% higher than observed). However, in another study by McNeill and Edwards (1997b), it was reported that carbonate can interfere with arsenic removal by iron hydroxide due to competition for sorption sites. Additionally, the available research provides little information on arsenic removal by coprecipitation with iron hydroxide at pH values greater than 8.5. Therefore, arsenic removal through adsorption and coprecipitation with iron hydroxide appeared to be limited by the lime softening process.

The Plant C water treatment system was not able to consistently remove arsenic to low levels (i.e., average total arsenic concentration in treated water was 16.6 µg/L). The literature indicates that removal efficiency would increase if the pH was increased. The primary arsenic removal mechanism is coprecipitation with the iron in the source water followed by sedimentation and filtration.

#### 4.4.4.2 Other Water Quality Parameters

As with Plants A and B, sampling and analysis of other water quality parameters were performed to provide insight into the arsenic removal efficiency at the plant.

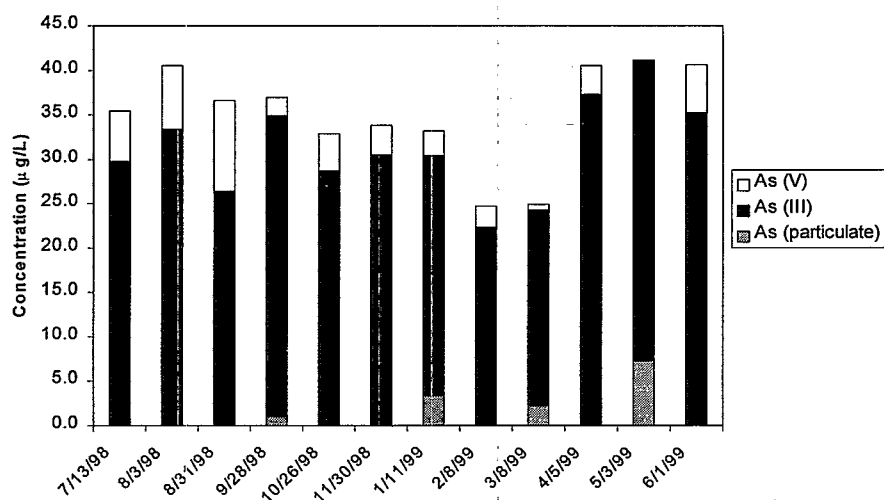
Table 4-19 summarizes the analytical results for several water quality parameters obtained during long-term sampling.

Inlet alkalinity concentrations were relatively constant, ranging from 300 to 411 mg/L (as CaCO<sub>3</sub>) with an average of 399 mg/L (see Figure 4-15). The alkalinity concentration decreased between the inlet and prefiltration sampling location and remained relatively constant between the prefiltration and after-filtration locations. This reduction in alkalinity was associated with hardness removal during the softening process.

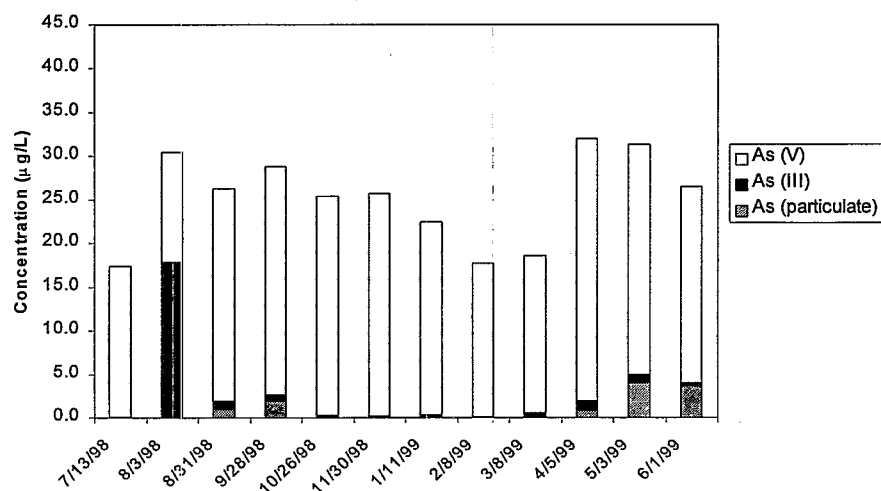
During long-term sampling, turbidity concentrations averaged 26.3 NTU at the inlet, 9.8 NTU at the prefiltration location, and 1.3 NTU at the after-filtration location. The inlet turbidity concentrations were relatively high, ranging from 16.1 to 33 NTU, and are plotted on Figure 4-15. The data show that Plant B achieves an average turbidity removal efficiency of approximately 95%.

The average pH was 7.2 at the inlet, 8.8 at the prefiltration sampling location, and 8.6 at the after-filtration location. Inlet pH was relatively constant (see Figure 4-15). The pH increased at the prefiltration location due to the

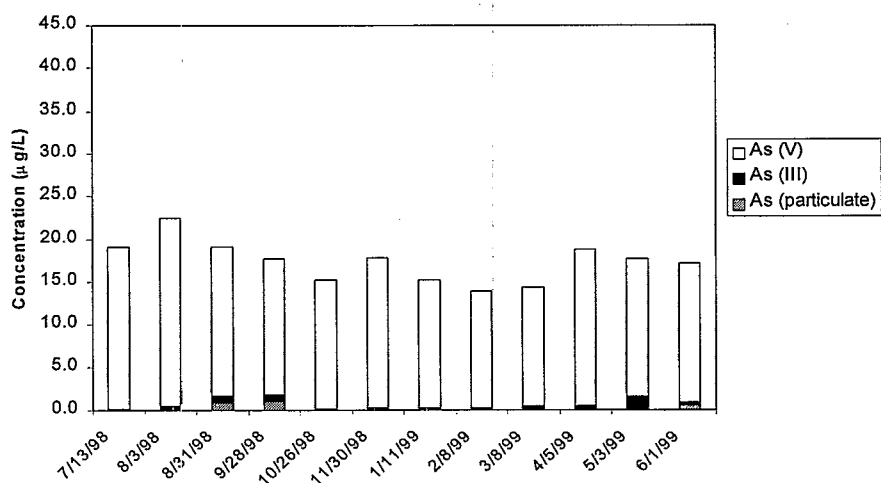
**Inlet**



**Prefiltration**



**After Filtration**



**Figure 4-14. Arsenic Form and Species Analytical Results During Long-Term Sampling at Plant C**

**Table 4-19. Summary of Water Quality Parameter Analytical Results at Plant C (June 1998–June 1999)**

Parameter	Sample Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Alkalinity	Inlet	mg/L	49	300	411	399	15.4
	Prefiltration	mg/L	49	125	382	214	40.9
	After filtration	mg/L	49	146	321	198	30.4
Turbidity	Inlet	NTU	49	16.1	33	26.3	4.2
	Prefiltration	NTU	49	0.7	25.5	9.8	5.9
	After filtration	NTU	49	<0.1	25	1.3	3.61
pH	Inlet	—	49	7.1	7.4	7.2	0.1
	Prefiltration	—	49	7.9	10.1	8.8	0.5
	After filtration	—	49	7.8	9.3	8.6	0.3
Total Hardness	Inlet	mg/L	49	267	353	318	17.6
	Prefiltration	mg/L	49	85	304	179	37.3
	After filtration	mg/L	49	110	290	163	29.1
Total Al	Inlet	µg/L	49	<11	63	12	13.3
	Prefiltration	µg/L	49	13.4	87	43	16.1
	After filtration	µg/L	49	<11	99	20	15.9
Total Fe	Inlet	µg/L	49	92	3768	2389	556.7
	Prefiltration	µg/L	49	81	766	397	181.8
	After filtration	µg/L	49	<30	1110	76	165.2
Total Mn	Inlet	µg/L	49	75.9	204	140	27.5
	Prefiltration	µg/L	49	3.6	48.9	12.6	8.2
	After filtration	µg/L	49	1.0	54.7	4.8	8.0
Dissolved Al	Inlet	µg/L	12	<11	<11	<11	NA
	Prefiltration	µg/L	12	<11	36	18	10.6
	After filtration	µg/L	12	<11	12	<11	2.0
Dissolved Fe	Inlet	µg/L	12	1512	2966	2303	363
	Prefiltration	µg/L	12	<30	<30	<30	NA
	After filtration	µg/L	12	<30	<30	<30	NA
Dissolved Mn	Inlet	µg/L	12	106	189	146	28.7
	Prefiltration	µg/L	12	<0.5	7.8	2.6	2.1
	After filtration	µg/L	12	0.7	4.6	1.9	1.2

One-half of the detection limit was used for nondetect samples for calculations.  
Primary and duplicate samples were averaged for calculations.

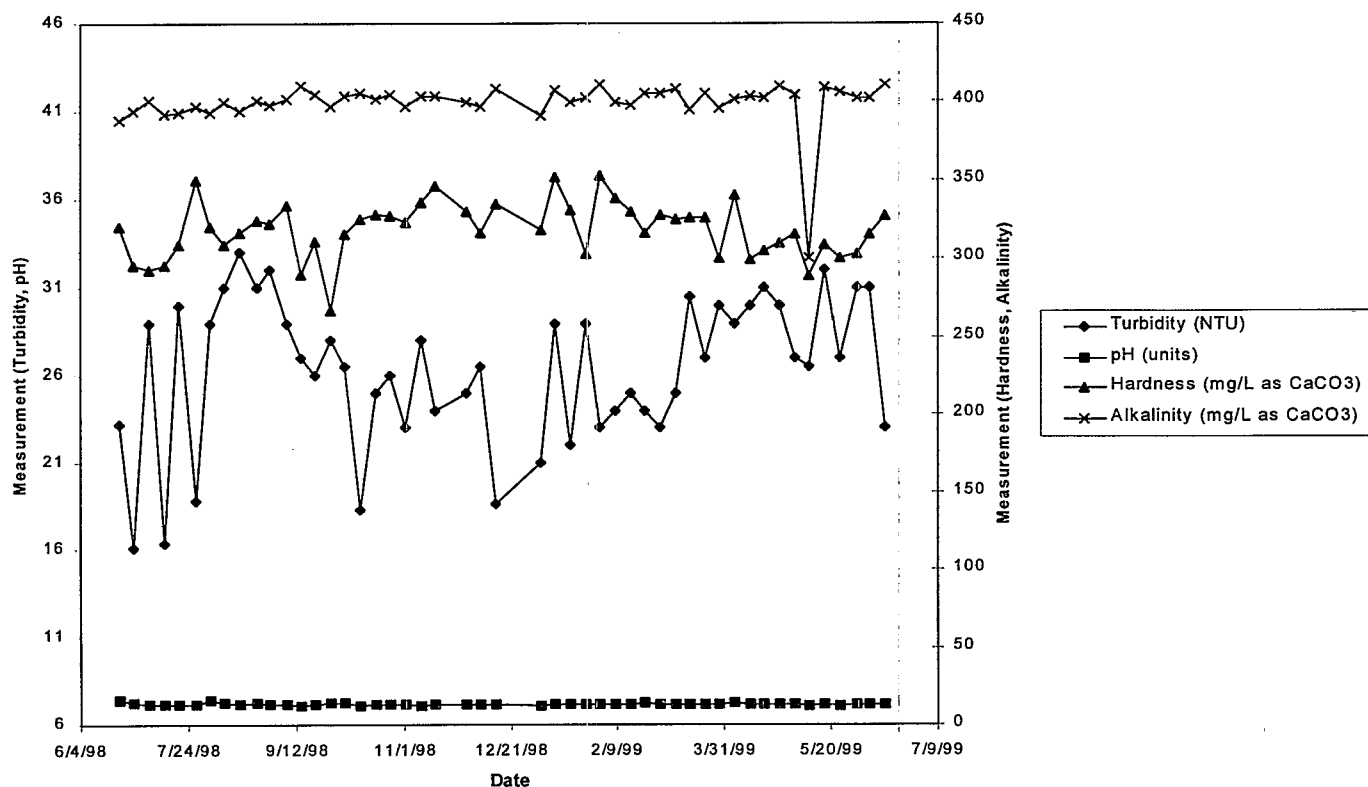
lime softening process. A similar trend was observed with total hardness concentrations; however, the hardness concentrations were relatively high at the inlet (average 318 mg/L as CaCO<sub>3</sub>) and decreased after the lime softening process to an average concentration of 179 mg/L at the prefiltration location and 163 at the after-filtration location. It is important to note that the hardness reduction consisted primarily of calcium hardness reduction; magnesium hardness was relatively constant throughout the treatment process. This result is not surprising considering that optimal magnesium hydroxide formation is achieved at pH 11. Precipitation of magnesium hydroxide is associated strongly with arsenic removal, because the arsenate adsorbs and coprecipitates with the Mg(OH)<sub>2</sub> (McNeill and Edwards, 1997b).

Total aluminum concentrations averaged 12 µg/L at the inlet, 43 µg/L at the prefiltration location, and 20 µg/L at the after-filtration location. The slight increase in aluminum at the prefiltration sampling location is probably due to trace amounts of aluminum in the lime. Manufacturers data indicated the lime contains 0.45% Al<sub>2</sub>O<sub>3</sub>. The aver-

age dissolved aluminum concentrations were <11 µg/L at the inlet, 18 µg/L at the prefiltration location, and <11 µg/L at the after-filtration location. Because of the low concentrations, aluminum is not considered a significant factor in arsenic removal.

Total manganese concentrations averaged 140 µg/L, 12.6 µg/L, and 4.8 µg/L, at the inlet, prefiltration, and after-filtration sampling locations, respectively. Average dissolved manganese concentrations were 146 µg/L at the inlet, 2.6 µg/L at the prefiltration location, and 1.9 µg/L at the after-filtration location. However, due to the relatively low concentrations of manganese compared to iron, it is not believed that the manganese is a significant factor in arsenic removal at Plant C.

Total iron concentrations at the inlet sampling location ranged from 92 to 3,768 µg/L and averaged 2,389 µg/L. At the prefiltration sampling location, total iron concentrations ranged from 81 to 766 µg/L and averaged 397 µg/L. The average total iron concentration at the after-filtration sampling location was 76 µg/L. Also, average dissolved



**Figure 4-15.** Inlet Turbidity, pH, Hardness, and Alkalinity Analytical Results at Plant C

iron concentrations were 2,303  $\mu\text{g/L}$  at the inlet and  $<30 \mu\text{g/L}$  at both the prefiltration and after-filtration locations. The data indicated that the iron in the source water was in the reduced state and was completely oxidized during the aeration and chlorination steps. The average concentration of total iron at the inlet was reduced 97% by the treatment process. It is believed that the primary arsenic removal mechanism was adsorption and coprecipitation of  $\text{As(V)}$  with the iron.

#### 4.4.4.3 Supernatant Discharge Water

The filter backwash water at Plant C is sent to a slurry tank and then to a sludge settling lagoon. The supernatant of the sludge lagoon is discharged to an adjacent creek under a state permit. The plant is required to monitor the supernatant discharge for pH weekly and total dissolved solids (TDS) monthly as part of its discharge permit. Supernatant discharge water samples were collected at the outfall of the sludge lagoon where it discharges to the creek.

Results of supernatant discharge water sampling are summarized in Table 4-20. Total arsenic concentrations averaged 20.8  $\mu\text{g/L}$ , consisting of an average of 21.2  $\mu\text{g/L}$  of soluble arsenic and 0.7  $\mu\text{g/L}$  of particulate arsenic.

The pH was elevated due to the lime softening process. As would be expected based on the concentrations in the source water, total iron concentrations in the supernatant water were relatively high and total aluminum and manganese concentrations were relatively low.

#### 4.4.4.4 Sludge

Sludge is generated from the lime softening precipitators and from backwashing the sand filters. Sludge is collected from the bottom of the four precipitators and sent to a slurry tank. Filter backwashing occurs approximately every 80 hours and the backwash water is combined with sludge from the precipitators in a slurry tank and then sent to a sludge lagoon. Approximately 230,000 gal/day of water goes to the lagoon. Approximately once every 2 years, or as required, the lagoon is dewatered using an underdrain system and the sludge is removed (approximately 14,500  $\text{yd}^3$  of sludge was removed in the spring of 1998). Sludge from the lagoon is used on local farm fields.

Sludge samples were collected on November 16, 1998 from three locations from within a dewatered sludge lagoon at Plant C. These sludge samples were analyzed for pH, percent moisture, total arsenic, total aluminum,

**Table 4-20.** Summary of Analytical Results from Supernatant Discharge Water Samples at Plant C (November 9, 1998–June 14, 1999)

Parameter	Units	Number of Sample Events	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	µg/L	8	14.7	27.2	20.8	4.3
As (soluble)	µg/L	8	14.9	27.2	21.2	4.0
As (particulate)	µg/L	8	<0.1	4.3	0.7	1.5
pH	—	8	9.0	9.7	9.3	0.3
Total Al	µg/L	8	35	98	60	24
Total Fe	µg/L	8	223	1,545	716	505
Total Mn	µg/L	8	7.2	35.2	19.3	10.1
Dissolved Al	µg/L	8	<11	24.3	<11	7.2
Dissolved Fe	µg/L	8	<30	44.3	<30	10.9
Dissolved Mn	µg/L	8	1.3	25.5	7.4	7.9

total iron, total manganese, and TCLP metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver). Total arsenic concentrations ranged from 17.0 to 35.3 mg/kg dry, and total iron concentrations ranged from 3,190 to 7,920 mg/kg dry. Arsenic was not detected in leachate from any of the three samples; how-

ever, minor concentrations of barium, cadmium, chromium, lead, and silver were detected. Consistent with Plants A and B, none of the sludge analytical results from Plant C indicate exceedances of regulatory levels. Table 4-21 presents the results of sludge analysis at each of the three sampling locations.

**Table 4-21.** Analytical Results of Sludge Sampling at Plant C (November 16, 1998)

Parameter	Unit	DL	Location 1	Location 2	Location 3
As-TCLP	mg/L	0.05	<0.05	<0.05	<0.05
Ba-TCLP	mg/L	1.0	3.3	2.6	3.9
Cd-TCLP	mg/L	0.020	0.03	0.03	0.03
Cr-TCLP	mg/L	0.030	0.06	0.06	0.05
Pb-TCLP	mg/L	0.20	0.25	0.27	0.25
Hg-TCLP	mg/L	0.0002	<0.0002	<0.0002	<0.0002
Se-TCLP	mg/L	0.05	<0.05	<0.05	<0.05
Ag-TCLP	mg/L	0.020	0.04	0.03	0.03
TCLP extraction	NA	NA	Complete	Complete	Complete
pH	—	—	9.7	10.3	9.5
Percent moisture	%	0.1	51.7	51.2	51.4
Total As	µg/g, dry	0.1 <sup>(a)</sup>	17.0	35.3	28.2
Total Al	µg/g, dry	11 <sup>(a)</sup>	1,370	841	919
Total Fe	µg/g, dry	30 <sup>(a)</sup>	3,190	7,920	6,510
Total Mn	µg/g, dry	0.5 <sup>(a)</sup>	230	261	281

(a) Detection limit is in units of µg/L for digestate.



## 5. Quality Assurance/Quality Control

### 5.1 Quality Assurance Objectives

The precision, accuracy, MDL, and completeness for each of the analytical measurements required for this study have been established in the QAPP (Battelle, 1998) and are listed in Table 1 of the QA/QC Summary Report, which is being prepared under separate cover. These terms serve as indicators of data quality and were calculated in accordance with the formulas provided in the QAPP. The precision, accuracy, and MDL of each of the measurements performed during the present study are presented in the summary report. These quality assurance (QA) data are organized according to the date of sample receipt or sample analysis and are not site-specific. Therefore, the QA/QC section of this report shares the same QA data with other water treatment plants that have been included in the study.

### 5.2 Overall Assessment of Data Quality

Quantitative QA objectives listed in the QA/QC Summary Report include precision as relative percent difference (RPD), accuracy as percent recovery (%R), MDL, and completeness. The precision, accuracy, and MDL or reporting limit of each of the measurements performed during the present study are presented. Total arsenic, aluminum, iron, and manganese analyses on water samples were conducted in Battelle's ICP-MS laboratory. The QA data associated with these metal analyses also are presented. Other water quality parameters, including alkalinity, pH, turbidity, hardness, nitrate-nitrite, sulfate, fluoride, TDS, and TSS, were analyzed by Wilson Environmental Laboratories and their QA data were summarized. QA data for TOC analysis performed by CT&E Environmental Laboratory are presented. The TCLP metal analysis on sludge samples also was conducted by Wilson Environmental Laboratories and its associated QA data are summarized. Overall, the QA objectives of precision, accuracy, MDL, and completeness were achieved by all laboratories. Therefore, all the valid data were used to evaluate the effectiveness of the treatment processes and support conclusions.

#### 5.2.1 Total Arsenic, Aluminum, Iron, and Manganese

At the early phase of the study, total arsenic analysis was performed by Battelle's ICP-MS laboratory, and total aluminum, iron, and manganese were analyzed by Wilson Environmental Laboratories. Starting from June 1998, all four metals were analyzed by Battelle ICP-MS laboratory. Therefore, QA data for only the total arsenic analysis before June 16, 1998, and QA data for all four metals afterwards are presented.

The laboratory duplicate and matrix spike (MS) analyses were performed every 10 samples instead of 20 samples as required by the QAPP. All the samples were analyzed for four metals although metals other than arsenic may not be required for every sample. Therefore, Battelle's ICP-MS laboratory performed more QA/QC analyses than what were specified in the QAPP. This fact should be considered when QC data are evaluated.

Greater than 99% of the precision results for all metals met the QA objective of  $\pm 25\%$  (with only two iron outliers: 27% on August 8, 1998, and 74% on December 22, 1998; three arsenic outliers: 27% on August 18, 1998, 182% on October 1, 1998, and 27% on July 30, 1999; and four aluminum outliers: 26% and 33% on August 18, 1998, 48% on December 15, 1998, and 48% on January 25, 1999). The majority of the accuracy data associated with MS analysis on August 31, 1998, exceeded the QA limits of 75 to 125%. It is suspected that MS analyses were not performed correctly on that day. After this problem had been identified, Battelle's WAL, laboratory QA officer, and Battelle's task leaders met to discuss the cause of the deviation. Corrective actions were taken including reanalyzing samples and adjusting the amount of spike added to samples (i.e., the iron spike was increased from 50 to 100, 200, 225, or even as high as 2,000  $\mu\text{g/L}$  due to the fact that most of samples contain much more than 50  $\mu\text{g/L}$  of iron). As indicated in the QA/QC Summary Report, the MS data quality was significantly improved since November 3,

1998. Excluding the data on August 31, 1998, only five As data were outside the acceptable range for accuracy. However, 15 Al, 26 Fe, and 14 Mn accuracy data did not meet the QA objective. With exceptions of one 23% and one 38% of accuracy, the Al accuracy data range from 65 to 125%. The Mn accuracy data range from 67 to 106%, with exception of one 37%. The Fe accuracy data range from 55 to 142%, with exceptions of one 14%, one 23%, and one 38%.

All laboratory control samples showed %R within the acceptable QA limit of 75 to 125% except for six outliers for total Fe with %R ranging from 73 to 143%. Al was not spiked to laboratory control samples until November 3, 1998, after corrective actions were taken. The MDL of Fe is the same as target MDL; however, MDLs of other three metals were far below the target levels as specified in the QAPP.

### **5.2.2 Water Quality Parameters**

Water quality parameters include alkalinity, pH, turbidity, hardness (Ca and Mg), nitrate-nitrite, sulfate, fluoride, TDS, TSS and TOC. As shown in Table 3 of the QA/QC Summary Report, all the precision data were within the acceptable QA limit of  $\pm 25\%$  except for two Mn analysis with a 29% RPD (April 10 and 17, 1998) and three nitrate-nitrite analyses with 40% RPD (August 6, 1998, January 13, 1999, and February 11, 1999). The high RPDs of these analyses might have been caused by the low measured concentrations in the samples that were

close to the detection limits for Mn and nitrate-nitrite. The accuracy data indicate that only one Al (70% on March 2, 1998), two Mn (66% and 64% on May 12, 1998), and one Mg (126% on August 7, 1998) %R slightly exceeded the QA objectives of 75 to 125%. Although the matrix spike duplicate (MSD) analysis was not required by the QAPP, the accuracy and the precision data relating to MSD also were presented. The MS/MSD analyses are not applicable to pH and turbidity measurements, though. The laboratory did not perform MS/MSD analyses on Ca and Mg hardness analyses till October 15, 1998 upon Battelle's request. All laboratory control samples showed %R within the acceptable QA limit of 75 to 125%. Reporting limits were below the required levels for all the analytes except for sulfate. The reporting limit of sulfate was 5 mg/L, exceeding the required MDL of 3.66 mg/L. All precision, accuracy, and %R values for the TOC analysis were within acceptable QA limits with the exception of one accuracy value that was slightly below the 75 to 125% range at 72% (February 21, 1999).

### **5.2.3 TCLP Metals in Sludge**

The TCLP metals analyzed in the sludge samples included As, Se, Hg, Ba, Cd, Cr, Pb, and Ag. The precision data were within QA limits of  $\pm 25\%$ . The accuracy of MSs and percent recovery of laboratory control samples were all within QA limits of 75 to 125%, except for one slightly elevated RPD for TCLP Se MS/MSD at 26% (November 17, 1998).

## 6. References

- Amirtharajah, A., and C.R. O'Melia. 1990. "Coagulation Processes: Destabilization, Mixing, and Flocculation." In American Water Works Association (Eds.), *Water Quality and Treatment: A Handbook of Community Water Supplies*. New York: McGraw-Hill.
- Andreae, M. 1977. "Determination of Arsenic Species in Natural Waters." *Anal. Chem.*, 49: 820-823.
- Battelle. 1998. *Quality Assurance Project Plan for Evaluation of Treatment Technology for the Removal of Arsenic from Drinking Water*. Prepared for EPA.
- Benefield, L.D., and J.S. Morgan. 1990. "Chemical Precipitation." *Water Quality and Treatment*.
- Chen, S.L., S.R. Dzeng, M. Yang, K. Chiu, G. Shieh, and C.M. Wai. 1994. "Arsenic Species in Groundwaters of the Blackfoot Disease Area, Taiwan." *Environmental Science and Technology*. 877-881.
- Chen, R.C., S. Liang, H.C. Wang, and M.D. Beuhler. 1994. "Enhanced Coagulation for Arsenic Removal." *J. AWWA* (September): 79-90.
- Clifford, D., L. Ceber, and S. Chow. 1983. "Arsenic(III)/Arsenic(V) Separation by Chloride-Form Ion-Exchange Resins." Proceedings of the XI AWWA WQTC.
- Eaton, A.D., H.C. Wang, and J. Northington. 1997. "Analytical Chemistry of Arsenic in Drinking Water." AWWARF Project 914.
- Edwards, M. 1994. "Chemistry of Arsenic Removal during Coagulation and Fe-Mn Oxidation." *J. AWWA* (September): 64-78.
- Edwards, M., S. Patel, L. McNeill, H. Chen, M. Frey, A.D. Eaton, R.C. Antweiler, and H.E. Taylor. 1998. "Considerations in As Analysis and Speciation." *J. AWWA* (March): 103-113.
- EPA, see U.S. Environmental Protection Agency.
- Ficklin, W.H. 1982. "Separation of Arsenic (III) and Arsenic (V) in Groundwaters by Ion Exchange." *Talanta*, 30(5): 371-373.
- Gulledge, J.H., and J.T. O'Conner. 1973. "Removal of Arsenic (V) from Water by Adsorption on Aluminum and Ferric Hydroxides." *J. AWWA* (August): 548-552.
- Hemond, H.F. 1995. "Movement and Distribution of Arsenic in the Aberjona Watershed." *Environmental Health Perspectives*.
- Hering, J.G., P.Y. Chen, J.A. Wilkie, M. Elimelech, and S. Lung. 1996. "Arsenic Removal by Ferric Chloride." *J. AWWA*. (April): 155-167.
- McNeill, L.S., and M. Edwards. 1995. "Soluble Arsenic Removal at Water Treatment Plants." *J. AWWA*. (April): 105-113.
- McNeill, L.S. and M. Edwards. 1997a. "Predicting As Removal During Metal Hydroxide Precipitation." *J. AWWA*. (January): 75-86.
- McNeill, L.S. and M. Edwards. 1997b. "Arsenic Removal During Precipitative Softening." *Journal of Environmental Engineering* (May): 453-460.
- Scott, K.N., J.F. Green, H.D. Do, and S.J. McLean. 1995. "Arsenic Removal by Coagulation." *J. AWWA* (April): 114-126.
- Sorg, T.J. 1993. "Removal of Arsenic From Drinking Water by Conventional Treatment Methods." *Proceedings of the 1993 AWWA WQTC*.
- Sorg, T.J., and G.S. Logsdon. 1978. "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics: Part 2." *J. AWWA* (July).

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Tate, C.H., and K.F. Arnold. 1990. "Health and Aesthetic Aspects of Water Quality." In American Water Works Association (Eds.), *Water Quality and Treatment: A Handbook of Community Water Supplies*. New York: McGraw-Hill.

U.S. Environmental Protection Agency. 1998. *Research Plan for Arsenic in Drinking Water*. EPA/600/4-98/042. Office of Research and Development, Washington, DC. February.

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## **APPENDIX A**

### **Complete Analytical Results from Long-Term Sampling at Plant A**

Table A-1. Analytical Results from Long Term Sampling, Plant A (June 24 to July 15, 1998)

Sampling Date		6/24/98			7/1/98			7/8/98			7/15/98		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	82	78	77	71	67	67	63	60	60	56	54	52
Turbidity	NTU	1.0	1.1	0.2	0.7	1.0	0.1	0.5	1.1	<0.1	1.8	2.4	<0.1
pH		8.2	8.0	7.9	8.0	7.9	7.7	7.9	7.8	7.7	8.1	7.9	7.7
TOC	mg/L	2.2	<1.0	2.1	2.0	2.0	2.0	2.1	2.2	2.2	2.5	2.6	2.2
As (total)	µg/L	12.1	9.3	3.9	7.0	8.1	3.1	7.0	8.0	3.1	7.1	6.5	2.3
As (total soluble)	µg/L										7.2	5.5	2.9
As (particulate)	µg/L										6.8	3.1	2.2
As (III)	µg/L										6.8	3.1	2.2
As (V)	µg/L										0.3	3.4	0.1
Total Al	µg/L	115	55.4	21.5	27.0	49.2	<11	35.6	53.9	14.7	58.0	45.6	13.5
Total Fe	µg/L	444	457	<30	108	<30	<30	73.7	464	<30	146	362	<30
Total Mn	µg/L	32.6	16.9	<0.5	7.5	14.4	<0.5	8.9	18.1	<0.5	22.4	19.1	<0.5
Dissolved Al	µg/L										<11	<11	<11
Dissolved Fe	µg/L										<30	<30	<30
Dissolved Mn	µg/L										<30	<30	<30
											1.9	3.0	<0.5
											1.5	3.0	<0.5

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table A-2. Analytical Results from Long Term Sampling, Plant A (July 22 to August 12, 1998)**

Sampling Date		7/22/98			7/29/98			8/5/98			8/12/98		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	51	49	50	47	44	44	45	44	42	45	42	42
		52	49	50							46	43	42
Turbidity	NTU	6.1	0.6	<0.1	0.6	1.5	<0.1	0.8	0.9	<0.1	0.4	1.2	<0.1
		5.0	0.6	<0.1							0.4	1.1	<0.1
pH		7.9	7.6	7.5	8.0	7.8	7.7	7.8	7.8	7.7	7.7	7.5	7.4
		7.9	7.6	7.5							7.7	7.5	7.4
TOC	mg/L	1.8	1.7	1.9	1.5	1.6	1.7	1.8	1.9	3.0	1.7	1.7	1.9
		1.8	1.8	1.7							1.8	1.8	1.6
As (total)	µg/L	10.5	7.6	2.3	5.6	10.0	2.1	4.8	5.9	2.3	4.8	4.7	0.8
								6.5	6.2	2.2			
As (total soluble)	µg/L							5.9	2.7	2.1			
								5.6	2.7	2.0			
As (particulate)	µg/L							<0.1	3.1	0.2			
								<0.1	3.5	0.2			
As (III)	µg/L							0.5	0.2	0.4			
								0.5	0.2	0.4			
As (V)	µg/L							5.4	2.5	1.7			
								5.1	2.5	1.6			
Total Al	µg/L	269	62.1	17.6	33.3	79.9	21.1	26.6	48.2	<11	48.2	35.6	21.7
								23.2	70.2	12.1			
Total Fe	µg/L	646	450	<30	83.5	780	60.5	94.7	526	<30	90.4	433	<30
								136	539	<30			
Total Mn	µg/L	112	23.9	<0.5	9.9	58.2	0.5	9.6	22.6	<0.5	12.5	25.9	<0.5
								13.9	22.9	<0.5			
Dissolved Al	µg/L							<11	<11	<11			
								<11	<11	<11			
Dissolved Fe	µg/L							45.7	<30	<30			
								<30	<30	<30			
Dissolved Mn	µg/L							1.8	4.9	0.8			
								1.6	4.7	<0.5			

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

Table A-3. Analytical Results from Long Term Sampling, Plant A (August 19 to September 9, 1998)

Sampling Date		8/19/98			8/26/98			9/2/98			9/9/98		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	51	47	48	63	61	61	66	62	62	75	75	76
Turbidity	NTU	0.6	1.2	<0.1	0.6	0.8	<0.1	2.1	0.5	<0.1	0.6	0.4	<0.1
pH		7.9	7.6	7.5	8.0	7.8	7.7	7.8	7.8	7.7	8.0	7.9	7.9
TOC	mg/L	1.7	1.6	1.5	1.9	2.0	1.9	1.9	1.9	2.0	2.1	2.2	2.0
As (total)	µg/L	5.9	5.4	1.3	6.6	7.1	3.2	6.9	6.7	2.7	7.2	7.0	4.0
As (total soluble)	µg/L							5.0	5.9	2.7			
As (particulate)	µg/L							6.7	3.8	3.4			
As (III)	µg/L							6.8	4.0	3.2			
As (V)	µg/L							0.2	2.9	<0.1			
Total Al	µg/L	36.4	57	26.8	46.9	32.4	39.2	0.3	<0.1	<0.1			
Total Fe	µg/L	77.5	486	<30	63.0	354	52.3	0.3	<0.1	<0.1			
Total Mn	µg/L	16.4	26.3	45.4	14.7	22.8	0.5	<0.1	<0.1	<0.1			
Dissolved Al	µg/L							44.7	22.9	13.3			
Dissolved Fe	µg/L							32.8	27.9	12.1			
Dissolved Mn	µg/L							144	306	<30			
								84.8	264	<30			
								47.2	18.2	<0.5			
								32.6	16.5	<0.5			
								<11	<11	<11			
								<11	<11	<11			
								<30	<30	<30			
								<30	<30	<30			
								2.2	2.9	<0.5			
								2.2	2.6	<0.5			

(a) As CaCO<sub>3</sub>,  
IN = inlet; PF = prefiltration; AF = after filtration.



**Table A-4. Analytical Results from Long Term Sampling, Plant A (September 16 to October 7, 1998 )**

Sampling Date		9/16/98			9/23/98			9/30/98			10/7/98		
Sampling Location	Parameter	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	74	73	73	74	74	74	81	78	79	88 87	83 84	82 82
Turbidity	NTU	1.1	0.4	<0.1	1.4	0.7	0.2	0.6	0.8	<0.1	1.2 1.2	1.1 1.1	<0.1 <0.1
pH		7.9	7.8	7.8	7.9	7.8	7.7	7.9	7.6	7.6	8.2 8.2	8.0 7.9	7.9 7.8
TOC	mg/L	2.7	2.6	2.3	2.3	2.4	2.3	2.6	2.4	2.3	2.4 2.4	2.6 2.5	2.5 2.6
As (total)	µg/L	8.1	7.9	4.6	8.9	9.9	4.2	8.2	4.3 <sup>(b)</sup>	4.4	7.8	7.7	4.2
As (total soluble)	µg/L							9.2	8.6	4.2			
As (particulate)	µg/L							8.1	4.8	3.8			
As (III)	µg/L							8.0	4.9	3.7			
As (V)	µg/L							0.1	<0.1	0.6			
Total Al	µg/L	30.5	36.6	<11	31.4	34.4	22.2	36.5	83.0	13.7	60.8	63.4	12.6
Total Fe	µg/L	48.5	303	<30	85.6	419	41.5	57.5	461	<30	81.8	374	31.0
Total Mn	µg/L	12.6	20.0	9.1	18.0	36.4	1.5	59.4	382	<30	15.1	22.2	0.6
Dissolved Al	µg/L							15.4	31.8	0.5			
Dissolved Fe	µg/L							15.3	24.5	0.6			
Dissolved Mn	µg/L							<11	<11	<11			
								<11	<11	<11			
								<30	<30	<30			
								<30	<30	<30			
								2.6	3.0	<0.5			
								2.6	2.9	<0.5			

(a) As CaCO<sub>3</sub>.

(b) Confirmed by sample re-analysis.

IN = inlet; PF = prefiltration; AF = after filtration.

Table A-5. Analytical Results from Long Term Sampling, Plant A (October 14 to November 4, 1998)

Sampling Date		10/14/98			10/21/98			10/28/98			11/4/98		
Sampling Location	Parameter	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
	Alkalinity	86	85	81	92	91	89	58	95	95	96	92	92
	Turbidity	0.7	1.1	<0.1	0.6	0.7	<0.1	0.6	0.9	<0.1	0.7	1.0	<0.1
	pH	7.9	7.7	7.6	8.0	7.8	7.7	8.1	7.8	7.7	8.0	7.7	<0.1
	TOC	2.9	3.1	2.9	2.5	2.6	2.3	2.8	2.9	2.5	2.1	2.3	1.9
	As (total)	5.0	2.0	4.2	7.8	8.0	6.0	7.4	13.9	4.7	7.8	9.1	4.9
	As (total soluble)							7.5	9.2	4.4			
	As (particulate)							8.2	5.3	4.5			
	As (III)							7.7	5.1	4.5			
	As (V)							<0.1	8.6	0.2			
	Total Al	<11	25.3	14.5	24.7	28.2	15.2	<0.1	4.1	<0.1			
	Total Fe	<30	67.8	<30	48.1	384	<30	38.6	2.0	1.9			
	Total Mn	14.2	20.1	<0.5	11.4	14.2	<0.5	38.9	2.2	2.0			
	Dissolved Al							12.7	3.3	2.6			
	Dissolved Fe							5.6	2.9	2.5			
	Dissolved Mn							27.8	176	<11	40.1	95.4	15.9
								36.8	75	<11			
								88.2	1,160	<30	88.2	597	<30
								11.7	1,565	<30	12.0	31.9	<0.5
								<11	80.3	0.6			
								<11	44.9	0.6			
								<30	<11	<11			
								<30	<30	<30			
								<30	<30	<30			
								4.5	5.4	0.7			
								4.7	5.7	<0.5			

(a) As CaCO<sub>3</sub>  
(b) Sample container broken in laboratory.  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table A-6. Analytical Results from Long Term Sampling, Plant A (November 11 to December 9, 1998)**

Sampling Date		11/11/98				11/18/98				11/25/98 <sup>(a)</sup>				12/2/98			
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF	AF
Alkalinity	mg/L <sup>(b)</sup>	98	95	95	99	94	95	99	94	95				99	97	94	94
Turbidity	NTU	0.4	0.7	<0.1	1.2	1.5	0.2	1.2	1.5	0.2				0.9	1.0	<0.1	<0.1
pH		8.0	7.8	7.7	7.9	7.8	7.7	7.9	7.8	7.7				8.0	7.8	7.7	7.7
TOC	mg/L	2.3	2.4	2.1	2.0	2.0	2.0	2.0	2.0	2.0				2.3	2.2	2.1	2.1
As (total)	µg/L	7.9	7.8	4.2	7.1	7.3	3.7	7.1	7.3	3.7				7.2	7.1	3.4	3.4
As (total soluble)	µg/L													7.3	7.7	3.3	3.3
As (particulate)	µg/L													7.0	4.5	3.6	3.6
As (III)	µg/L													6.9	4.6	3.6	3.6
As (V)	µg/L													0.2	2.6	<0.1	<0.1
Total Al	µg/L	59.2	62.1	11.3	71.0	73.9	14.2	71.0	73.9	14.2				0.4	3.1	<0.1	<0.1
Total Fe	µg/L	112	459	<30	156	416	<30	156	416	<30				1.1	0.9	0.7	0.7
Total Mn	µg/L	20.0	23.1	0.6	19.2	19.0	<0.5	19.2	19.0	<0.5				1.2	0.9	0.9	0.9
Dissolved Al	µg/L													5.9	3.6	2.9	2.9
Dissolved Fe	µg/L													5.7	3.7	2.7	2.7
Dissolved Mn	µg/L													47.2	45.0	29.4	29.4
														43.0	70.0	18.5	18.5
														150	483	39.7	39.7
														145	460	88.0	88.0
														14.5	17.7	1.3	1.3
														14.3	18.4	1.1	1.1
														<11	<11	<11	<11
														<11	<11	18.4	18.4
														<30	<30	<30	<30
														<30	<30	<30	<30
														3.4	3.4	1.0	1.0
														3.7	3.6	1.1	1.1

(a) As CaCO<sub>3</sub>,  
(b) No sampling due to Thanksgiving holiday.  
IN = inlet; PF = prefiltration; AF = after filtration.

Table A-7. Analytical Results from Long Term Sampling, Plant A (December 9 to 30, 1998)

Sampling Date		12/9/98			12/16/98			12/23/98			12/30/98		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	98 97	94 95	94 94	98	95	96						
Turbidity	NTU	0.6 0.6	0.8 0.8	<0.1 <0.1	0.7	0.9	<0.1						
pH		8.0 8.0	7.8 7.8	7.7 7.7	8.1	7.8	7.7						
TOC	mg/L	2.3 -	2.2 2.2	1.9 2.1	2.3	2.5	2.1						
As (total)	µg/L	7.2	7.4	3.3	7.0	6.9	2.9						
As (total soluble)	µg/L												
As (particulate)	µg/L												
As (III)	µg/L												
As (V)	µg/L												
Total Al	µg/L	40.5	36.4	11.2	37.0	24.7	<11						
Total Fe	µg/L	60.9	373	<30	46.8	374	<30						
Total Mn	µg/L	11.2	14.9	1.0	8.8	12.4	<0.5						
Dissolved Al	µg/L												
Dissolved Fe	µg/L												
Dissolved Mn	µg/L												

(a) As CaCO<sub>3</sub>.

(b) No sampling due to Christmas holiday.

IN = inlet; PF = prefiltration; AF = after filtration.

**Table A-8. Analytical Results from Long Term Sampling, Plant A (January 6 to 27, 1999)**

Sampling Date		01/06/99			01/13/99			01/20/99			01/27/99		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	103	100	99	103	96	99	103	100	101	103	105	103
Turbidity	NTU	0.3	1.2	<0.1	0.3	0.8	<0.1	0.3	1.7	<0.1	0.4	3.0	<0.1
pH		7.9	7.8	7.8	8.0	7.8	7.8	8.1	8.0	8.0	8.2	8.0	8.0
TOC	mg/L	2.4	3.9	1.9	2.2	2.3	1.9	2.5	2.7	2.7	2.0	2.5	2.2
As (total)	µg/L	6.8	14.5	3.5	8.6	9.9	3.8	7.5	10.8	4.8	5.4	7.0	3.0
As (total soluble)	µg/L				8.8	3.0	4.0						
As (particulate)	µg/L				9.6	2.9	4.0						
As (III)	µg/L				<0.1	6.9	<0.1						
As (V)	µg/L				<0.1	5.8	<0.1						
Total Al	µg/L	20.3	50.5	<11	30.7	22.2	<11	41.5	94.7	<11	14.8	33.7	<11
Total Fe	µg/L	19.7	1,276	62.6	29.3	31.3	<11	56.6	925	<30	60.8	920	33.9
Total Mn	µg/L	4.4	40.5	14.7	47.0	811	<30	6.0	22.1	4.8	8.0	19.0	3.6
Dissolved Al	µg/L				41.7	806	<30						
Dissolved Fe	µg/L				6.8	10.2	<0.5						
Dissolved Mn	µg/L				6.6	9.5	<0.5						

(a) As CaCO<sub>3</sub>,  
IN = inlet; PF = prefiltration; AF = after filtration.

Table A-9. Analytical Results from Long Term Sampling, Plant A (Feb 3 to 24, 1999)

Sampling Date		02/03/99			02/11/99			02/17/99			02/24/99		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	103	100	99	102	102	101	104	105	102	100	99	100
Turbidity	NTU	0.7	1.3	<0.1	2.4	1.3	<0.1	1.1	1.3	<0.1	2.8	1.2	<0.1
pH		8.3	8.0	8.0	8.2	8.0	8.0	8.2	8.0	7.9	8.2	8.0	8.0
TOC	mg/L	2.4	2.6	2.1	2.5	2.7	2.3	2.6	2.7	2.0	3.3	3.0	2.8
As (total)	µg/L	2.6	7.8	2.7	7.4	7.0	2.7	6.0	6.0	2.5	4.1	3.9	1.8
As (total soluble)	µg/L				6.8	9.0	2.7						
As (particulate)	µg/L				5.0	3.6	2.8						
As (III)	µg/L				5.3	3.9	2.7						
As (IV)	µg/L				2.4	3.4	<0.1						
Total Al	µg/L	717	32.9	23.8	143	42.4	<11	29.7	32.3	<11	33.0	38.3	<11
Total Fe	µg/L	767	1,050	55.7	543	652	<30	118	753	<30	104	642	48.8
Total Mn	µg/L	54.5	23.3	4.9	45.6	81.3	5.6	26.6	33.7	14.9	11.9	15.7	9.6
Dissolved Al	µg/L				<11	<11	<11						
Dissolved Fe	µg/L				<30	<30	<30						
Dissolved Mn	µg/L				1.9	63.6	5.8						

(a) As CaCO<sub>3</sub>

IN = inlet; PF = prefiltration; AF = after filtration.

**Table A-10.** Analytical Results from Long Term Sampling, Plant A (Mar 3 to Mar 24, 1999)

Sampling Date		03/03/99			03/10/99			03/17/99			03/24/99		
Parameter	Sampling Location Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	105	103	103	109	110	109	104 104	101 102	102 102	104	103	103
Turbidity	NTU	0.9	1.3	<0.1	0.5	0.7	<0.1	1.4 1.4	1.7 1.7	<0.1 <0.1	1.2	1.7	<0.1
pH		8.2	8.0	8.0	8.3	8.1	8.0	8.2 8.2	8.0 8.0	8.0 8.0	8.2	8.0	8.0
TOC	mg/L	<sup>(b)</sup>	3.2	2.8	2.6	2.5	2.2	2.9 3.1	3.1 2.6	2.6 2.4	2.5	2.4	2.2
As (total)	µg/L	4.5	4.6	2.1	6.6 6.5	6.0 6.1	3.3 3.4	8.4	8.0	4.4	11.3	13.9	5.3
As (total soluble)	µg/L				6.3 6.4	4.3 4.4	3.6 3.6						
As (particulate)	µg/L				0.3 0.1	1.7 1.7	<0.1 <0.1						
As (III)	µg/L				0.6 0.6	0.5 0.6	0.5 0.5						
As (V)	µg/L				5.7 5.8	3.8 3.8	3.1 3.1						
Total Al	µg/L	30.5	34.3	<11	21.0 19.5	17.1 19.5	<11 <11	59.3	56.7	12.0	46.1	55.6	<11
Total Fe	µg/L	70.9	542	<30	<30 <30	444 459	<30 <30	116	512	36.4	96.8	628	<30
Total Mn	µg/L	9.8	13.8	7.3	5.6 5.5	8.8 9.1	4.5 4.6	24.5	26.0	15.8	15.3	22.3	6.8
Dissolved Al	µg/L				<11 <11	<11 <11	<11 <11						
Dissolved Fe	µg/L				<30 <30	<30 <30	<30 <30						
Dissolved Mn	µg/L				2.9 1.6	2.4 2.7	5.2 5.0						

(a) As CaCO<sub>3</sub>.

(b) Sample container broken in laboratory.

IN = inlet; PF = prefiltration; AF = after filtration.

Table A-11. Analytical Results from Long Term Sampling, Plant A (Mar 31 to Apr 21, 1999)

Sampling Date		03/31/99			04/07/99			04/14/99			04/21/99		
Sampling Location	Parameter	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	106	105	102	107	106	105	108	106	106	105	104	105
Turbidity	NTU	0.9	1.4	0.2	2.4	2.7	<0.1	2.3	2.4	<0.1	2.9	1.0	<0.1
pH		8.1	7.9	7.9	8.1	7.9	7.9	8.1	8.0	7.9	8.1	8.0	7.9
TOC	mg/L	2.0	2.5	2.3	2.5	2.6	1.9	2.4	2.8	2.5	2.8	3.2	3.0
As (total)	µg/L	11.0	10.7	4.5	10.8	10.6	4.5	10.5	8.5	4.3	7.6	6.8	(b)
As (total soluble)	µg/L				10.8	10.6	4.8						
As (particulate)	µg/L				10.9	10.9	4.8						
As (III)	µg/L				<0.1	4.5	<0.1						
As (V)	µg/L				<0.1	5.4	<0.1						
Total Al	µg/L	29.8	37.4	<11	10.3	5.7	4.3						
Total Fe	µg/L	59.9	534	<30	10.2	5.2	4.3						
Total Mn	µg/L	11.0	15.9	6.3	18.6	24.2	5.5						
Dissolved Al	µg/L				<11	<11	<11						
Dissolved Fe	µg/L				<30	<30	<30						
Dissolved Mn	µg/L				2.0	1.2	5.3						

(a) As CaCO<sub>3</sub>.

(b) Sample container contaminated.

IN = inlet; PF = prefiltration; AF = after filtration.



**Table A-12. Analytical Results from Long Term Sampling, Plant A (Apr 28 to May 19, 1999)**

Sampling Date		04/28/99				05/05/99				05/12/99				05/19/99			
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF	
Alkalinity	mg/L <sup>(a)</sup>	107	106	105	112	110	109	111	109	108	112	109	108	112	111	109	
Turbidity	NTU	1.6	1.7	<0.1	2.7	6.2	<0.1	1.2	2.1	<0.1	1.1	18.5	<0.1	1.1	18.5	0.1	
pH		8.2	8.0	7.9	8.2	8.0	8.0	8.2	8.0	8.0	8.2	8.0	8.0	8.2	8.0	8.0	
TOC	mg/L	2.9	2.6	2.3	4.8	4.4	7.4	2.8	3.0	2.3	4.3	12.0	2.3	4.3	12.0	5.4	
As (total)	µg/L	6.8	6.2	3.1	9.6	13.1	4.6	11.1	9.3	4.3	8.8	23.4	4.3	8.8	23.4	4.4	
As (total soluble)	µg/L				9.5	13.0	4.6										
As (particulate)	µg/L				9.1	5.2	4.5										
As (III)	µg/L				0.5	7.9	<0.1										
As (V)	µg/L				0.4	7.8	<0.1										
Total Al	µg/L	100	67.7	17.9	122	231	<11	76.5	35.7	17.3	32.8	246	17.3	32.8	246	<11	
Total Fe	µg/L	103	601	23.2	241	1,316	<30	752	102.5	<30	75.7	2,646	<30	75.7	2,646	<30	
Total Mn	µg/L	17.8	15.5	6.4	24.7	62.0	5.6	74.3	12.8	3.9	12.1	72.2	3.9	12.1	72.2	4.7	
Dissolved Al	µg/L				<11	<11	<11										
Dissolved Fe	µg/L				<30	<30	<30										
Dissolved Mn	µg/L				1.2	3.0	4.8										

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

Table A-13. Analytical Results from Long Term Sampling, Plant A (May 26 to June 16, 1999)

Sampling Date		05/28/99			08/02/99			06/09/99			06/16/99		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	107	105	104	101	100	100	97	96	96	97	96	96
Turbidity	NTU	0.8	3.8	<0.1	2.7	1.7	<0.1	1.9	1.6	<0.1	1.9	1.5	<0.1
pH		8.2	8.0	8.0	8.2	8.0	7.9	8.2	7.9	7.8	8.2	7.9	7.9
TOC	mg/L	2.4	2.5	2.0	2.6	2.6	2.2	2.0	2.4	2.2	2.5	2.5	2.1
As (total)	µg/L	9.0	16.7	4.2	11.4	9.5	3.5	7.4	10.3	2.8	8.5	16.6	3.3
As (total soluble)	µg/L				10.0	8.9	3.5						
As (particulate)	µg/L				9.4	4.3	3.6						
As (III)	µg/L				9.5	4.2	3.5						
As (V)	µg/L				2.0	5.2	0.1						
Total Al	µg/L	39.8	193	9.0	111	54.1	19.7	79.0	100	<11	17.8	134	18.3
Total Fe	µg/L	84.4	1,812	<30	254	605	<30	144	870	<30	42.0	1,664	<30
Total Mn	µg/L	10.0	51.5	3.7	85.8	28.7	3.8	24.7	33.7	3.9	8.8	52.7	5.2
Dissolved Al	µg/L				53.0	28.3	3.4						
Dissolved Fe	µg/L				22.6	<11	<11						
Dissolved Mn	µg/L				<11	<11	<11						
	µg/L				<30	<30	<30						
	µg/L				<30	<30	<30						
	µg/L				1.4	2.3	3.4						
	µg/L				1.1	2.5	3.2						

(a) As CaCO<sub>3</sub>  
IN = inlet; PF = prefiltration; AF = after filtration.

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## **APPENDIX B**

### **Complete Analytical Results from Long-Term Sampling at Plant B**

Table B-1. Analytical Results from Long Term Sampling, Plant B (June 25 to July 16, 1998)

Sampling Date		6/25/98			6/30/98			7/9/98			7/16/98		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>10</sup>	132	108	106	126	105	104	125	100	101	120	96	96
Turbidity	NTU	11.8	0.9	0.3	9.5	0.6	<0.1	7.2	0.8	<0.1	8.7	0.8	<0.1
pH		8.4	7.4	7.3	8.3	7.3	7.2	8.2	7.3	7.3	8.6	7.3	7.3
TOC	mg/L	3.2	2.6	2.6	3.2	2.6	2.6	3.9	3.6	4.4	3.9	3.2	3.2
As (total)	µg/L	15.8	3.6	1.7	16.6	3.0	1.8	15.0	3.6	2.0	18.7	4.6	2.7
As (total soluble)	µg/L										17.7	4.4	2.6
As (particulate)	µg/L										19.4	2.6	2.9
As (III)	µg/L										19.3	2.6	2.9
As (V)	µg/L										<0.1	2.0	<0.1
Total Al	µg/L	493	353	41.1	441	266	49.1	325	345	60.1	488	528	63.7
Total Fe	µg/L	507	<30	<30	456	<30	<30	345	<30	<30	471	<30	<30
Total Mn	µg/L	36.6	8.3	0.5	36.4	6.9	<0.5	27.5	7.6	<0.5	31.4	8.9	0.6
Dissolved Al	µg/L										32.1	8.9	<0.5
Dissolved Fe	µg/L										1.5	57.7	38.4
Dissolved Mn	µg/L										1.2	58.3	36.6
											<30	<30	<30
											<30	<30	<30
											2.7	5.3	<0.5
											2.8	5.3	<0.5

(a) As CaCO<sub>3</sub>.

IN = inlet; PF = prefiltration; AF = after filtration.

**Table B-2. Analytical Results from Long Term Sampling, Plant B (July 23 to August 13, 1998)**

Sampling Date		7/23/98			7/30/98			8/6/98			8/13/98		
Parameter	Sampling Location Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	147 146	122 123	100 100	122	96.0	97.0	123	99.0	100	121 120	100 99	98.0 98.0
Turbidity	NTU	6.8 7.1	1.0 1.0	<0.1 <0.1	6.0	0.8	<0.1	3.6	1.2	<0.1	3.5 3.3	1.1 1.1	<0.1 <0.1
pH		8.1 8.1	7.5 7.4	7.4 7.4	8.6	7.4	7.3	8.4	7.5	7.4	8.5 8.5	7.3 7.3	7.3 7.3
TOC	mg/L	3.6 3.8	2.9 2.8	2.9 3.0	3.5	2.9	3.0	3.3	3.0	1.7	3.5 3.3	2.8 2.9	2.8 2.7
As (total)	µg/L	18.2	6.0	3.3	15.8	4.8	3.1	17.9 16.1	5.7 5.2	4.1 3.7	17.3	5.2	2.7
As (total soluble)	µg/L							18.0 18.6	2.8 2.8	3.8 3.7			
As (particulate)	µg/L							<0.1 <0.1	2.9 2.4	0.3 <0.1			
As (III)	µg/L							0.4 0.4	0.3 0.2	0.2 0.2			
As (V)	µg/L							17.6 18.2	2.6 2.5	3.6 3.5			
Total Al	µg/L	501	598	77.5	141	521	81.2	114 109	602 519	63.9 61.1	241	695	81.6
Total Fe	µg/L	498	33.2	<30	164	<30	<30	128 126	<30 <30	<30 <30	245	41.1	<30
Total Mn	µg/L	39.0	8.2	<0.5	21.3	13.6	0.9	14.4 13.4	14.5 12.6	0.7 0.8	18.4	15.7	0.8
Dissolved Al	µg/L							<11 <11	69.2 70.1	49.2 50.0			
Dissolved Fe	µg/L							<30 <30	<30 <30	<30 <30			
Dissolved Mn	µg/L							2.7 2.8	8.8 8.8	<0.5 <0.5			

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

Table B-3. Analytical Results from Long Term Sampling, Plant B (August 20 to September 10, 1998)

Sampling Date		8/20/98			8/27/98			9/3/98			9/10/98		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	122	101	103	120	102	102	120	98.0	102	119	100	100
Turbidity	NTU	3.6	0.9	<0.1	4.4	0.7	<0.1	4.6	1.0	<0.1	4.4	0.5	<0.1
pH		8.6	7.6	7.5	8.4	7.3	7.3	8.4	7.3	7.3	8.3	7.3	7.3
TOC	mg/L	3.7	3.1	2.9	3.7	3.2	3.0	3.7	3.2	3.1	4.1	3.0	3.5
As (total)	µg/L	15.8	5.6	2.7	19.1	5.9	3.7	16.0	5.5	3.1	16.3	4.1	3.1
As (total soluble)	µg/L							19.3	2.8	3.8			
As (particulate)	µg/L							19.5	2.7	3.6			
As (III)	µg/L							<0.1	2.7	<0.1			
As (V)	µg/L							<0.1	1.9	<0.1			
Total Al	µg/L	307	67.6	62.9	84.8	466	71.0	78.1	588	58.8	76.5	309	56.3
Total Fe	µg/L	282	30.4	<30	76.2	<30	<30	84.2	<30	<30	84.6	<30	<30
Total Mn	µg/L	18.1	14.0	0.7	15.5	10.3	0.8	16.1	12.7	0.5	14.7	7.4	<0.5
Dissolved Al	µg/L							15.6	10.9	0.5			
Dissolved Fe	µg/L							<11	76.7	47.9			
Dissolved Mn	µg/L							<11	77.1	47.2			
								<30	<30	<30			
								<30	<30	<30			
								4.8	9.8	<0.5			
								4.7	9.7	<0.5			

(a) As CaCO<sub>3</sub>,  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table B-4. Analytical Results from Long Term Sampling, Plant B (September 17 to October 8, 1998)**

Sampling Date		9/17/98			9/24/98			10/1/98			10/8/98		
Parameter	Sampling Location Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	119	98.0	100	122	97.0	99.0	120	105	101	123 124	105 105	105 103
Turbidity	NTU	4.4	0.7	<0.1	2.9	0.4	<0.1	2.0	1.2	<0.1	2.1 2.3	.8 .8	<.1 <.1
pH		8.3	7.3	7.3	8.3	7.3	7.3	8.3	7.4	7.3	8.4 8.4	7.4 7.4	7.4 7.4
TOC	mg/L	3.9	3.3	3.7	3.9	3.0	3.1	3.9	3.3	3.2	3.8 3.9	4.3 3.3	3.2 3.2
As (total)	µg/L	18.2	5.3	4.0	18.5	5.0	3.9	19.3 19.0	7.8 7.9	3.3 3.4	18.2	7.5	3.4
As (total soluble)	µg/L							19.2 19.4	3.4 3.3	3.3			
As (particulate)	µg/L							0.1 <0.1	4.4 4.6	<0.1 <0.1			
As (III)	µg/L							0.6 0.6	0.5 0.5	0.5			
As (V)	µg/L							18.6 18.8	2.9 2.8	2.8			
Total Al	µg/L	74.7	406	64.0	77.0	382	71.7	84.7 88.3	644 637	56.0 57.6	147	809	60.3
Total Fe	µg/L	77.6	<30	<30	78.8	<30	<30	75.7 78.4	<30 <30	<30 <30	121	<30	<30
Total Mn	µg/L	17.0	10.9	0.5	14.0	10.7	0.7	13.8 13.8	17.9 17.8	0.7 0.8	15.3	12.1	0.5
Dissolved Al	µg/L							<11 <11	64.3 66.8	43.6 39.2			
Dissolved Fe	µg/L							<30 <30	<30 <30	<30 <30			
Dissolved Mn	µg/L							3.3 3.4	9.1 9.1	<0.5 <0.5			

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table B-5. Analytical Results from Long Term Sampling, Plant B (October 15 to November 5, 1998)**

Sampling Date		10/15/98			10/22/98			10/29/98 <sup>(a)</sup>			11/5/98		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	124	110	108	124	104	104	122	116	116	124 126	119 118	119 119
Turbidity	NTU	2.8	0.7	<0.1	1.7	0.6	<0.1	1.4	0.6	<0.1	1.2 1.2	0.6 0.6	<0.1 <0.1
pH		8.3	7.4	7.4	8.3	7.4	7.3	8.4	7.8	7.7	8.2 8.2	8.2 8.0	8.0 8.0
TOC	mg/L	3.7	3.7	3.8	3.7	3.0	3.1	3.7	3.3	3.4	3.4 3.5	3.0 3.0	3.1 3.2
As (total)	µg/L	18.7	6.5	3.9	17.9	5.0	2.8	19.8 19.7	12.3 12.4	9.8 10.2	20.8	15.5	11.8
As (total soluble)	µg/L							19.4 19.2	9.5 9.5	10.1 10.1			
As (particulate)	µg/L							0.4 0.5	2.8 2.9	<0.1 <0.1			
As (III)	µg/L							0.4 0.4	0.3 0.3	0.3 0.3			
As (V)	µg/L							19.0 18.8	9.2 9.2	9.8 9.8			
Total Al	µg/L	160	578	54.1	443	580	46.2	62.5 72.2	494 497	79.3 84.6	109	563	98.4
Total Fe	µg/L	107	<30	<30	90.4	70.0	<30	67.7 73.7	<30 <30	<30 <30	78.7	<30	<30
Total Mn	µg/L	18.5	8.3	0.5	11.5	15.0	0.6	20.7 21.0	8.5 8.7	0.8 0.8	21.9	8.7	0.9
Dissolved Al	µg/L							<11 <11	123 118	75.6 78.2			
Dissolved Fe	µg/L							<30 <30	<30 <30	<30 <30			
Dissolved Mn	µg/L							4.3 4.4	1.7 1.0	<0.5 <0.5			

(a) As  $\text{CaCO}_3$ .  
(b) The plant started using polyaluminum chloride (PAX-18) instead of alum since 10/27/98.  
IN = inlet; PF = prefiltration; AF = after filtration.



**Table B-6.** Analytical Results from Long Term Sampling, Plant B (November 12 to December 3, 1998)

Sampling Date		11/12/98			11/19/98			11/26/98 <sup>(a)</sup>			12/3/98		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(b)</sup>	126	121	120	129	123	122				132	127	125
Turbidity	NTU	1.0	0.6	<0.1	1.2	0.7	<0.1				1.5	0.8	0.2
pH		8.2	7.8	7.8	7.9	7.8	7.7				8.1	7.8	7.8
TOC	mg/L	3.1	3.0	3.0	3.0	3.0	3.0				3.5	2.9	2.9
As (total)	µg/L	18.6	10.6	10.5	17.4	12.3	10.2				17.0	12.9	11.0
As (total soluble)	µg/L										17.2	12.6	10.9
As (particulate)	µg/L										20.1	12.3	12.3
As (III)	µg/L										19.3	12.0	12.7
As (V)	µg/L										<0.1	0.6	<0.1
Total Al	µg/L	75.7	89.3	87.9	59.6	474	90.4				<0.1	0.6	<0.1
Total Fe	µg/L	55.0	<30	<30	32.2	<30	<30				<0.1	0.6	<0.1
Total Mn	µg/L	15.1	0.6	0.5	13.1	4.6	<0.5				0.4	0.4	0.4
Dissolved Al	µg/L										0.4	0.3	0.4
Dissolved Fe	µg/L										19.7	11.9	11.9
Dissolved Mn	µg/L										18.9	11.7	12.3
											152	458	96.4
											101	423	96.3
											164	54.4	82.1
											126	45.0	32.7
											15.5	6.4	0.9
											14.9	6.1	0.7
											<11	105	76.2
											<11	106	74.9
											<30	<30	<30
											<30	<30	<30
											4.3	2.1	<0.5
											4.2	2.1	<0.5

(a) As CaCO<sub>3</sub>.  
(b) No sampling due to Thanksgiving holiday.  
IN = inlet; PF = prefiltration; AF = after filtration.

Table B-7. Analytical Results from Long Term Sampling, Plant B (December 10 to 31, 1999)

Sampling Date		12/10/98			12/17/98 <sup>(a)</sup>			12/24/98 <sup>(b)</sup>			12/31/98 <sup>(c)</sup>		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	134 135	126 127	126 126	134	120	119						
Turbidity	NTU	1.9 1.9	0.6 0.7	<0.1 <0.1	2.0	0.5	<0.1						
pH		8.3 8.3	7.8 7.8	7.8 7.8	8.3	7.4	7.4						
TOC	mg/L	3.2 4.3	3.2 3.1	2.9 3.2	3.2	2.9	2.8						
As (total)	µg/L	19.2	13.8	11.2	17.7	4.7	2.5						
As (total soluble)	µg/L												
As (particulate)	µg/L												
As (III)	µg/L												
As (V)	µg/L												
Total Al	µg/L	128	473	87.5	137	509	42.3						
Total Fe	µg/L	52.9	<30	<30	48.5	<30	<30						
Total Mn	µg/L	15.9	4.7	0.6	16.0	6.6	<0.5						
Dissolved Al	µg/L												
Dissolved Fe	µg/L												
Dissolved Mn	µg/L												

(a) As CaCO<sub>3</sub>.  
(b) The plant stopped using polyaluminum chloride (PAX-18) since 12/15/98 a<0.1 uses alum instead.  
(c) No sampling due to Christmas holiday.  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table B-8. Analytical Results from Long Term Sampling, Plant B (January 7 to 28, 1999)**

Sampling Date		01/07/99			01/14/99			01/21/99			01/28/99		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	131	117	118	131	117	114	134	117	117	137	132	119
Turbidity	NTU	1.1	0.8	<0.1	1.6	0.8	<0.1	2.7	1.1	<0.1	1.3	0.8	<0.1
pH		8.1	7.4	7.3	8.3	7.4	7.4	8.3	7.4	7.4	8.3	7.4	7.4
TOC	mg/L	3.5	2.8	2.8	3.2	2.7	2.8	3.9	3.0	3.0	2.9	2.4	2.4
As (total)	µg/L	15.3	4.8	2.3	21.0	6.2	1.9	16.5	5.5	1.6	18.0	5.3	1.6
As (total soluble)	µg/L				20.1	5.8	1.8						
As (particulate)	µg/L				21.0	2.3	2.3						
As (III)	µg/L				<0.1	3.9	<0.1						
As (V)	µg/L				<0.1	3.5	<0.1						
Total Al	µg/L	43.4	481	35.0	70.6	700	49.2	133	629	43.1	66.5	660	40.9
Total Fe	µg/L	82.3	43.9	<30	47.2	681	48.0	142	<30	<30	79.8	32.5	<30
Total Mn	µg/L	13.8	8.0	<0.5	13.5	5.2	1.0	13.7	4.9	0.6	13.4	18.2	0.7
Dissolved Al	µg/L				13.4	5.3	1.1						
Dissolved Fe	µg/L				<11	72.7	40.8						
Dissolved Mn	µg/L				<30	<30	<30						
					2.0	3.8	<0.5						
					1.6	3.7	<0.5						

(a) As CaCO<sub>3</sub>.

IN = inlet; PF = prefiltration; AF = after filtration.

Table B-9. Analytical Results from Long Term Sampling, Plant B (Feb 4 to Feb 25, 1999)

Sampling Date		02/04/99			02/11/99			02/18/99			02/25/99		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	136	121	117	136	118	119	134 135	118 118	118 110	134	120	118
Turbidity	NTU	3.4	1.1	<0.1	1.8	0.9	<0.1	2.8 2.8	1.0 1.0	<0.1 <0.1	2.6	0.7	<0.1
pH		8.3	7.5	7.4	8.3	7.5	7.5	8.4 8.4	7.5 7.5	7.5 7.5	8.4	7.5	7.4
TOC	mg/L	3.1	2.7	2.5	3.2	2.4	2.5	3.0 3.3	2.6 2.7	2.5 2.6	3.5	3.4	3.7
As (total)	µg/L	19.4	5.2	1.7	18.9 18.4	6.5 6.3	2.0 2.0	15.0	4.7	1.5	19.2	5.7	2.6
As (total soluble)	µg/L				20.1 20.9	2.2 2.1	2.2 2.2						
As (particulate)	µg/L				<0.1 <0.1	4.3 4.2	<0.1 <0.1						
As (III)	µg/L				0.3 0.3	0.2 0.2	0.3 0.3						
As (V)	µg/L				19.8 20.6	2.0 1.9	1.9 1.9						
Total Al	µg/L	141	591	41.4	99.1 95.4	597 606	43.8 37.5	88.3	506	28.9	104	470	44.1
Total Fe	µg/L	180	<30	<30	120 112	32.2 <30	<30 <30	96.9	<30	<30	152	30.9	<30
Total Mn	µg/L	14.5	10.9	<0.5	11.0 11.0	7.9 7.4	<0.5 <0.5	11.7	6.5	0.6	16.1	13.8	<0.5
Dissolved Al	µg/L				<11 <11	66.3 67.1	30.6 29.9						
Dissolved Fe	µg/L				<30 <30	<30 <30	<30 <30						
Dissolved Mn	µg/L				2.1 1.9	5.0 5.1	<0.5 <0.5						

(a) As CaCO<sub>3</sub>,  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table B-10. Analytical Results from Long Term Sampling, Plant B (Mar 4 to Mar 25, 1999)**

Sampling Date		03/04/99			03/11/99			03/18/99			03/25/99		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	131	119	122	138	122	122	136 137	123 122	123 123	138	123	123
Turbidity	NTU	1.7	0.8	<0.1	1.5	0.8	<0.1	3.1 3.0	0.9 0.9	<0.1 <0.1	4.5	1.1	<0.1
pH		8.4	7.4	7.5	8.4	7.5	7.5	8.4 8.4	7.5 7.5	7.5 7.5	8.5	7.5	7.5
TOC	mg/L	4.7	2.8	2.8	3.0	2.6	2.5	3.0 3.4	2.8 2.7	2.8 2.8	3.2	2.8	3.2
As (total)	µg/L	20.8	6.6	3.1	21.5 20.6	7.4 7.4	3.2 3.2	20.2	6.6	3.3	21.4	8.6	3.9
As (total soluble)	µg/L				20.9 20.8	3.6 3.8	3.6 3.7						
As (particulate)	µg/L				0.6 <0.1	3.8 3.6	<0.1 <0.1						
As (III)	µg/L				0.7 0.6	0.5 0.5	0.6 0.6						
As (V)	µg/L				20.2 20.2	3.1 3.3	3.0 3.1						
Total Al	µg/L	107	478	48.5	110 91.4	599 593	44.9 39.6	101	614	55.4	314	710	60.5
Total Fe	µg/L	137	<30	<30	83.2 79.1	<30 <30	<30 <30	118	<30	<30	326	<30	<30
Total Mn	µg/L	16.5	7.8	0.5	15.8 14.7	8.6 8.9	<0.5 <0.5	20.9	12.1	5.8	32.5	17.0	1.9
Dissolved Al	µg/L				<11 <11	59.3 57.8	29.9 33.8						
Dissolved Fe	µg/L				<30 <30	<30 <30	<30 <30						
Dissolved Mn	µg/L				3.2 3.2	5.9 5.9	<0.5 <0.5						

(a) As CaCO<sub>3</sub>.

IN = inlet; PF = prefiltration; AF = after filtration.

Table B-11. Analytical Results from Long Term Sampling, Plant B (Apr 1 to Apr 22, 1999)

Sampling Date		04/01/99			04/08/99			04/15/99			04/22/99		
Sampling Parameter	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	141	124	125	142	127	125	142	126	123	142	124	121
Turbidity	NTU	2.9	0.8	<0.1	3.5	0.6	<0.1	1.4	0.6	<0.1	2.0	0.6	<0.1
pH		8.5	7.5	7.5	8.4	7.5	7.5	8.4	7.5	7.4	8.3	7.4	7.4
TOC	mg/L	3.2	3.4	3.1	3.6	2.9	2.6	3.3	2.9	3.0	3.6	3.1	2.6
As (total)	µg/L	21.3	6.2	3.9	22.4	6.5	4.7	21.8	6.2	4.1	22.8	5.9	3.8
As (total soluble)	µg/L				22.0	6.2	4.6						
As (particulate)	µg/L				21.8	4.5	4.5						
As (III)	µg/L				0.6	2.0	0.2						
As (IV)	µg/L				0.3	2.1	0.1						
Total Al	µg/L	159	493	42.4	171	431	47.6	87.0	400	39.9	153	499	47.9
Total Fe	µg/L	150	33.8	<30	137	420	45.3	74.2	<30	<30	105	<30	<30
Total Mn	µg/L	20.3	9.3	<0.5	158	10.9	0.7	23.0	8.0	0.7	23.5	10.3	0.5
Dissolved Al	µg/L				113	10.5	0.7						
Dissolved Fe	µg/L				<11	73.7	29.5						
Dissolved Mn	µg/L				<30	<30	<30						
					7.4	7.5	<0.5						
					7.6	7.1	<0.5						

(a) As CaCO<sub>3</sub>  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table B-12. Analytical Results from Long Term Sampling, Plant B (Apr 29 to May 20, 1999)**

Sampling Date		04/29/99			05/06/99			05/13/99			05/20/99		
Parameter	Sampling Location Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	140	122	120	140	121	119	137 140	121 120	118 118	139	122	119
Turbidity	NTU	3.3	0.6	<0.1	2.7	0.6	<0.1	1.2 1.2	0.3 0.3	<0.1 <0.1	2.4	0.9	<0.1
pH		8.4	7.4	7.4	8.4	7.4	7.4	8.6 8.6	7.4 7.4	7.4 7.4	8.6	7.4	7.4
TOC	mg/L	2.8	2.3	2.3	4.6	3.2	3.1	3.5 3.2	3.0 3.0	2.6 3.2	9.8	8.6	8.7
As (total)	µg/L	20.9	6.1	4.1	22.7 22.1	6.0 6.0	3.8 3.8	23.9	5.7	3.4	23.5	7.0	3.9
As (total soluble)	µg/L				23.1 23.0	3.7 3.7	3.8 3.8						
As (particulate)	µg/L				<0.1 <0.1	2.3 2.3	<0.1 <0.1						
As (III)	µg/L				1.2 1.3	1.3 1.2	0.8 0.9						
As (V)	µg/L				21.9 21.7	2.4 2.5	3.0 2.9						
Total Al	µg/L	167	370	38.7	88.9 75.9	464 462	34.9 34.0	100	406	36.3	136	603	52.5
Total Fe	µg/L	162	<30	<30	109 87.9	<30 <30	<30 <30	102	<30	<30	135	<30	<30
Total Mn	µg/L	23.2	8.1	1.1	14.7 14.6	5.9 5.9	0.5 0.5	20.5	5.6	0.5	18.3	6.2	<0.5
Dissolved Al	µg/L				<11 <11	53.7 52.0	30.8 32.9						
Dissolved Fe	µg/L				<30 <30	<30 <30	<30 <30						
Dissolved Mn	µg/L				3.7 3.8	3.5 3.5	<0.5 <0.5						

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

Table B-13. Analytical Results from Long Term Sampling, Plant B (May 27 to June 17, 1999)

Sampling Date		05/27/99			06/03/99			06/10/99			06/17/99		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	136	116	116	134	112	112	138 137	115 116	115 114	136	111	111
Turbidity	NTU	3.6	1.1	<0.1	3.8	0.6	<0.1	5.5 5.7	0.5 0.5	<0.1 <0.1	6.6	0.7	<0.1
pH		8.5	7.3	7.3	8.3	7.3	7.3	8.4 8.4	7.3 7.3	7.2 7.2	8.4	7.2	7.2
TOC	mg/L	3.3	2.7	3.2	3.6	2.8	2.9	3.0 4.7	2.5 2.8	2.6 2.7	3.6	3.2	3.2
As (total)	µg/L	21.1	6.2	3.8	20.8 20.4	3.7 3.7	2.8 2.7	21.7	3.8	2.4	23.1	4.2	2.5
As (total soluble)	µg/L				21.5 20.7	2.7 2.7	2.7 2.7						
As (particulate)	µg/L				<0.1 <0.1	1.0 1.0	0.1 <0.1						
As (III)	µg/L				0.8 0.7	0.4 0.4	0.3 0.3						
As (V)	µg/L				20.8 20.0	2.3 2.3	2.4 2.3						
Total Al	µg/L	180	658	58.8	205 167	296 291	28.4 27.8	409	362	37.2	366	442	43.7
Total Fe	µg/L	167	35.7	30.8	185 175	37.3 32.8	<30 <30	379	<30	17.9	437	18.8	<30
Total Mn	µg/L	20.5	7.0	0.5	20.8 20.3	13.0 6.9	<0.5 <0.5	25.7	5.6	<0.5	36.0	8.9	<0.5
Dissolved Al	µg/L				<11 <11	41.4 42.1	26.2 25.2						
Dissolved Fe	µg/L				<30 <30	<30 <30	<30 <30						
Dissolved Mn	µg/L				7.5 7.4	4.5 5.1	<0.5 <0.5						

(a) As CaCO<sub>3</sub>  
IN = inlet; PF = prefiltration; AF = after filtration.



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## **APPENDIX C**

### **Complete Analytical Results from Long-Term Sampling at Plant C**

Table C-1. Analytical Results from Long-Term Sampling, Plant C (June 22 to July 13, 1998)

Sampling Date		6/22/98			6/23/98			7/6/98			7/13/98		
Parameter	Sampling Location Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	388	232	199	394	239	175	400	382	193	392	136	183
Turbidity	NTU	23.2	6.3	1.6	16.1	7.6	0.6	29.0	18.3	0.8	16.3	3.3	0.4
pH		7.4	8.7	8.8	7.3	8.7	9.0	7.2	8.1	8.8	7.2	10.1	9.0
Total Hardness	mg/L <sup>(a)</sup>	320	158	189	296	244	143	293	304	148	296	89.1	136
Ca Hardness	mg/L <sup>(a)</sup>	200	56.0	72.0	180	132	45.0	177	180	51.0	180	27.7	42.9
Mg Hardness	mg/L <sup>(a)</sup>	120	102	118	117	112	98.0	115	124	96.8	116	61.4	93.1
As (total)	µg/L	42.5	27.8	21.7	26.7	23.9	19.8	34.0	22.9	17.6	25.7	16.8	17.2
As (total soluble)	µg/L										27.9	16.6	17.0
As (particulate)	µg/L										35.5	17.4	18.8
As (III)	µg/L										35.4	17.3	19.2
As (IV)	µg/L										<0.1	<0.1	<0.1
Total Al	µg/L	<11	28.5	17.0	<11	41.8	13.4	11.5	46.2	17.2	43.6	24.9	12.4
Total Fe	µg/L	2,217	258	64.9	1,155	401	<30	1,828	742	<30	1,571	81.4	<30
Total Mn	µg/L	117	7.1	4.4	103	12.8	3.7	101	48.9	2.9	114	3.7	2.0
Dissolved Al	µg/L										129	3.5	2.1
Dissolved Fe	µg/L										<11	11.3	<11
Dissolved Mn	µg/L										<11	<11	<11
											1,506	<30	<30
											1,518	<30	<30
											108	<0.5	1.4
											105	<0.5	1.4

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table C-2. Analytical Results from Long Term Sampling, Plant C (July 20 to August 10, 1998)**

Sampling Date		7/20/98			7/28/98			8/3/98			8/10/98		
Parameter	Sampling Location Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	392 394	224 222	147 146	397	229	194	393	204	168	400 399	247 246	184 182
Turbidity	NTU	31.0 30.0	5.1 4.9	0.3 0.3	18.8	5.8	0.6	29.0	3.1	0.5	31.0 31.0	26.0 25.0	0.2 0.2
pH		7.3 7.2	8.6 8.6	9.2 9.2	7.2	8.5	8.6	7.4	9.0	9.0	7.3 7.3	8.7 8.7	8.8 8.8
Total Hardness	mg/L <sup>(a)</sup>	321 298	176 181	112 108	350	206	174	320	169	138	314 305	215 221	149 147
Ca Hardness	mg/L <sup>(a)</sup>	202 185	62.7 66.9	31.7 31.0	217	82.4	56.4	195	54.2	36.2	192 187	103 107	47.2 45.7
Mg Hardness	mg/L <sup>(a)</sup>	119 113	113 114	79.9 77.4	133	124	117.4	125	115	102	122 117	112 115	102 101
As (total)	µg/L	37.1	28.5	19.3	38.6	29.2	20.8	33.6 37.3	29.0 28.7	20.9 20.6	35.7	28.1	19.4
As (total soluble)	µg/L							41.0 39.8	30.3 30.7	22.4 22.7			
As (particulate)	µg/L							<0.1 <0.1	<0.1 <0.1	<0.1 <0.1			
As (III)	µg/L							32.5 34.1	17.9 17.8	0.4 0.4			
As (V)	µg/L							8.5 5.7	12.4 12.9	22.0 22.3			
Total Al	µg/L	38.3	31.4	12.9	11.2	40.2	15.4	<11 23.4	43.0 38.9	22.6 16.0	<11	47.6	16.1
Total Fe	µg/L	1,879	205	<30	2,066	359	<30	1,934 2,092	322 337	34.6 31.6	2,173	704	<30
Total Mn	µg/L	106	4.6	1.0	104	7.7	3.2	98.7 105	7.1 7.1	1.8 1.7	101	18.4	3.3
Dissolved Al	µg/L							<11 <11	14.7 15.3	<11 <11			
Dissolved Fe	µg/L							2,382 2,157	<30 <30	<30 <30			
Dissolved Mn	µg/L							126 120	1.4 1.4	0.9 0.9			

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

Table C-3. Analytical Results from Long Term Sampling, Plant C (August 17 to September 8, 1998)

Sampling Date		8/17/98			8/25/98			8/31/98			9/8/98		
Sampling Parameter	Sampling Location Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	394	181	177	400	235	195	398	225	189	403	189	184
Turbidity	NTU	33.0	25.0	0.2	31	8.4	0.2	32.0	11.3	1.9	30.0	5.7	183
pH		7.2	9.6	8.8	7.3	8.4	8.4	7.2	8.7	8.5	7.2	9.0	0.3
Total Hardness	mg/L <sup>(a)</sup>	317	175	151	324	202	158	322	194	157	341	157	155
Ca Hardness	mg/L <sup>(a)</sup>	192	73.7	43.9	197	82.2	43.7	200	85.4	50.9	212	44.9	43.4
Mg Hardness	mg/L <sup>(a)</sup>	124	101	108	126	119	114	123	109	106	129	112	53.4
As (total)	µg/L	33.2	24.2	18.3	19.4	28.2	17.3	31.5	25.5	18.7	28.7	21.9	15.9
As (total soluble)	µg/L							31.9	25.6	18.7			
As (particulate)	µg/L							35.9	24.5	18.7			
As (III)	µg/L							37.5	26.2	17.8			
As (V)	µg/L							<0.1	1.0	<0.1			
Total Al	µg/L	11.7	50.4	13.8	22.1	57.5	23.0	<0.1	<0.1	0.9			
Total Fe	µg/L	2,597	587	<30	91.5	458	235	26.1	1.0	0.7	<11	32.6	17.8
Total Mn	µg/L	129	15.8	1.8	121	11.5	2.3	26.7	1.0	0.7	1,989	269	<30
Dissolved Al	µg/L							9.8	23.5	18.0	108	5.1	1.5
Dissolved Fe	µg/L							10.8	25.2	17.1			
Dissolved Mn	µg/L							15.5	48.0	35.9			
								12.7	46.5	29.8			
								2,279	661	253			
								2,310	644	255			
								117	16.1	6.6			
								118	15.0	6.7			
								<11	22.7	<11			
								<11	22.7	<11			
								2,224	<30	<30			
								2,239	<30	<30			
								122	5.0	2.0			
								120	5.0	1.9			

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table C-4. Analytical Results from Long Term Sampling, Plant C (September 14 to October 5, 1998)**

Sampling Date		9/14/98			9/21/98			9/28/98			10/5/98		
Parameter	Sampling Location Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	410	197	214	404	252	209	397	216	212	403 404	201 199	197 197
Turbidity	NTU	27	11.1	0.2	26.0	4.2	0.6	28.0	18.0	0.5	27.0 26.0	9.7 10.0	1.2 1.2
pH		7.1	8.8	8.3	7.2	8.0	8.1	7.3	9.0	8.4	7.3 7.3	9.1 9.2	8.5 8.5
Total Hardness	mg/L	290	178	173	311	214	176	267	183	183	316 317	163 152	164 164
Ca Hardness	mg/L	170	69.2	61.7	190	95.6	66.4	167	73.4	68.4	195 195	52.7 44.7	54.4 53.4
Mg Hardness	mg/L	120	109	112	122	119	110	99.2	110	115	122 122	110 107	110 111
As (total)	µg/L	16.2	20.2	13.1	28.9	21.6	14.0	35.0 36.8	28.8 28.8	17.5 17.9	28.0	20.6	14.9
As (total soluble)	µg/L							36.0 35.7	26.8 26.8	16.3 16.9			
As (particulate)	µg/L							<0.1 1.1	2.0 2.0	1.2 1.0			
As (III)	µg/L							34.0 33.7	0.7 0.7	0.7 0.7			
As (V)	µg/L							2.0 2.0	26.1 26.1	15.6 16.2			
Total Al	µg/L	<11	50.0	22.2	<11	27.7	31.8	<11 <11	44.9 41.9	15.9 21.0	<11	28.7	18.7
Total Fe	µg/L	1,498	473	<30	2,229	206	161	2,218 2,331	313 312	34.2 35.4	1,967	273	58.1
Total Mn	µg/L	75.9	10.6	2.7	114	11.9	7.1	111 116	12.2 12.2	3.1 3.1	109	6.2	3.6
Dissolved Al	µg/L							<11 <11	16.4 16.4	<11 <11			
Dissolved Fe	µg/L							2,003 1,780	<30 <30	<30 <30			
Dissolved Mn	µg/L							106 107	0.9 0.9	1.6 1.6			

(a) As CaCO<sub>3</sub>  
IN = inlet; PF = prefiltration; AF = outlet.

Table C-5. Analytical Results from Long Term Sampling, Plant C (October 12 to November 2, 1998)

Sampling Date		10/12/98			10/19/98			10/26/98			11/2/98		
Sampling Location	Parameter	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	405	274	173	401	184	212	404	211	251	397 398	228 229	202 203
Turbidity	NTU	18.3	5.7	1.1	25.0	7.1	0.8	26.0	6.1	0.4	22.0 24.0	6.8 6.5	0.1 0.1
pH		7.1	8.2	8.8	7.2	9.0	8.4	7.2	8.6	8.1	7.2 7.2	8.2 8.2	8.5 8.5
Total Hardness	mg/L <sup>(a)</sup>	325	225	149	328	140	174	327	169	216	321 325	186 186	163 170
Ca Hardness	mg/L <sup>(a)</sup>	205	83.9	45.2	205	40.0	66.7	205	52.9	100	202 202	66.7 67.4	50.2 59.2
Mg Hardness	mg/L <sup>(a)</sup>	120	141	103	124	101	108	122	117	116	119 123	119 118	113 111
As (total)	µg/L	26.4	17.6	13.1	26.0	21.4	12.3	29.0 28.5	22.1 21.4	12.8 12.3	31.6	23.3	18.2
As (total soluble)	µg/L							33.1 32.7	24.6 26.0	15.2 15.0			
As (particulate)	µg/L							<0.1 <0.1	<0.1 <0.1	<0.1 <0.1			
As (III)	µg/L							28.4 <sup>(b)</sup> 28.9 <sup>(b)</sup>	0.4 0.2	<0.1 <0.1			
As (V)	µg/L							4.7 3.8	24.2 25.8	15.2 15.0			
Total Al	µg/L	<11	17.2	20.3	16.0	28.5	14.0	<11 <11	40.2 46.1	15.1 14.2	<11	33.1	<11
Total Fe	µg/L	2,785	145	56.3	3,768	295	<30	2,386 2,373	285 301	96.5 40.0	2,385	159	<30
Total Mn	µg/L	145	7.3	2.7	204	6.5	1.9	154 154	6.5 6.4	5.9 5.7	147	7.0	2.1
Dissolved Al	µg/L							<11 <11	23.0 23.1	<11 <11			
Dissolved Fe	µg/L							2,316 2,115	<30 <30	<30 <30			
Dissolved Mn	µg/L							148 145	1.8 1.8	4.7 4.6			

(a) As CaCO<sub>3</sub>.

(b) Filtered data.

IN = inlet; PF = prefiltration; AF = after filtration.

**Table C-6. Analytical Results from Long Term Sampling, Plant C (November 9 to November 30, 1998)**

Sampling Date		11/9/98			11/16/98			11/23/98 <sup>(a)</sup>			11/30/98		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	403	267	194	403	125	181				399	201	153
Turbidity	NTU	28	1.5	<0.1	24	11.3	0.2				25	2.8	0.3
pH		7.1	8.0	8.4	7.2	10.1	8.9				7.2	8.6	8.9
Total Hardness	mg/L <sup>(a)</sup>	336	226	170	346	85	150				330	161	129
Ca Hardness	mg/L <sup>(a)</sup>	212	99.6	55.4	225	35.7	46.7				207	42.9	32.7
Mg Hardness	mg/L <sup>(a)</sup>	124	126	115	122	49.4	103				123	118	96.4
As (total)	µg/L	34.5	26.0	16.9	32.3	14.2	14.7				31.4	23.4	15.6
As (total soluble)	µg/L										30.5	24.0	15.7
As (particulate)	µg/L										33.7	25.6	17.9
As (III)	µg/L										33.4	25.9	17.6
As (V)	µg/L										<0.1	<0.1	<0.1
	µg/L										<0.1	<0.1	<0.1
	µg/L										29.7	0.3	0.2
	µg/L										30.8	0.2	0.2
	µg/L										4.0	25.3	17.7
	µg/L										2.6	25.7	17.4
Total Al	µg/L	<11	42.7	12.9	<11	35.6	17.8				<11	16.4	19.1
Total Fe	µg/L	2,680	159	35.3	2,704	119	<30				19.6	18.7	21.8
Total Mn	µg/L	164	12.1	2.4	146	5.0	1.0				2,600	270	61.5
	µg/L										2,585	268	56.3
Dissolved Al	µg/L										150	4.8	1.6
Dissolved Fe	µg/L										149	4.9	1.6
Dissolved Mn	µg/L										<11	<11	<11
	µg/L										<11	<11	<11
	µg/L										2,495	<30	<30
	µg/L										2,458	<30	<30
	µg/L										147	1.9	0.9
	µg/L										147	1.9	0.8

(a) As CaCO<sub>3</sub>.

(b) No sampling due to the Thanksgiving Holiday  
IN = inlet; PF = prefiltration; AF = after filtration.

Table C-7. Analytical Results from Long Term Sampling, Plant C (December 7, 1998 to December 28, 1998)

Sampling Date		12/7/98			12/14/98			12/21/98 <sup>a</sup>			12/28/98 <sup>a</sup>		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	396	173	205	408	143	188						
		398	174	204									
Turbidity	NTU	27	9.2	0.3	18.6	20	1.2						
		26	9.1	0.4									
pH		7.3	9.7	8.3	7.2	10.1	8.8						
		7.2	9.7	8.3									
Total Hardness	mg/L <sup>(a)</sup>	320	133	168	335	147	157						
		314	133	167									
Ca Hardness	mg/L <sup>(a)</sup>	200	44.9	58.9	212	77.2	44.4						
		195	44.7	58.9									
Mg Hardness	mg/L <sup>(a)</sup>	121	88.5	109	123	69.6	113						
		119	88.1	108									
As (total)	µg/L	32.7	22.6	17.3	32.4	16.5	16.0						
As (total soluble)	µg/L												
As (particulate)	µg/L												
As (III)	µg/L												
As (V)	µg/L												
Total Al	µg/L	<11	41.1	12.6	<11	29.4	11.1						
Total Fe	µg/L	2,756	376	<30	2,774	220	<30						
Total Mn	µg/L	159	10.9	2.9	177	4.8	1.1						
Dissolved Al	µg/L												
Dissolved Fe	µg/L												
Dissolved Mn	µg/L												

(a) As CaCO<sub>3</sub>.

(b) No sampling due to Christmas Holiday.

IN = inlet; PF = prefiltration; AF = after filtration.



**Table C-8. Analytical Results from Long Term Sampling, Plant C (January 4 to January 25, 1999)**

Sampling Date		01/04/99			01/11/99			01/18/99			01/25/99		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	391	195	217	407	228	195	400	231	187	402	236	192
Turbidity	NTU	21	0.7	0.7	29	11.6	0.3	22	16.8	0.9	29	5.6	0.7
pH		7.1	9.0	8.5	7.2	8.5	8.4	7.2	8.7	8.5	7.2	8.8	8.8
Total Hardness	mg/L <sup>(a)</sup>	318	166	180	352	190	159	342	188	154	303	170	149
Ca Hardness	mg/L <sup>(a)</sup>	200	61.4	66.7	232	78.4	52.2	215	76.9	42.4	185	57.2	38.7
Mg Hardness	mg/L <sup>(a)</sup>	119	105	113	120	111	107	127	111	112	118	113	110
As (total)	µg/L	41.1	32.6	18.9	33.5	21.0	13.5	33.5	21.0	13.5	30.3	25.5	17.6
As (total soluble)	µg/L				29.7	22.1	15.2						
As (particulate)	µg/L				3.8	<0.1	<0.1						
As (III)	µg/L				26.9	0.3	0.3						
As (V)	µg/L				27.1	0.3	0.2						
Total Al	µg/L	<11	58.1	20.0	<11	55.6	19.6	<11	71.9	13.4	<11	29.9	11.6
Total Fe	µg/L	2,920	613	211	2,596	490	<30	2,134	617	53.0	2,322	403	50.6
Total Mn	µg/L	156	13.3	6.6	132	9.5	3.9	118	14.8	2.4	128	7.4	1.7
Dissolved Al	µg/L				<11	32.1	<11						
Dissolved Fe	µg/L				2,426	<30	<30						
Dissolved Mn	µg/L				181	2.7	1.8						

(a) As CaCO<sub>3</sub>.

IN = inlet; PF = prefiltration; AF = after filtration.

Table C-9. Analytical Results from Long Term Sampling, Plant C (February 1, 1999 to February 22, 1999)

Sampling Date		02/01/99			02/08/99			02/15/99			02/22/99		
Parameter	Sampling Location Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	411	181	193	399	196	210	399	222	212	405	237	193
Turbidity	NTU	23	6.5	0.6	24	3.3	0.7	25	8.1	1.0	24	9.3	0.5
pH		7.2	9.2	8.7	7.2	8.6	8.3	7.2	8.8	8.4	7.3	8.6	8.4
Total Hardness	mg/L <sup>(a)</sup>	353	160	157	338	157	174	323	187	184	317	183	153
Ca Hardness	mg/L <sup>(a)</sup>	225	55.2	46.4	207	44.9	58.2	207	75.7	69.2	197	75.9	42.9
Mg Hardness	mg/L <sup>(a)</sup>	128	105	111	123	112	116	115	111	115	119	108	110
As (total)	µg/L	19.1	14.6	11.7	20.9	16.3	12.1	33.4	26.2	17.0	20.4	17.0	11.2
As (total soluble)	µg/L				26.0	18.0	14.0						
As (particulate)	µg/L				23.4	17.6	13.9						
As (III)	µg/L				<0.1	<0.1	<0.1						
As (V)	µg/L				<0.1	<0.1	<0.1						
Total Al	µg/L	<11	67.7	98.8	40.7	138	17.3	<11	34.8	17.3	<11	61.0	11.9
Total Fe	µg/L	2,029	399	49.9	2,269	269	35.2	2,865	472	31.6	2,476	621	34.0
Total Mn	µg/L	136	8.9	1.9	185	6.0	4.0	166	13.9	4.0	178	16.0	2.6
Dissolved Al	µg/L				181	6.5	3.9						
Dissolved Fe	µg/L				<11	16.2	<11						
Dissolved Mn	µg/L				<11	16.1	<11						
					2,175	<30	<30						
					2,095	<30	<30						
					185	0.9	3.2						
					193	1.0	3.1						

(a) As CaCO<sub>3</sub>

IN = inlet; PF = prefiltration; AF = after filtration.

**Table C-10. Analytical Results from Long Term Sampling, Plant C (Mar 1, 1999 to Mar 22, 1999)**

Sampling Date		03/01/99			03/08/99			03/15/99			03/22/99		
Sampling Location	Parameter	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	405	157	185	408	253	211	394	192	321	405	218	200
Turbidity	NTU	23	7.2	0.1	25	18.1	0.4	31	6.4	24	27	5.8	0.3
pH		7.2	9.3	8.7	7.2	8.5	8.7	7.2	9.1	7.9	7.2	8.6	8.4
Total Hardness	mg/L <sup>(a)</sup>	328	142	143	325	225	183	331	155	291	326	178	187
Ca Hardness	mg/L <sup>(a)</sup>	207	59.2	44.2	200	105	71.9	210	49.9	165	205	63.2	67.4
Mg Hardness	mg/L <sup>(a)</sup>	121	82.4	98.8	125	120	111	121	105	126	122	115	120
As (total)	µg/L	21.9	13.5	13.7	23.9	17.1	11.6	36.3	28.4	17.3	21.7	17.4	33.1
As (total soluble)	µg/L				24.5	16.9	12.0						
As (particulate)	µg/L				22.1	18.3	14.4						
As (III)	µg/L				21.7	18.9	14.4						
As (V)	µg/L				1.8	<0.1	<0.1						
Total Al	µg/L	<11	41.6	17.7	<11	60.5	15.0	<11	44.8	84.8	<11	51.0	21.7
Total Fe	µg/L	2,536	346	<30	2,464	617	<30	2,901	401	1,110	2,501	378	<30
Total Mn	µg/L	169	13.8	2.4	151	26.1	4.2	148	21.4	54.7	166	9.7	6.7
Dissolved Al	µg/L				162	25.1	4.3						
Dissolved Fe	µg/L				<11	35.9	12.6						
Dissolved Mn	µg/L				<11	35.9	12.2						
					2,534	<30	<30						
					2,523	<30	<30						
					162	7.8	1.9						
					163	7.9	2.0						

(a) As CaCO<sub>3</sub>.  
IN = inlet; PF = prefiltration; AF = after filtration.

Table C-11. Analytical Results from Long Term Sampling, Plant C (Mar 29, 1999 to Apr 19, 1999)

Sampling Date		03/29/99			04/05/99			04/12/99			04/19/99		
Sampling Location	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	396	227	308	401	238	166	405	182	183	402	232	238
Turbidity	NTU	30	5.3	1.0	29	8.3	0.4	30	3.7	5.8	31	9.2	1.4
pH		7.2	8.6	7.8	7.3	8.5	9.3	7.2	9.3	8.8	7.2	8.6	8.8
Total Hardness	mg/L <sup>(a)</sup>	300	165	242	340	222	125	303	132	144	305	181	179
Ca Hardness	mg/L <sup>(a)</sup>	185	55.7	122	215	109	37.2	187	37.5	47.9	187	70.2	69.7
Mg Hardness	mg/L <sup>(a)</sup>	115	109	119	125	113	87.7	116	94.7	96.4	118	111	110
As (total)	µg/L	36.5	27.2	12.1	40.1	31.4	18.8	34.8	26.7	21.5	36.3	26.8	21.7
As (total soluble)	µg/L				39.2	30.8	18.2						
As (particulate)	µg/L				40.6	30.5	18.7						
As (III)	µg/L				<0.1	0.9	0.1						
As (IV)	µg/L				<0.1	<0.1	<0.1						
Total Al	µg/L	<11	40.5	17.9	<11	47.6	13.9	5.1	23.6	21.0	12.3	51.9	18.0
Total Fe	µg/L	2,571	273	63.6	2,518	451	<30	3,073	323	156	2,954	411	55.8
Total Mn	µg/L	147	6.2	22.8	140	11.1	1.4	177	7.2	8.7	168	12.8	6.6
Dissolved Al	µg/L				<11	23.5	<11						
Dissolved Fe	µg/L				<11	34.1	<11						
Dissolved Mn	µg/L				2,611	<30	<30						
					2,437	<30	<30						
					152	4.2	0.7						
					151	4.2	0.7						

(a) As CaCO<sub>3</sub>,  
IN = inlet; PF = prefiltration; AF = after filtration.

**Table C-12. Analytical Results from Long Term Sampling, Plant C (Apr 26, 1999 to May 17, 1999)**

Sampling Date		04/26/99				05/03/99				05/10/99				05/17/99			
Sampling Location	Unit	IN	PF	AF	IN	AR	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	410	210	193	404	403	223	194	293	225	212	409	188	190			
Turbidity	NTU	30.0	13.9	1.6	27.0	11.0	10.6	0.4	307	226	213	32	16.4	0.6			
pH		7.2	9.0	8.7	7.2	7.6	8.9	9.2	26	17.2	0.7	7.2	9.3	9.0			
									27	17.1	0.7	7.1					
Total Hardness	mg/L <sup>(a)</sup>	310	212	167	316	303	171	148	298	203	181	309	161	139			
Ca Hardness	mg/L <sup>(a)</sup>	195	109	63.9	197	187	59.7	41.9	299	198	185	200	66.7	43.9			
Mg Hardness	mg/L <sup>(a)</sup>	115	104	103	119	116	111	106	180	93.6	67.4	109	94.3	94.7			
As (total)	µg/L	84.9	25.8	16.0	40.4	43.5	30.2	17.2	182	91.4	71.4	40.9	30.2	22.4			
As (total soluble)	µg/L				39.4	36.7	32.4	16.8	118	109	114						
As (particulate)	µg/L				31.2	33.3	27.4	17.3	117	107	113						
As (III)	µg/L				9.2	10.2	2.8	<0.1									
As (V)	µg/L				5.5	3.1	5.2	<0.1									
Total Al	µg/L	20.8	52.1	15.0	<0.1	<11	25.5	11.4	33.9	28.5	0.9	32.1	77.8	13.5			
Total Fe	µg/L	2,435	663	<30	2,396	2,945	443	<30	<0.1	3.8	26.1	<11	57.6				
Total Mn	µg/L	135	18.6	3.2	2,318	3,684	410	<30	2,931	766	40.4	2,546	624	<30			
Dissolved Al	µg/L				134	139	9.6	2.2	156	23.7	4.1	143	17.3	3.6			
Dissolved Fe	µg/L				<11	<11	<11	<11									
Dissolved Mn	µg/L				<11	<11	<11	<11									
					2,485	891	<30	<30									
					2,456	1,017	<30	<30									
					136	134	2.1	0.9									
					134	132	2.1	1.1									

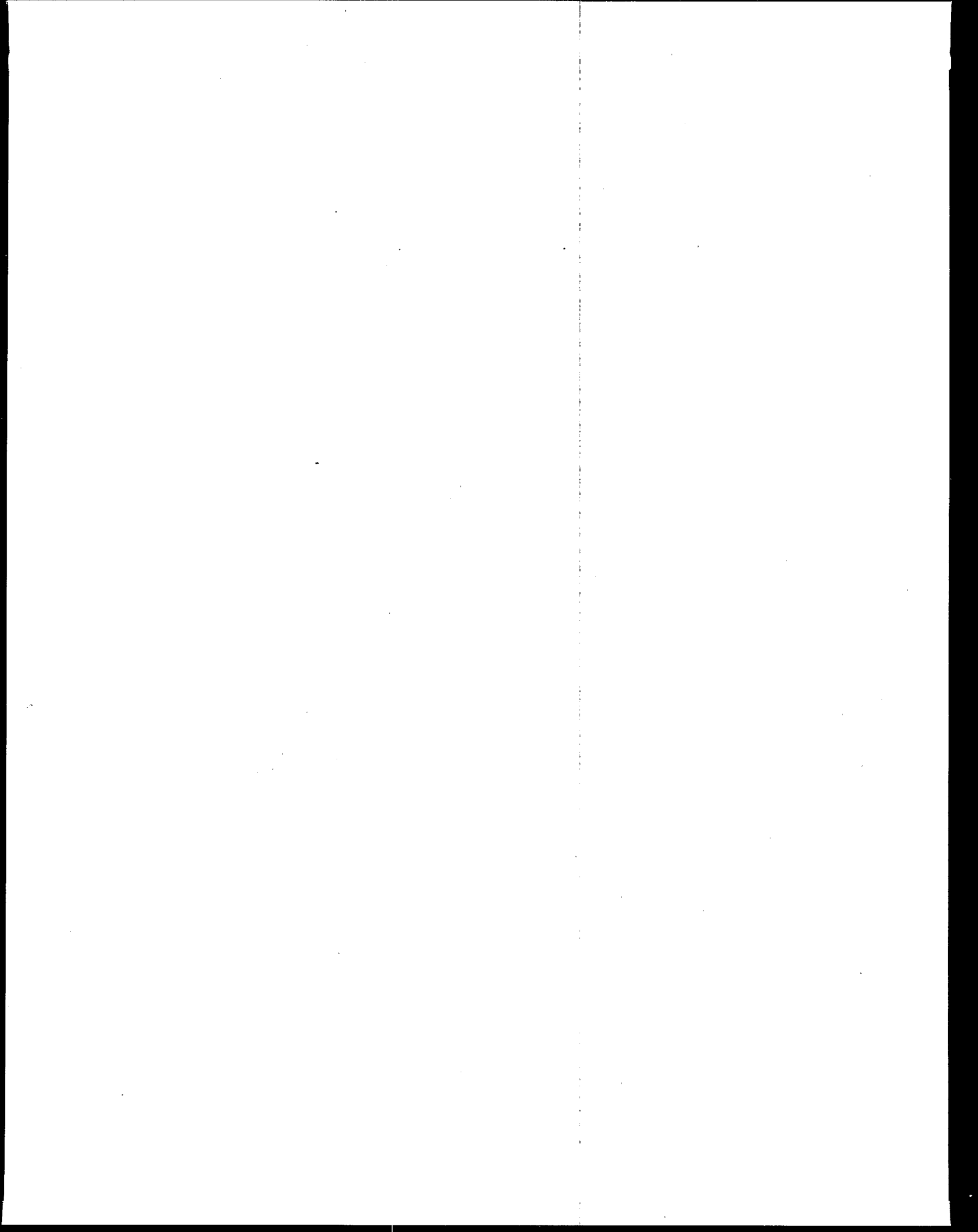
(a) As CaCO<sub>3</sub>.  
IN = inlet; AR = after-aeration; PF = prefiltration; AF = after filtration.

Table C-13. Analytical Results from Long Term Sampling, Plant C (May 24, 1999 to Jun 14, 1999)

Sampling Date		05/24/99			06/01/99			06/07/99			06/14/99		
Sampling Location	Unit	IN	PF	AF	IN	AR	PF	AF	IN	PF	IN	PF	AF
Alkalinity	mg/L <sup>(a)</sup>	406	248	189	402	399	178	192	400	169	411	242	184
Turbidity	NTU	27.0	18.2	0.5	31.0	8.3	10.2	0.6	31.0	14.2	23.0	13.1	0.4
pH		7.1	8.6	8.7	7.2	7.7	7.9	8.9	7.2	9.8	7.2	8.5	8.9
Total Hardness	mg/L <sup>(a)</sup>	300	187	146	303	296	172	153	327	145	327	220	151
Ca Hardness	mg/L <sup>(a)</sup>	187	73.7	45.7	190	185	83.9	54.2	220	68.4	207	110	51.2
Mg Hardness	mg/L <sup>(a)</sup>	112	113	100	113	112	88.5	98.4	108	77.0	120	110	100
As (total)	µg/L	35.1	27.4	18.5	38.4	36.3	26.6	16.3	39.0	24.5	16.5	7.7	6.3
As (total soluble)	µg/L				39.1	35.8	26.6	16.6					
As (particulate)	µg/L				40.8	36.1	22.9	17.2					
As (III)	µg/L				40.7	36.9	22.8	16.0					
As (V)	µg/L				<0.1	0.2	3.7	<0.1					
Total Al	µg/L	<11	36.8	13.0	<11	<11	19.0	11.3	48.8	43.6	<11	66.2	14.9
Total Fe	µg/L	2,872	220	<30	2,892	2,784	687	33.7	2,746	558	2,341	544	97.0
Total Mn	µg/L	178	12.7	1.7	173	177	21.6	2.5	142	17.7	147	34.0	1.3
Dissolved Al	µg/L				<11	<11	<11	<11					
Dissolved Fe	µg/L				2,964	462	<30	<30					
Dissolved Mn	µg/L				2,969	788	<30	<30					
					180	179	2.2	1.7					
					183	183	2.2	1.6					

(a) As CaCO<sub>3</sub>

IN = inlet; AR = after-aeration; PF = prefiltration; AF = after filtration.



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